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RESEARCH ARTICLE

Declining population trends of Hawaiian Petrel and Newell's Shearwater on the island of Kauaʻi, Hawaii, USA

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ABSTRACT
The island of Kauaʻi, Hawaii, USA, holds a large breeding populations of the endangered Hawaiian Petrel (*Pterodroma sandwichensis*) and a majority of the world population of the threatened Newell's Shearwater (*Puffinus newelli*). We evaluated island-wide population trends of both species. For Newell's Shearwaters, we considered radar counts at 13 sites between 1993 and 2013 and annual island-wide tallies of fledglings retrieved after being grounded by light attraction in 1979–2015 (Save Our Shearwaters [SOS] program). For Hawaiian Petrels, we considered radar counts alone. Radar data indicated a 78% decline overall in numbers of Hawaiian Petrels (at an average rate of ∼6% per year) and a 94% decline overall in numbers of Newell's Shearwaters (at an average rate of ∼13% per year) during the survey period. Most (92%) radar sites showed significant declines of Newell's Shearwaters across the entire survey period, as did 62% of sites for Hawaiian Petrels. The SOS recovery effort collected 30,522 Newell's Shearwater fledglings between 1979 and 2015. When we compared this dataset in pre- and post-Hurricane Iniki (September 1992) periods, we found a significant downward trend after Hurricane Iniki, similar to the trend seen in the radar data. The large-scale declines found in this study are not surprising, considering the significant threats facing both species on Kauaʻi, which include powerline collisions, light attraction, introduced predators, and habitat modification—threats which were potentially exacerbated after Hurricane Iniki. Improved conservation initiatives and an increased understanding of the various threats facing the 2 species are key to reversing these declines.

Keywords: seabird, Hawaiian Petrel, monitoring, Newell's Shearwater, population trends, radar

Tendencias poblacionales decrecientes para *Pterodroma sandwichensis* y *Puffinus newelli* en la Isla de Kauaʼi

RESUMEN
La isla de Kauaʼi alberga grandes poblaciones reproductivas de la especie en peligro *Pterodroma sandwichensis* y la mayoría de la población mundial de la especie amenazada *Puffinus newelli*. Evaluamos las tendencias poblacionales de dos maneras para ambas especies en toda la isla. Para *P. newelli*, consideramos los conteos de radar en 13 sitios entre 1993–2013 y recuentos anuales en toda la isla de volantones recuperados después de ser atraídos con luz a tierra entre 1979–2015 (Programa Salve Nuestras Pardelas [SNP]); para *P. sandwichensis*, consideramos solamente los conteos de radar. Los datos de radar indican una disminución global del 78% en el número de individuos de *P. sandwichensis* (a una tasa promedio anual de 6%) y una disminución global del 94% en el número de individuos de *P. newelli* (a una tasa promedio anual de 13%) durante el período de muestreo. La mayoría (92%) de los sitios de radar mostraron disminuciones significativas para *P. newelli* a lo largo de todo el período de muestreo, así como para el 62% de los sitios para *P. sandwichensis*. El esfuerzo de recuperación del programa SNP colectó 30,522 volantones de *P. newelli* entre 1979 y 2015. Cuando comparamos este set de datos entre los períodos previo y posterior al Huracán Iniki (septiembre 1992), encontramos una tendencia decreciente significativa luego del Huracán Iniki, similar a la tendencia vista en los datos de radar. Las disminuciones a gran escala encontradas en este estudio no son sorprendentes, considerando las amenazas significativas que enfrentan las especies en Kauaʼi, que incluyen colisiones con líneas eléctricas, atracción de la luz, depredadores introducidos y modificación del hábitat– amenazas que se han visto potencialmente exacerbadas luego del Huracán Iniki. Es fundamental contar con iniciativas de conservación mejoradas y con un mejor entendimiento de las múltiples amenazas que enfrentan las dos especies para revertir esta disminución.

Palabras clave: aves marinas, monitoreo, *Pterodroma sandwichensis*, *Puffinus newelli*, radar, tendencias poblacionales

INTRODUCTION

The Hawaiian island of Kaua'i holds internationally important populations of 2 endangered seabird species—the Hawaiian Petrel (*Pterodroma sandwichensis*; 'Ua'u in Hawaiian) and the Newell's Shearwater (*Puffinus newelli*; 'A'o in Hawaiian). The Newell's Shearwater was thought to be extinct until it was rediscovered in 1947, and was only confirmed to be breeding on Kaua'i 2 decades later, in 1967 (Sincock and Swedberg 1969). Kaua'i holds a significant proportion of the breeding population of the Hawaiian Petrel (Ainley et al. 1997) and the majority of the remaining breeding populations of Newell's Shearwater (Harrison 1990, Day and Cooper 1995, Spear et al. 1995).

Both species share threats common to Hawaiian birds, including collisions with powerlines (Cooper and Day 1998, Podolsky et al. 1998, Ainley et al. 2001, Travers et al. 2014); attraction of fledglings to artificial lights, where they then die after grounding due to predation, collisions with infrastructure, dehydration, and starvation (Reed et al. 1985, Telfer et al. 1987, Ainley et al. 1997, Cooper and Day 1998, Rodríguez et al. 2017); predation by introduced predators, particularly feral cats (*Felis cattus*), feral pigs (*Sus scrofa*), Barn Owls (*Tyto alba*), black rats (*Rattus rattus*), and Polynesian rats (*Rattus exulans*; Ainley et al. 2001, Hodges and Nagata 2001, Raine and Banfield 2015a, 2015b); diseases such as avian pox and avian malaria (Warner 1968, Simons 1985, VanderWerf and Young 2016); and habitat modification within breeding colonies due to invasive plants and pigs (Duffy 2010, VanZandt et al. 2014). These seabirds also undoubtedly face threats at sea that, while poorly known, are recognized to be important issues for similar species worldwide and could include marine pollution (Sileo et al. 1990, Derraik 2002), plastic ingestion (Kain et al. 2016), overfishing (Ainley et al. 2014), and the effects of climate change and fisheries bycatch (Gilman et al. 2008). Based on a combination of many of these factors, the Hawaiian Petrel is listed under the U.S. Endangered Species Act as Endangered and the Newell's Shearwater as Threatened (USFWS 1983). On the IUCN Red List, the Hawaiian Petrel is listed as Vulnerable (BirdLife International 2016a) and the Newell's Shearwater as Endangered (Birdlife International 2016b).

Most breeding colonies of both species are concentrated in areas that are remote and difficult to access, particularly in the northwestern section of Kaua'i (Ainley and Holmes 2011, Kaua'i Endangered Species Recovery Program [KESRP], http://kauaiseabirdproject.org/index.php/the-birds/). However, monitoring population trends is critical for an understanding of the current conservation needs of the 2 species and to assess whether the significant population declines of the Newell's Shearwater described between 1993 and 2001 (Day et al. 2003a) have continued. It is equally important to assess long-term population trends for the Hawaiian Petrel because recent genetic work has indicated strong genetic differentiation between populations on the islands of Hawaii and Kaua'i (Wiley et al. 2012), increasing the importance of understanding the population trends of this species at an island level. Remote nesting sites and nocturnal habits make it challenging to monitor these populations, but radar has proved to be a highly effective method (e.g., Day and Cooper 1995, Cooper and Day 2003, Day et al. 2003a, 2003b, Gauthreaux and Belser 2003, Burger et al. 2004, Cooper et al. 2006, Bertram et al. 2015). This technique also has been used extensively in the past for surveying both Hawaiian Petrels and Newell's Shearwaters on most of the southeastern Hawaiian Islands, including Kaua'i (Day and Cooper 1995, Reynolds et al. 1997, Cooper and Day 2003, Day et al. 2003a, 2003b, Swift and Burt-Toland 2009). Here, we combine radar data used by Day et al. (2003b) and more recent data from contemporary radar surveys to assess long-term trends for the 2 species on Kaua'i.

We also use a second, complementary dataset to assess long-term population trends of Newell's Shearwaters based on the "fallout" of fledglings collected over 37 yr by the "Save Our Shearwaters" (SOS) program on Kaua'i. The SOS is a citizen conservation program created by the State of Hawaii's Department of Land and Natural Resources, Division of Forestry and Wildlife, in 1979; its primary focus has been to collect and release seabirds grounded by light pollution, which fledgling Newell's Shearwaters are particularly affected by (Reed et al. 1985, Telfer et al. 1987, Ainley et al. 1997, Cooper and Day 1998). Hawaiian Petrels also are found by the project, but in such low numbers annually that they do not provide useful trend data.

The objectives of this study were threefold. First, we assessed whether the long-term population decline of the Newell's Shearwater found in previous studies continued in the following 2 decades. Second, we assessed whether the Hawaiian Petrel followed a similar declining trend on Kaua'i. These analyses update those presented in Ainley et al. (2001) and Day et al. (2003b). Finally, we used the most recent radar data collected to assess the contemporary distribution of the 2 species on the island, to allow us to focus future conservation planning and effort.

METHODS

Visual Sampling

We conducted visual sampling at 6 of the radar survey sites (Kekaha, Waimea, 'Ele'ele, Wailua, Kēālia, and Hanalei; Figure 1) in 2012 and 2013 to count and identify all birds passing overhead. Observers detected birds and, during daylight hours, used binoculars as needed for identification purposes. After dark, night-vision goggles (model PVS-7, Generation 3, 40° field of view, 1× magnification; U.S.

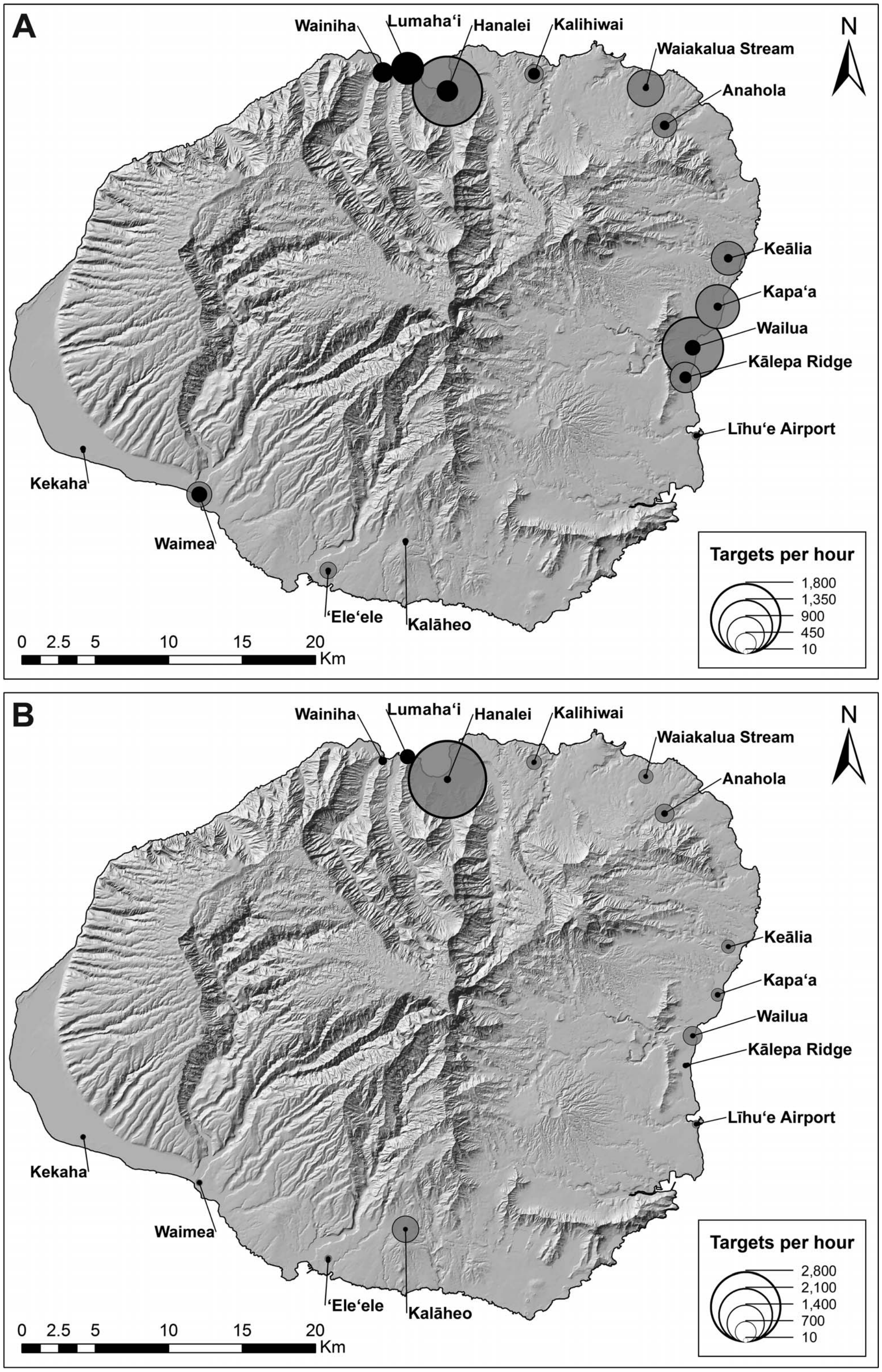

FIGURE 1. (**A**) Mean movement rate (targets hr^{-1}) of radar targets during session 2 (Hawaiian Petrel) recorded at each survey site on Kauaʻi Island, Hawaii, USA, in 1993 (gray circles) and 2013 (black circles). (**B**) Mean movement rates (targets hr^{-1}) of radar targets during sessions 3 and 4 combined (Newell's Shearwater) recorded at each survey site on Kauaʻi Island in 1993 (gray circles) and 2013 (black circles). See Figure 2 for explanation of radar sessions. Note that no data are available for Wainiha and Lumahaʻi in 1993. Contemporary breeding distributions of both species are now concentrated in the northwest of the island.

Night Vision, Roseville, California, USA) were used to identify and count birds passing overhead. Near-infrared illuminators (Raymax 300 Platinum; Raytec, Ashington, Northumberland, UK) were used to increase night-vision capabilities and helped to ensure consistent light levels and night-vision monitoring across sites and nights that varied in ambient light levels. We standardized the area sampled by only counting birds that flew between 2 measured points (adjacent power poles). All birds that flew between the poles were included, regardless of flight altitude (i.e. birds flying high, but between the poles, were also counted). The monitoring distance was deliberately kept narrow (100–200 m) so that observers could effectively monitor the entire airspace, regardless of light levels or optical tool being used, thus ensuring that detection distance was not biased toward daylight hours or a particular species. Visual surveys were conducted in the same manner as radar surveys (see below), starting 15 min before sunset and running for 2 hr, divided into 4 consecutive 30-min sampling sessions (sessions 1–4). Unlike the radar surveys, they were conducted continuously throughout the whole 2-hr period. Surveys were conducted by the same 3 observers in both years.

Birds were identified to species whenever possible by observers trained in identification techniques for all species likely to be found on Kaua'i. Birds were counted only if they were deemed to be in transit—that is, flying in a direct and steady route over a long distance (the same characteristics used for radar surveys). We did not count birds observed to take off or land. Species, time, and flight direction were noted using voice recorders to allow the visual observers to watch the sky continuously. We used these data to assess when peak movement rates occurred for Hawaiian Petrels and Newell's Shearwaters.

Radar Sampling

On Kaua'i, ornithological radar has been used to monitor the summer movement patterns of Hawaiian Petrels and Newell's Shearwaters at 13 sites since 1993 (Figure 1), with repeat surveys occurring in 1999–2001, 2004–2010, and 2012–2013. In 1999, we added 2 radar sites on the North Shore (Lumaha'i and Wainiha) to obtain more data from the northern part of the island, where some of the largest populations of these species remain (Ainley and Holmes 2011, http://kauaiseabirdproject.org/index.php/the-birds/, R. Day and B. Cooper personal observations). Following Day and Cooper (1995), radar sites were located at the mouths of all accessible major drainages around the island. The only area on Kaua'i that was not covered by these surveys was the northwestern part of the island (the Nāpali coast, where Newell's Shearwater colonies are known to exist; http://kauaiseabirdproject.org/index.php/the-birds/nesh-fact-sheet/), due to its inaccessibility to a truck-mounted radar unit.

Radar operation and target identification followed the protocol outlined in Day and Cooper (1995) and Day et al. (2003b). We used an FR1510MK3 radar unit (FURUNO, Camas, Washington, USA) mounted horizontally on top of a truck and tilted upward at an angle of 10°, with a 38.1-cm (15-in) radar screen inside the vehicle. This was an X-band radar transmitting at 9.410 GHz, with a peak power output of 12 kW (10 kW in 1993). The pulse setting was set to 0.07 μsec, the antenna spun at a rate of 24 rpm, and the range setting was 1.5 km.

Surveys were conducted each year from late May to mid-July. Based on burrow-monitoring data from colonies on Kaua'i, this period covered the egg laying, incubation, and early hatching stages of both species on the island (http://kauaiseabirdproject.org/index.php/the-birds/). Surveys prior to 2006 started at 1900 hours (typically 10–25 min before sunset). For analysis we recalculated these data from 15 min before sunset for 2 hr. Surveys from 2006 onward started 15 min prior to sunset, thus standardizing the 2-hr survey period to timing of sunset, avoiding bias associated with variability in available light. From 2006 onward, we also surveyed a subset of 7 of the 13 sites on 3 nonconsecutive nights to estimate among-night variation in movement rates; for these surveys, the average number of targets over the 3 surveys was used in regression analyses. Due to the 1-mo period in which all surveys had to be conducted, we could not survey all sites for 3 nights each.

Each survey consisted of 4 consecutive 30-min sampling sessions (sessions 1–4). We used the first 5 min of each sampling session to collect weather data, then counted targets for 25 min. Targets were recorded only when moving at a velocity $\geq$48 km hr^{-1}, which is the groundspeed of $>$99% of all Newell's Shearwaters and Hawaiian Petrels unless they are climbing steeply, and also excluded other bird species potentially flying in the area during the radar period (Day and Cooper 1995). For all targets recorded, we collected time, number of targets, cardinal transect crossed (north, south, east, west), flight direction (to the nearest 10°), minimum distance from the radar truck (to the nearest 100 m), velocity (to the nearest 8 km hr^{-1}), and flight behavior (straight-line, erratic, or circling; for examples of these flight behaviors, see Day et al. 2015:370). For analysis, we only included targets flying inland.

The only exceptions to this protocol were at the 3 northernmost sites (Hanalei, Lumaha'i, and Wainiha), where steep terrain lies immediately adjacent to the ocean. Here, visual observations have indicated that seabirds transiting over these areas need to gain elevation rapidly, and thus appear to fly more slowly than elsewhere on Kaua'i (Day and Cooper 1995, Ainley et al. 1997). At these sites, the projected speed on radar can sometimes appear to be $<$48 km hr^{-1} because the radar's 2-dimensional screen projects only horizontal distance covered and not total horizontal plus vertical distances combined. At these 3 sites, targets moving at 40 km hr^{-1} were also included when their behavior indicated that they were seabirds moving inland.

Clear plastic transparencies were overlaid on the radar screen, and major features of topography, radar shadows, and bird traffic were drawn in most years of radar surveys. These transparences were compared for all sites between the earlier surveys and surveys after 2006 to assess whether there were any significant changes in radar coverage that might have affected counts of targets. The only site where radar coverage changed was Hanalei, where the location of the survey site had to be moved to the east ~1.5 km because the original location eroded into the sea. To account for this change, the subsequent data collection strategy required using only half of the radar screen to ensure that only the portion of the original flyway covered in earlier surveys was sampled. To test any impact on results, we undertook analyses with and without the Hanalei site.

We did not survey when rain or other forms of clutter such as insects obscured potential radar targets (i.e. if >20% of the display screen was obscured for more than 1 min). During these conditions, we stopped surveys until conditions improved. If <10 min of sampling time (excluding the collection of weather data) was conducted between 15 and 45 min after sunset, we canceled the entire sampling session and returned the following day.

"Save Our Shearwaters" Data

The SOS program is a state-run project based at the Kaua'i Humane Society. The ongoing project collects and releases endangered seabirds and other bird species. The SOS program was initiated in 1979; thus, it represents a continuous dataset of 37 yr, with 30,552 fledgling Newell's Shearwaters collected to date. We used this second, independent dataset to assess long-term population trends of Newell's Shearwaters from fledglings collected annually. Adults are less attracted to lights on the coast (Ainley et al. 2001, Duffy 2010), and are only sporadically recovered by SOS. Likewise, too few Hawaiian Petrel fledglings or adults are collected every year to allow for any meaningful trend analysis.

Data Analyses

We conducted all statistical analyses with Excel 2013 (Microsoft, Redmond, Washington, USA) and SPSS Statistics 23 (IBM, Armonk, New York, USA).

For the radar data, we calculated linear regressions on log-transformed data to test for change in mean movement rates by year over the 20-yr period and for each site individually over the entire 20-yr period, and used paired *t*-tests to compare mean movement rates at each site between the first and last years of the study. We conducted linear regression analyses on log-transformed data with and without the Hanalei radar site. We also conducted the linear regression analysis with and without data from 1993, the year after Hurricane Iniki devastated Kaua'i. Day and Cooper (1995) and Day et al. (2003a) suggested that seabird populations may have had unusually high productivity in 1993 following the poor 1992 breeding season caused by the hurricane, potentially resulting in abnormally high numbers that year.

For the SOS data, we calculated linear regressions on log-transformed data to test for changes in the numbers of fledgling Newell's Shearwaters collected by the project every fallout season during 2 periods: (1) 1979 to 1991 (pre-Hurricane Iniki), and (2) 1992–2015 (post-Hurricane Iniki).

We present the slope for site-specific regressions by back-transforming the slope from regression equations. For all tests, we used $\alpha = 0.05$ for statistical significance. Means are presented ± sandard error (SE).

RESULTS

Visual Data

Observers recorded 1,279 birds during visual surveys between May and October of 2012 and 2013. Of these, 114 were identified as Hawaiian Petrels, 678 were Newell's Shearwaters, and 487 were nonseabird targets, including 347 Cattle Egrets (*Bubulcus ibis*), 124 songbirds of various species, and 16 Hawaiian Ducks (*Anas wyvilliana*). Bird movements during session 1 consisted primarily of non-seabird targets, which were the numerically dominant birds in the sky between 15 min before and 20 min after sunset; they composed 95% of all targets during session 1. No Hawaiian Petrels were observed prior to sunset, and only 6% and 14% of all Hawaiian Petrels were recorded by 10 and 15 min after sunset, respectively. No Newell's Shearwaters were observed prior to 20 min after sunset. By 21 min after sunset, all movement was numerically dominated by either Hawaiian Petrels or Newell's Shearwaters (Figure 2). Peak movement of Hawaiian Petrels was centered on the end of civil twilight (23 min after sunset), when the sun is 6° below the horizon, whereas the peak movement of Newell's Shearwaters was centered on nautical twilight (52 min after sunset), when the sun is 12° below the horizon.

We excluded session 1 data from further analysis because it contained mainly nontarget bird species and did not encompass the movement periods of petrel and shearwater targets, apart from the very end of that session, when Hawaiian Petrels began moving. Session 2 constituted the vast majority of Hawaiian Petrel targets and included the peak period of this species' inbound movements (with Newell's Shearwater movements beginning toward the end

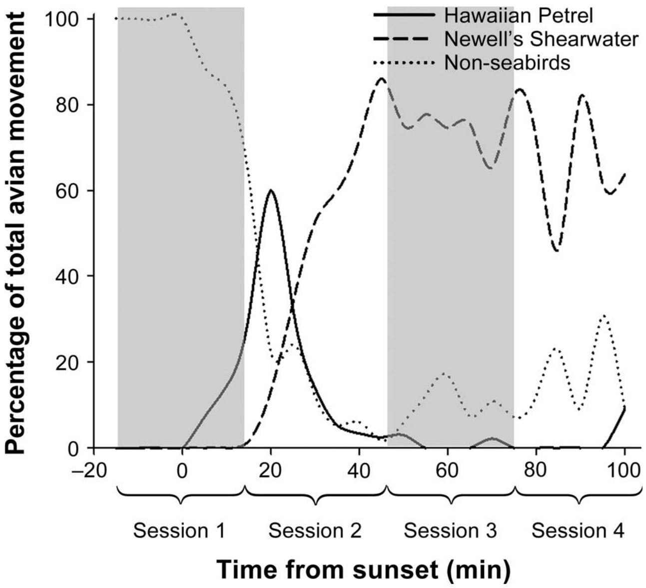

FIGURE 2. Percentages of avian movement by time, based on visual observations, on Kaua'i Island, Hawaii, USA, 2012–2013. Sampling (visual and radar surveys) started 15 min before sunset and ran for 2 hr, divided into 4 consecutive 30-min sampling sessions. Shaded and unshaded areas depict, in order, session 1 (which was excluded from all further analysis because it consisted almost entirely of nontarget species), session 2, session 3, and session 4.

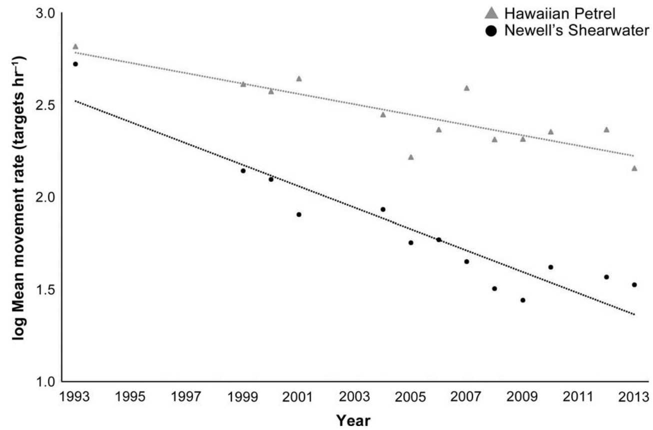

FIGURE 3. Linear regressions of log-transformed mean movement rates (targets hr^{-1} from 13 sites surveyed since 1993) recorded by radar during session 2 (Hawaiian Petrel) and sessions 3 and 4 combined (Newell's Shearwater). See Figure 2 for explanation of sessions.

of the session). Sessions 3 and 4 consisted almost exclusively of Newell's Shearwaters. We used data from session 2 to assess trends in radar detections for Hawaiian Petrels and data from sessions 3 and 4 to assess trends in radar detections for Newell's Shearwaters. Because similar patterns in the timing of movements of both species were recorded on Kaua'i in the 1990s (Day and Cooper 1995), we assume that species-specific timing of movement did not change over the time series.

Radar Trends—Hawaiian Petrel

Movement rates of Hawaiian Petrels in 2013 were highest on the North Shore (Figure 1A). The 3 sites with the highest movement rates in 2013 were Hanalei, Wainiha, and Lumaha'i, all on the North Shore. The 3 sites with the lowest movement rates were 'Ele'ele, Kekaha, and Kalāheo, all on the South Shore. To examine the change in passage rates from 1993 to 2013, we included the 13 sites surveyed over the entire study period (i.e. excluding Lumaha'i and Wainiha, which were not surveyed in 1993). The overall mean movement rate across all 13 sites combined dropped ~78%, from 654 ± 145 targets hr^{-1} in 1993 to 143 ± 36 targets hr^{-1} in 2013. A paired t-test revealed a significant decline for individual sites ($t_{24} = 3.43$, $P < 0.002$).

A linear regression showed a strongly significant decline over the period 1993–2013 ($y = -0.028x + 2.811$, $r^2 = 0.71$, $F_{11} = 26.26$, $P < 0.001$; Figure 3). Back-transforming the slope gave a lambda of 0.938, or an average decline of ~6% per year. The same decline remained significant when Hanalei was removed from the analysis ($F_{11} = 21.14$, $P = 0.001$). Removing 1993 as a potential outlier from the analysis also did not change the relationship ($F_{10} = 12.44$, $P = 0.005$). Eight of 13 (62%) sites showed significant declines across the entire study period (Table 1). Three southern sites (Kalāheo, Waimea, and Kekaha) did not show significant differences in movement rates over the time period, presumably because movement rates at these sites were already low when the surveys began in 1993.

Radar Trends—Newell's Shearwater

As with Hawaiian Petrels, movement rates of Newell's Shearwater in 2013 were highest on the North Shore (Figure 1B). The 3 sites with the highest movement rates in 2013 were Lumaha'i, Wainiha, and Hanalei, all on the North Shore. The 3 sites with the lowest movement rates were 'Ele'ele, Kalāheo, and Kekaha, all on the South Shore. To examine the change in passage rates from 1993 to 2013, we included the 13 sites surveyed over the entire study period (excluding Lumaha'i and Wainiha). The overall mean movement rate across all 13 sites dropped ~94% from 524 ± 207 targets hr^{-1} in 1993 to 34 ± 9 targets hr^{-1} in 2013. A paired t-test revealed a significant decline for individual sites ($t_{24} = 2.37$, $P = 0.03$).

A linear regression on the log-transformed data showed a strongly significant decline over the period 1993–2013 ($y = -0.058x + 2.577$, $r^2 = 0.88$, $F_{11} = 81.64$, $P < 0.001$; Figure 3). Back-transforming the slope gave a lambda of 0.875, or an average decline of ~13% per year. The same decline remained statistically significant when the Hanalei site was removed from the analysis ($F_{11} = 54.30$, $P < 0.001$). Removing 1993 as a potential outlier from the analysis also

TABLE 1. Results of individual site linear regressions of log-transformed radar targets recorded during session 2 (Hawaiian Petrel) and sessions 3 and 4 combined (Newell's Shearwater) on Kaua'i Island, Hawaii, USA, between 1993 and 2013. *ns* = not significant. See Figure 2 for explanation of sessions.

	Hawaiian Petrel			Newell's Shearwater		
Site	Slope	r^2	P	Slope	r^2	P
Hanalei	0.925	0.72	<0.001	0.833	0.85	0.001
Kalihiwai	0.956	0.62	0.002	0.811	0.68	0.001
Waiakalua Stream	0.889	0.61	0.005	0.822	0.51	0.01
Anahola	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*
Keālia	0.926	0.61	0.002	0.870	0.82	<0.001
Kapa'a	0.943	0.61	0.002	0.922	0.43	0.02
Wailua	0.940	0.36	0.03	0.881	0.52	0.008
Kālepa Ridge	*ns*	*ns*	*ns*	0.919	0.59	0.01
Līhu'e Airport	0.953	0.31	0.06	0.896	0.61	0.005
Kalāheo	*ns*	*ns*	*ns*	0.839	0.54	0.01
'Ele'ele	0.917	0.44	0.01	0.855	0.62	0.001
Waimea	*ns*	*ns*	*ns*	0.911	0.35	0.03
Kekaha	*ns*	*ns*	*ns*	0.911	0.64	0.02

indicated a significant negative relationship between 1999 and 2013 ($F_{10} = 48.35$, $P < 0.001$). Twelve of 13 (92%) sites showed statistically significant declines across the entire study period (Table 1).

SOS Fallout Data

A total of 30,552 Newell's Shearwater fledglings was collected by the SOS program between 1979 and 2015. Before Hurricane Iniki in 1992, annual numbers varied between 2,235 and 1,141 (average: 1,511 ± 79), but with no trend ($r^2 = 0.003$, $F_{11} = 2.26$, $P > 0.05$; Figure 4). From 1992 (the year of Hurricane Iniki) to 2015, numbers declined strongly, from 955 to 157 annually ($r^2 = 0.91$, $F_{22} = 250.25$, $P < 0.001$; Figure 4).

DISCUSSION

Long-term monitoring data are critical for making informed decisions about threatened species (Yoccoz et al. 2001), and monitoring should be undertaken over biologically relevant timeframes (Beltran et al. 2014). For long-lived species with low fecundity, like many seabirds, decades of repeated measurements may be required before biological trends become evident. We were able to use 21 yr of radar data and 37 yr of data on fledglings rescued by the SOS program to assess trends in the abundance of 2 endangered seabirds on the island of Kaua'i. Ornithological radar surveys provided insights into the annual numbers of adult Hawaiian Petrels and Newell's Shearwaters flying from the ocean to inland breeding grounds during the peak seasonal period of incubation. Likewise, analysis of trends from the 37-yr dataset of the SOS program highlighted changes in the numbers of fallout-related fledglings of Newell's Shearwaters (i.e. reproductive output). These 2 datasets offered an island-scale view over multiple generations, allowing us to determine population trends and the current conservation status of these 2 species.

Radar data clearly indicated that both seabird species have experienced long-term population declines across the island during the last 21 yr, regardless of whether data from the (possibly) high production year of 1993 were included in the analysis. By stratifying these data into periods that encapsulated nightly movement patterns for each species, we were able to conclude that the decline was not restricted to Newell's Shearwaters but was also occurring in Hawaiian Petrels. For survey session 2, which included most of the Hawaiian Petrel movements recorded during visual surveys, radar sites experienced a 78%

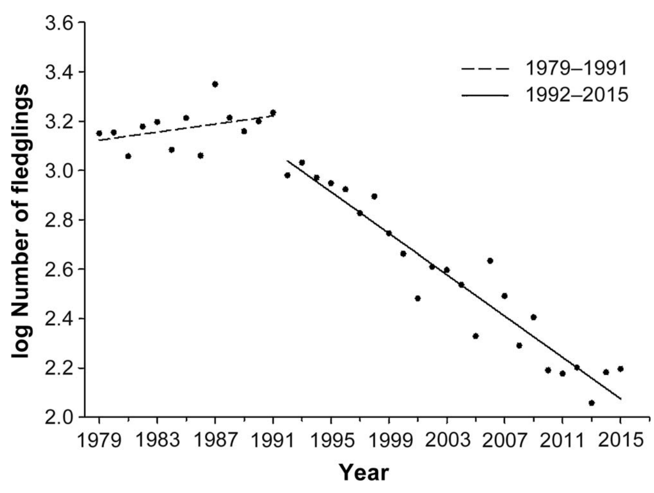

FIGURE 4. Linear regressions showing the annual numbers of fledgling Newell's Shearwaters recovered by the "Save Our Shearwaters" program on Kaua'i Island, Hawaii, USA, before Hurricane Iniki (1979–1991) and from the year of the hurricane onward (1992–2015).

reduction in radar targets between 1993 and 2013. For sessions 3 and 4 combined, which encompassed the movements of most of the Newell's Shearwaters, radar sites experienced a 94% reduction in radar targets over the same period. These patterns were true both for the entire 21-yr period and for 1999 onward (i.e. with the initial, possibly high, production year of 1993 removed). In all instances, radar detections were recorded primarily at radar sites in the western part of northern Kauaʻi, particularly in the Wainiha, Lumahaʻi, and Hanalei valleys. This part of Kauaʻi is known to be the primary remaining stronghold of both species on the island. In contrast, radar sites in the southern parts of the island recorded few targets. Several formerly large colonies in these areas, such as those at Kalāheo and Kaluahonu, have declined dramatically in recent decades and now face localized colony extinction (A. Raine and N. Holmes personal observations).

For the Newell's Shearwater, the markedly steep decline is consistent with earlier published work (i.e. Ainley et al. 1997, 2001, Day et al. 2003b). For the Hawaiian Petrel, however, the results of our analyses differ from those of Day et al. (2003a), who suggested that populations of this species had possibly increased over the period 1993–2001. Our revised results reflect the reanalysis of the early dataset to ensure that the starting times for all radar sessions were standardized relative to sunset. This approach standardized the radar data on a nightly basis, and thus changed the overall time periods encompassed by the radar sessions. As highlighted by our data collected by visual observers, 95% of the session 1 radar data was composed of nontarget birds, and thus data from this session were excluded. Session 2 clearly encapsulated the peak of inbound movements of Hawaiian Petrel targets, and sessions 3 and 4 primarily captured Newell's Shearwater movements. Therefore, we suggest that our reanalysis of the data more accurately reflects Hawaiian Petrel trends through time. That the Hawaiian Petrel population on Kauaʻi is suffering a decline comparable with that of the Newell's Shearwater is not surprising. On Kauaʻi, this species nests in habitats similar to those used by the Newell's Shearwater and faces the same suite of threats.

The decline in radar-based population counts for both species is dramatic and indicates 2 decades of decline on Kauaʻi. The decline in radar-based counts of Newell's Shearwaters is also mirrored in the numbers of fledgling Newell's Shearwaters recovered by the SOS program since its inception in 1979. In the 1980s, the project was processing on average 1,495 fledglings yr^{-1}, with a high of 2,235 fledglings in 1987. That number has declined since then by an order of magnitude, with an average of only 146 fledglings yr^{-1} processed since 2010. The SOS data also suggest that the decline may have commenced in earnest after Hurricane Iniki hit the island in 1992. While it is unlikely that the hurricane itself caused direct mortality of adults, as it struck the island during the day while adults were out at sea, it could have had knock-on effects on these seabird populations. These effects could include increased impacts of introduced predators (by opening up ingress routes into the remote interior), habitat modification (by encouraging the spread of introduced plants into the interior), and powerline collisions (due to infrastructure change, or the removal of considerable vegetation shielding powerlines after large trees were blown over).

It is appropriate to assess whether other factors may be responsible for the apparent trends. For the radar data, methodologies and equipment capabilities have remained constant throughout the time series, radar operators have been trained with the same protocols, and vegetation and topography have remained constant at all but one site (i.e. there have been no significant changes in tree heights that could have added new radar shadows to the sites). Only the Hanalei site changed to some degree, and overall population trends were the same with or without this location. Thus, we do not expect our results to be an artifact of methodology or survey site changes over time.

For the SOS data, an alternative hypothesis is that reduced numbers of Newell's Shearwater fledglings collected over time reflect reduced light pollution threat (i.e. levels of light pollution have decreased over time, thereby decreasing fallout). Although it is true that, in recent years, some private businesses and Kauaʻi County itself have decreased light pollution in certain areas through shielding, removed "problem" lights where many birds were grounded, and reduced overall light intensity (particularly during the fledging period), recent analyses of light levels on the island of Kauaʻi continue to show high levels of artificial light around coastal areas (Troy et al. 2011, 2013). Hence, there still are very few places on Kauaʻi where a fledgling seabird would not be exposed to artificial light as it headed out to sea (Troy et al. 2013). In addition, the correlation of radar as a second independent dataset counters this hypothesis and strongly indicates that the decline of Newell's Shearwater is a real trend.

During our study period, several conservation projects to benefit both species were undertaken, such as control of introduced predators and powerline- and light-minimization projects; however, significant threats still exist. Predator control will reduce predation, but will not eliminate it (Cromarty et al. 2002), and mortality does still occur at seabird colonies receiving this conservation intervention, albeit at a lower rate (Raine and Banfield 2015a, 2015b). Both species are also targeted regularly by introduced Barn Owls, which are frequently seen hunting for seabirds over breeding colonies when the 2 focal species are returning inland to their burrows (A. Raine, N. Holmes, R. Day, and B. Cooper personal observations).

Recent monitoring of powerline collisions in key areas indicates that this remains a critical threat to the species as well, particularly at cross-island powerlines (Ainley et al. 2001, Travers et al. 2016). Therefore, while each of these conservation actions represent an important positive contribution toward the recovery potential of these threatened seabirds, they must be increased in scope, scale, and impact to reverse the declines and allow recovery.

Radar surveys will continue to be an important method for assessing island-wide population trends for both species on Kauaʻi into the future. The inclusion of the Nāpali Coast (which is known to hold large colonies of Newell's Shearwater; A. Raine and N. Holmes personal observations) in future radar surveys would be an important addition to this monitoring program. This area is inaccessible to radar mounted on trucks, but could be surveyed by slinging in a radar unit via helicopter and then mounting it on a tripod. Likewise, the SOS program represents both an important monitoring technique and a conservation tool for rehabilitating and releasing downed fledglings that face a high risk of mortality from predation, being run over by cars, or dehydration and starvation if they are not recovered and released at sea.

Conservation efforts should focus on reducing powerline collisions and light-attraction issues, controlling introduced predators, and creating protected colonies within predator-proof fences, and should focus on the locations with the greatest remaining concentrations of birds in northwestern Kauaʻi. This effort should include the installation of predator-proof fences encompassing colonies in upper montane areas wherever logistically feasible, and the creation of new colonies within predator-proof fences using assisted-colonization techniques, such as social attraction and chick translocation (Miskelly et al. 2009), in more accessible areas, such as the recent Nihoku Ecosystem Restoration Project at Kīlauea National Wildlife Refuge on the northern shore of Kauaʻi. Continued and long-term investment in conservation actions at both montane colonies and lowland translocation sites is critical for the success of these important conservation measures. Finally, refugia free of lights, powerlines, and predators should also be considered via the eradication of introduced predators and assisted colonization techniques at locations such as Lehua Islet and Mokuʻaeʻae Rock Islet, to ensure that a component of the population can persist in areas free of nonnative predators, powerlines, and artificial light sources.

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