Post-release survival of fallout Newell's shearwater fledglings from a rescue and rehabilitation program on Kaua'i, Hawai'i

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ABSTRACT: Light attraction impacts nocturnally active fledgling seabirds worldwide and is a particularly acute problem on Kaua'i (the northern-most island in the main Hawaiian Island archipelago) for the Critically Endangered Newell's shearwater *Puffinus newelli*. The Save Our Shearwaters (SOS) program was created in 1979 to address this issue and to date has recovered and released to sea more than 30 500 fledglings. Although the value of the program for animal welfare is clear, as birds cannot simply be left to die, no evaluation exists to inform post-release survival. We used satellite transmitters to track 38 fledglings released by SOS and compared their survival rates (assessed by tag transmission duration) to those of 12 chicks that fledged naturally from the mountains of Kaua'i. Wild fledglings transmitted longer than SOS birds, and SOS birds with longer rehabilitation periods transmitted for a shorter duration than birds released immediately or rehabilitated for only 1 d. Although transmitter durations from grounded fledglings were shorter (indicating impacts to survivorship), some SOS birds did survive and dispersed out to sea. All surviving birds (wild and SOS) traveled more than 2000 km to the southwest of Kaua'i, where they concentrated mostly in the North Pacific Equatorial Countercurrent Province, revealing a large-scale annual post-breeding aggregation zone for fledgling Newell's shearwaters. While there was reduced survival among birds undergoing rehabilitation, SOS remains an important contribution toward the conservation of Newell's shearwater because a proportion of released birds do indeed survive. However, light attraction, the root cause of fallout, remains a serious unresolved issue on Kaua'i.

KEY WORDS: Rehabilitation · Survival · Shearwater · Tracking · Light attraction

1. INTRODUCTION

Light attraction is a well-known threat to seabirds, particularly for fledglings, and has been shown to affect more than 50 burrow-nesting petrel species worldwide (Rodríguez et al. 2017b, 2019). The impact of light attraction can lead to the grounding of large numbers of fledglings on their first flight out to sea

from their burrows (known as 'fallout'), with examples including Manx shearwater *Puffinus puffinus* in Scotland (Syposz et al. 2018), Atlantic puffin *Fratercula arctica* in Canada (Wilhelm et al. 2013), multiple species in the Canary Islands (Rodríguez & Rodríguez 2009), short-tailed shearwaters *Ardenna tenuirostris* in Australia (Rodríguez et al. 2014), and multiple species on Reunion Island (Le Corre et al. 2002, 2003).

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Fledgling mortality from fallout can occur for a number of reasons, including injuries sustained from colliding with human infrastructure, depredation by cats and dogs, being struck by cars, or succumbing to dehydration and starvation (Rodríguez et al. 2012). The grounding phenomenon has led to the establishment of multiple rescue programs designed to recover, rehabilitate, and release grounded birds to the sea. These programs usually rely on citizen involvement and often involve significant public participation and community outreach (Rodríguez et al. 2017c).

On the island of Kaua'i, in the Hawaiian Archipelago, 2 endangered seabird species — Newell's shearwater *Puffinus newelli* and Hawaiian petrel *Pterodroma sandwichensis* — are vulnerable to light attraction. Historically, fallout of Newell's shearwater fledglings on Kaua'i was extremely high, with thousands of birds grounded each year throughout the 1980s and 1990s (Reed et al. 1985, Telfer et al. 1987, Raine et al. 2017). Both species also face numerous other conservation threats throughout the main Hawaiian Islands, including high levels of mortality due to powerline collisions (Cooper & Day 1998, Podolsky et al. 1998, Ainley et al. 2001, Travers et al. 2017) and the impacts of introduced predators such as cats, rats, barn owls *Tyto alba*, and pigs (Simons 1985, Raine et al. 2019, 2020). Cumulative impacts on land together with suspected threats at sea have led to the Hawaiian petrel being globally listed by the IUCN as Endangered (BirdLife International 2018) and Newell's shearwater being listed as Critically Endangered (BirdLife International 2019). Furthermore, both species are known to be in sharp decline on Kaua'i, with recent historical population trends showing a 94% decline for Newell's shearwaters and a 78% decline for Hawaiian petrels between 1993 and 2013 (Raine et al. 2017).

To address the issue of light attraction and subsequent fallout, the State of Hawai'i Division of Land and Natural Resources created the Save Our Shearwaters (SOS) program in 1979. The SOS program is one of the longest-running seabird rescue programs in the world and relies heavily on public participation, with residents encouraged to pick up downed seabirds and place them in aid stations located around the island. During the fallout season (late September to mid-December), aid stations are checked every morning by SOS staff. SOS personnel examine all fledglings at the aid stations and then either release them that day or take them to the care facility for rehabilitation and subsequent release. Between 1979 and 2019, SOS processed more than 31 812 Newell's shearwaters (of which 30 552 [96%] were fledglings).

One key knowledge gap for SOS is post-release survival. Although the value of SOS for animal welfare is clear (i.e. grounded birds cannot simply be left to die after anthropogenic grounding), rehabilitation efficacy has not been evaluated. Recovered and released birds may have reduced survival rates due to a greater likelihood that they were compromised by factors including undetected injuries, decreased health parameters (weight, hydration), or secondary complications (e.g. exposure to disease, or compromised waterproofing) (Rodríguez et al. 2017c). Despite such compromising factors, we expected that at least a proportion of the birds recovered by the SOS program would survive and thus contribute to the overall population of the species. Through time, SOS has also improved its evaluation, treatment, release criteria, and captive care protocols to increase the chances of post-release survival for seabirds released by the program. Understanding post-release survival was identified as a critical research element for SOS, particularly due to the importance of the program in 2 Kaua'i-specific Habitat Conservation Plans currently in preparation. To date, the only information on post-release survival was from band recoveries, of which there have been very few. From 1979–2017, only 24 adult and sub-adult recoveries among birds banded by SOS in previous years were documented (mostly dead birds killed by collisions with powerlines). Ainley et al. (1995) reported only 1 banded SOS bird from 39 burrows monitored at the Kalaheo colony in 1992 and 1993, despite the Kalaheo area being a fallout hotspot. Similarly, of 235 Newell's shearwater burrows currently monitored by the Kaua'i Endangered Seabird Recovery Project (https://kauaiseabirdproject. org/; KESRP) on Kaua'i, only 1 bird rehabilitated from the SOS program has ever been found (KESRP unpubl. data). This low band recovery rate has led to questions being raised as to whether birds recovered, rehabilitated, and released by SOS survive.

We recognize that band recoveries are insufficient for assessing the efficacy of Newell's shearwater rehabilitation. Shearwaters are especially philopatric and typically recruit to their natal colonies (Harris 1966, Perrins et al. 1973, Warham 1980). Band returns likely are rare because few colonies are actively monitored at the individual burrow level (and thus efforts to relocate SOS-banded birds are limited). Also, most monitored colonies are located in the north-west of Kaua'i, where fledglings are presumably less likely to be affected by fallout because there are fewer sources of artificial light (although it is possible that birds can be attracted to light sources anywhere on Kaua'i; see Troy et al. 2011, 2013). Furthermore, bird banding

and handling in colonies is not a primary objective, and most band recoveries are from mortalities collected opportunistically under powerlines. Powerline mortalities are rarely detected due to terrain, dense vegetation, and the fact that most birds hitting powerlines do not drop immediately under the lines themselves (Podolsky et al. 1998, Travers et al. 2017).

In this study, we evaluated post-release survival of Newell's shearwaters by using satellite transmitters to track the transmission duration and movements at sea among fledglings recovered and released by SOS compared with birds that fledged directly from their burrows, presumably without incident. The principal objectives were to assess whether SOS birds survived after release and to consider any differences between apparent survival rates of birds from these 2 study groups.

2. MATERIALS AND METHODS

2.1 Morphometrics and tag attachment

Between 2014 and 2018, we tagged and evaluated transmission duration among 50 fledgling and 4 breeding adult Newell's shearwaters. Tags attached to fledglings were split between 38 birds collected by the SOS program and 12 birds captured by hand at burrows located in the Upper Limahuli Preserve (ULP, Fig. 1). ULP (153 ha) is located in north-western Kaua'i and is owned and managed in perpetuity as a
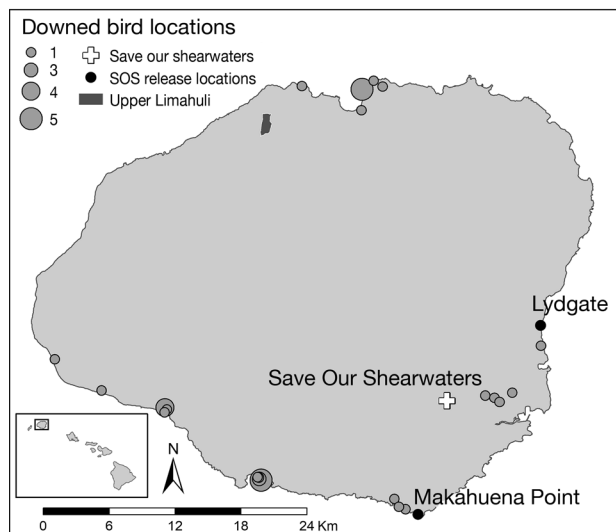

Fig. 1. Island of Kaua'i, Hawai'i, showing location of Upper Limahuli Preserve, Save Our Shearwaters Program (SOS) building location, 2 SOS release locations (Lydgate and Makahuena Point), and all downed bird (fallout) locations (where known) for birds used in this study

Conservation Area by the National Tropical Botanical Gardens (Kaua'i, Hawai'i). The site holds the largest monitored colony of Newell's shearwaters in the world and is actively managed to protect the species and co-occurring Endangered Hawaiian petrels. The site is also located in a relatively dark portion of the island, with limited artificial lighting and powerlines on the adjacent coast; therefore, birds from this colony are considered less susceptible to light-induced fallout and powerline collisions. We weighed all study birds (±1.0 g) and collected morphometric measurements (wing chord, tarsus, head–bill length, bill width at proximal end of nares, and bill depth at proximal end of nares, all ±1.0 mm). All birds handled were banded with a stainless steel band (Bird Banding Lab band size 4 or 4A, depending on tarsus width).

After measuring and banding, birds were held by experienced seabird handlers and their heads were covered by a lightweight cloth to shield them from light and keep them calm during tag attachment. We attached modified satellite transmitters (Microwave Technology; BirdSolar PTT 100, 9.5 g transmitters [hereafter, tags]). Tags were potted to withstand hydrostatic pressure expected during occasional dives that can reach depths >50 m (T. Joyce unpubl. data) and further modified with the addition of 4 copper suture tubes, resulting in a tag weight of 11–12 g. The modified tags were the lightest, depth-resistant units available and were 2.2–3.4% of shearwater body mass (depending on the bird tagged), below the maximum recommended mass of 5% for devices attached to procellariid seabirds (Phillips et al. 2003). The tag profile (~2.5 cm^2) represented approximately 3% of the frontal area of a Newell's shearwater. We acknowledge that the increase in cross-sectional area would, to some degree, have affected the hydrodynamics of the tagged birds. Ropert-Coudert et al. (2007) found that tag placement (3.4% of frontal area) on little penguins *Eudyptula minor* had little effect on diving performance compared with effects of tag size. Yet, from a hydrodynamic perspective, modeling results on seals have shown that tag position can cause variation in drag by up to 11% and that tag shape is also important (Kay et al. 2019). Shearwaters rely on long-distance flights, but also spend appreciable time foraging underwater. For shearwaters, tag placement presents complex trade-offs regarding drag, weight burden, and balance (see also Vandenabeele et al. 2012, 2014). In anticipation of potentially long-distance flights, we preferred to attach the tags consistent with the bird's center of mass (Fig. 2) to minimize interference with flight, balance, and behavior (Healy et al. 2004, Vandenabeele et al. 2014).

Fig. 2. Newell's shearwater in a rehabilitation pool at the Save Our Shearwaters facility, showing satellite tag placement

Most tags were programmed to transmit continuously every 60 s, but 14 tags in 2016 were delivered by the supplier with a pre-programmed, default 'on-off' duty cycle where tags cycled on for 10 h and off for 48 h. We employed the same technique in all 4 years, with tags attached by the same individual (A.F.R.) in all years except in year 1 when tags were attached by A.F.R. and J.A. We used a suture-tape-glue attachment technique following Newman et al. (1999) and modified by J.A. for petrels and shearwaters (MacLeod et al. 2008, Adams et al. 2012, Jodice et al. 2015). Specifically, several feathers on the central, dorsal surface between the scapulae were lifted and 1 strip (0.5 × 2.0 cm) of waterproof tape (Tesa® 4651) was inserted adhesive-side-up and wrapped over on itself to secure several feathers. The tape served to mark the location where the center of the tag would sit and also provided a non-feather surface to glue (Loctite® 421) the tag to the tape for added stability. We used 4 sterile surgical sutures (2-0 Pro-lene monofilament, non-absorbable sutures, Ethicon) to attach the transmitter to the skin. For each suture, the skin below the tag's custom suture tubes was pinched using the thumb and forefinger, a sterile 21 gauge × 3.8 cm hypodermic needle was inserted through the pinched skin, and the suture was then threaded through the needle. When the needle was removed, the suture was retained under a 17 mm wide section of skin (equivalent to the width of the base of the tag). The sutures were then threaded back through the tubes at the base of the tag and secured snug to the skin and feathers with 4 surgical square knots. Care was taken to ensure that each suture was snug to minimize risk to the bird for entanglement.

2.2. SOS treatment groups

We classified fledglings that passed through the SOS program according to 3 levels of rehabilitation: same-day release (no rehabilitation, N = 17 birds), 1-day rehabilitation (N = 10), and ≥2-day rehabilitation (N = 11). Same-day release birds were not transported to the SOS facility but instead were released by SOS staff after inspection (see details below) at 1 of 2 release sites after their morning work recovering downed birds. Number of fledglings tagged in each year (2014 = 12, 2016 = 12, 2017 = 19, 2018 = 7) varied because of funding constraints, the small number of tags available in any given year, and the uncertainty that additional funding would be available to deploy tags in each following year of the study. Therefore, while we were not able to allocate tags equally to each treatment group in any given year, during the 4 yr period we allocated tags to maintain appropriate replication overall among the 3 SOS treatment groups.

We selected fledglings from the 3 SOS treatment groups for tagging if they met standard release requirements outlined in the SOS Operations Manual (Anderson 2019). Selected birds had to be free from apparent injuries, in good body condition (at least a 2 ('Normal – indicates a well fleshed bird') on a 3-point scale, quantifying amount of muscle covering the keel), display normal mentation, pass a 'flap test' (where the body of the bird is held gently and firmly with both hands with the wings free, the bird is allowed to flap, while strength and symmetry are assessed), and individuals had to have non-damaged/non-contaminated plumage. If birds spent time in rehabilitation, they had to be confirmed to be waterproof after spending time in conditioning pools. Birds also had to be able to consistently maintain their temperature above 100°F (~37.78°C) and below 106°F (~41.11°C) when housed on cold water for 8–10 h) and have blood values (packed cell volume, total protein, and glucose) within the normal range for the species (Work 1996, Anderson 2019). We did not tag birds determined to be 'marginal' (i.e. severely compromised due to injuries or heavily damaged feathers) because we assumed additional stress of adding tags might increase variability or potentially bias tracking duration. Therefore, the results of this study apply specifically to birds that met the standard release requirements set out by SOS and do not entirely represent the population of released birds because a small proportion of birds released by SOS each year (0–2, M. Bache pers. comm.) were considered 'marginal'. After handling and tag attachment, we introduced tagged birds to

the SOS rehabilitation pool to assess attachments, monitor behavior, and ensure that birds were waterproof. Based on weather and prevailing wind, we released all tagged fledglings according to SOS release protocols at 2 standard SOS release sites: Makahuena Point (south shore of Kaua'i) and Lydgate Beach (east shore of Kaua'i) (Fig. 1).

2.3. ULP wild fledglings

We tagged 12 fledglings (6 in 2016, 1 in 2017, and 5 in 2018) in ULP using the same attachment method outlined above. Similar to the SOS group, the number of fledglings tagged in each year varied because of funding constraints and the small number of tags available in any given year. Chicks were tagged in mid-October as close to estimated fledging as possible (Newell's shearwaters on Kaua'i typically fledge from late September to mid-November, with a peak in mid-October; Ainley et al. 2019). To prevent the tags from snagging on the burrow entrance, we chose fledglings from wide-mouthed burrows and attached tags as near to fledging as possible to reduce the amount of time individuals were likely to spend in the burrow with their tag. We did not use mass and general condition to select individuals for tagging and assumed individuals represented natural fledgling body condition during 2016–2018. Because it is extremely unlikely that any fledglings banded or tagged would ever be re-sighted again to assess survival, we also tagged 4 individual adult breeding birds from 4 different known burrows in ULP in 2016 and 2018 (2 birds in each year) to evaluate potential tag effects and assist us with interpretation of survival among fledglings by comparing tag duration and tag sensor patterns of the adults (described in Section 2.3). These burrows associated with the tagged adults were part of an established monitoring program and had been followed annually for at least 2 yr prior to this study and throughout the study itself. We re-captured these site-faithful birds during subsequent breeding seasons to evaluate their condition and verify band numbers to confirm tag attachments had failed and tags were indeed lost at sea.

2.4. Assessing fate of tagged birds

For this study, we assessed survival rate through the duration of tag transmission, because it was not possible to determine the actual fate of each bird at sea. Therefore, as a proxy for survival, we compared tag transmission duration (days at sea) between wild birds and SOS birds, and among the 3 SOS rehabilitation groups. Furthermore, the tags had an activity sensor in the form of a tilt switch orientated horizontally within the base of the tag. As the bird tilted back and forth during flight, the sensor increased in increments from 1 to 255 then re-set to 1 again. If the bird was not moving for extended periods of time (i.e. if it was floating on the water), the sensor maintained a constant integer that, when graphed versus time, appeared as a flat line or as an incremental series of flat lines. For all tags programmed to transmit continuously (excluding 2016, see Section 2.1), we evaluated tilt switch integers graphically to assess the behavior of the bird before the tag stopped transmitting. If the integers continued to increment through time consistent with the pattern observed throughout the tag's deployment, we considered this indicative of the tag falling off during normal movement behavior. If incrementation slowed down (e.g. we observed a stair-step pattern indicating periods with constant integer values through time) or ceased (e.g. we observed a prolonged flatline of constant integer value) preceding the loss of tag transmission, we considered this to be a period of inactivity, with the terminal flatline pattern in particular more likely indicating a moribund condition preceding presumed mortality.

2.5. Statistical analyses

Throughout the study, a total of 15 969 post-filtered location fixes were recorded for all fledglings combined. Unfiltered locations were initially processed by Argos Kalman filtering (Lopez & Malarde 2014), and locations of class Z were omitted. Remaining location fixes were further filtered using the Douglas Argos Filter (Douglas et al. 2012), through the Movebank website (www.movebank. org, Kranstauber et al. 2011), using the MAXREDUN threshold of 15 km. All mapping and spatial analyses related to tracking data and the generation of movement metrics used ArcGIS 10.3.1 (ESRI) or R statistical programming language version 3.6.0. Metrics generated for each bird included maximum straight-line distance reached from Kaua'i (km), total distance traveled (km), final latitude, final longitude, and mean speed (m s^{-1}). Distances were calculated using the 'distHaversine' function in the R package 'geosphere' (Hijmans 2017), and speed was calculated for each tracking point as the distance from the previous point divided by the

interval between timestamps. Because several birds crossed the 180th meridian, the final longitude for these birds was rescaled by adding 180 minus the observed degrees east longitude (as an integer) to 180. All statistical analyses were performed using SPSS version 26 (IBM) or R version 3.6.0. We chose non-parametric tests instead of comparable parametric tests to account for certain statistical assumptions (i.e. normality of residuals and homogeneity of variance) and unequal sampling across groups and years. Comparisons were made between rehabilitation groups across years and between years within groups (Kruskal-Wallis test), between groups with all years pooled (Mann-Whitney U-test), and transmission duration between groups using chi-squared tests. A p-value of <0.05 was considered significant, and p-values were adjusted for multiple comparisons using the Benjamini-Hochberg false discovery rate method (Benjamini & Hochberg 1995); post hoc comparisons (where applicable) were carried out using the Dunn test for multiple comparisons.

2.6. Ethics statement

We conducted this study according to the guidelines for the ethical use of wild birds in research outlined by the North American Ornithological Council (Fair et al. 2010). All work was conducted under State Migratory Bird Master Permit (MB673451-0) and Section 6 Co-operative Agreement between the US Fish and Wildlife Service and the State of Hawai'i Division of Land and Natural Resources. All tag attachment and banding work for this project was authorized by the USGS Bird Banding Lab Permit DOFAW Master Permit 08487-I with an Experimental Authorization.

3. RESULTS

In total, we tagged 12 wild fledglings, 4 breeding adults, and 38 fledglings recovered by the SOS program (17 same-day release birds, 10 one-day rehabilitation, and 11 ≥2-day rehabilitation birds). Among SOS fledglings that spent more than 1 d in rehabilitation, the average stay at the facility was 5.3 d (range = 2–14 d). One bird in the ≥2-day group was originally released by SOS (banded but not tagged) and subsequently found back on land after 2 d. This individual was rehabilitated for 2 more days, after which it was tagged, released, and included in this study. Of 38 SOS birds tagged, 35 flew and headed directly out

to sea immediately after release. Two of the remaining 3 (all from 2014) were blown over the edge of the release site and landed in the water after a very short glide. Neither was seen flying after landing in the water and both were last observed swimming out to sea. The third bird, released at Lydgate Beach, initially flew strongly out to sea, but was attacked by a great frigatebird *Fregata minor.* After a series of attacks, the shearwater landed in an area of high surf, and was not seen regaining flight. However, all 3 birds were subsequently recorded transmitting on the day after their release, indicating that all 38 (100%) survived immediate release and were free-ranging at sea. All 12 ULP birds fledged and subsequently transmitted at sea, indicating that all (100%) survived immediate (24 h) post-fledging and were free-ranging at sea.

3.1. Post-release and post-fledging dispersal

All fledglings (from all groups and all 4 years) traveled toward a region of the central Pacific, southwest of the Hawaiian Islands (bounded by 5° S–10° N, 164° E–162° W, Fig. 3). This area is influenced by the Inter-Tropical Convergence Zone (approximately 5°–15° N) and the frontal zone that separates the westward-flowing North Equatorial Current from the eastward-flowing North Equatorial Counter Current (i.e. Pacific Equatorial Divergence and extending into the Pacific Warm Pool ecological provinces; Longhurst 2010). A large core area (761 000 km^2; 20% fixed kernel density contour at 9 km with a 250 km smoothing factor/search radius) of concentration for all locations determined after 14 d at sea was centered over the western half of the North Pacific Equatorial Countercurrent Province (Fig. 3). We compared movement metrics between wild fledglings (all years combined) with all SOS birds (all treatment groups and years pooled; Table 1). There was no significant difference between wild and SOS fledglings (SOS treatment groups pooled) for straight-line distance (Mann-Whitney U-test, $U = 207.00$, $p > 0.05$). Similarly, there was no significant difference between wild vs. SOS fledglings for total distance traveled ($U = 200.00$, $p > 0.05$), final latitude ($U = 284.00$, $p > 0.05$), final longitude ($U = 244$, $p > 0.05$), or mean flight speed ($U = 224.00$, $p > 0.05$). For SOS birds, we also considered differences among the 3 SOS treatment groups for movement metrics. Although there were no significant differences among the 3 SOS treatment groups for maximum straight-line distance (Kruskal Wallis test, $\chi^2 = 3.936$, df = 2, $p > 0.05$), final longitude ($\chi^2 = $
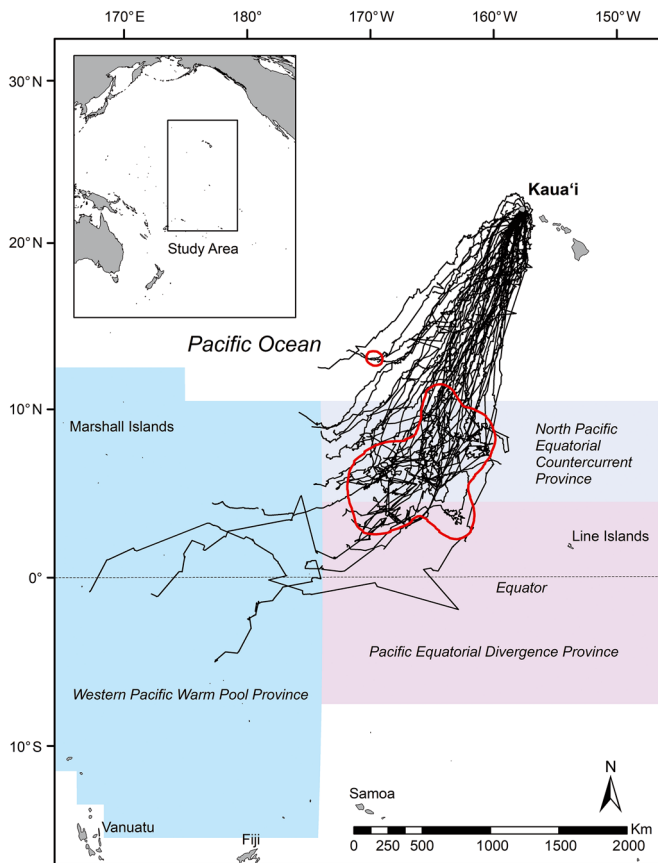
Fig. 3. Overview of tracks for all 50 Newell's shearwater fledglings tracked during this study (all years combined) and superimposed over 3 discrete oceanographic provinces (i.e. Longhurst Provinces) described by Longhurst (2010). Red line indicates 20% fixed kernel density contour at 9 km with a 250 km smoothing factor/search radius) of concentration for all locations determined after 14 d at sea. Inset shows study area within the greater central-western Pacific Ocean

Table 1. Summary statistics for movement metrics calculated for Newell's shearwaters: wild fledglings (all years combined) and Save Our Shearwaters (SOS) rehabilitated fledglings (all treatment groups and years pooled)

Measurement	Group	n	Mean	Min	Max
Maximum straight-line distance (km)	SOS	38	2057	169	4395
	Wild	12	2425	1469	4019
Total distance traveled (km)	SOS	38	3149	317	6932
	Wild	12	3860	1691	8501
Final latitude (degrees)	SOS	38	8.25	−0.84	21.38
	Wild	12	5.40	−4.99	11.66
Final longitude (degrees)	SOS	38	−170.8	−192.50[a]	−160.90
	Wild	12	−172.9	−188.06	−163.32
Mean speed (m s^{-1})	SOS	38	3.81	1.35	7.30
	Wild	12	3.97	2.13	6.49

[a]Rescaled by adding 180 minus the observed degrees east longitude (as an integer) to 180

0.86, df = 2, p > 0.05), or mean speed traveled (χ^2 = 0.30, df = 2, p > 0.05), the total distance traveled was significantly less for birds in the ≥2-day rehabilitation group than for birds in the 1-day rehabilitation group (χ^2 = 7.74, df = 2, p = 0.021; Dunn test, Z = 2.78, p = 0.016). Birds in the ≥2-day rehabilitation group also stopped transmitting at significantly more northern latitudes than same-day release birds (χ^2 = 6.43, df = 2, p = 0.040; Z = 2.42, p = 0.047).

3.2. Tag transmission duration

For all tagged fledglings, we evaluated tag duration between wild fledglings and SOS fledglings (all SOS treatment groups pooled). Wild fledglings transmitted for significantly longer than SOS birds (wild: 33.7 ± 8.6 d, SOS: 20.6 ± 1.9 d; Mann-Whitney U-test, U = 138.5, p < 0.05). Furthermore, while there was no significant difference between the number of wild birds and SOS birds (pooled) still transmitting on Day 7 and on Day 14, significantly more wild birds were still transmitting after 21 d than SOS fledglings (chi-squared test, χ^2 = 8.9, df = 2, p = 0.01). We then compared wild fledglings to birds in each of the SOS treatment groups (Table 2). Wild fledglings (ULP) had significantly longer average transmission duration than any other fledgling group, whereas birds in the SOS ≥2-day group had the shortest average transmission duration (Kruskal Wallis test, χ^2 = 10.5, df = 3, p < 0.05) (Fig. 4).

We also evaluated groups according to the proportion of tags still transmitting after 7, 14, and 21 d (Fig. 5). After 21 d, 28.9% of SOS birds (29.4% same-day release, 50.0% 1-day rehabilitation, and 9.1% ≥2-day rehabilitation) and 50.0% of wild fledglings were still transmitting. There were disproportionally more birds in the wild group transmitting after 21d and disproportionally fewer birds in the ≥2-day group transmitting after 14 and 21 d than expected (chi-squared test, χ^2 = 28.6, df = 6, p <0.001). For the 4 adult birds tagged in 2016 and 2018, average transmission duration was 82.3 d (min = 71 d, max = 100 d). All 4 were observed at their burrows apparently unharmed in the following year without their tags. We evaluated activity sensor patterns for all birds with pre-programmed con-

Table 2. Tag durations for Newell's shearwater treatment groups

Treatment group	n	Average ±SE transmission (d)	Range (d)
Same-day release	17	22.6 ± 3.8	3–71
1 d rehabilitation	10	22.7 ± 2.3	12–36
≥2 d rehabilitation	11	15.6 ± 1.1	7–22
Wild fledgling	12	33.8 ± 8.6	12–111
Wild adult	4	82.3 ± 6.8	71–100
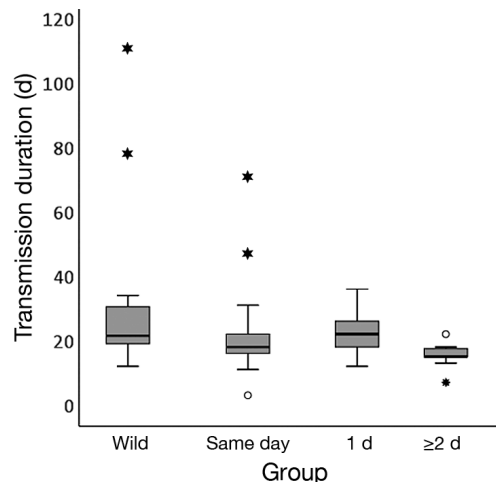
Fig. 4. Median tag duration (with first and third quartiles) of the 3 Save Our Shearwaters (SOS) rehabilitated fledgling groups and the wild fledglings tagged during this study. Whiskers are the maximum and minimum values, with outliers provided as circles and extremes as asterisks. Tag durations were significantly different, with wild fledglings having the longest transmission duration and birds in the SOS ≥2-day group the shortest (Kruskal Wallis test, $\chi^2 = 10.5$, df = 3, p < 0.05)
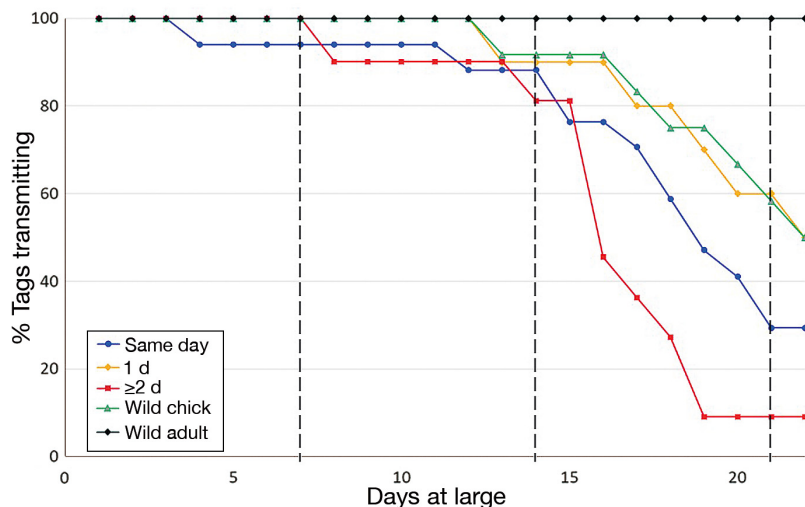

Fig. 5. Percentage of tags still transmitting in each of 5 groups: (1) Save Our Shearwaters (SOS) same day, (2) SOS 1-day rehabilitation, (3) SOS ≥2-day rehabilitation, (4) Upper Limahuli Preserve (ULP) fledglings, and (5) ULP adults. Vertical dashed lines indicate 7, 14, and 21 d

tinuous transmission setting (i.e. all tags except 2016). Of 38 tags with continuous transmission, the 2 deployed on adult birds demonstrated uninterrupted 'normal' activity patterns until the tag ceased to transmit. Of 36 remaining tags on fledglings, 4 (11.1%) demonstrated uninterrupted 'normal' activity patterns until the tag ceased to transmit, 36.1% indicated decreased activity (i.e. stair-step pattern) prior to final transmission, and 52.8% exhibited a flat-line pattern consistent with limited activity and potential morbidity. There were significantly more wild fledged birds where the sensor activity terminated abruptly or slowed down prior to final transmission, and significantly fewer wild fledglings where the sensor values flat-lined compared with birds in the SOS group (Table 3, chi-squared test, $\chi^2 = 39.9$, df = 2, p <0.001).

3.3. Testing for year effects

Because tags were unequally distributed among groups in each year, our ability to quantify year effects was limited. Although we acknowledge a small sample size, we evaluated interannual differences for birds in the same-day release treatment group (n = 17) and for birds in the 'wild group' because birds in these groups were tagged in 3 of the 4 years (same-day group: 2014, 2016, and 2017; wild group: 2016, 2017, and 2018). There was no significant difference among years for maximum straight-line distance (Kruskal-Wallis test, $\chi^2 = 0.12$, df = 2, p > 0.05), total distance traveled ($\chi^2 = 3.33$, df = 2, p > 0.05), final latitude ($\chi^2 = 1.40$, df = 2, p > 0.05), final longitude ($\chi^2 = 1.30$, df = 2, p > 0.05), or mean speed ($\chi^2 = 0.64$, df = 2, p > 0.05). Similarly, for wild chicks, we found no significant difference among years for maximum straight-line distance ($\chi^2 = 1.88$, df = 2, p > 0.05), total distance traveled ($\chi^2 = 0.61$, df = 2, p > 0.05), final latitude ($\chi^2 = 0.74$, df = 2, p > 0.05), final longitude ($\chi^2 = 3.12$, df = 2, p > 0.05), or mean speed ($\chi^2 = 3.109$, df = 2, p > 0.05).

3.4. Body condition

Lastly, among the 3 SOS groups, we evaluated if body condition (mass and size [weight divided by wing chord]) before release was related to transmis-

Table 3. Activity sensor patterns for all tags where activity sensor pattern data were available, showing the percentage of birds in each group (wild adults, wild fledglings, and Save Our Shearwaters [SOS] rehabilitated fledglings [pooled]) within each of 3 activity sensor patterns

Group	n	Stop (%)	Decreased activity (%)	Flat line (%)
Wild adults	2	100	0	0
Wild fledglings	6	16.7	66.6	16.7
SOS fledglings	30	10	30	60

sion duration. There was no difference among the 3 groups for either mass (Kruskal Wallis test, $\chi^2 = 1.56$, df = 2, p > 0.05) or size ($\chi^2 = 1.4$, df = 2, p > 0.05). Pooling all 3 SOS groups, there was no relationship between mass before release and transmission duration ($y = 0.0045x + 19.25$, $R^2 = 0.0001$, $F = 0.002$, df = 1, p > 0.05, mean ±SE = 441.3 ± 0.8 g, variance = 125.9 g), or between size and transmission duration ($y = -4.86x + 29.20$, $R^2 = 0.003$, $F = 0.086$, df = 1, p > 0.05, mean = 1.9 ± 0.005, variance = 0.004).

4. DISCUSSION

The primary aim of this study was to evaluate post-release survival of fledgling Newell's shearwaters after fallout, and recovery, rehabilitation, and release by the SOS program. As the efficacy of the program was unknown, understanding the fate of these birds is important when evaluating the conservation value of the program for the species. While the conservation value of rehabilitation programs has previously been considered indirectly (e.g. Gineste et al. 2017), our results offer a rare insight into the survival of rehabilitated seabirds after release.

Our results demonstrate that a proportion of rehabilitated birds do indeed survive after release; however, prolonged rehabilitation or severity of fallout-related injuries negatively impacted survival. Wild fledglings transmitted for longer than SOS birds, and SOS birds with longer rehabilitation periods transmitted for shorter durations than birds released immediately or rehabilitated for only 1 d. These differences may have resulted in part from a number of reasons, including undetected injuries or secondary complications such as exposure to disease, parasites, or compromised waterproofing (Rodríguez et al. 2017c). Interestingly, birds that spent only 1 d in rehabilitation had greater apparent survival (although this was not statistically significant) than those released on the same day. Although birds spending only 1 d in rehab may have been in better condition than birds that required longer rehab, rehabilitation efforts might consider taking birds into rehabilitation for a day to rehydrate and undertake a more thorough inspection for potential injuries (although this has to be weighed in the context of available space and resources within the program).

SOS birds that survived the critical early stages at sea after release traveled toward the same first wintering grounds as naturally fledging birds, indicating that their natural dispersal patterns were not altered by the rehabilitation process. All fledglings in all years headed directly to an area encompassing the North Pacific Equatorial Counter Current and Pacific Equatorial Divergence Provinces, and extending into the Western Pacific Warm Pool Province), bounded by 4°–13° N, 165°–178° W. This is an area of elevated relative oceanic productivity and food availability that supports a large biomass of skipjack tuna *Katsuwonus pelamis* (Bell et al. 2013), which are known to feed in association with Newell's shearwaters (Ainley et al. 2014). The annual concentration of our tagged birds in this region may indicate an important large-scale zone of aggregation used annually by fledgling Newell's shearwaters from Kaua'i. Previous boat-based surveys also recorded Newell's shearwaters in the eastern portion of the area identified by our tracking study (Joyce et al. 2013). Assessing potential threats within this region, including marine pollution (Sileo et al. 1990, Derraik 2002, Kain et al. 2016), overfishing (Ainley et al. 2014, Morra et al. 2019), effects of climate change (Bell et al. 2013), and bycatch (Gilman et al. 2008, Rodríguez et al. 2019), are important to consider for the conservation of this species.

It is important to address the degree to which our results could have been influenced by tagging effects and to acknowledge that carrying tags may impose burdens such as drag (Kay et al. 2019) and compromised balance (Vandenabeele et al. 2014)) to the shearwaters in this study. Although tracking technology is widely used and important for seabird research and conservation globally (Burger & Shaffer 2008), some studies have found varying impacts on survival or behavior (Massey et al. 1988, Wanless et al. 1988, Phillips et al. 2003, Elliott et al. 2012). Although smaller and lighter satellite tags are available for non-diving seabirds, to minimize impact on individual Newell's shearwaters, we used the lightest depth-reinforced satellite tags available that were less than the maximum recommended mass for devices intended for procellariid seabirds (Phillips et al. 2003). Furthermore, we opted to attach tags in a posi-

tion on the body which minimized interference with flight, balance, and behavior (Healy et al. 2004, Vandenabeele et al. 2014). All 4 (100.0%) adult shearwaters tagged for this study were re-sighted at their burrows in the following year without their tags, indicating that tag attachment did not impact the survival of the only cohort where we could directly measure survival rates.

It is also important to consider our results within the context of the life history of this species. Among seabirds, naturally fledging shearwaters and petrels have relatively low survival rates in the first year of their lives, followed by relatively high survival rates once they reach adulthood (Perrins et al. 1973, Warham 1980, Serventy & Curry 1984, Harrison 1990, Mougin et al. 2000). Weimerskirch et al. (2019) found that up to 50% of all tagged fledgling Barau's petrels *Pterodroma baraui* died immediately after reaching the sea due to compromised waterproofing. For the closely related Manx shearwaters, only 33.3% of fledged chicks were estimated to survive to breeding age (Brooke 1977), and for Hawaiian petrels (breeding in the same areas as Newell's shearwaters), survival rate to breeding age was estimated to be as low as 27.0% (Simons 1984). The apparently low survival rates for fledglings in this study are not wholly unexpected, but rather they are somewhat consistent with those published for other closely related species.

The outcome of our results should also be considered in the context of light attraction — the root cause for fledgling fallout — which remains a serious issue on Kaua'i (Ainley et al. 2001, Troy et al. 2011, 2013, Raine et al. 2017). The number of grounded seabirds recovered by SOS is a fraction of the number of birds that actually fall out in any given year. For example, members of the public are very unlikely to collect dead birds, but studies have found that a large proportion of fallout birds are already dead when encountered. On Kaua'i, one study (Podolsky et al 1998) found that 43% of fallout fledglings were dead, and none of the 44 dead shearwaters found, tagged, and left in place in 1993 and 1994 were ever reported to SOS (Ainley et al. 1995, Podolsky et al. 1998). A similar study in Australia found that 39% of grounded short-tailed shearwaters were either dead or dying (Rodríguez et al. 2014). Furthermore, grounded birds typically try to hide in small dark places where they are only found with concerted search efforts. Previous authors have suggested that discovery rate could be 50.0% of grounded live birds (Ainley et al. 2001); from our own observations, the discovery rate is probably even lower. Furthermore, of birds that are found, a proportion are never released because they

die in care from severe injuries (i.e. during the last 5 yr [2014–2018], an average of 6.4% of Newell's shearwaters died or were euthanized because their injuries were too severe [SOS unpubl. data]) which is similar to other programs, such as those on Réunion Island (Le Corre et al. 2002). The overall impact of light attraction and grounding of Newell's shearwaters is therefore still of major concern.

Conservation efforts focused on Newell's shearwaters on Kaua'i will benefit by reducing the impacts of light attraction to this Critically Endangered seabird. A wide range of options are available to address this issue, including light shielding (which alone reduced fallout by 40% at one Newell's shearwater fallout hotspot on Kaua'i in the 1980s; Reed et al. 1985), switching outdoor lighting to appropriate seabird-friendly light types (Rodríguez et al. 2017a), perhaps adjusting spectral qualities like intensity and color (Longcore et al. 2018), installing timer switches on outdoor lighting to allow automatic switch-off when lights are not in use, significantly reducing lights during the peak fledging period (which for all endangered seabird species runs from late September to mid-December on Kaua'i), adopting a light ordinance for the county with appropriate enforcement (especially in new construction zones or redevelopments, as this is currently lacking), targeted education campaigns and mitigation efforts through the creation of Habitat Conservation Plans to offset the impact of individual entities and businesses (e.g. the Kaua'i Seabird Habitat Conservation Plan that was accepted in May of 2020). Furthermore, our tracking study could be expanded by having larger and equal sample sizes for all groups in multiple years. This would help to strengthen the results presented in this paper. However, preventing seabirds from being grounded in the first place, by targeting light attraction, is likely the most effective conservation action.

In conclusion, while our results provide evidence of reduced survivorship for rehabilitated fledglings compared with wild fledglings, a proportion of rehabilitated birds did survive release and migrated successfully toward their first wintering grounds. Grounded birds not recovered by SOS are highly unlikely to survive due to a range of factors including depredation by introduced predators (such as cats or dogs), collisions with cars, or exposure and starvation due to an inability to reach the sea (Le Corre et al. 2002). The SOS program therefore remains an important component of the overall conservation efforts for this species, and the maintenance of this program, in conjunction with concerted efforts to reduce light pollution on the island of Kaua'i, will benefit Newell's shearwaters.

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