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Post-fledging distribution of ʻuaʻu (Hawaiian petrel *Pterodroma sandwichensis*) from Kauaʻi, Hawaiʻi and effectiveness of rehabilitation

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ABSTRACT: The ʻuaʻu (Hawaiian petrel *Pterodroma sandwichensis*) is an Endangered seabird endemic to the Hawaiian Islands. The at-sea distribution of this species is an under-studied aspect of its ecology. We tracked 10 petrels fledging from the island of Kauaʻi to their first wintering grounds, an area which has not previously been described. We also compare birds fledging naturally from their burrows with birds that were grounded by light attraction, rehabilitated, and released. All fledglings travelled over 2000 km southwest after leaving Kauaʻi until they reached the Inter-Tropical Convergence Zone and the frontal zone that separates the westward-flowing North Equatorial Current from the eastward-flowing North Equatorial Counter Current. At this point, birds still transmitting turned west, passing through Micronesia before eventually reaching the Philippines. Three birds entered the Lagonoy Gulf in the Philippines, 2 birds briefly entered the South China Sea and the waters off Taiwan, and 1 bird flew up to Japan before returning to the waters off the Philippines. The core use area within the wintering ground was characterized by higher temperatures, lower sea level anomaly, and higher chlorophyll *a* concentrations. While wild fledglings transmitted longer than rehabilitated birds, this was only weakly significant, and the fact that several rehabilitated birds made it to their first wintering grounds highlights the importance of rescue and rehabilitation efforts. The potential threats to birds over-wintering in this area include concentrated fishing activity in the Lagonoy Gulf, nocturnal squid fishing vessels across the region, marine pollution, and the impacts of climate change to the region's marine environment.

KEY WORDS: Tracking · Hawaiian petrel · Post-fledging · Rehabilitation · Kauaʻi · Hawaiʻi

1. INTRODUCTION

The ʻuaʻu, or Hawaiian petrel *Pterodroma sandwichensis*, is a *Pterodroma* petrel endemic to the Hawaiian Islands, where the main breeding populations are found on the islands of Kauaʻi, Maui, Lānaʻi, and Hawaiʻi Island (Pyle & Pyle 2017). On the island of Kauaʻi, which holds a third of the population, the species has suffered an estimated 78% decline between 1993 and 2013 (Raine et al. 2017a). The reason for these declines are manifold, and include collisions with powerlines (Cooper & Day 1998, Podolsky et al. 1998, Raine et al. 2017a, Travers et al. 2021), the impact of introduced predators such as cats *Felis catus*, black rats *Rattus rattus*, pigs *Sus scrofa*, and barn owls *Tyto alba* (Simons 1985, Raine et al. 2019, 2020b), and habitat modification within breeding colonies due to invasive plants and pigs

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(Duffy 2010, VanZandt et al. 2014, Raine et al. 2021). A small number of fledglings are also attracted annually to artificial lights, although this is not as important an issue as it is for another endangered seabird on Kaua'i, i.e. the 'a'o or Newell's shearwater *Puffinus newelli* (Reed et al. 1985, Telfer et al. 1987, Raine et al. 2017a). This combination of factors has led to the Hawaiian petrel being listed as 'Endangered' both under the IUCN Red Data List (Birdlife International 2018) and the Endangered Species Act (USFWS 1983).

While the impacts to the species on land are well documented, less is known about threats at sea. These presumably include marine threats that impact similar species of seabirds worldwide, including marine pollution (Sileo et al. 1990, Derraik 2002, Kain et al. 2016), overfishing (Ainley et al. 2014, Morra et al. 2019), and the effects of climate change and bycatch (Gilman et al. 2008). Understanding the marine distribution of this species at different life stages is therefore an important step in assessing which threats this species may be exposed to. Post-fledging movement patterns of Hawaiian petrels have not previously been described. To locate the first wintering grounds of Hawaiian petrels, we attached satellite transmitters to Hawaiian petrels fledging from Kaua'i.

Secondly, we provide an initial comparison between birds fledging naturally from their burrows and those that were rescued after being grounded by artificial lights, rehabilitated, and released from the Save Our Shearwaters (SOS) Program. SOS was created by the State of Hawai'i – Division of Land and Natural Resources (DLNR) – in 1979, became a non-governmental organization (NGO) in 2022, and is one of the longest-running seabird rescue programs in the world (Rodríguez et al. 2017a). It 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 seabird fallout season (late September–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 (Anderson 2019). Between 1979 and 2021, SOS processed 424 Hawaiian petrels (of which the vast majority were fledglings) — as well as over 32 000 Newell's shearwater fledglings.

One key knowledge gap for SOS is post-release survival of birds released after rehabilitation. 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 for Hawaiian petrel fledglings that pass through the program. 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, compromised waterproofing) (Rodríguez et al. 2017b). Despite such compromising factors, it seems reasonable to expect 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 (Fontaine et al. 2011, Gineste et al. 2017). A previous tracking study on fledgling Newell's shearwater rescued and rehabilitated by SOS showed that a proportion of these birds do survive post-release and successfully complete their post-fledgling migration to wintering grounds 2500 km to the southwest of Kaua'i (Raine et al. 2020a). Although these birds had a reduced survival rate compared to birds that had fledged without being attracted and grounded by lights, this highlighted the importance of SOS to the conservation of the Newell's shearwater. In this study, we evaluated post-release survival of the Hawaiian petrel by considering the transmission duration (as a proxy for survival) and movements at sea among fledglings recovered and released by SOS compared with birds that had fledged directly from their burrows without apparent incident. While our sample size in this study is small (limited due to funding constraints), this is an important first step in assessing the relative importance of SOS as a conservation action for this endangered *Pterodroma* petrel.

2. MATERIALS AND METHODS

We tagged 10 birds over 4 breeding seasons (2017 and 2020), with 1 bird tagged in 2017, 4 in 2019, and 5 in 2020. Tags were split between 4 birds collected by the SOS program ('SOS cohort') and 6 birds captured by hand at burrows ('wild cohort') located in a seabird management site called North Bog (Fig. 1).

2.1. Wild cohort

North Bog is located in the Hono O Nā Pali Natural Area Reserve (NAR) in northwestern Kaua'i which covers an area of 3578 acres (1448 ha) and is owned and managed by the State of Hawaii under its Native

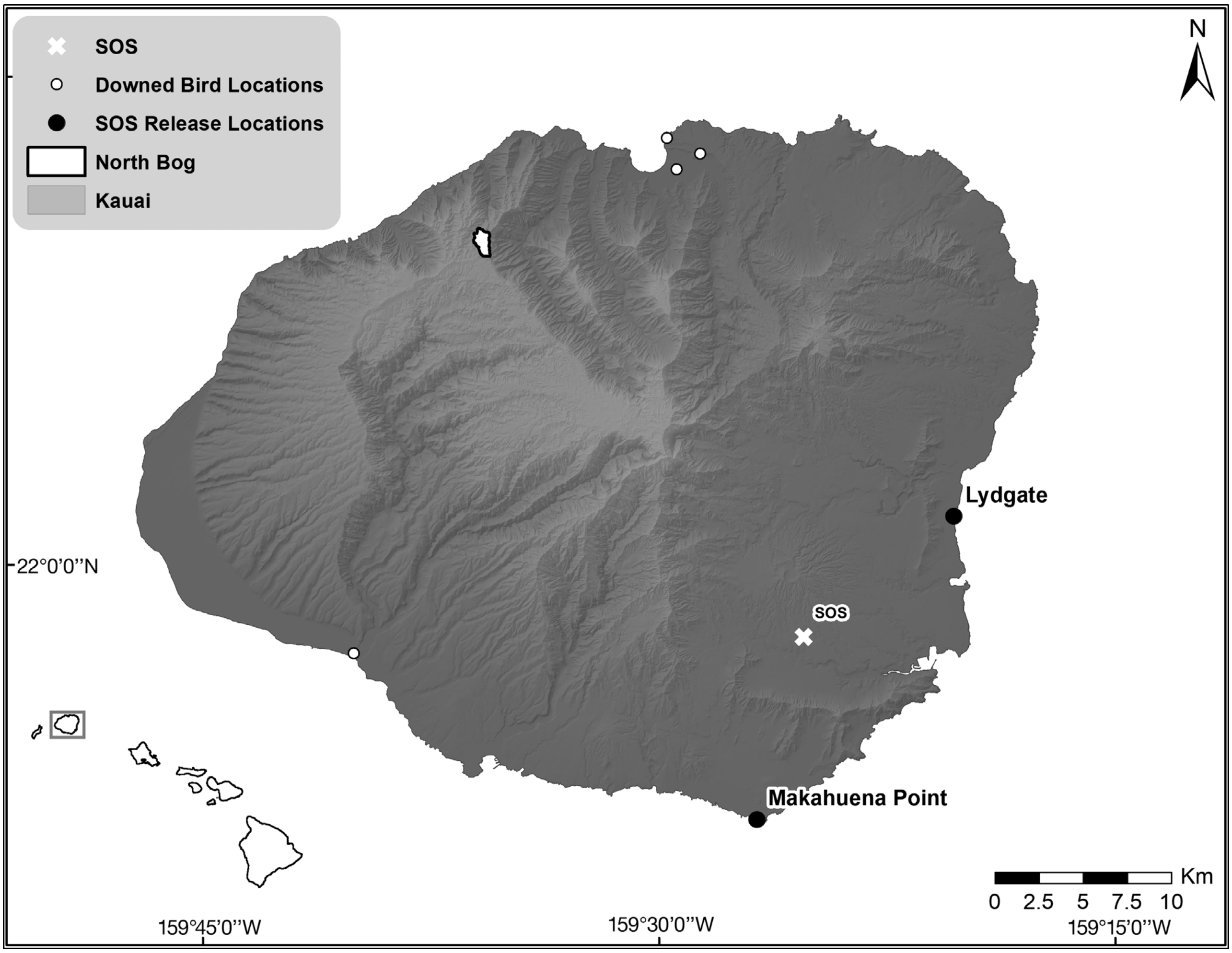

Fig. 1. Map of Kauaʻi, showing location of the North Bog colony where wild Hawaiian petrel fledglings were tagged, as well as the locations of grounded petrels tagged for this study and release locations for tagged rehabilitation birds (note 2 birds were found in the same location). SOS: Save Our Shearwaters headquarters at the time of the study

Ecosystem and Restoration Program (NEPM). The site holds one of the largest monitored colonies of Hawaiian petrels on the island of Kauaʻi (estimated at 905–1315 breeding pairs (Raine et al. 2023), with management consisting primarily of active predator control. A total of 279 Hawaiian petrel burrows are currently monitored annually at the site.

For tagging purposes, we selected only birds in burrows with wide entrances to reduce the risk of entanglement. Birds were only tagged when they were deemed to be within a few days of fledging (based on plumage and amount of down present at time of handling). 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 (size 3A). After measuring and banding, birds were held by experienced seabird handlers and their heads were covered by a light-weight 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 modified with the addition of 4 copper suture tubes, resulting in a tag weight of 11 g. The modified tags were the lightest and most depth-resistant units available and were 1.9 to 3.8% of petrel body mass (depending on the bird tagged), which is below the maximum recommended mass 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 Hawaiian petrel.

We acknowledge that the increase in cross-sectional area could, to some degree, have affected the hydrodynamics of Hawaiian petrel. However, as this species does not undertake deep dives during foraging (Adams & Flora 2010, Morra et al. 2019), this was of less concern than weight burden and balance. In anticipation of potentially long-distance flights, we preferred to attach the tags consistent with the bird's center of mass to minimize interference with flight, balance, and behavior (Healy et al. 2004, Vandenabeele et al. 2014). In the past we have successfully used this technique on breeding adults of the same species on both Kaua'i and Lāna'i with no impact on survival (Raine et al. 2017b, Raine & Driskill 2019). The same attachment method was used on Newell's shearwater fledglings in a previous SOS study (Raine et al. 2020a) and to track adult Hawaiian petrels back to their burrows on Hawai'i Island (Raine et al. 2022). Tags were programmed to transmit continuously every 60 s, with no off cycle. This sampling regime is recommended in tropical areas where there is available light for frequent recharge and greater temporal resolution (McDuie et al. 2015).

We employed the same technique in all 3 yr, with tags attached by the same individual (A. F. Raine) in all years. We used a suture-tape-glue attachment technique following Newman et al. (1999) and modified 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 centre of the tag would sit. We used 4 sterile surgical sutures (2-0 Prolene™ 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 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 snugly secured 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, which was of particular concern for birds tagged at burrows.

2.2. SOS cohort

We selected Hawaiian petrel fledglings from the SOS program for tagging if they met standard release requirements outlined in the SOS Operations Manual (Anderson 2019). All birds selected for tagging were birds that had been brought to the SOS headquarters for evaluation (i.e. we did not tag any birds that were released straight out to sea without an evaluation). 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. Birds also had to be able to consistently maintain their temperature above 100°F (ca. 38°C) and below 106°F (ca. 41°C) when housed on cold water for 8–10 h and have blood values (packed cell volume [PCV], total protein [TP] and glucose [BG]) within the normal range for the species (Work 1996, Anderson 2019). We did not tag birds determined to be 'marginal' (individuals with abnormalities that may impact survivability, despite meeting established minimum standards for release; Miller 2012), e.g. significant damage to non-critical 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 proportion of birds released by SOS each year, i.e. 0–2 individuals out of an average of 5.8 petrel fledglings received each year (avg. calculated from the last 5 yr: 2018–2022; M. Bache pers. comm.), are considered 'marginal.'

After handling and tag attachment, we introduced tagged birds to the SOS rehabilitation pool to assess attachments, monitor behaviour, and ensure that birds were waterproof. Birds were only released after they were confirmed to be waterproof. Based on weather conditions at the time of release (birds were released at the site where there was less rain and high winds that may have affected release) and prevailing wind (birds were released at the site where wind was blowing out to sea), we released all tagged fledglings according to SOS release protocols at 2 standard SOS release sites: Makahū'ena Point (south shore of Kaua'i) and Lydgate Beach (east shore of Kaua'i) (Fig. 1).

2.3. 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. 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. We therefore 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 more likely indicating a moribund condition preceding presumed mortality. We also compared a number of movement metrics between the 2 cohorts to assess whether there were any differences. Due to the small sample sizes, we used Mann-Whitney *U*-tests, and for comparisons that showed significance (alpha of 0.05), calculated effect size as Vargha-Delaney A. All statistical analyses were carried out in R Statistical software version 4.0.2.

2.4. Spatial and statistical analyses

All tags had the same sampling interval/duty cycle (60 s intervals continuous with no off cycle). Raw locational fixes of 1 and above were automatically retained. Locational fixes of the remaining classes (Z, A, B, or 0) were filtered using a Douglas Argos Filter (Douglas et al. 2012), on the Movebank website (www.movebank.org; Kranstauber et al. 2011). A distance threshold of 2 km was used to retain points, and a speed threshold of 50 km h^{-1} was used to filter points beyond the distance threshold, in conjunction with a turning angle tolerance of 25° within 3 consecutive points. Approximately 15% of outliers were removed from the data, with a total of 9725 filtered location fixes retained across all years.

To differentiate between locational fixes transiting to the wintering area near the Philippines Sea and those within the wintering area, a 1000 km buffer was delineated from the landmasses of the Philippines and Taiwan using the GSHHG global coastlines dataset (Wessel & Smith 1996). The resulting dataset was reduced to in order to investigate differences in habitat use at varying spatial scales; a series of utilization distributions were calculated using the *adehabitatHR* package in R (Calenge 2006), using the ‘ad-hoc’ method for bandwidth selection. We calculated 95 and 50% utilization distributions to represent broader active use and core use areas, respectively. Utilization distributions at these levels were calculated for locational fixes within the wintering area subset.

A total of 6 environmental variables were collected and averaged within 0.25° of each locational fix using the rerddapXtracto r package (Mendelssohn 2018). These were sea surface temperature, chlorophyll *a* concentration, sea surface level height anomaly, ocean depth, wind velocity in the *x* direction (zonal wind), and wind velocity in the *y* direction (meridional wind). Dynamic variables were captured at varying temporal scales to reduce potentially missing data and matched to the timestamp of each location. These variables were compared across utilization distributions using a series of random forest binary classification models that predicted which utilization distribution each locational fix belongs to.

In order to discriminate between locational fixes comprising the areas of core use and active use within the wintering area, a random forest classification model was built using the randomForest R package (Liaw & Wiener 2002). We utilized this approach due to the non-parametric nature, ability to account for widely varying patterns in the data, implicit measures of variable importances, and the ability of this approach to effectively identify the relative importance of multiple predictors in the presence of interactive effects. Locational fixes were inspected for those occurring over land masses and omitted. Environmental variables were assessed for collinearity using pairwise correlation tests, with no variables having a correlation coefficient > |0.70|. Missing data values among environmental variables were imputed using median values of respective predictor variables. The dataset was then divided into a training (80%) and test (20%) dataset using the caret package in R (Kuhn 2008). Random forest models were fitted by growing 1000 trees. Variable importance was assessed by global mean decrease accuracy. To account for unbalanced sample size, a subsample of 200 records from each stratum (core use area vs. active use area) was used in model fitting. The classification ability of the model was assessed by calculating the overall classification accuracy on the test dataset.

3. RESULTS

3.1. Tagging

In total, we tagged 6 wild fledglings from North Bog and 4 fledglings recovered by the SOS program. A seventh fledgling was tagged at North Bog but was subsequently killed and eaten by a cat a few days before it was due to fledge, highlighting the threat of introduced predators to Hawaiian seabirds. Among the 4 SOS fledglings, the average stay at the facility was 5 d (range 1–11 d). For wild fledglings, all fledged within 5 d of tagging. All SOS birds flew upon release and headed directly out to sea and all wild birds fledged and subsequently transmitted at sea. Therefore, all tagged birds (100%) survived immediate (24 h) post-fledging or release and were subsequently free-ranging at sea.

3.2. Post-release and post-fledging dispersal

All Hawaiian petrel fledglings (from both groups and all 3 yr) travelled over 2000 km southwest after leaving Kaua'i until they reached 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). At this point, birds still transmitting turned west, passed through Micronesia (via the Marianas, Carolines, and Marshalls), before eventually reaching the Philippines. Three birds entered the Lagonoy Gulf in the Philippines, 2 birds briefly entered the South China Sea and the waters off Taiwan, and 1 bird flew up to Japan before returning to the waters off the Philippines (Fig. 2). A core use wintering area was identified (based on a 50% fixed kernel density contour for all locations within the wider wintering area) consisting of a 70 km^2 area within the Philippines Sea which included the Luzon Strait and the Lagonoy Gulf (Fig. 3). Four (40.0%) of our tagged birds made it to the wintering area, all of which were from the wild cohort.

Also of interest are the final transmission locations for tag 179813, also from the wild cohort. The tag from this bird transmitted sporadically on land on the Philippines over a 94 d period between 30 December 2020 and 2 April 2021, with all locations between the towns of Mabuhay and Tongo-Bantigue, 44 km from the Lagonoy Gulf. The fate of the bird is unknown although clearly at the time it was deceased as this is not normal behavior for a *Pterodroma* petrel.

The core use area within the wintering ground was characterized by higher temperatures, lower sea level anomaly, and higher chlorophyll *a* concentrations (Table 1, Fig. 4), with a random forest classification model of locational fixes indicating these variables as the 3 most important in accurate discrimination between the groups according to mean decrease accuracy (MDA) (Fig. 5). Overall, the random forest was accurate in classifying between locational fixes between 50 and 95% contours, with an out-of-bag error rate of 8.0% (considered a reasonable approximation of predictions made with an independent data set; Cutler et al. 2007) and an overall classification accuracy on the test dataset of 92.4%.

3.3. Comparison between wild and SOS fledglings

Considering the small sample size (which was limited due to the cost of tags and funding availability), comparisons between the 2 groups were limited. For all tagged fledglings, we evaluated tag duration between wild fledglings and SOS fledglings. Although wild fledglings transmitted for longer than SOS birds, this was only weakly significant (wild: 69.5 ± 31.2 d, SOS: 30.0 ± 14 d; Mann-Whitney *U*-test, $U = 3$, $p = 0.067$, effect size = large [Vargha-Delaney A: 0.875]), with 83.3% of wild birds still transmitting after 1 mo, compared to 50.0% of the SOS fledglings. Additional movement metrics were compared between wild fledglings (all years combined) and SOS birds (all years combined). There was no difference in mean speed (km h^{-1}), mean distance travelled in a 72 h period, or maximum distance travelled in a 72 h period (Mann-Whitney *U*-test, $p > 0.05$). However, wild fledglings traveled further than SOS fledglings (wild: 17 209.0 ± 9954.1 km, SOS: 6114.5 km ± 3158.4 km; Mann-Whitney *U*-test, $U = 3$, $p = 0.067$, effect size = large [Vargha-Delaney

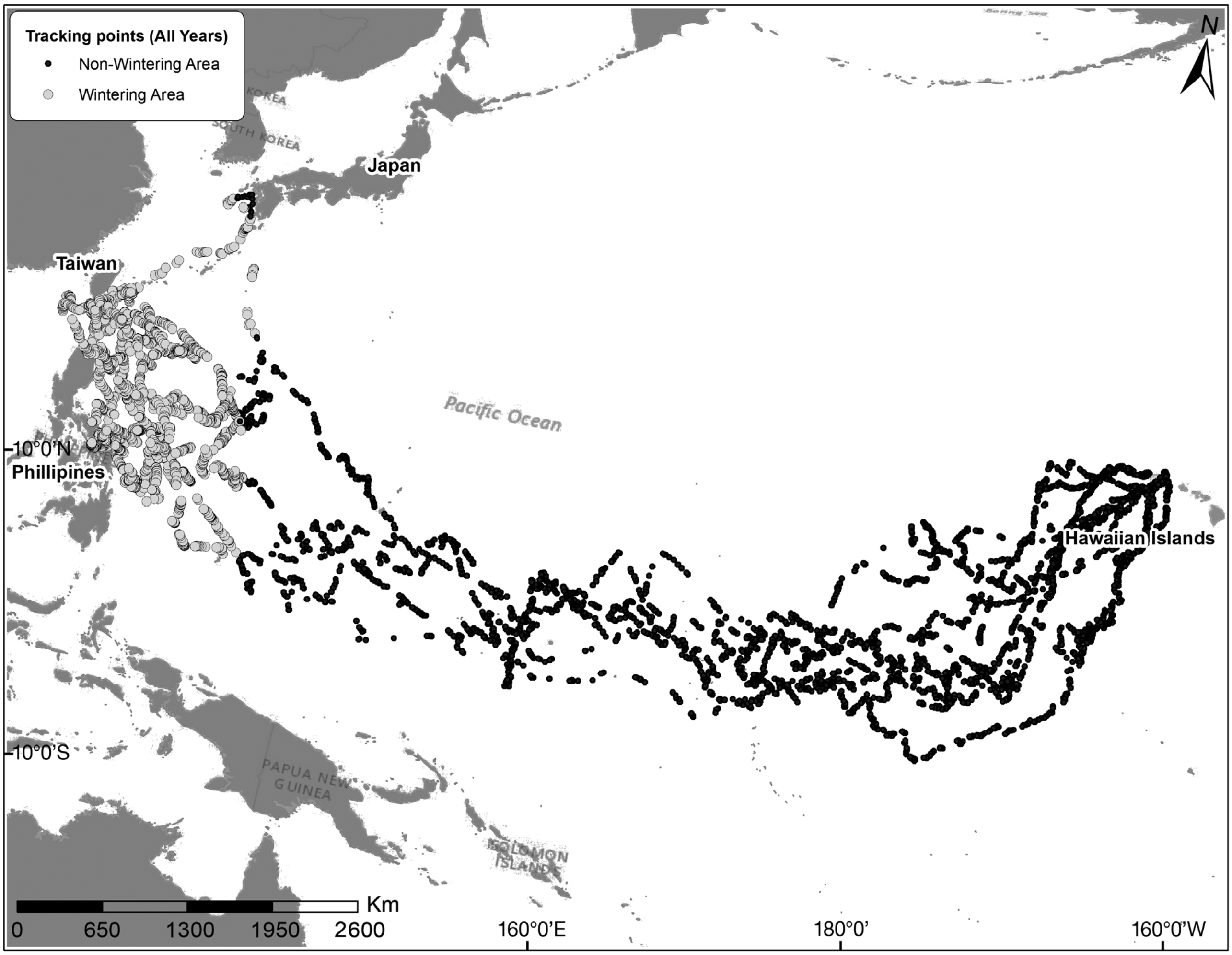

Fig. 2. All location fixes of Hawaiian petrel fledglings from all years and treatments. Gray dots: those within 1000 km of the Philippines and Taiwan coastlines (defined as the wintering grounds); black dots: those outside this distance (defined as transit points)

A: 0.125]) and had a larger maximum distance reached (wild: 6833.3 ± 2563 km, SOS: 3485.7 km ± 1987.7 km; Mann-Whitney *U*-test, $U = 3$, $p = 0.067$, effect size = large [Vargha-Delaney A: 0.125]), although these differences were also only weakly significant.

We also evaluated activity sensor patterns for all tagged birds. Of the 4 tagged SOS birds, 2 (50%) demonstrated uninterrupted ‘normal’ activity patterns until the tag ceased to transmit, 1 (25%) indicated decreased activity (i.e. stair-stepped pattern) prior to final transmission, and 1 (25%) exhibited a flat-line pattern consistent with limited activity and presumed morbidity. The latter 2 birds had the shortest transmission periods of the SOS cohort (13 and 25 d). Of the 6 tagged wild fledglings, 5 (83.3%) demonstrated uninterrupted ‘normal’ activity patterns until the tag ceased to transmit, and 1 (16.7%) exhibited a flat-line pattern consistent with limited activity and potential morbidity. In this case, the flat-lined bird had the shortest transmission period of the wild fledging cohort (22 d). There was, however, no significant difference between the 2 cohorts for activity sensor pattern (chi-squared test, $\chi^2 = 1.27$, df = 2, $p > 0.05$).

4. DISCUSSION

This paper describes the first wintering grounds of Hawaiian petrels fledging from Kaua’i, an area previously unknown for this species. Furthermore, birds tracked during this study represent the first published records of this species for the Marianas, Carolines and Marshalls, as well as Micronesia as a whole. Although all birds tracked were from Kaua’i,

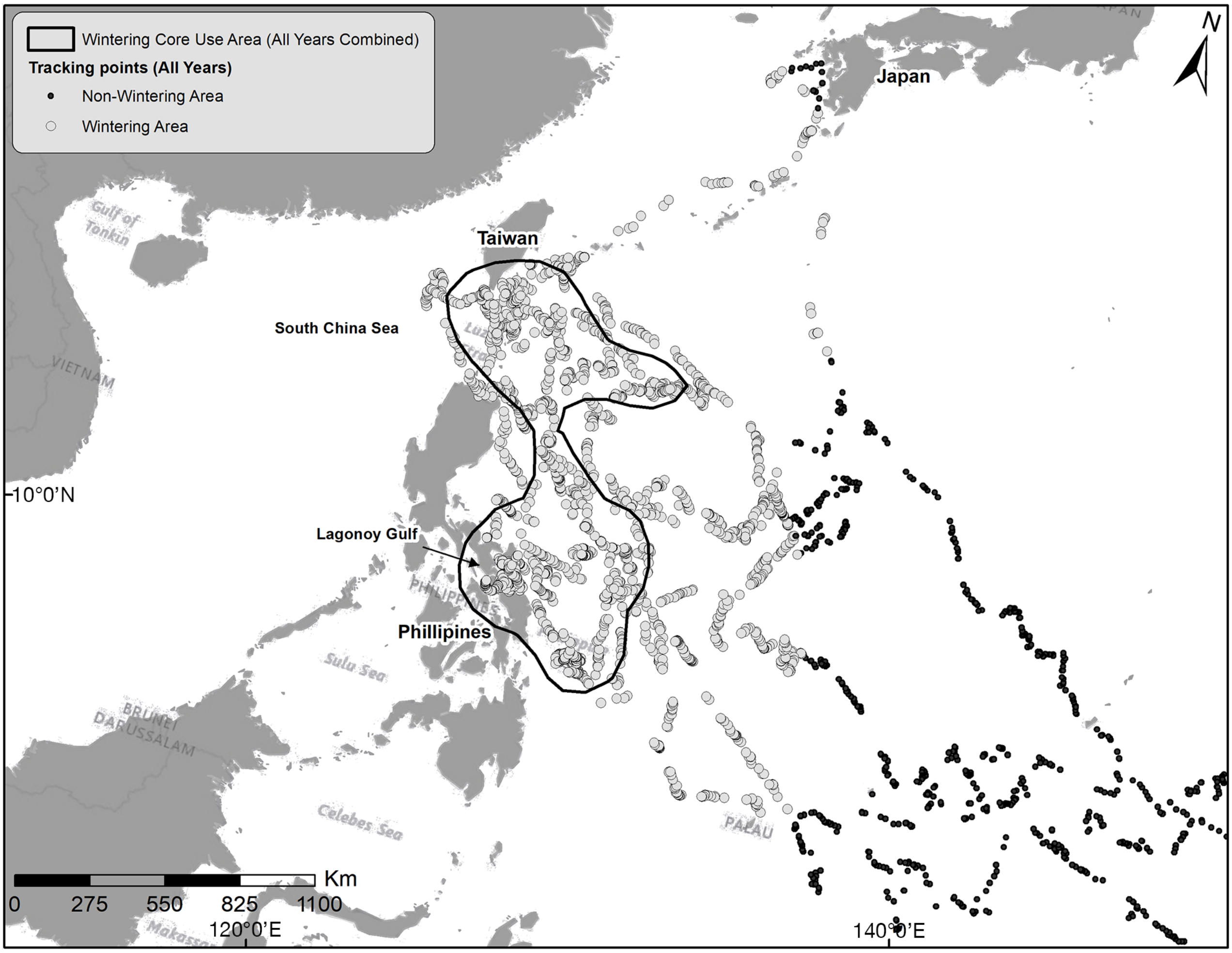

Fig. 3. Wintering area of Hawaiian petrel fledglings with core use area (50% UD) indicated by the black line. Gray dots: those within 1000 km of the Philippines and Taiwan coastlines; black dots: those outside this distance

it seems reasonable to assume that Hawaiian petrels fledging from other islands within the Main Hawaiian Islands also migrate to the same area, although further tracking studies are needed to confirm this.

Table 1. Summary statistics for environmental metrics in the core use (50% utilization distribution [UD]) vs. active use areas (95% UD) of Hawaiian petrel fledglings

Metric	Core use (50% UD) Mean	Core use (50% UD) SD	Active use (95% UD) Mean	Active use (95% UD) SD
Sea.Surface.Temperature (°C)	27.04	1.51	26.99	2.48
Sea.Level.Anomaly (m)	0.00	0.09	0.04	0.12
Wind.X (m s^{-1})	−5.83	1.64	−5.50	2.44
Wind.Y (m s^{-1})	−3.90	2.43	−3.29	2.92
Depth (m)	−3829.99	2153.63	−4367.81	1692.98
Chlorophyll.A (mg m^{-3})	0.13	0.17	0.11	0.09

The Philippine Sea is clearly important to birds in the first few months after leaving Kaua'i, particularly the area around the Lagonoy Gulf and Luzon Strait. These wintering grounds are different from those of adult birds breeding in the Hawaiian Islands. Data from 2 adult birds tracked from the island of Lāna'i showed that they headed south-east towards the equator and utilized the Pacific North Equatorial Current outside the breeding season (VanZandt 2012), which was similar to the wintering distribution of birds tracked from Kaua'i (A. F. Raine unpubl. data).

The Philippines is a region of high marine productivity and is well known as a marine biodiversity hotspot (Carpenter & Springer 2005), being part of

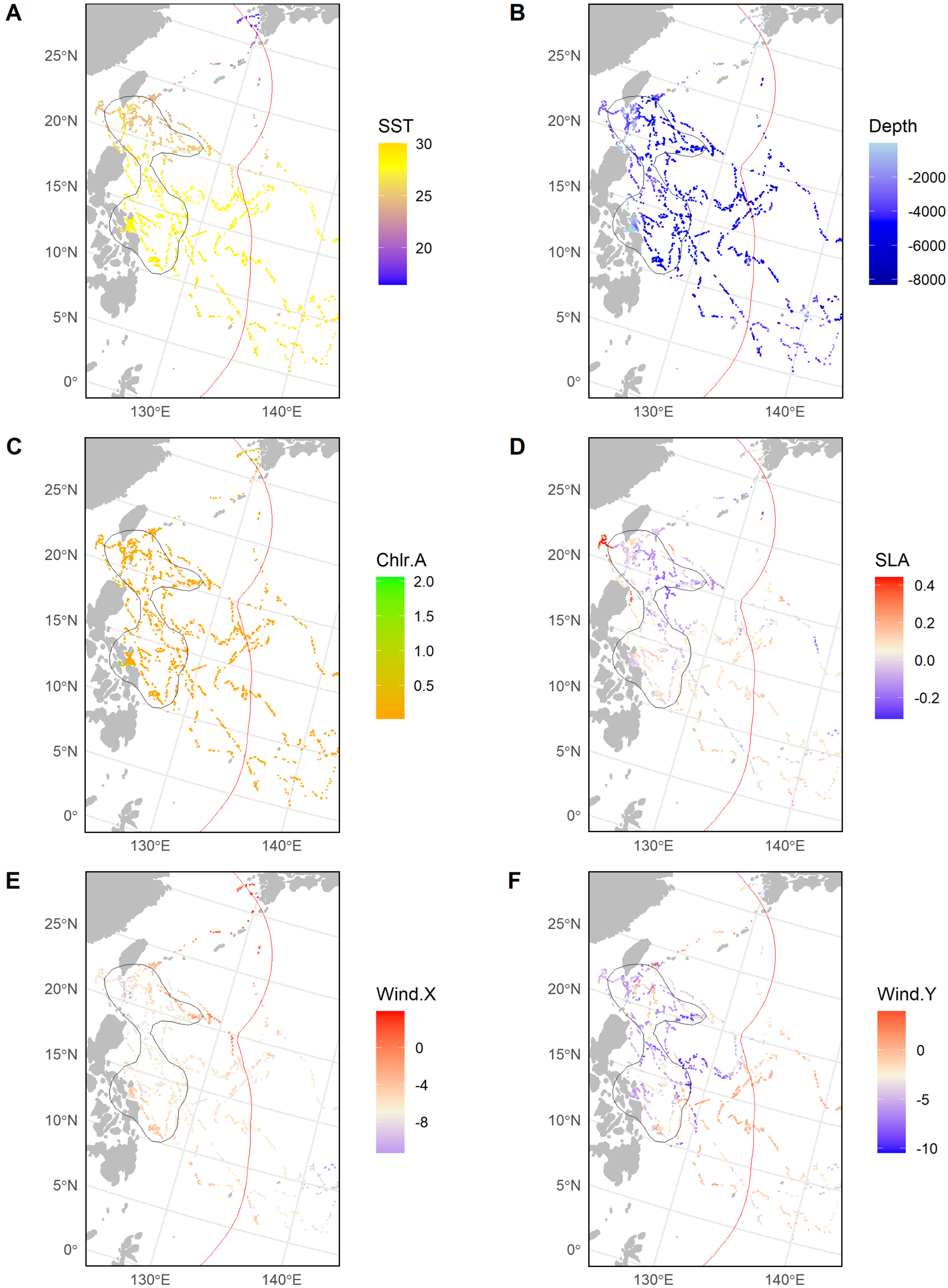

Fig. 4. Environmental variables at locational fixes within the wintering area of Hawaiian petrel fledglings. Red lines: wintering area boundary; black lines: core use areas within the wintering area. SST: sea surface temperature; Chlr.A: chlorophyll *a*; SLA: sea level anomaly; Wind.X: wind velocity in the *x* direction (zonal wind), Wind.Y: wind velocity in the *y* direction (meridional wind)

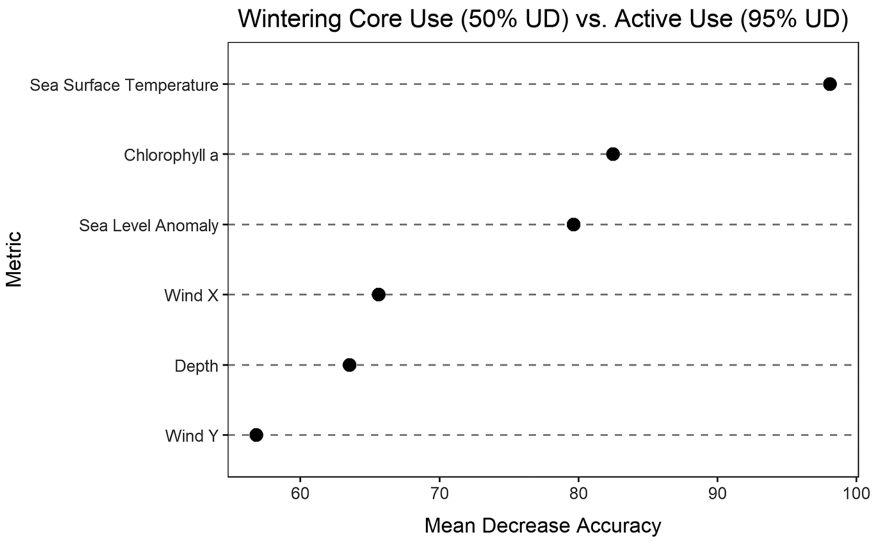

Fig. 5. Global variable importance ranking by mean decrease accuracy of environmental metrics used to classify location fixes of Hawaiian petrel fledglings into 50 or 95% utilization distributions (UDs) within the wintering area (core use vs. active use)

the Coral Triangle. Fish diversity is very high in the region, which is important for numerous species of large and small pelagics. The Philippines Pacific Seaboard is a known migration route for various tuna species (including yellowfin *Thunnus albacares*, bigeye *T. obesus*, skipjack *Katsuwonus pelamis*, eastern little *Euthynnus affinis*, frigate *Auxis thazard* and bullet tuna *A. rochei*), as they utilize favorable currents such as the North Equatorial Current (Nepomuceno et al. 2016). Likewise, the region represents important spawning grounds for tuna and other predatory fish. The Philippines is also a hotspot for sardines (having one of the highest diversities of sardine species in the world; Whitehead 1985), which peak in productivity in the latter half of the year (when Hawaiian petrel fledglings arrive) (Dalzell et al. 1990). The wider region is rich in multiple species of squid (Hernando & Flores 1981), including the Japanese common squid *Todarodes pacificus*, which has its peak spawning period in autumn and winter (Kidokoro et al. 2010) and smaller fish species such as mackerel, herring, and goatfish (Clarito & Suerte 2021). This high productivity is presumably why Hawaiian petrel fledglings are concentrating in this area, as they are known to feed extensively on certain squid species and utilize predatory fish such as tuna to force prey items up to the surface to feed upon (Simons 1985, Wiley et al. 2012, Morra et al. 2019).

Because of this, the area is also a major fishing ground and is thus heavily fished by artisanal and commercial fisheries (Hernando & Flores 1981, Barut et al. 2004, Clarito & Suerte 2021). Indeed, it is estimated that at least 60 percent of the human population of the Philippines is dependent on fisheries, either for food or livelihood (Burke et al. 2011, Eluriaga et al. 2019). Fish such as sardines are some of the most important sources of protein for Filipinos, and as such fish stocks are heavily exploited (Willette et al. 2011). The core wintering grounds identified for Hawaiian petrel also correspond to some of the areas with the highest landings by fisheries (Olaño et al. 2018). Catch composition within the region is dominated by both small pelagics (such as sardine) and large pelagics (such as tuna), and it has been noted that the mean standard length of several species caught within these fisheries is less than that at first maturity (Guanco et al. 2009), which would have obvious impacts on long-term sustainability. The same is true for some demersal species, such as goatfish (Clarito & Suerte 2021). The region has also seen declining catches in recent years, presumably due to overfishing (Olaño et al. 2018). Night fishing for squid using bright lights is also a major fishery in the Philippines (Hernando & Flores 1981) as well as further north off the coast of Japan, South Korea, and China (Bower & Ichii 2005, Sakurai et al. 2013) — areas the petrels also used. These squid fisheries not only remove huge quantities of squid (some of which are major prey species for Hawaiian petrel), but also operate at night using extremely bright lights (Court 1980). As Hawaiian petrels are prone to light attraction, this could be a source of significant mortality in first-year Hawaiian petrels, either by attracting birds and grounding them on boats or by increasing the chances of bycatch. While bycatch has not been previously identified as a conservation threat for this species, the transmission of one of the tags from this study on land near the Lagonoy Gulf for several months allows for some speculation that the bird could have been caught by a fisherperson and the tag kept afterwards (although the bird could also have been found dead and the tag collected).

As well as the impact of fisheries in the region, other conservation concerns within the region are worth discussing. The Philippines is considered to have the second-largest area of threatened reef in the world (after Indonesia), due to a combination of overfishing, watershed-based pollution, and coastal development (Burke et al. 2011). This is compounded by the looming issues of climate change which could cause long-term damage to the marine ecosystem of the region (Burke et al. 2011, Willette et al. 2011) and has already begun to manifest in the form of coral bleaching. While coral bleaching has not been reported for the core wintering area identified in this study, it has been reported at a high level in other areas across the Philippines (Arceo et al. 2001, Licuanan et al. 2019). This will have serious ramifications for marine life across the region, which could have knock-on effects on Hawaiian petrel. Petrels foraging near the Philippine coast are also likely to be exposed to high levels of micro- and macro-plastic marine debris compared to the open equatorial Pacific (Jambeck et al. 2015, Uchida et al. 2016). While petrels are not as heavily impacted by plastic ingestion as larger seabirds such as albatross, recent studies have suggested that microplastic ingestion can reduce survivorship and fertility in smaller procellariids (Hutton et al. 2008, Lavers et al. 2014, Biamis et al. 2021), and plastic debris are regularly found outside Hawaiian petrel burrows on Kaua‘i during the breeding season (A. F. Raine & J. Rothe pers. obs.). Recent studies have ranked the Philippines in the top 5 sources of plastic marine debris globally with 0.28–0.75 million metric tons in 2010, and that number is predicted to rise (Jambeck et al. 2015).

The results of this study should also be considered in terms of existing population estimates for Hawaiian petrel. Widely used historical and contemporary population estimates for the species are those developed from at-sea studies by Spear et al. (1995) and Joyce (2013). While these are important sources of data (and at the time they were published represented the best available data), they were created using at-sea transects that focused on a wide swath of ocean between Hawaii and the western seaboard of North America. Without the benefit of tracking data from studies such as ours, it was not clear whether these at-sea surveys captured the bulk of the Hawaiian petrel population. Based on the results of our study (and our previous study assessing the first wintering grounds of the Newell's shearwater; Raine et al. 2020a), it is evident that these at-sea surveys would have missed almost all of the fledglings for Kaua‘i (and quite possibly those fledging across the entire Hawaiian archipelago). Furthermore, tracking data showing the foraging trips of breeding adults and adults during the winter show that the area covered by these original transects miss a significant proportion of adults too (VanZandt 2012, A. F. Raine unpubl. data). Therefore, population estimates presented in these 2 studies should be viewed in this context and be considered an under-estimate of the true population size. Additional work is needed to obtain true population estimates for the species (potentially using land-based counts of birds transiting to breeding colonies or habitat suitability models combined with data from observational surveys).

A second aim of our study was to assess whether petrel fledglings that are attracted to artificial lights on their first flight out to sea, become grounded and are subsequently rescued, rehabilitated, and released, survive this process. While we only had a small sample size, we feel these initial results are an important first step to assessing the effectiveness of rehabilitation. Our results demonstrate that a proportion of rehabilitated birds do indeed survive after release. However, there appeared to be an impact on survival rates of this cohort of birds, with wild fledglings transmitting for longer than SOS birds and travelling further. These apparent differences may be caused by a number of reasons, including undetected injuries or increased exposure to disease or parasites (Rodríguez et al. 2017b). 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, indicating that their natural dispersal patterns were not altered by the rehabilitation process.

These results are similar to our findings with a much larger sample size of rehabilitated Newell's shearwater fledglings on Kaua‘i (Raine et al. 2020a). Recent changes in protocol at SOS — based on the results of our Newell's shearwater study — have resulted in fewer birds being directly released after recovery. Release criteria were strengthened so that even birds with negligible abnormalities (e.g. small amount of dirt on plumage) are brought into the facility and receive at least 1 d of supportive care. This change will hopefully increase survival rates of these birds further as it allows for more recuperation after grounding and a greater span of time for staff to assess the birds for more difficult-to-detect injuries. It is also important to note that grounded birds not recovered by SOS are highly unlikely to survive due to a wide range of factors including depredation by introduced predators (such as cats or dogs), being run over, 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 overall conservation efforts for this species, and its maintenance, in conjunction with a renewed focus on reducing light pollution on the island of Kaua'i, will benefit this endangered seabird species.

This study has identified the first post-fledging wintering grounds for the Hawaiian petrel. Future work should concentrate on tracking fledglings from other Hawaiian islands to see whether birds from other populations overwinter in the same area, as well as attempting to track birds for longer periods of time to discern what they do after the first few months at sea. Additionally, tracking more birds being released from SOS (as well as other rehabilitation centres in the Hawaiian archipelago) will build upon our understanding of the effectiveness of rescue efforts. Furthermore, as the region where the birds are migrating to appears to have multiple serious conservation challenges, it would be prudent to collaborate with partner organisations in the Philippines, Japan, and South Korea to assess what steps could be taken to protect Hawaiian petrel fledglings whilst they are in the region.

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