

Technical Report HCSU-078

# ACOUSTIC SURVEYS OF HAWAIIAN HOARY BATS IN KAHIKINUI FOREST RESERVE AND NAKULA NATURAL AREA RESERVE ON THE ISLAND OF MAUI

Christopher M. Todd<sup>1</sup>, Corinna A. Pinzari<sup>1</sup>, and Frank J. Bonaccorso<sup>2</sup>

<sup>1</sup>U.S. Geological Survey, Pacific Island Ecosystems Research Center, Kilauea Field Station,

P.O. Box 44, Hawai`i National Park, HI 96718 <sup>2</sup>Hawai`i Cooperative Studies Unit, University of Hawai`i at Hilo, Pacific Aquaculture and Coastal Resources Center (PACRC), P.O. Box 44, Hawai`i National Park, HI 96718

> Hawai`i Cooperative Studies Unit University of Hawai`i at Hilo 200 W. Kawili St. Hilo, HI 96720 (808) 933-0706



July 2016



UNIVERSITY of HAWAI'I® HILO This product was prepared under Cooperative Agreement G12AC20054 for the Pacific Island Ecosystems Research Center of the U.S. Geological Survey.

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#### ABSTRACT

The Kahikinui Forest Reserve and the adjoining Nakula Natural Area Reserve (KFR-NNAR) was established in 2011 as a conservation area on the leeward slope of Haleakalā Volcano on the island of Maui to protect unique natural features and endangered species including the Hawaiian hoary bat, Lasiurus cinereus semotus. We recorded bat vocalizations from July 2012 to November 2014 using automated echolocation detectors at 14 point locations in the KFR-NNAR. Our study area included remnants of recovering mesic montane forest with interspersed grasses (1,250–1,850 m elevation, hereafter called "forest") and xeric subalpine shrubland plant communities (1,860-2,800 m, hereafter called "shrubland"). Monthly detections of Hawaiian hoary bats, Lasiurus cinereus semotus, within the KFR-NNAR identified areas of high and low detection probability as well as foraging activity. Sixty per cent of all detector-nights had confirmed bat vocalizations and included detections in every month of the study. Monthly detection probability values were highest from July to November 2012; these values were significantly greater than values measured in any month thereafter. Pooled values of detection probabilities, mean pulses/night, percentage of nights with feeding activity, and acoustic detections all were greater in the recovering forest zone than corresponding values from the shrublands. Our data provide baseline levels of hoary bat echolocation activity that may be compared with future studies in the KFR-NNAR relative to success criteria for Hawaiian hoary bat habitat restoration.

#### INTRODUCTION

Wind energy is among the alternative energy sources in Hawai`i undergoing rapid expansion. In 2008 the legislature of the State of Hawai`i passed an energy initiative, Act 207, to reduce dependence on imported oil consumption with a goal of producing 70 percent of its energy use for electricity and transportation as clean, renewable energy by the year 2030 (Hawai`i revised statutes 2015). Six wind energy facilities are currently operational on the islands of Hawaii (n = 3), Maui (n = 3) and Oahu (n = 2), and new facilities are proposed for development across the state. Unfortunately, wind farm developments pose a risk of incidental take for some threatened and endangered species. In 2012, an estimated 888,000 bat and 573,000 bird fatalities occurred at wind-energy facilities across the United States (Smallwood 2013). Endangered species experiencing incidental take from wind facilities in Hawai`i (State of Hawai`i 2015a and b) include the Hawaiian petrel (*Pterodroma sandwichensis*), Hawaiian goose (*Branta sandwichensis*), Hawaiian short-eared owl (*Asio flammeus sandwichensis*), and the Hawaiian hoary bat (*Lasiurus cinereus semotus*).

This report uses echolocation calls as an indication of activity of Hawaiian hoary bats in the Kahikinui Forest Reserve and adjoining Nakula Natural Area Reserve (jointly referred hereafter as KFR-NNAR). These data provide a baseline of monthly presence and foraging activity. KFR-NNAR serves as a conservation area to offset take of endangered bats and birds resulting from the wind energy industry in Hawai`i (State of Hawai`i 2015b). A management plan for the KFR-NNAR is improving 8,000 acres of habitat for seabirds and bats, through fencing for exclusion of non-native herbivores, restoration of native vegetation, weed control, and predator removal (State of Hawai`i 2015b). Quantifying the net benefit for hoary bats requires that baseline occupancy and habitat-use surveys be conducted at the beginning of restoration efforts (DLNR 2011, 2015). Subsequent surveys may be compared to our baseline data to evaluate the effectiveness of habitat restoration efforts.

The Hawaiian hoary bat is widely distributed across all of the major volcanic islands of the Hawaiian Archipelago (Gorresen *et al.* 2013). It is Federally and State listed as an endangered species due to apparent population declines, lack of knowledge concerning distribution, and habitat loss (USFWS 1998). It roosts in both native and non-native trees and primarily feeds on moths and beetles (Todd 2012) which it hunts in flight across a wide array of habitat types and plant communities from sea level to at least 3,600 m above sea level (Bonaccorso *et al.* 2015).

We conducted automated acoustic surveys of hoary bats at 14 stations in the KFR-NNAR from July 2012 to November 2013 and from May 2014 to November 2014. Our objectives were to evaluate 1) seasonal occurrence and distribution of bats through more than one annual cycle, 2) identify areas of high, low, or zero detection probability, and 3) identify foraging areas.

#### **M**ETHODS

#### **Study Area**

The KFR-NNAR consists of 1,539 ha on the leeward slope of Haleakalā Volcano of the island of Maui and spans elevations from approximately 1,200 to 2,800 m (Fig. 1). Mean monthly rainfall averaged from two weather stations within the HaleNet climate network located on the leeward slope of Haleakalā nearby KFR-NNAR was 14.4 mm ± 5.4 SE in 2012, 44.7 mm ± 13.0 SE in 2013, and 94.2 mm ± 21.3 SE in 2014 (T. Giambelluca personal communication and Longman et al. 2015). Above 1,850 m, vegetation is comprised of native shrubland that is primarily pūkiawe (Styphelia tameiameiae) and 'ohelo (Vaccinium reticulatum), interspersed with mixed grasses (Price et al 2012 and Fig. 2A). Lower on the mountain and particularly below the 1,700 m cloud inversion boundary (Giambelluca et al. 2013), the vegetation consisted of large expanses of alien grasses and remnants of mesic forest that before ungulate removal was restricted to steep gulches (Loope 2000, Jacobi pers. communication, and Fig. 2B). However, recovery of native vegetation is progressing since fence construction and removal of ungulates in 2012, transforming the landscape from Kikuyu grass (*Pennisetum clandestinum*) to forest (Fig. 3A and B). The forest is comprised of koa (Acacia koa), `ōhi`a-lehua (Metrosideros polymorpha), and pilo (Coprosma ochracea) with understory components of hapu`u (Cibotium glaucum), uluhe (Dicranopteris linearis), `ākala (Rubus hawaiiensis), and `ōlapa (Cheirodendron trigynum (Fig. 2C and D).

We deployed monitoring stations both in recovering mesic montane forest (1,250–1,850 m elevation, hereafter called "forest") and xeric subalpine shrubland plant communities (1,860–2,800 m, hereafter called "shrubland") within (Table 1).



Figure 1. Hawaii (inset) and the Nakula Natural Area Reserve (NNAR) and the Kahikinui Forest Reserve (KFR) on the southeast slope of Halekalā Volcano.



Figure 2. Typical vegetation near bat detection stations in KFR-NNAR. (A) Native shrubland ( $\sim$ 2,500 m). (B). Alien grasses with sparse koa-`ohi`a forest in gulches ( $\sim$ 1,800 m). (C and D) Open koa-`ohi`a forest with alien grassland ( $\sim$ 1,600 and  $\sim$ 1,300 meters respectively). Photos by C. Pinzari.



Figure 3. (A) Typical habitat ~1,640 meters before ungulate removal, July 2012. (B) Koa regeneration around the same detector station 2 years after ungulate removal, June 2014. Photos by C. Pinzari.

#### **Echolocation Call Analysis**

We recorded echolocation calls with Song Meter 2 BAT+ (SM2BAT+) detectors equipped with high frequency microphones (SMX-US, Wildlife Acoustics, Inc., Maynard, Massachusetts). Fourteen SM2BAT+ units were distributed throughout the KFR-NNAR at elevations ranging from 1,256 to 2,728 m (Fig. 4; Table 1). Nine units were deployed from July/August 2012 to November 2014. Five additional units recorded simultaneous bat and seabird calls from separate microphone ports from March to October 2013. Recording locations were chosen to represent the range of habitats and extremes of elevation in KFR-NNAR (Table. 1). All units recorded continuously from one hour before sunset to one hour after sunrise and were powered by six v/36 amp-h batteries connected to 6.4 w/8–10 v/950 milliamps. ThinFilm Solar Panels (Silicon Solar, Inc., Bainbridge, New York). The microphones for all recording units were elevated 3 m above ground on poles and protected from wind and moisture inside polyvinyl chloride tubing but still providing omnidirectional sensitivity. Setting configurations of SM2BAT+ units follow Gorresen *et al.* (2015) as suggested for optimal call quality and background noise minimization (Appendix 1). Call files with associated dates and times were stored on memory cards in the SM2BAT+ units and were downloaded every two to three months.



Figure 4. Recording locations in KFR-NNAR. Circles represent detectors recording from July 2012 to November 2014, triangles were recording from March–October 2013. Elevation contours are in m.

Station ID	Location	UTM Easting	UTM Northing	Elevation (m)	Habitat	Survey Period*
NAK4	NNARS	788643	2287729	1256	Koa-`Ohi`a mesic forest/alien grassland	1
NAK3	NNARS	788321	2287992	1389	Koa-`Ohi`a mesic forest/alien grassland	1
KFRL3	KFR	789659	2288692	1478	alien grassland/Koa-`Ohi`a mesic forest	1
NAK2	KFR	787919	2288546	1622	alien grassland/Koa-`Ohi`a mesic forest	1
KFRL2	NNARS	789518	2289050	1640	alien grassland/Koa-`Ohi`a mesic forest	1
NAK1	NNARS	787845	2289056	1822	alien grassland/Koa-`Ohi`a mesic forest	1
KFRL1	KFR	789480	2289509	1834	alien mesic grassland	1
KAH05	KFR	793046	2289783	1861	native mesic shrubland/Koa-`Ohi`a fores	st 2
KAH28	KFR	789795	2290047	2020	mixed mesic grassland/shrubland	2
KAH31	KFR	791140	2290424	2056	native mesic shrubland/Koa-`Ohi`a forest	2
KAH09	KFR	791512	2290689	2081	native mesic shrubland	2
KAH32	KFR	790855	2291384	2472	native dry shrubland	2
KFRH2	KFR	787794	2290532	2472	native dry shrubland	3
KFRH1	KFR	787802	2291192	2728	native dry shrubland	3

Table 1. Location a	attributes of	ultrasonic	recorders i	in KFR	-NNAR.
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Survey Period \* 1 = July 2012 to November 2013, plus April to November 2014; 2 = March 2013 to October 2013; 3 = September 2012 to November 2013, plus April to November 2014.

We processed echolocation files (Appendix 1) in Kaleidoscope Version 1.1.22 (Wildlife Acoustics 2013). We used the automated detection feature in call Viewer 18 (Skowronski and Fenton 2008) to tabulate the number of sound pulses emitted and the number of call events (defined as a sequence of ultrasonic pulses over a time span of milliseconds recorded from bats passing a microphone). Feeding buzzes, the series of echolocation pulses with an accelerated repetition rate and a decrease in inter-pulse intervals, indicative of prey-capture attempts (Britton and Jones, 1999 and Griffin *et al.*, 1960), were identified in Song Scope (Wildlife Acoustics). Recognizers built from previous Hawaiian hoary bat recordings were used to identify feeding buzzes and then visually verified in Song Scope and Sonobat (J. Szewczak, Arcata, California).

Recording locations were divided into forest and shrubland zones, each sampled by seven recording units (Table 1). Activity patterns were assessed for each location to identify high use areas and feeding sites. The hourly number of pulses and feeding buzzes recorded from sunset to sunrise were summed for each elevation class and averaged by the number of detector stations present. We also tabulated the mean number of pulses/night, the percentage of nights with feeding buzzes, and the percentage of nights with echolocation calls for each detector.

We defined high activity events as occasions having exceeded the 3<sup>rd</sup> quartile of recorded pulses/night. High activity events were coded as 1 in a matrix of sites and nights. Zeros were assigned for nights below the activity threshold (Goressen *et al.*, 2008). We transposed the standard detection history matrix following Weller and Baldwin (2011) such that the matrices were populated by presence or absence. Detection probability ( $\rho$ ) and 95% confidence intervals were calculated using Unmarked (Fiske & Chandler 2016; version 0.10–4) in R (R Core Team 2012). Baseline estimates of  $\rho$  and 95% confidence intervals were calculated monthly for forest and shrubland from July 2012 to November 2014 and annually for each of the three years. We compared monthly differences of  $\rho$  among the two elevation zones using a z-test conducted in R (R Core Team 2012) at an alpha level of p ≤ 0.05.

#### **Vegetation surveys**

We collected data on vegetative cover around recording stations using both ground surveys and satellite imagery from ArcGIS. Vegetation surveys (Appendix 2) were conducted within a 50 m radius for seven detector stations. Diameter at breast height (DBH) for trees was measured using a Spencer loggers tape (U.S. Tape, Pennsburg, Pennsylvania). Tree height was measured using an electronic clinometer (Haglof, Långsele, Sweden). Canopy density was measured using a convex spherical crown densitometer (Forestry Suppliers, Jackson, Mississippi). Vegetation surveys for two high elevations sites were not conducted because the vegetation lacked trees  $\geq$  2 m and was primarily comprised of small pūkiawe and `ōhelo shrubs. Vegetation was examined further from satellite imagery over a 100 m radius of all detector stations. We then used an unsupervised classification cluster analysis in ArcGIS 10.2 (ESRI 2014), and categorized vegetation as tree cover, grass cover, or no vegetation (Appendix 3).

#### RESULTS

#### **Echolocation Activity and Foraging Behavior**

Across all sites, we recorded 526,807 echolocation calls during 7,688 detector nights with a mean rate of 68.5 bat pulses/detector-night (range 0–25,385). Sixty percent of detector-nights had  $\geq$  1 pulse, the median was 6, and the 3<sup>rd</sup> quartile was 37 (Fig. 5). Twenty-five percent of

detector-night had activity greater than the 3<sup>rd</sup> quartile threshold. The nine detectors in the NNAR were operational during 97% of our sampling effort over a span of 25 months. The five KFR sites were operational during 92% of our sampling schedule over nine months.



Figure 5. Frequency distribution of the number of echolocation pulses per call event across all detector stations from July 2012–November 2014.

Feeding buzzes were recorded across all elevations indicating that feeding commenced at approximately sunset (Fig. 6A and B). Generally, more call events and feeding buzzes were recorded in the forest zone (< 1,850 m) than in the subalpine shrubland (Fig 6. A and B, Table 2). Echolocation call frequency distribution in the forest was bimodal with a major peak 2 hr after sunset and a secondary peak ~6 hr after sunset (Fig. 6A). Pooled recordings of feeding buzzes in the forest zone showed activity peaks 2 to 7 hr after sunset (Fig. 6B). Echolocation calls in the alpine zone peaked ~2 hr after sunset and diminished sharply thereafter with very few calls recorded beyond 4 hrs after sunset (Fig. 6A and B).



Figure 6. Hourly mean number of pulses and feeding buzzes at all recording stations

There were significant differences between forest and shrubland (Table 2 and Figure 7) in mean pulses recorded per night (forest:  $94.7 \pm 48.5$ , shrubland:  $23.9 \pm 13.2$ ; t = -3.8, df = 7, p = 0.01), the percent of nights with feeding buzzes (forest:  $7.0 \pm 5.7$ , shrubland:  $1.1 \pm 0.9$ ; t = -2.7, df = 6, p = 0.03) and the percentage of nights with bat detections (forest: 68.1 percent  $\pm 13.9$  percent, shrubland: 47.7 percent  $\pm 11.7$  percent; t = -3.0, df = 12, p = 0.01).

Station ID	Mean pulses/ night	percent nights with feeding buzzes	percent nights with detections
		Forest	
NAK4	95	1.25	71
NAK3	165	8.61	83
KFRL3	130	3.60	59
NAK2	74	6.95	43
KFRL2	51	9.72	68
NAK1	122	17.41	82
KFRL1	26	1.39	71
		Shrubland	
KAH05	13	0.50	50
KAH28	37	1.46	69
KAH31	8	0.40	45
KAH09	15	1.18	56
KAH32	19	0.00	36
HFRH2	34	1.97	39
KFRH1	41	2.28	39

Table 2. Summary of bat activity for detector stations in each elevation region.



Figure 7. Graded classification of the mean number of echolocation pulses/detector-night at 14 recording stations. The base map is from World View 2 Imagery, http://www.digitalglobe.com

### **Detection Probability**

Detection probability when pooled into monthly intervals for all detector stations ranged from 0.07 to 0.92, SE  $\pm$  0.02 (Fig. 8). July (p = 0.92) and August (p = 0.78) of 2012 accounted for the highest detection probabilities during the survey and mean probability thereafter through November 2014 was 0.27 (range 0.07–0.56, SE  $\pm$  0.02).



Jul-12 Sep-12 Nov-12 Jan-13 Mar-13 May-13 Jul-13 Sep-13 Nov-13 Jan-14 Mar-14 May-14 Jul-14 Sep-14 Nov-14

Figure 8. Monthly detection probability and 95 percent CI (shaded areas) pooled across all recording locations.

Pooled detector stations in the forest had a higher mean detection probability than the shrubland during all three years of sampling. The mean detection probability in the forest was 0.31 (range 0.08–0.56, SE ± 0.03) compared to a mean of 0.17 (range 0–0.55, SE ± 0.03) for the shrubland (Fig. 9). Pooling all detectors, there was a significant difference between years as determined by one-way ANOVA (F(2, 22) = 20.05, p = 0.00). A Tukey's post-hoc test indicated the mean detection probability for 2012 (0.53; range 0.26–0.92, SE ± 0.07), was significantly greater than 2013 (0.20; range 0.02–0.44, SE ± 0.03, p = 0.00) as well as 2014 (0.19; range 0–0.39, SE ± 0.03, p = 0.00). However, there was no significant difference between 2013 and 2014 (p = 1.0). Monthly detection probabilities in forest were significantly greater than in the shrubland in every month excluding October, November, and January (Appendix 4).



Figure 9. Pooled monthly detection probability. Vertical lines are 95 percent confidence intervals.

#### DISCUSSION

Echolocating Hawaiian hoary bats were detected in every month that we sampled across the entire KFR-NNAR. Sixty-five percent of all detector-nights included confirmed bat calls. The significantly higher detection probability for bat calls during 2012 and particularly in July and August of that year coincided with at least two environmental variables: low rainfall and presence of high ungulate density in the reserve. During 2012, the reserve experienced very low average annual rainfall which was followed by higher annual rainfall in 2013 and 2014. Bonaccorso *et al.* (2016) demonstrated that foraging activity in Hawaiian hoary bats was influenced by temperature and wind and Bonaccorso *et. al.* 2015 documented that flight activity ceased during periods of rain within a night as bats shelter in night roosts. Low annual rainfall with increased clear, calm nights can lead to improved conditions for bat foraging which possibly contributed to locally increased bat activity in the KFR-NNAR area in 2012. In the two following years, higher rainfall and possibly other climatic variables in KFR-NNAR may have contributed to increased foraging time elsewhere by these highly mobile animals.

A high density of axis deer and goats may have been positively linked to the singularly large echolocation call parameters we measured in the KFR-NNAR in July 2012. By the close of 2012 ungulate eradication and exclusion fencing eliminated these animals from the NNAR. Both the presence of high ungulate densities and the dung deposited by these animals have been shown in numerous studies to be associated with significantly increased insectivorous bat presence and foraging activity (e.g. Entwistle et al. 2001; Downs and Sanderson 2010 for reviews of this literature). In particular, dung feeding beetles and flies that associate with cattle and other herding ungulates are important food items for a number of vespertilionid and rhinolophid bats (Shiel et al. 1991; Ransome 1996; Duverge and Jones 2003). Both scarab beetles and flies have been identified from fecal pellets of Hawaiian hoary bats captured near cattle farms on Hawai`i Island (Todd 2012). Thus, we conclude that this bat is among the increasing number of insectivorous bats recognized to seek out and feed in areas with ungulates. The reduction in bat activity in 2013 and 2014 possibly is associated with the elimination of ungulates in the NNAR; however, this could be a temporary phenomenon and bat presence and foraging activity may rise over time as forest recovery resulting from ungulate exclusion and the associated turnover in plant and insect communities occurs. Noted as a generalist aerial insectivore feeding principally on moths and a diverse array of beetles in Hawai'i (Whitaker and Tomich 1983; Jacobs 1999; Todd 2012), Hawaiian hoary bats should benefit in the long term as forest productivity associated moths and beetles increases across the KFR-NNAR.

Compared to measured seasonal variation reported elsewhere in Hawai'i, little seasonal variation in bat detection probability occurred in 2013 and 2014 in the KFR-NNAR (Gorresen et al. 2013 and 2015; Todd 2012). For example, the magnitude in annual variation of several measures of activity found in a subalpine shrubland zone in the Mauna Loa Forest Reserve (Bonaccorso et al. 2016) at times far exceeded similar measures in the KFR-NNAR shrubland. At Mauna Loa, the winter peak in alpine activity has been purported to be driven by a food source, cave sheltering moths, not found in KFR-NNAR (Bonaccorso et al. 2016). In the KFR-NNAR montane forest the largest distinct peak of bat echolocation activity occurred in July-August 2012, a pattern that was not repeated in 2013 or 2014. Although July to October 2012 had higher monthly detection probability trends than during at any other period in our study at KFR-NNAR there were no significant seasonal differences within this year (with the caveat that no acoustic sampling was conducted in the first half of 2012). July to October is the period corresponding to birth/lactation and for copulation (Menard 2001, Todd 2012, Gorresen et al. 2013) and during this time breeding bats have high energetic demands. Also, beginning in August each year, fledgling bats add an annual pulse of new individuals to the volant bat population in Hawai'i. Thus, it is reasonable to expect increased echolocation activity in late summer and early fall months and such a pattern is typical of lowland habitats where bats rear young.

All of our measures of bat activity, detection probability, mean pulses/night, percentage of nights with feeding buzzes, were greatest in the montane forest within the KFR-NNAR. The nightly bimodal pattern in echolocation calls (having a larger peak early in the night) found in our pooled forest samples resembles patterns commonly found among insectivorous bat species (Kunz 1974; Rydell 1993; Hayes 1997). Foraging activity can be inhibited by precipitation, low air temperature, high wind speed, or fog, all of which can interfere with the detection of flying insects and increase the metabolic costs of flight (Belwood and Fullard 1984; Arnet *et al.* 2008, Voight *et al.* 2011; Gorresen *et al.* 2015). Furthermore, beetles and moths, the two most important prey items of Hawaiian hoary bats (Todd 2012) and among the most abundant insect orders in the NNAR (Peck *et al.* 2015), reduce flight activity in many of these same weather

conditions. Some beetles require a minimum temperature of 17°C before the initiation of flight (Caprio *et al.* 1990) and significant decreases in moth activity occur at temperatures below 10°C (Butler *et al.* 1999). Menard (2001), Todd (2012), and Bonaccorso *et al.* (2016) each found correlation between low temperatures and decreased foraging activity of bats on Hawai`i Island. Bonaccorso *et al.* (2016) found that Hawaiian hoary bat activity declined sharply at temperatures  $\leq 6-7$ °C. At the summit of Haleakalā Volcano air temperatures drop from a mean 10.4°C to 7.4°C within the first two hours following sunset. By 4 hr after sunset, bat echolocation pulse emission in our study approached zero across our subalpine sites and air temperature averaged 6.5°C (Longman *et al.* 2015). Thus, the single early night peak in both call activity and feeding buzz frequency in the subalpine shrubland, appears linked each night to a brief window of suitable foraging conditions at these high elevations.

Feeding buzzes were recorded at all of our detector stations except KAH32 in the subalpine shrubland (Table 2). Feeding buzz activity was most concentrated at stations between 1,389 and 1,822 m (Table 2). The low 1 to 1,000 ratio of feeding buzzes to search calls that we found at KFR-NNAR is typical of results observed elsewhere for Hawaiian hoary bats (Pinzari *et al.* 2014; Bonaccorso *et al.* 2016). Such ratios between feeding buzz and search calls is a result of both the natural behavior of the bats and the difficulty in recording and confirming recognizable feeding buzzes. Conservative call analysis that counts only confirmed call types, will count feeding buzzes with lower efficiency than search calls such that feeding buzzes generally are under-represented (Bonaccorso *et al.* 2016).

The greater proportion of feeding buzzes recorded early in the night at subalpine shrubland compared to the montane forest below may be attributed both to the cloud inversion layer that often forms on Haleakala in the early afternoon between 1,300 and 1,850 m and the suitable temperatures for insect activity found early in the night. The inversion layer frequently remains until 2100 hr (C. Todd, personal observation). Thus, bats may often find suitable foraging conditions in the subalpine shrubland early in the night, while avoiding the precipitation and fog that commonly occur below the inversion layer. By 2100 hr subalpine elevations are exposed to temperatures too low for insect activity and bats apparently move to other foraging locations including the forest zone in the KFR-NNRA as the inversion layer clouds dissipate.

Our study provides a baseline of bat echolocation detectability during the early phases of habitat restoration in KFR-NNAR. As both hardware for recording bat calls and software for analysis of these recordings are improving continually, future studies that wish to compare our results with new data must consider the ever changing sampling capabilities in the technological realm of bat acoustic monitoring. This may somewhat be mollified by use of the thresholding of data in our report. We recommend that to better understand Hawaiian hoary bat foraging activity and the seasonal and annual trends in bat echolocation detectability that future studies incorporate sampling of the insect prey base in the KFR-NNAR which we were not able to undertake.

#### ACKNOWLEDGMENTS

We thank S. Fretz, Sandee Hufana, and F. Duvall, Division of Land and Natural Resources, for generously providing logistical support for this project. J. Penniman, M. VanZandt, A.Rhoades, I. Walker, V. Stout and J. McPherson from the Maui Nui Seabird Recovery Project, H. Mounce, P. Motyka, and C. Warren from the Maui Forest Bird Recovery Project, and C. Farmer from the American Bird Conservancy offered logistical support and field assistance. B. Brookes, S. Meidell

and G. Friel from Haleakalā Ranch provided us with property access. We thank K. Brink, M. Gorresen, and P. Berkowitz for analytical advice. The staff from Windward Aviation provided logistical support and helicopter transportation into the KFR-NAR. This survey was funded by Hawai`i Department of Land and Natural Resources through interagency agreement number 12WSZB000000002 to the USGS. Work was facilitated through administrative and logistical support provided by the Pacific Island Ecosystems Research Center, U.S. Geological Survey (Gordon Tribble, Center Director), and by the Hawai`i Cooperative Studies Unit, University of Hawai`i at Hilo.

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#### **APPENDICES**

Song Meter SM2BAT+		Call Viewer	
Parameter Setting		Parameter	Setting
Sampling Rate Compression Gain Dig HPF DIG LPF Trigger Level Trigger Win Right Div Ratio Channel	192 kHz None 36 dB fs/16 Off 18 SNR 2 s 16 Mono-R	Min. Link Length [frames] Window Length [ms] Frame rate [fps] Chunk Size [sec] Min. Energy [dB] Echo Filter threshold [db] UPPER Cutoff Freq. [kHz] LOWER Cuttoff Freq. [kHz] Window Type Delta Size [+/- frames]	6 0.3 10000 1 10 5 inf 10 Blackman 1
		Delta Size [+/- frames]	1

Appendix 1. Settings for SM2BAT+ and Call Viewer 18.

Appendix 2. Characteristics of trees within 50 m of recording stations.

Station ID	Mean height (m)	Mean dbh (cm)	Mean % canopy density	Number of trees	
NAK4	8.5 ± 1.2	82.5 ± 17.5	34.4 ± 6	9	
NAK3	$8.1 \pm 1.1$	44 ± 6.9	52.4 ± 3	29	
KFRL3	$8.1 \pm 1.1$	52 ± 9.8	$38.3 \pm 3.6$	18	
NAK2	12.3 ± 0.9	33.2 ± 2.7	$36.1 \pm 2.5$	42	
KFRL2	9.0 ± 0.8	47.6 ± 5.4	58.8 ± 4.3	14	
NAK1	7.9 ± 1.1	44.8 ± 3.3	17 ± 4.9	13	
KFRL1	7.5 ± 1.5	78.7 ± 14.4	45.7 ± 4.2	5	
KFRH2	0	0	0	0	
KFRH1	0	0	0	0	

Station	percent tree cover	percent grass cover	percent barren ground	
NAK 4	7.35	68.90	23.75	
NAK 3	33.29	45.24	21.48	
KFRL3	10.99	65.14	23.88	
NAK 2	23.49	63.88	12.64	
KFRL2	4.81	56.44	38.75	
NAK 1	6.00	74.85	19.15	
KFRL1	6.61	71.13	22.26	
KAH05	27.05	0.00	72.95	
KAH28	23.33	0.00	76.67	
KAH31	28.77	24.04	47.19	
KAH09	24.75	0.00	75.25	
KAH32	35.61	0.00	64.39	
KFRH2	13.26	0.00	86.74	
KFRH1	11.21	0.00	88.79	

Appendix 3. Percent tree and grass cover within 100 m of recording stations.

Appendix 4. Monthly detection probability (p) and 95% CI at recording stations.

		Elevation R	legion			
Date	1250-	-1850 m	1850-	-2700 m		
Date	р	95% CI	р	95% CI	z value	p value
1 1 2012	0.00	0.04.0.00			<b>N</b> 1 A	
Jul 2012	0.92	0.84-0.96	NA	NA	NA	NA
Aug 2012	0.78	0.72–0.83	NA	NA	NA	NA
Sep 2012	0.50	0.43-0.56	0.33	0.23-0.46	-2.19	0.02*
Oct 2012	0.40	0.33-0.47	0.53	0.41–0.65	1.84	0.07
Nov 2012	0.56	0.49-0.63	0.55	0.42-0.67	-0.15	0.90
Dec 2012	0.44	0.36-0.52	0.26	0.16-0.38	-2.44	0.01*
Jan 2013	0.30	0.23-0.37	0.13	0.04-0.31	-1.80	0.07
Feb 2013	0.21	0.16-0.29	0.02	0.00-0.09	-2.11	0.03*
Mar 2013	0.42	0.36-0.49	0.11	0.07–0.18	-4.36	0.00*
Apr 2013	0.15	0.10-0.21	0.03	0.01-0.08	-3.51	0.00*
May 2013	0.24	0.19-0.30	0.02	0.01-0.06	-1.86	0.05
Jun 2013	0.27	0.21-0.33	0.03	0.02-0.07	-5.80	0.00*
Jul 2013	0.30	0.25-0.37	0.12	0.08-0.19	-3.60	0.00*
Aug 2013	0.44	0.38-0.51	0.11	0.07-0.17	-6.74	0.00*
Sep 2013	0.26	0.20-0.33	0.16	0.11-0.23	-1.82	0.06

0.36	0.29-0.43	0.34	0.26-0.44	-0.30	0.76
0.22	0.14-0.34	NA	NA	NA	NA
NA	NA	NA	NA	NA	NA
NA	NA	NA	NA	NA	NA
NA	NA	NA	NA	NA	NA
NA	NA	NA	NA	NA	NA
0.24	0.17-0.32	0.20	0.10-0.34	-0.53	0.60
0.21	0.16-0.27	0	0	-	-
0.22	0.17-0.29	0	0	-	-
0.39	0.33-0.46	0.06	0.02-0.16	-4.17	0.00*
0.34	0.28-0.40	0.1	0.04-0.20	-3.43	0.00*
0.18	0.12-0.26	0.27	0.17-0.39	1.29	0.20
0.32	0.25-0.41	0.34	0.23-0.46	0.22	0.83
0.08	0.04-0.14	0.02	0.00-0.14	-1.31	0.20
	0.36 0.22 NA NA NA 0.24 0.21 0.22 0.39 0.34 0.18 0.32 0.08	0.36 0.29–0.43   0.22 0.14–0.34   NA NA   NA NA   NA NA   NA NA   NA NA   0.24 0.17–0.32   0.21 0.16–0.27   0.22 0.17–0.29   0.39 0.33–0.46   0.34 0.28–0.40   0.18 0.12–0.26   0.32 0.25–0.41   0.08 0.04–0.14	0.36 0.29–0.43 0.34   0.22 0.14–0.34 NA   NA NA NA   0.24 0.17–0.32 0.20   0.21 0.16–0.27 0   0.22 0.17–0.29 0   0.39 0.33–0.46 0.06   0.34 0.28–0.40 0.1   0.18 0.12–0.26 0.27   0.32 0.25–0.41 0.34   0.08 0.04–0.14 0.02	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$

Significant p values indicated by \*.