Technical Report HCSU-100

HAWAIIAN HOARY BAT ACOUSTIC SURVEYS ON MARINE CORPS BASE HAWAII, 2019-2021

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ABSTRACT

The endangered Hawaiian hoary bat (*Lasiurus semotus*, Vespertilionidae, also known as *Aeorestes semotus* and ʻōpeʻapeʻa) occurs on all the principal volcanic islands in Hawaiʻi. Advances in acoustic bat monitoring techniques have contributed to the body of knowledge of bat activity and behavior in many areas of the State of Hawaiʻi; however, there is still much that is unknown about the population and seasonal distribution of Hawaiian hoary bats on Oʻahu. A two-year acoustic survey for presence of Hawaiian hoary bats was conducted at 17 stations across four Marine Corps Base Hawaii (MCBH) properties on Oʻahu to document distribution, seasonal patterns, and foraging activity. Bats were confirmed present at all properties; MCBH Kaneohe Bay on Mōkapu Peninsula, Marine Corps Training Area Bellows (MCTAB) in Waimanalo, Camp H M Smith in Halawa Heights, and Puuloa Range Training Facility (RTF) on the ʻEwa coastal plain. Hawaiian hoary bats were recorded in airspace at all four properties during important periods of Hawaiian hoary bat life history, including periods of pregnancy, lactation, and pup fledging; however, overall presence was low. Foraging activity as identified from characteristic feeding buzzes was very rare and was recorded on only three nights over the entire study. Within-night bat detection pooled for all nights and stations at each property showed that bat activity was mostly confined to the first several hours of the night at MCBH Kaneohe Bay and Puuloa RTF, whereas bat activity was spread throughout the night at Camp H M Smith and MCTAB. Overall, detection frequency was low (year 1 = 0.009, year 2 = 0.007, average = 0.008) at the study sites on Oʻahu compared to results from acoustic monitoring studies on the islands of Maui and Hawaiʻi. However, the low rate of bat presence on MCBH properties is consistent with recent studies at other locations on the Island of Oʻahu. Monitoring the seasonal presence and distribution of Hawaiian hoary bats on MCBH facilities, especially at forest and wetland habitats, could contribute to the broader scientific understanding of island-wide distribution and behavior on Oʻahu, which is essential for species recovery planning and implementation of best management practices.

INTRODUCTION

The Hawaiian hoary bat (*Lasiurus semotus*, Vespertilionidae, also known as *Aeorestes semotus* and ʻōpeʻapeʻa) is the only extant native terrestrial mammal and sole bat species in Hawaiʻi. This endemic species of hoary bat occurs on all of the principal volcanic islands of Hawaiʻi (Tomich 1986) and was listed as endangered in 1970 by the U.S. Fish and Wildlife Service, with a recovery plan developed in 1998 (USFWS 1998). The bat is also listed as endangered by the State of Hawaiʻi Division of Forestry and Wildlife. The listing reflects a limited knowledge of current distribution, suspected habitat loss, and an unknown population status or size (USFWS 2021).

Hawaiian hoary bats are solitary and foliage roosting (Jacobs 1992, Bonaccorso *et al.* 2015, Montoya-Aiona 2020) and utilize varied habitat types across a wide elevation gradient from sea level to at least 3,600 m above sea level (asl; Bonaccorso *et al.* 2015, 2016; H. T. Harvey and Associates 2020). The species forages by aerial-hawking prey captured and consumed during flight and feeds primarily on Coleoptera and Lepidoptera (Whitaker and Tomich 1983, Belwood and Fullard 1984, Jacobs 1999, Todd 2012, Pinzari *et al.* 2019, H. T. Harvey and Associates 2020). On the islands of Hawaiʻi and Maui, bat acoustic activity has been shown to display a seasonal cycle with more activity in the mid to low elevations during the reproductive season compared to upper elevations, where there is more acoustic activity during the non-

reproductive season (Menard 2001, Gorresen *et al.* 2013, Todd *et al.* 2016). Individual bats are highly mobile, have shown large variability in core use area size (averaging 22.5 ha for the Island of Hawai'i to 3,700 ha for Maui) and regularly forage in multiple disjunct feeding areas that may be up to 15 km apart as demonstrated in radio-telemetry studies conducted on the islands of Hawai'i and Maui (Bonaccorso *et al.* 2015, H. T. Harvey and Associates 2020).

Ultrasonic acoustic monitoring techniques have revealed hoary bat seasonal presence and behavioral patterns across many areas of the state (Gorresen *et al.* 2013, Pinzari *et al.* 2014, Bonaccorso *et al.* 2016, Todd *et al.* 2016, Montoya-Aiona *et al.* 2019, Pinzari *et al.* 2019, Montoya-Aiona *et al.* 2020, Thompson and Starcevich 2021); however, additional localized studies conducted since 2015 (Gorresen *et al.* 2015, 2018; Bonaccorso *et al.* 2019; Montoya-Aiona *et al.* 2020) have contributed to the body of knowledge concerning contemporary distribution of the species on O'ahu. Although surveys have documented bat presence on other U.S. Department of Defense managed lands across O'ahu, including those close to Marine Corps Base Hawaii (MCBH) properties, there have been no formal surveys to confirm the species' presence on MCBH properties.

The main objectives of this acoustic monitoring effort were to (1) assess Hawaiian hoary bat presence and distribution during important life history periods, (2) document within-night activity patterns and foraging activity, and (3) provide baseline data to support Hawaiian hoary bat conservation strategies in the MCBH Integrated Natural Resources Management Plan (INRMP 2017). We present information on seasonal presence, foraging behavior, and nightly activity patterns of the Hawaiian hoary bat gathered at 17 passive acoustic monitoring stations on four MCBH properties during a two-year monitoring effort from February 2019 through March 2021.

METHODS

Study Area

A preliminary site evaluation by U.S. Geological Survey and Hawai'i Cooperative Studies Unit personnel was conducted on 3–4 May 2016 to identify locations within MCBH properties suitable for passive acoustic bat monitoring stations. Suitable locations were identified as those where the stations could be accessed safely for maintenance, the equipment would be secure, and where natural features occurred nearby that could be potential bat habitat such as vegetation, forest edges, and wetlands. MCBH properties selected for bat surveys on the windward side of O'ahu in the Ko'olaupoko District included MCBH Kaneohe Bay on Mōkapu Peninsula and Marine Corps Training Area Bellows (MCTAB) in Waimanalo (Figure 1). Selected MCBH properties on the leeward side included Camp H M Smith in Halawa Heights and Puuloa Range Training Facility (RTF) on the 'Ewa coastal plain (Figure 1). The MCBH Waikane Valley property was not surveyed due to concerns with road conditions and equipment security. Property names follow Marine Corps Base Hawaii conventions.

Acoustic monitoring was conducted concurrently at 17 stations on MCBH installations on O'ahu between 11 February 2019 and 24 March 2021 (Figure 1). Acoustic monitoring station locations ranged in elevation from 10 to 226 m asl and were in lowland coastal wetland and mesic forest habitats within otherwise developed areas (Table 1). Where possible, stations were placed in open areas or along vegetation edges (see Appendix I) to ensure adequate sunlight to power solar panels and recharge batteries, and because Hawaiian hoary bats frequently fly and forage along vegetation edges and open areas. Station TA20 was re-positioned three times during the study (exact positions reflected in Table 1); however, positions were not far from each other,

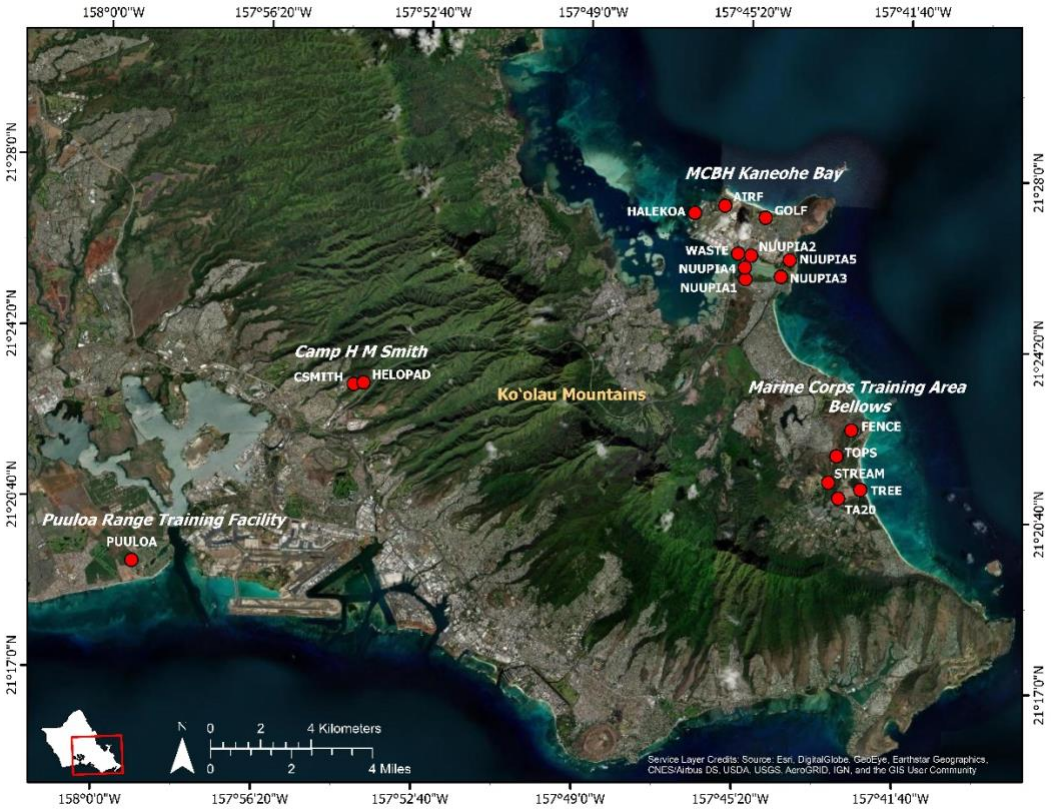

Figure 1. Locations of 17 acoustic bat detector stations (red dots) across four Marine Corps Base Hawaii properties, O'ahu. Service layer credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.

thus the singular name TA20 is used to describe all data for those positions. Station TOPS_2 is also referred to in the report as the singular name TOPS.

Acoustic Monitoring

Ultrasonic vocalizations (echolocation calls) of Hawaiian hoary bats were recorded using Song Meter bioacoustics recorders (Wildlife Acoustics Inc., Concord, Massachusetts) capable of recording ultrasound between 10 kilohertz (kHz) and 100 kHz deployed at each station (Table 1). Each station consisted of an SM4BAT recorder in waterproof housing, a 6-volt battery, a 6-watt solar panel, and an SMM-U1 model ultrasonic microphone (Wildlife Acoustics Inc., Concord, Massachusetts). Microphones were placed at the top of a metal conduit 3 m above the ground and connected by a cable to the SM4BAT recorder microphone port. Microphones are omnidirectional and capable of detecting bat calls at distances up to 30 m under ideal conditions (described in Adams *et al.* 2012), although the range of detection varies with weather conditions and orientation of the bat relative to the microphone. Acoustic events were recorded with digital compression (W4V-8) as full-spectrum Waveform Audio File Format (.wav) sound files onto Secure Digital (SD) cards with corresponding times and dates. SM4BAT recording settings used sampling rate of 192 kHz; gain of 12 decibels (db); digital high pass

Table 1. Hawaiian hoary bat acoustic survey stations across four Marine Corps Base Hawaii properties on O'ahu, including property name, station name, Universal Transverse Mercator (UTM) locations (Zone 4, datum WGS84), elevation above sea level in meters, and habitat description. Note: developed areas are defined as landcover with industrial and/or housing development present.

Property	Monitoring station	UTM Easting	UTM Northing	Elevation (m)	Habitat description
Camp H M Smith	CSMITH	613630	2365434	211	Mid-elevation mesic habitat; forest edge with non-native tree species
	HELOPAD	614016	2365508	252	Mid-elevation mesic habitat; forest edge with non-native tree species near open grass field
Marine Corps Base Hawaii (MCBH) Kaneohe Bay	HALEKOA	626877	2372727	4	Lowland coastal habitat; near ephemeral wetland with non-native tree and plant species
	WASTE	628644	2371170	10	Lowland coastal habitat; near developed area (open wastewater treatment pools) and forest edge with non-native tree species
	GOLF	629680	2372634	3	Lowland coastal habitat; golf course grass turf near man-made ponds with non-native tree and shrub species
	AIRF	628063	2373053	7	Lowland coastal habitat; developed area (airplane landing strip) near forest edge with non-native tree species and grasses
	NUUPIA1	628976	2370178	6	Lowland coastal wetland habitat; with non-native tree and plant species
	NUUPIA2	628933	2370632	3	Lowland coastal wetland habitat; with non-native tree and plant species
	NUUPIA3	630377	2370319	3	Lowland coastal wetland habitat; with non-native tree and plant species
	NUUPIA4	629164	2371112	2	Lowland coastal wetland habitat; with non-native tree and plant species
	NUUPIA5	630701	2370989	3	Lowland coastal wetland habitat (fishpond); with non-native tree and plant species

Property	Monitoring station	UTM Easting	UTM Northing	Elevation (m)	Habitat description
Marine Corps Training Area Bellows (MCTAB)	TREE	633837	2361999	7	Lowland mesic habitat, near forest edge with non-native tree species
	TA20_4[1]	632973	2361625	7	Lowland mesic habitat, near forest edge and open grass area with non-native tree species
	TA20_3[1]	633117	2361643	7	Lowland mesic habitat, near forest edge and open grass area with non-native tree species
	TA20_2[1]	633131	2361673	7	Lowland mesic habitat, near forest edge and open grass area with non-native tree species
	STREAM	632561	2362240	1	Lowland mesic habitat, near forest edge with non-native tree species, along stream
	TOPS_2[2]	632850	2363291	27	Lowland mesic habitat, near forest edge with non-native tree species
	FENCE	633392	2364338	7	Lowland mesic habitat, near forest edge with non-native tree species, along fence line
Puuloa Range Training Facility (RTF)	PUULOA	605093	2358130	13	Lowland mesic habitat, near forest edge and developed area with non-native tree species, along fence line

[1] Positions of monitoring station TA20 moved to better accommodate monitoring equipment (solar panels, etc.) within the location selected.

[2] TOPS_2, also referred to as TOPS.

filter of 16 kHz "on"; trigger level 12 db; trigger window 3.0 sec; trigger minimum duration 1.5 milliseconds (ms); trigger maximum duration none; minimum trigger frequency 16 kHz; maximum file length was set at 15 sec. All detectors recorded from one hour before local sunset until one hour after local sunrise. Detectors were checked at two- to three-month intervals to exchange SD cards and to test battery levels and microphone function.

Acoustic data were downloaded from SD cards, filtered, and organized into folders of call-events per night using Kaleidoscope Viewer 5.1.9h software (Wildlife Acoustics Inc., Concord, Massachusetts). This software filtered out acoustic background noise from potential bat call-events using the following settings: 15–70 kHz, 1–7 ms pulse duration, 250 ms maximum inter-syllable gap, and a minimum of 3 pulses per event. Any files containing acoustic pulses outside of these constraints were filtered into a noise file. Call-events (also referred to as "bat passes" in the literature) are defined as a sequence of ultrasonic pulses over a span of milliseconds that can be detected by an ultrasonic microphone as an individual bat flies within the effective range of the microphone (Figure 2). A call-event was defined as a series of ≥3 echolocation pulses within a recording file. Call-events may contain search-phase calls made by a bat moving about an area, often for the purpose of searching for prey and may end with a feeding buzz (also referred to as "terminal-phase calls"; Griffin 1958; see Figure 2). Feeding buzzes indicative of foraging activity are characterized by a rapid series of pulses made by a bat closely approaching prey. All echolocation pulses, call-events, and feeding buzzes were verified and counted by audio and visual inspection of echolocation recording spectrograms using Kaleidoscope Viewer 5.1.9h software. We discarded any ultrasonic recording files outside of standard Hawaiian hoary bat vocalization parameters (see example in Figure 2) such as insect calls and noise.

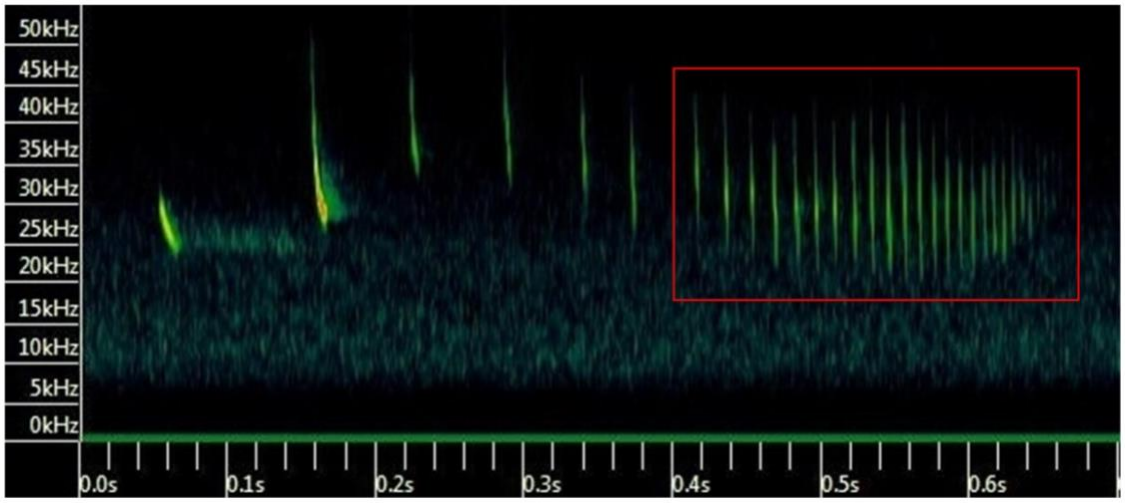

Figure 2. Sample spectrogram of a call-event: search-phase call pulses (left and center) followed by a terminal-phase series of pulses ("feeding buzz" far right in the box) in one echolocation call event. The x-axis represents time in seconds and y-axis represents frequency in kilohertz (kHz).

Quality Control and Quality Assurance

Kaleidoscope Viewer software has the potential to misclassify a small percentage of low amplitude bat calls due to the filter settings used. For quality assurance, a subsample of more than 47,000 noise files were examined from each of the 10 sites where bat activity was recorded: PUULOA, CSMITH, HELOPAD, NUUPIA3, NUUPIA5, FENCE, STREAM, TOPS (TOPS_2), TREE, and TA20. A random number generator was used to determine which dates to inspect within the most active month(s) at each site. In the subsample of noise files inspected, a total of 5 files (0.01%) were found to contain bat calls.

Analyses

Detection frequency, number of call-events, and presence of feeding buzzes were used to examine seasonal variation in activity, foraging, and timing of nightly use at each station and across properties. Acoustic recordings of bats were used to produce monthly detection frequency, defined as the proportion of sample nights with at least one bat echolocation detection for each one-month sample period, thus effectively weighting the values by sampling effort. A sample night was defined as a night when a detector at a station was fully operational through the entire night. A detection frequency equal to 1.0 (100%) is equivalent to recording bat calls at a single station every night of the month while a detection frequency of 0.0 indicates there were no verifiable bat calls during the sampling period.

The detection frequency was also averaged over the reproductive and fledging periods (May to October). The Hawaiian hoary bat reproductive season (as adapted from Menard 2001) includes periods of pregnancy (typically May to June) and lactation (late June to August). The remainder of the year includes fledging/post-lactation (August and September), mating (October to December), and pre-pregnancy (January to April) periods during which there is little to no reproductive activity or parental care shown by adult females. Overlap and variability in the timing of these seasons may occur year-to-year and among locations (Menard 2001, Gorresen *et al.* 2013). Additional study would be helpful to determine if the reproductive period spans a broader time period.

Total counts of echolocation call-events, pooled over the duration of the survey for all stations at a property, were used to examine nightly activity patterns at each property. Acoustic recordings of feeding buzzes were reported by month, if they occurred, for individual stations to indicate the presence of foraging.

Some acoustic monitoring stations had equipment malfunctions that resulted in lapses in monitoring. Although monitoring was conducted during a pilot period prior to mid-February 2019, these data were not analyzed due to longer lapses in monitoring and different recording settings. Data from this pilot period can be found in Appendix III. Complete acoustic data and metadata associated with this report are available at https://doi.org/10.5066/P9L9HY6D (Gross *et al.* 2021).

RESULTS

Bat Distribution and Presence

From 11 February 2019 to 24 March 2021, Hawaiian hoary bat activity was acoustically sampled for a total of 11,117 recording nights at 17 monitoring stations across MCBH properties on O'ahu (Table 2). Monitoring stations were maintained for up to 771 nights each. Stations recorded approximately 654 nights on average. Technical problems with acoustic recording devices, combined with staggered start and finish dates, resulted in fewer than 500 nights

Table 2. Survey effort and summary details at 17 Hawaiian hoary bat monitoring stations on Marine Corps Base Hawaii (MCBH) properties including acoustic monitoring station name, total nights sampled, detection frequency, total number of call-events, total nights with feeding buzzes observed, and operational start and end dates for acoustic monitoring between February 2019 and March 2021.

Property and monitoring station	Total nights sampled	Detection frequency	Total call-events	Total nights with feeding buzzes	Start date	End date
Camp H M Smith						
CSMITH	771	0.0324	27	1	2/12/2019	3/24/2021
HELOPAD	771	0.0415	35	0	2/12/2019	3/24/2021
MCBH Kaneohe Bay						
HALEKOA	414	0	0	0	2/11/2019	1/27/2021
WASTE	758	0	0	0	2/11/2019	3/22/2021
GOLF	752	0	0	0	2/11/2019	3/22/2021
AIRF	480	0	0	0	2/11/2019	2/8/2021
NUUPIA1	771	0.0026	2	0	2/11/2019	3/23/2021
NUUPIA2	394	0	0	0	2/11/2019	12/24/2020
NUUPIA3	612	0.0016	1	0	2/11/2019	12/21/2020
NUUPIA4	650	0.0015	1	0	6/11/2019	3/22/2021
NUUPIA5	448	0.0089	4	0	6/11/2019	1/13/2021
Marine Corps Training Area Bellows						
TREE	765	0.0144	10	1	2/12/2019	3/23/2021
TA20	659	0.0076	6	0	2/12/2019	3/22/2021
STREAM	667	0.0120	8	0	2/12/2019	3/23/2021
FENCE	770	0.0026	4	0	2/12/2019	3/23/2021
TOPS	770	0.0065	6	0	2/12/2019	3/23/2021
Puuloa Range Training Facility						
PUULOA	665	0.0150	12	1	2/12/2019	3/24/2021

sampled at stations AIRF, HALEKOA, NUUPIA2, and NUUPIA5 (Table 2). Echolocation calls of Hawaiian hoary bats were detected at 12 of 17 (70.5%) stations across the four MCBH properties with varying degrees of activity, but overall, on fewer than 5% of all nights sampled (Table 2).

Bats were not detected at five stations: HALEKOA, WASTE, GOLF, AIRF, and NUUPIA2. Of all stations across the two years of sampling, detection frequency was greatest at stations HELOPAD (0.0415) and CSMITH (0.0324), both located at mid-elevation at the Camp H M Smith property (Table 2). At the MCTAB property, bats were detected at all five stations but at a lower detection frequency (0.0026-0.0144) than the Camp H M Smith property. Bat acoustic activity was generally lowest at MCBH Kaneohe Bay property, with bats being detected at the stations

on 0 to 0.0089 of sampled nights and only at stations placed around the Nu'upia wetlands (Table 2). The single acoustic station at Puuloa RTF detected bat activity on 0.0150 of the nights sampled (Table 2).

Seasonal Bat Activity

Bat presence varied seasonally among survey stations and properties as indicated by the distribution of monthly detections (Figure 3, Table 3a, Table 3b). Camp H M Smith was the only property at which bats were detected almost year-round, where they were detected in all months except June. Bat presence at all other properties was detected only between July and December with the greatest detection frequency in October (mating period), when bat activity was detected at 85.7% stations (12 of the 14 stations functioning during the time) across the four MCBH properties. Bats were detected across the four stations at MCTAB in September and October in both years (Figure 3). During the pregnancy period (May through June) bats were detected only at HELOPAD at Camp H M Smith; however, during the periods of lactation through fledging (July through September) bats were detected at MCTAB, Puuloa RTF, and stations in the Nu'upia wetlands at MCBH Kaneohe Bay.

Detection frequency for all stations over the two-year sampling period averaged 0.008 ± 0.001 and was similar between year 1 (0.009 ± 0.004) and year 2 (0.007 ± 0.002; Tables 3a, 3b). Although the monthly detection frequency was low for all stations (0–0.23), bat call-events were detected at all properties during one or more months of the reproductive season. The detection frequency during the reproductive season (May–October) varied among stations (Tables 3a, 3b). Even among proximate stations at MCTAB and MCBH Kaneohe Bay detections differed; for example, seven of the nine MCBH Kaneohe Bay stations recorded no bat detections during the reproductive period, while bat detections were recorded at two stations on the property (NUUPIA1 and NUUPIA5; Figure 4). The stations on Camp H M Smith had the highest mean detection frequency across the months of the reproductive season over the two years sampled (0.063 ± 0.007), followed by the single station at Puuloa RTF (0.027 ± 0.012) and one station (TREE) at MCTAB (0.026 ± 0.011; Figure 4). Lower mean detection frequency was observed across the remaining four MCTAB stations (0.014 ± 0.004; Figure 4). Overall mean detection frequency at all stations across the months of the reproductive season averaged only 0.015 ± 0.005 (year 1 = 0.019 ± 0.008; year 2 = 0.011 ± 0.004).

Nightly and Foraging Activity

Within-night bat activity pooled for all nights and stations at each property showed bat activity was mostly confined to the first six hours of the night (≤360 minutes after sunset) at MCBH Kaneohe Bay and Puuloa RTF, while bat activity was spread throughout the night at Camp H M Smith and MCTAB (Figure 5). The number of call-events was greatest at Camp H M Smith, followed by MCTAB and Puuloa RTF, and fewest at MCBH Kaneohe Bay.

Although bats were recorded at 12 of the 17 stations, foraging activity as indicated by feeding buzzes was observed rarely and only on a single night during either September or October at Camp H M Smith (CSMITH), MCTAB (TREE), and Puuloa RTF (PUULOA) monitoring stations (Table 2).

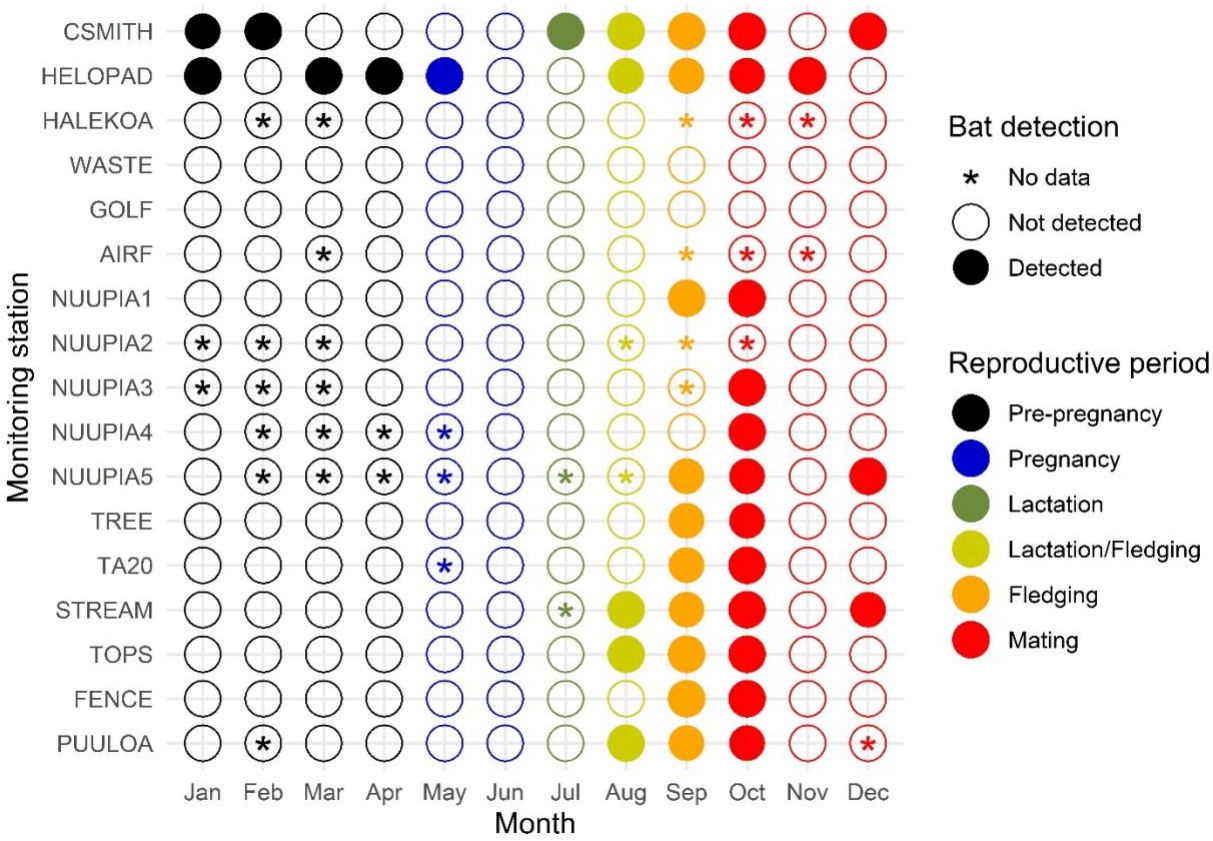

Figure 3. Confirmed bat presence or presumed absence by survey month and survey monitoring station for the study period of February 2019 through March 2021, on four Marine Corps Base Hawaii properties. A solid circle indicates bats were detected, hollow circles indicate no bats were detected, and an asterisk with no circle indicates no data were collected in that month. A circle with an asterisk inside indicates bats were not detected during that month in one year of the study, and no data were collected during the same month in the other year(s). Circles are colored to distinguish stages of the Hawaiian hoary bat reproductive cycle from pre-pregnancy (Jan–Apr), pregnancy (May–Jun), lactation (Jul–Aug), fledging (Sep), and mating (Oct–Dec). An expanded version for the two-year monitoring period is in Appendix II.

Table 3a. Sampling effort by month at 17 monitoring stations on Marine Corps Base Hawaii (MCBH) properties surveyed from February 2019 through February 2020. For each station, the first row indicates the number of nights with bat detections over the number of sample nights, and the second row is the monthly detection frequency. Dashes indicate no data were collected.

	2019											2020	
Property and monitoring station	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb
Camp H M Smith													
CSMITH	0/17	0/31	0/30	0/31	0/30	1/31	7/31	6/30	7/31	0/30	0/31	1/31	1/29
	0	0	0	0	0	0.03	0.22	0.20	0.23	0	0	0.03	0.03
HELOPAD	0/17	1/31	0/30	0/31	0/30	0/31	6/31	6/30	5/31	0/30	0/31	0/31	0/29
	0	0.03	0	0	0	0	0.19	0.20	0.16	0	0	0	0
MCBH Kaneohe Bay													
HALEKOA	-	-	0/29	0/15	0/21	0/31	0/12	-	-	0/23	0/31	0/31	0/29
	-	-	0	0	0	0	0	-	-	0	0	0	0
WASTE	0/18	0/31	0/30	0/31	0/30	0/31	0/31	0/30	0/31	0/30	0/31	0/19	0/29
	0	0	0	0	0	0	0	0	0	0	0	0	0
GOLF	0/18	0/31	0/30	0/31	0/30	0/31	0/31	0/30	0/17	0/26	0/31	0/31	0/29
	0	0	0	0	0	0	0	0	0	0	0	0	0
AIRF	0/18	0/31	0/30	0/3	0/21	0/31	0/9	-	-	0/23	0/31	0/31	0/29
	0	0	0	0	0	0	0	-	-	0	0	0	0
NUUPIA1	0/18	0/31	0/30	0/31	0/30	0/31	0/31	0/30	0/31	0/30	0/31	0/31	0/29
	0	0	0	0	0	0	0	0	0	0	0	0	0
NUUPIA2	0/18	0/31	0/30	0/22	0/21	0/31	0/21	-	-	0/23	0/31	0/17	-
	0	0	0	0	0	0	0	-	-	0	0	0	-
NUUPIA3	0/18	0/31	0/30	0/31	0/30	0/31	0/31	0/30	1/31	0/30	0/31	0/31	0/29
	0	0	0	0	0	0	0	0	0.03	0	0	0	0
NUUPIA4	-	-	-	-	0/20	0/31	0/31	0/30	0/31	0/30	0/31	0/31	0/29
	-	-	-	-	0	0	0	0	0	0	0	0	0
NUUPIA5	-	-	-	-	0/20	0/31	0/31	1/30	1/31	0/30	0/20	0/19	0/29
	-	-	-	-	0	0	0	0.03	0.03	0	0	0	0
Marine Corps Training Area Bellows													
TREE	0/17	0/31	0/30	0/31	0/30	0/31	0/31	1/30	2/31	0/30	0/31	0/26	0/29
	0	0	0	0	0	0	0	0.03	0.06	0	0	0	0
TA20	0/17	0/31	0/2	-	0/23	0/31	0/31	1/30	1/31	0/30	0/31	0/13	0/28

	0	0	0	-	0	0	0	0.03	0.03	0	0	0	0
STREAM	0/17	0/31	0/30	0/31	0/23	-	1/26	3/30	0/31	0/15	-	0/17	0/29
	0	0	0	0	0	-	0.04	0.10	0	0	-	0	0
FENCE	0/17	0/31	0/30	0/31	0/30	0/31	0/31	1/30	0/31	0/30	0/31	0/31	0/29
	0	0	0	0	0	0	0	0.03	0	0	0	0	0
TOPS	0/17	0/31	0/30	0/31	0/30	0/31	2/31	1/30	2/31	0/30	0/31	0/31	0/29
	0	0	0	0	0	0	0.06	0.03	0.06	0	0	0	0
Puuloa Range Training Facility													
PUULOA	0/17	0/31	0/30	0/31	0/30	0/31	0/31	1/30	2/31	0/9	-	0/15	-
	0	0	0	0	0	0	0	0.03	0.06	0	-	0	-

Table 3b. Sampling effort by month at 17 monitoring stations on Marine Corps Base Hawaii (MCBH) properties surveyed from March 2020 through March 2021. For each station, the first row indicates the number of nights with bat detections over the number of sample nights, and the second row is the monthly detection frequency. Dashes indicate no data were collected.

	2020										2021		
Property and monitoring station	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
Camp H M Smith													
CSMITH	0/31	0/30	0/31	0/30	0/31	0/31	0/30	0/31	0/30	1/31	1/31	0/28	0/23
	0	0	0	0	0	0	0	0	0	0.03	0.03	0	0
HELOPAD	0/31	1/30	1/31	0/30	0/31	1/31	3/30	4/31	2/30	0/31	1/31	0/28	1/23
	0	0.03	0.03	0	0	0.03	0.10	0.13	0.07	0	0.03	0	0.04
MCBH Kaneohe Bay													
HALEKOA	0/31	0/30	0/12	0/2	0/31	0/31	-	0/4	-	0/25	0/26	-	-
	0	0	0	0	0	0	-	0	-	0	0	-	-
WASTE	0/31	0/30	0/31	0/30	0/31	0/31	0/30	0/31	0/30	0/31	0/31	0/28	0/21
	0	0	0	0	0	0	0	0	0	0	0	0	0
GOLF	0/31	0/30	0/31	0/30	0/31	0/31	0/30	0/31	0/30	0/31	0/31	0/28	0/21
	0	0	0	0	0	0	0	0	0	0	0	0	0
AIRF	0/31	0/30	0/27	0/2	0/31	0/24	-	0/15	-	0/25	0/31	0/7	-

	0	0	0	0	0	0	-	0	-	0	0	0	-
NUUPIA1	0/31 0	0/30 0	0/31 0	0/30 0	0/31 0	0/31 0	1/30 0.03	1/31 0.03	0/30 0	0/31 0	0/31 0	0/28 0	0/22 0
NUUPIA2	0/23 0	0/30 0	0/23 0	0/2 0	0/15 0	- -	- -	0/18 0	0/21 0	0/17 0	- -	- -	- -
NUUPIA3	0/31 0	0/30 0	0/31 0	0/23 0	0/31 0	0/19 0	- -	0/18 0	0/30 0	0/15 0	- -	- -	- -
NUUPIA4	0/31 0	0/30 0	0/31 0	0/30 0	0/31 0	0/31 0	0/30 0	1/31 0.03	0/30 0	0/31 0	0/31 0	0/28 0	0/21 0
NUUPIA5	0/31 0	0/30 0	0/31 0	0/28 0	- -	- -	- -	1/19 0.05	0/30 0	1/26 0.04	0/12 0	- -	- -
Marine Corps Training Area Bellows													
TREE	0/31 0	0/30 0	0/31 0	0/30 0	0/31 0	0/31 0	5/30 0.16	2/31 0.06	0/30 0	0/31 0	0/31 0	0/28 0	0/22 0
TA20	0/10 0	0/26 0	0/31 0	0/30 0	0/31 0	0/31 0	3/30 0.10	0/31 0	0/30 0	0/31 0	0/31 0	0/28 0	0/21 0
STREAM	0/31 0	0/30 0	0/31 0	0/30 0	0/31 0	0/31 0	2/30 0.07	1/31 0.03	0/30 0	1/31 0.03	0/31 0	0/28 0	0/22 0
FENCE	0/31 0	0/30 0	0/31 0	0/30 0	0/31 0	0/31 0	0/30 0	1/31 0.03	0/30 0	0/31 0	0/31 0	0/28 0	0/22 0
TOPS	0/31 0	0/30 0	0/31 0	0/30 0	0/31 0	0/31 0	0/30 0	0/31 0	0/30 0	0/31 0	0/31 0	0/28 0	0/22 0
Puuloa Range Training Facility													
PUULOA	0/22 0	0/30 0	0/31 0	0/30 0	0/31 0	1/31 0.03	5/30 0.17	1/31 0.03	0/30 0	0/31 0	0/31 0	0/28 0	0/23 0

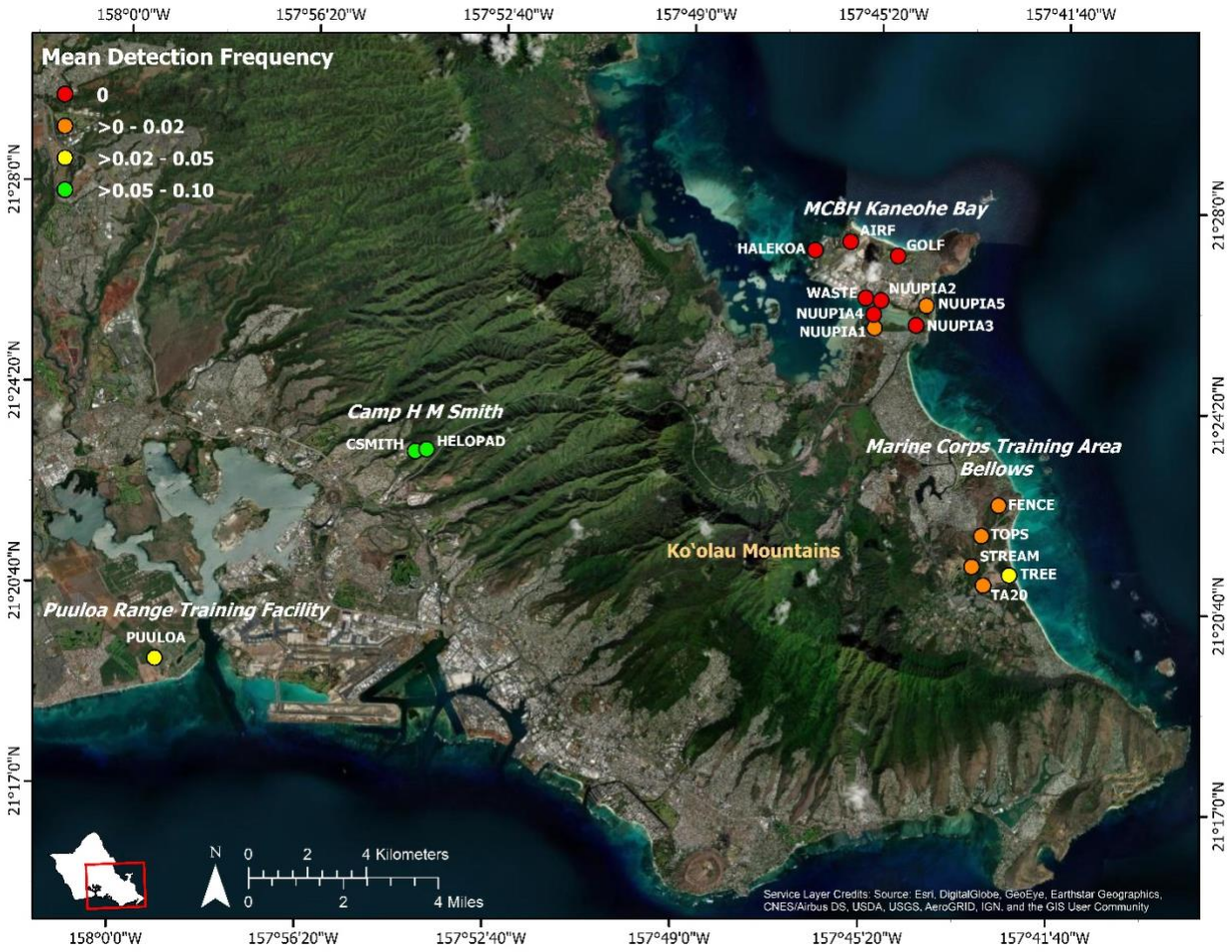

Figure 4. Mean bat detection frequency across the months of Hawaiian hoary bat reproductive and fledging periods (May–October) at 17 Marine Corps Base Hawaii (MCBH) monitoring stations on O'ahu, during 2019–2020. Service layer credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.

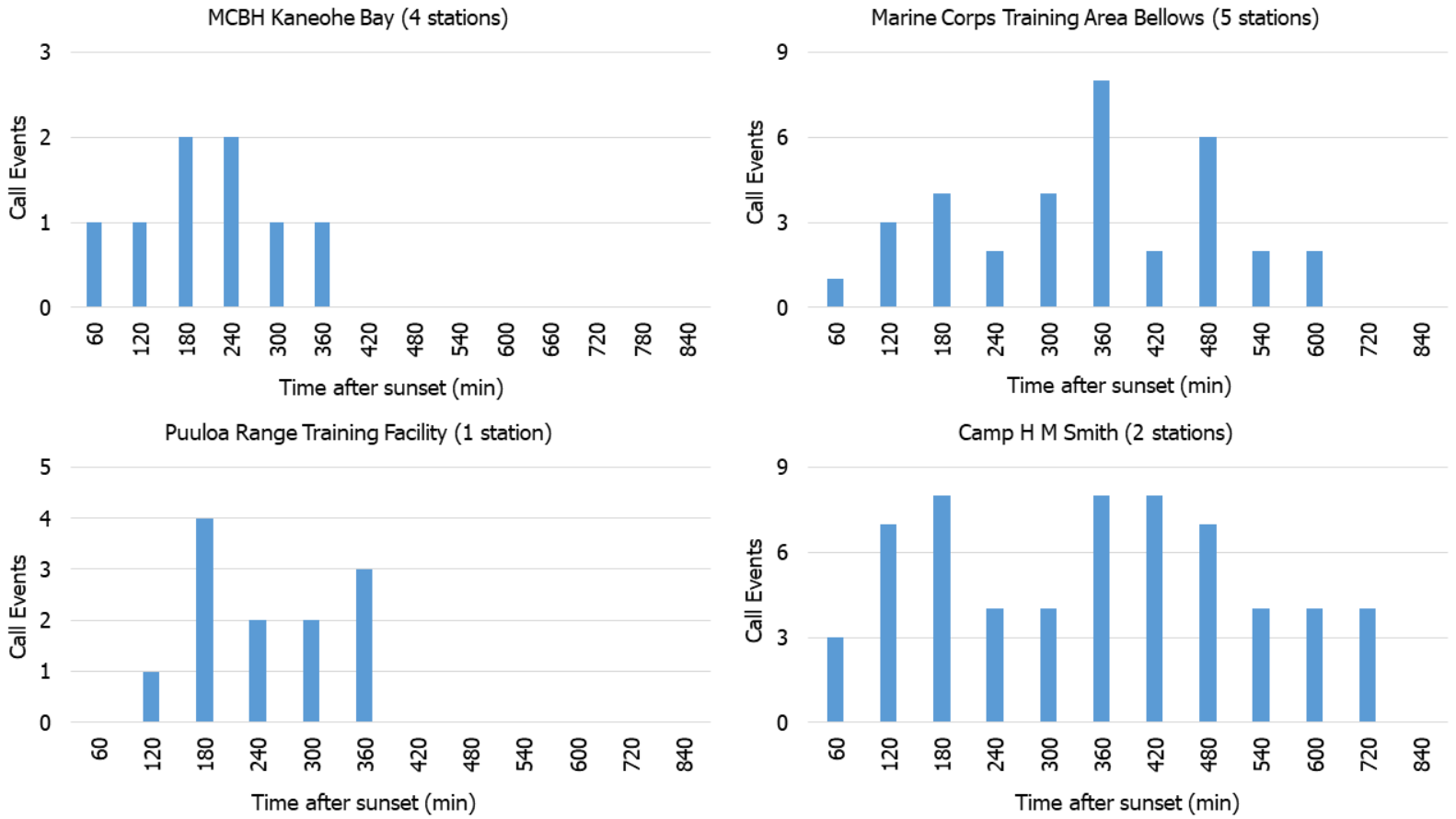

Figure 5. Total number of bat echolocation call-events relative to sunset recorded by station for the entire sampling period on Marine Corps Base Hawaii (MCBH) properties on O'ahu. To account for seasonal changes in the length of night, the time of recorded detection was standardized relative to sunset time. See Tables 3a and 3b for sampling effort.

DISCUSSION

Acoustic monitoring confirmed that Hawaiian hoary bat activity occurred at 12 of 17 acoustic monitoring stations across the four MCBH properties surveyed on O'ahu, and overall detection frequency was low at the study sites. Although data gaps in monitoring and limitations associated with acoustic monitoring techniques have the potential to underestimate bat presence, the low detection frequencies recorded in this study are comparable to other localized studies conducted on O'ahu. There was no bat activity detected at the three low-elevation properties of MCBH Kaneohe Bay, MCTAB, and Puuloa RTF during January through July, but activity did occur at these properties during August through December, which overlaps the reproductive season. Bat activity was slightly greater at the mid-elevation Camp H M Smith property, where bat activity was detected throughout most of the year. Bat activity at Camp H M Smith also occurred at greater detection frequency compared to the low-elevation properties during July through October.

The seasonal patterns of bat presence are similar to patterns previously observed in acoustic monitoring studies on the islands of Hawai'i (Gorresen *et al.* 2013, Montoya-Aiona *et al.* 2019, 2020), Maui (Todd *et al.* 2016, Pinzari *et al.* 2019, Montoya-Aiona *et al.* 2020), and O'ahu (Bonaccorso *et al.* 2019, Montoya-Aiona *et al.* 2020, Thompson and Starcevich 2021), with peak acoustic activity detected between May and October. During the pregnancy and lactation periods (May–August), adult females can be expected to have their highest energy demands and need to actively forage to support reproductive activities. During the fledging and mating period (September–December), the total bat population is expected to be at its annual maximum, thus potentially contributing to increased bat activity and detection rates (Gorresen *et al.* 2013). Additional studies on the Island of Hawai'i (Menard 2001, Gorresen *et al.* 2013, Bonaccorso *et al.* 2016) indicate bats make seasonal movements from coastal lowlands at or below 1,000 m asl during the pregnancy through fledging periods (May–October) to interior highlands up to 3,600 m asl during the pre-pregnancy period (January–March). With all stations located well below 1,000 m asl, greater detections across all properties during August through October compared to the rest of the year may be consistent with documented seasonal elevation patterns. However, there are very few locations on O'ahu higher than 1,000 m asl; thus, elevation alone may not have strong effects on bat seasonal patterns. Instead, these patterns may be driven by leeward/windward differences and resulting dry/wet habitat regimes as documented in an island-wide acoustic study by Thompson and Starcevich (2021).

Hawaiian hoary bats have been described as habitat generalists that use a wide range of habitat types over a broad elevational band (Gorresen *et al.* 2013, Bonaccorso *et al.* 2016). While increased detection frequency and bat activity have been associated with forest edge and corridor habitat (areas of narrow, open conduit for unimpeded flight such as roads, windrows of trees, etc.; Gorresen *et al.* 2013, Montoya-Aiona *et al.* 2019), bat activity has also been detected in developed and urban environments similar to the MCBH properties where bats were identified in this study (Bonaccorso *et al.* 2019, Montoya-Aiona *et al.* 2020, Thompson and Starcevich 2021). Although detection rates are low in the developed and urban areas, bats are using coastal, mesic, wetland, and forest edge habitats within the properties monitored. Among the MCBH properties, the forest edge sites at Camp H M Smith and MCTAB had the greatest rates of detection. Coastal wetland and stream habitats (and restoration actions on such habitats) have not been well researched on O'ahu with respect to bats, yet bat use of these habitat types is known to be important and has been demonstrated on the Island of Hawai'i (Pinzari *et al.* 2014, Montoya-Aiona *et al.* 2019). We documented bat activity, although low, at

the coastal wetlands of Nu'upia Ponds Wildlife Management Area at MCBH Kaneohe Bay and along the Waimanalo Stream corridor at MCTAB. Additional acoustic monitoring during the reproductive season could improve understanding with regards to conservation measures, such as how protection and enhancement of wetland habitats may affect bat presence, activity, or foraging activities associated with such habitats on O'ahu.

Foraging activity was detected very rarely and at only three acoustic monitoring stations, one at each of Camp H M Smith, Puuloa RTF, and MCTAB. Similarly, Montoya-Aiona *et al.* (2020) recorded only a single feeding buzz (in September 2017) during 594 nights of monitoring at the nearby Hawai'i Army National Guard property at Kalaeloa, Barber's Point, also on the 'Ewa coastal plain. Likewise, Thompson and Starcevich (2021) did not record any feeding buzzes at their monitoring stations on the 'Ewa coastal plain in over three years of monitoring (2017–2020); however, they did record feeding buzzes at low elevation in north O'ahu, from Lā'ie to just north of Mākaha. Feeding buzz documentation differences between the current island-wide study and this survey may be due to differences in sampling intensity levels as this survey sampled properties more intensely using a greater number of stations. Bonaccorso *et al*. (2019) documented bat foraging activity only at interior higher elevation forested sites at Schofield Barracks East and West ranges in August and September of 2015. Generally, within-night acoustic activity was confined to the first six hours after sunset at Puuloa RTF and MCBH Kaneohe Bay but occurred throughout the night at Camp H M Smith and MCTAB. These previously mentioned studies on O'ahu have also shown no clear patterns of nightly activity across lower elevation acoustic monitoring stations. The variability in nightly activity may be influenced by many factors, including irruption events of insect prey, weather events, and localized habitat changes (Gorresen *et al.* 2013).

Acoustic monitoring confirmed that Hawaiian hoary bats infrequently used habitats at most monitoring stations during pregnancy, birth, and pup rearing. The overall low numbers of call-events and feeding buzzes (maximum 5% of nights) perhaps indicate that bats are traveling through these areas while searching for prey or moving to better foraging areas, as most sites were not used with any foraging regularity. These periods begin during pregnancy (May) and continue through fledging and maternal care, a period that includes knowledge transfer from mother to volant juveniles as they forage in tandem after the initial juvenile fledging (September). July–August is the most critical time for mothers with pups because this tree roosting species may be unable to effectively relocate pups if a roosting tree is disturbed or felled. This is particularly the case in late June and early July when pups are no longer carried by a mother, are approaching adult body mass, and cannot yet fly. Searches for roost trees were not conducted during this study; thus, no evaluations could be made concerning the potential presence of mothers with pups on properties such as Camp H M Smith and MCTAB, where detections were recorded during the reproductive season.

The overall low rates of detection and seasonal activity patterns documented during two years of monitoring at MCBH properties are supported by the growing body of results from small-scale and island-wide seasonal distribution studies on O'ahu. The low rate of bat presence on MCBH properties is consistent with detection results from prior acoustic studies conducted on O'ahu; a year-long monitoring study in the northern Ko'olau Mountains in 2014 (0.08; Gorresen *et al.* 2015), a year-long monitoring study across U.S. Army facilities in 2015 (0.08; Bonaccorso *et al.* 2019), a seasonal foraging habitat use study in Kawailoa in 2017 (0.04; Gorresen *et al.* 2018), and a multi-year monitoring survey on urban Hawai'i Army National Guard properties from 2012 to 2018 (0.003; Montoya-Aiona *et al.* 2019).

A multi-year study to determine the island-wide occupancy and population trends of Hawaiian hoary bats using similar year-round acoustic collection methods has been underway on Oʻahu from mid-2017 to the present (~84 random sites by 2021; Thompson and Starcevich 2021). Preliminary results from Thompson and Starcevich (2021) report a wide range of 0 to 0.44 for the proportion of detector nights with bat activity across three years on Oʻahu; however, at the majority of individual stations, the proportion of detector nights with detections was less than 0.05. This range is low compared to findings on the Islands of Hawaiʻi (0.56, Gorresen *et al.* 2013) and Maui (0.60, Todd *et al.* 2016; 0.14–0.93, Pinzari *et al.* 2019; 0.19–0.96, Thompson 2020). Mean detections (similar to call-events) per detector night across all seasons and years only reached high values at very few monitoring stations, mostly at higher elevations in the north Koʻolau Mountains, and west Waiʻanae Mountains (Thompson and Starcevich 2021).

As in this study on MCBH properties, detection rates were highest during the post-lactation season in the island-wide study, with peak detections during September to December (Thompson and Starcevich 2021). In the island-wide study, bat occupancy in the post-lactation (fledging/mating) season was positively associated with percentage of tree habitat and negatively associated with elevation. They also reported that higher human population density (urban) was associated with lower bat occupancy. Similarly, our results found that the stations at Camp H M Smith, which are near upland forest and situated relatively distant from urban areas, were also most frequented by Hawaiian hoary bats.

In conclusion, although acoustic detection rates are relatively low at the monitored MCBH properties, these areas are used by foraging bats and some locations may harbor suitable roost habitat. Management options available to MCBH include wetland restoration, reforestation, and avoidance of roost disturbance prior to juvenile fledging. Existing management actions that may serve to guide such efforts are described in "Hawaiian Hoary Bat Guidance for Wind Energy Projects" (ESRC 2021) and the "5-year status review Lasiurus cinereus semotus" (USFWS 2021).

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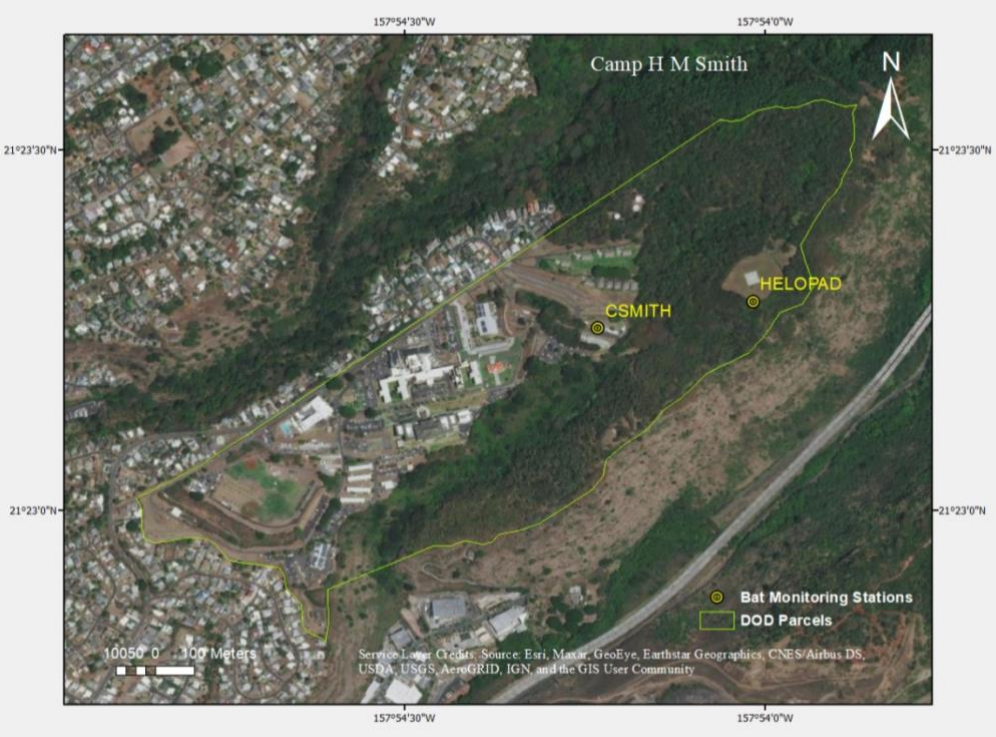
APPENDIX I. BAT ACOUSTIC MONITORING STATIONS

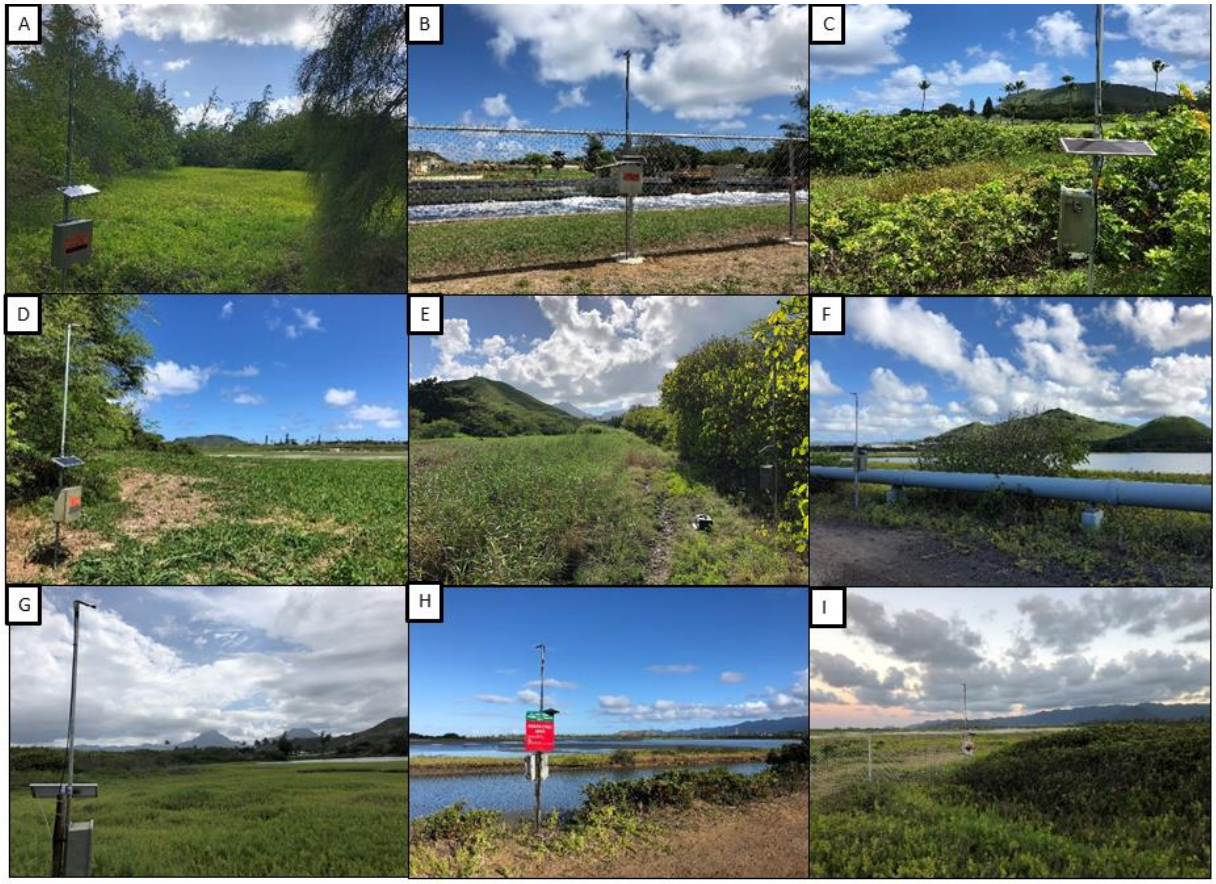
Aerial maps and habitat photographs of Marine Corps Base Hawaii properties with point locations of Hawaiian hoary bat acoustic monitoring stations.



Appendix I, Figure 1. Camp H M Smith at Halawa Heights aerial map of acoustic monitoring stations (yellow dots). Service Layer Credits: Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.

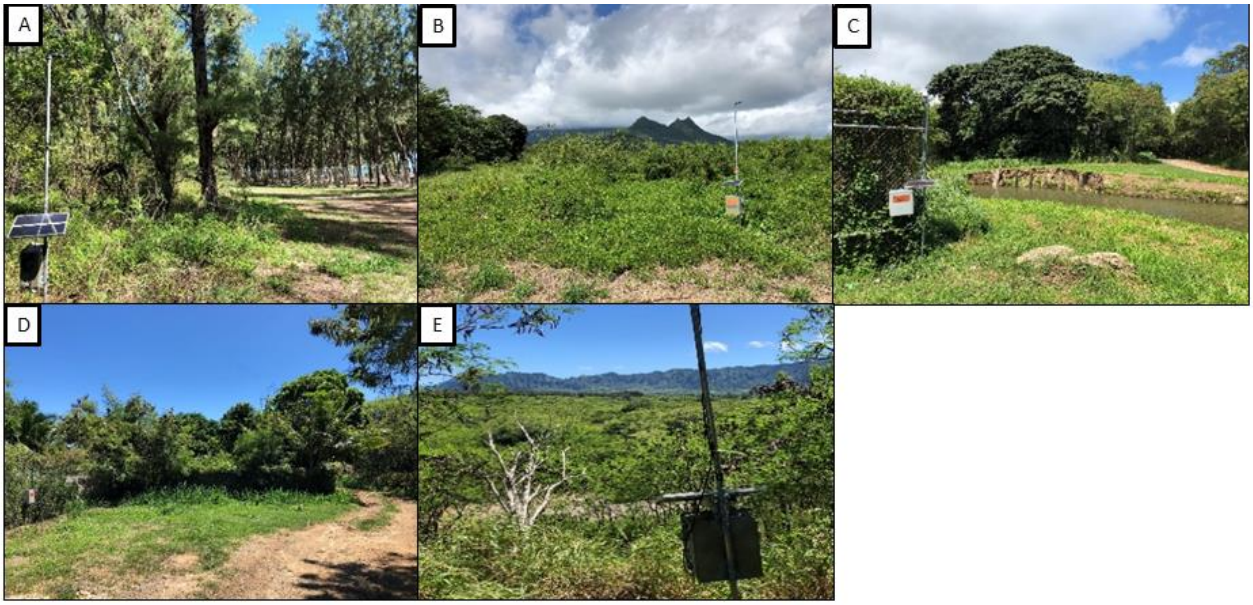
Appendix I, Figure 2. Bat acoustic recording stations at Camp H M Smith at Halawa Heights, and surrounding habitats. CSMITH (left) placed next to retired horse stables and HELOPAD (right) on edge of helicopter landing zone. Photographs taken by authors.

Appendix I, Figure 3. Marine Corps Base Hawaii Kaneohe Bay on Mōkapu Peninsula aerial map of acoustic monitoring locations (yellow dots). Service Layer Credits: Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.



Appendix I, Figure 4. Bat acoustic recording stations at Marine Corps Base Hawaii Kaneohe Bay (MCBH) on Mōkapu Peninsula, and surrounding habitats. (A) HALEKOA, (B) WASTE, (C) GOLF, (D) AIRF, (E) NUUPIA1, (F) NUUPIA2, (G) NUUPIA3, (H) NUUPIA4, (I) NUUPIA5. Photographs taken by authors.

Appendix I, Figure 5. Marine Corps Training Area Bellows (MCTAB) in Waimanalo aerial map of acoustic monitoring locations (yellow dots). Service Layer Credits: Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.

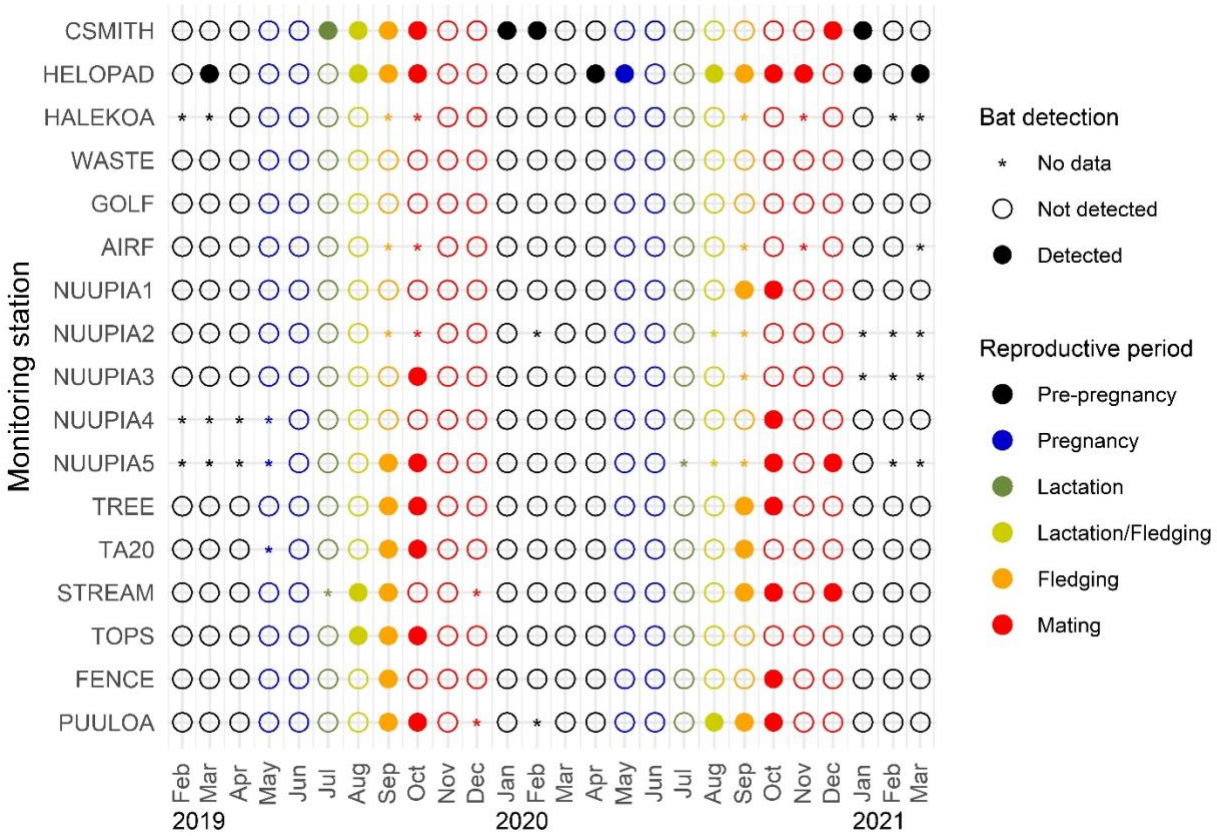


Appendix I, Figure 6. Bat acoustic recording stations at Marine Corps Training Area Bellows (MCTAB) in Waimanalo, and surrounding habitats. (A) TREE, (B) TA20 (includes TA20_2, TA20_3, TA20_4), (C) STREAM, (D) FENCE, and (E) TOPS (TOPS_2). Photographs taken by authors.

Appendix I, Figure 7. Puuloa Range Training Facility (RTF) on the ʻEwa coastal plain aerial map of acoustic monitoring locations (yellow dot). Service Layer Credits: Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.

Appendix I, Figure 8. Bat acoustic recording station (PUULOA) along fence line at Puuloa Range Training Facility (RTF) on the ʻEwa coastal plain, and surrounding habitats. Photograph taken by authors.

APPENDIX II. BAT PRESENCE OR ABSENCE OVER REPRODUCTIVE SEASONS



Appendix II, Figure 1. Confirmed bat presence or presumed absence by survey month and survey monitoring station from February 2019 through March 2021. A solid circle indicates that bats were detected, hollow circles indicate that no bats were detected, and an asterisk with no circle indicates that no data were collected in that month. A circle with an asterisk inside indicates that bats were not detected during that month in one year of the study, but no data were collected during the same month in the other year. Circles are colored to distinguish stages of the Hawaiian hoary bat reproductive cycle from pre-pregnancy (Jan–Apr), pregnancy (May–Jun), lactation (Jul–Aug), fledging (Sep), and mating (Oct–Dec).

APPENDIX III. PRE-2019 SAMPLING INFORMATION

Appendix III, Table 1. Sampling effort by month at locations surveyed from September 2018 through February 2019 at Marine Corps Base Hawaii (MCBH) properties. The first row indicates the number of detection nights out of the number of sample nights, and the second row is the monthly frequency of detections. Dashes indicate no data were collected. *1 feeding buzz was found for PUULOA on 9/28/18.

	2018				2019	
Property and monitoring station	Sep	Oct	Nov	Dec	Jan	Feb
Camp H M Smith						
CSMITH	3/11	3/24	-	1/21	0/26	-
	0.27	0.13	-	0.05	0	-
HELOPAD	0/11	2/31	0/1	0/21	0/3	-
	0	0.06	1	0	0	-
MCBH Kaneohe Bay						
HALEKOA	0/13	-	-	0/4	-	-
	0	-	-	0	-	-
WASTE	0/13	0/31	-	0/22	0/12	-
	0	0	-	0	0	-
GOLF	0/13	0/13	-	0/14	-	-
	0	0	-	0	-	-
AIRF	0/13	0/2	-	0/22	-	-
	0	0	-	0	-	-
NUUPIA1	0/13	0/5	-	0/13	-	-
	0	0	-	0	-	-
NUUPIA2	1/13	0/5	-	0/17	-	-
	0.08	0	-	0	-	-
NUUPIA3	-	-	-	1/21	0/31	0/10
	-	-	-	0.05	0	0
NUUPIA4	-	-	-	-	-	-
	-	-	-	-	-	-
NUUPIA5	-	-	-	-	-	-
	-	-	-	-	-	-
Marine Corps Training Area Bellows						
TREE	0/12	0/3	-	0/9	-	-
	0	0	-	0	-	-
TA20	0/12	0/3	-	0/21	0/31	0/1
	0	0	-	0	0	0
STREAM	1/12	0/3	-	0/9	-	-
	0.08	0	-	0	-	-
FENCE	1/12	0/8	-	0/11	-	-
	0.08	0	-	0	-	-
TOPS	0/12	0/2	-	0/21	0/5	-
	0		-	0	0	-
Puuloa Range Training Facility						
PUULOA	3/11*	0/1	-	0/12	-	-
	0.27	0	-	0	-	-