

NĀ PUA MAKANI WIND ENERGY PROJECT
Habitat Conservation Plan
FY 2023 Annual Report
(July 1, 2022 – June 30, 2023)



Prepared for:

Nā Pua Makani Power Partners, LLC

Prepared by:



July 2023

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1.0 Introduction

Nā Pua Makani Power Partners, LLC (NPMPP) developed a Habitat Conservation Plan (HCP; Tetra Tech 2016) for the Nā Pua Makani Wind Energy Project (Project) and received a U.S. Fish and Wildlife Service (USFWS) incidental take permit on September 7, 2018 (ITP; TE63452B-0) and the Hawaii Department of Land and Natural Resources, Division of Forestry and Wildlife (DOFAW) incidental take license on April 30, 2019 (ITL; ITL-21). Covered Species include:

- Hawaiian hoary bat (*Lasiurus cinereus semotus*) or ‘ōpe‘ape‘a,
- Newell’s shearwater (*Puffinus newelli*) or ‘a‘o,
- Hawaiian goose (*Branta sandvicensis*) or nēnē,
- Hawaiian duck (*Anas wyvilliana*) or koloa maoli,
- Hawaiian coot (*Fulica alai*) or ‘alae ke‘oke‘o,
- Hawaiian gallinule (*Gallinula chloropus sandvicensis*) or ‘alae ‘ula,
- Hawaiian stilt (*Himantopus mexicanus knudseni*) or ae‘o, and
- Hawaiian short-eared owl (*Asio flammeus sandwichensis*) or pueo.

Project construction began in FY 2019 and continued into FY 2021. Concrete pouring for the first turbine foundation began on April 30, 2019, and coincides with the effective start date of the ITL. Project commissioning began on August 16, 2020, and commercial operations began on December 11, 2020. During commissioning Project components and the interconnection and transmission capabilities of the system are tested before the initiation of full commercial operation.

On behalf of NPMPP, Tetra Tech, Inc. (Tetra Tech) has prepared this report to describe activities relating to the Project HCP for the State of Hawaii fiscal year (FY) 2023,¹ from July 1, 2022, through June 30, 2023, pursuant to the terms and obligations of the approved HCP, ITL, and ITP. The Project has previously submitted annual HCP progress reports to DOFAW and USFWS for FY 2019 through FY 2022 (Tetra Tech 2019a, Tetra Tech 2020, Tetra Tech 2021, Tetra Tech 2022a).

2.0 On-Site HCP-Related Management

2.1 Avoidance and Minimization

NPMPP has worked to minimize risk to wildlife through avoidance and minimization measures outlined in the HCP. In addition, NPMPP has implemented monitoring approaches to document potential impacts to wildlife.

¹ Fiscal year references in this report refer to the State of Hawaii fiscal year, which begins every July 1st and ends every June 30th.

To minimize potential impacts to wildlife, on-site lighting at the O&M building and substation is directed downward and fitted with non-white light bulbs. Lighting in the vicinity of the turbines is only used when workers are at the site at night. No night work requiring lights that could attract wildlife occurred in FY 2023.

NPMPP implements low wind speed curtailment to reduce potential impacts to Hawaiian hoary bats. Implementation included increasing manufacturer's recommended cut-in speeds to 16 feet per second (ft/s; 5 meter per second [m/s]) and feathering turbine blades into the wind below 16 ft/s (5 m/s). Low wind speed curtailment is instituted annually March – November between sunset and sunrise; in FY 2023 this included implementation July – November 2022 and March – June 2023. In addition to the intended benefit of reducing bat fatalities, low wind speed curtailment reduced risk to Covered Species such as the Newell's shearwaters and Hawaiian short-eared owl, which could transit the Project at night.

NPMPP installed an NRG ultrasonic acoustic bat deterrent system on turbines 2, 3, 4, and 6 prior to the initiation of commercial operations to further reduce the collision risk to the Hawaiian hoary bat. These turbines were selected due to their proximity to forest edge and gulch habitat, which have been correlated with increased bat activity.

2.2 Downed Wildlife Monitoring

On August 26, 2020, the Project initiated standardized carcass searches according to the Project's Post-construction Mortality Monitoring (PCMM) Implementation Plan (Tetra Tech 2022b), concurrent with the beginning of periodic turbine testing during the Project commissioning phase (August 16, 2020). While input had not yet been received from USFWS or DOFAW on the PCMM Implementation Plan, there was a need to implement a standardized monitoring approach suitable for yielding robust statistical estimates of take.

Based on input on the PCMM Implementation Plan from USFWS and DOFAW, NPMPP and Tetra Tech have updated the document incorporating additional information and commitments to address agency questions and concerns through two revisions. In FY 2022, searches in supplemental (agricultural areas) and bias associated correction testing were incorporated into the analysis. In FY 2023, carcass persistence testing protocols were further refined.

Throughout FY 2023 downed wildlife monitoring at the Project consisted of standardized fatality monitoring according to the Project's PCMM Implementation Plan (Tetra Tech 2022b) and a revised plan submitted in April 2023, following an agency site visit (Tetra Tech 2023). The PCMM Implementation Plan describes how the Project implements the PCMM program provided in the HCP based on the Project construction footprint, current land use patterns, and topography. The elements of the PCMM program used to estimate fatality rates of Covered Species include:

- The specific delineation of:
 - systematic search areas,

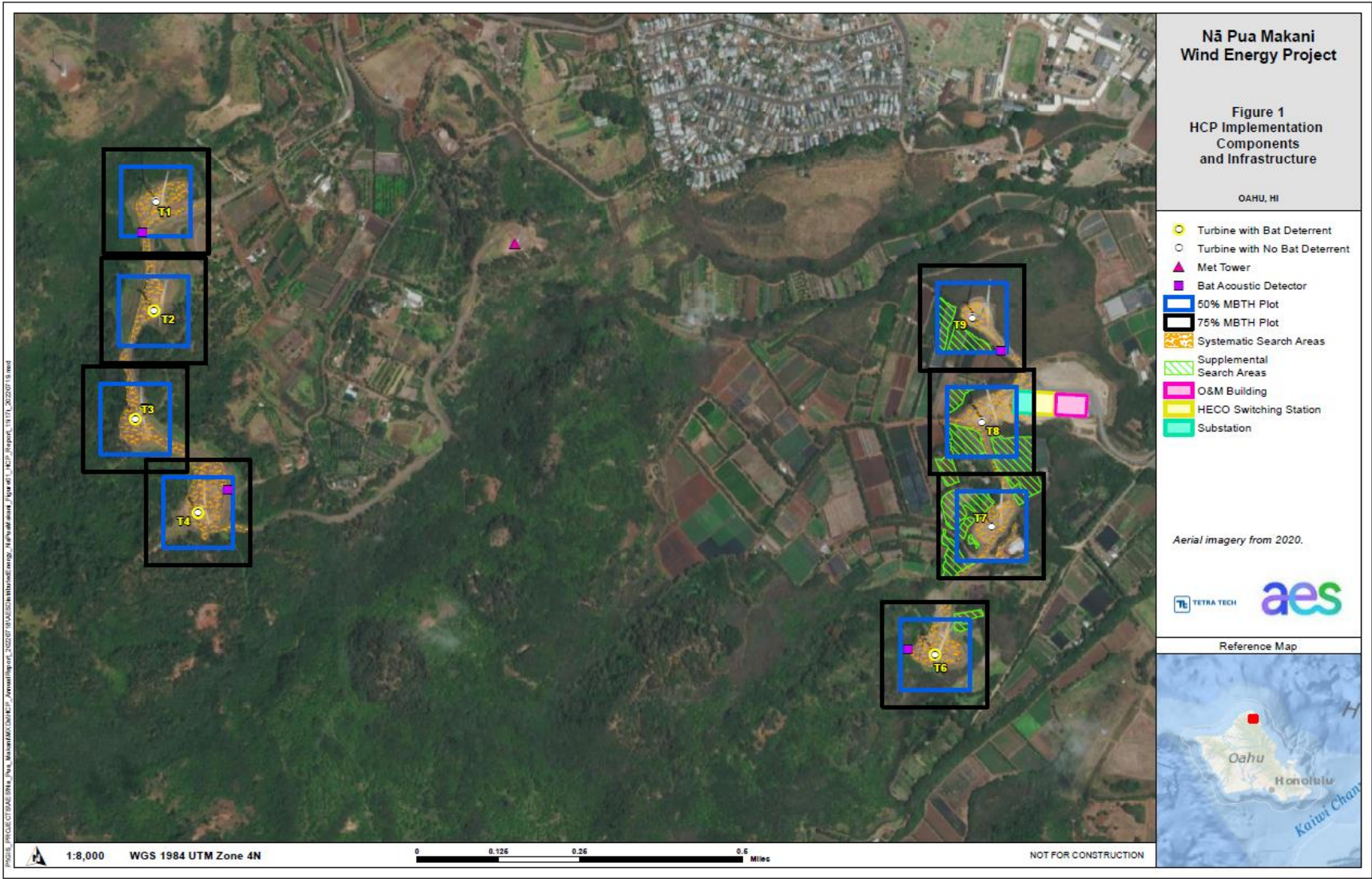
- supplemental (agricultural) search areas within active agricultural areas in the vicinity of turbines 6 – 9, where canine search teams can at least periodically safely perform searches
- Search frequency,
- Bias correction testing protocols (see sections 2.3 – 2.4 below), and
- Methods and results for the calculation of the proportion of the carcass distributions planned for searching.

In FY 2022, based on recommendations from DOFAW and USFWS to increase the search areas around the turbines, NPMPP and Tetra Tech incorporated protocols to augment the systematic search area results with search results from supplemental (agricultural) search areas where consistent and effective searching can take place. This process included extensive outreach to the farmers working adjacent to the Project turbines, hiring of an additional canine handler, and significant logistical and methodological adjustments to ensure that health and safety requirements are met, landowner and farmer relationships are maintained, and quality data can be collected.

Under the PCMM Implementation Plan as performed in FY 2023, NPMPP conducted weekly searches with trained canine search teams within systematic search areas (Figure 1). These systematic search areas consist of areas that were cleared and graded during Project construction at each of the Project's eight turbines and can be practicably maintained in low-growing vegetation through mowing. Cleared and maintained areas include roads and pads and additional areas cleared during construction on low or moderate slopes that can be practicably maintained. In addition, as site conditions allowed, a canine search team performed supplemental searches within active agricultural areas. All such areas that can be searched consistently during any fiscal quarter will be incorporated into fatality estimate(s); we performed associated bias correction trials (see sections 2.3 and 2.4) and searches throughout FY 2023 and incorporated consistently searched supplemental search area results into the analysis of the take estimate (Section 2.7).

Supplemental areas are not always searchable,² can be highly variable in terms of the vegetative growth, evolve quickly, and are relatively small. These challenges mean that it is likely that not all supplemental search areas will be used in the statistical analyses. Nevertheless, such supplemental search areas will continue to be evaluated and considered for incorporation in future analyses and are likely to provide opportunities for an improved understanding of the carcass distribution at the site and may facilitate the establishment of more robust fatality estimates.

² Some supplemental search areas regularly or occasionally have loose dogs which threaten the safety of the canine search team. Similarly, other conditions, such as the periodic application of herbicide or other chemicals, may make searching a supplemental search area unsafe or impractical during a particular week.



2.3 Carcass Persistence Trials

Within the systematic search areas, 80, 28-day carcass persistence trials were conducted in FY 2023 using black rats (*Rattus rattus*) for Hawaiian hoary bat surrogates, and chukars (*Alectoris chukar*) or wedge-tailed shearwater (*Ardenna pacifica*) carcasses collected or procured under the Project's Special Purpose Utility Permit (MB79835D-0) and Hawaii Protected Wildlife Permit (WL20-18) as surrogates for the avian Covered Species.

Based on concerns that carcass persistence trials conducted within agricultural areas with tender young crops could result in damage due to the canine searcher energetically pursuing the scent of the carcass. Therefore, in Quarter 1 and Quarter 2 FY 2023 trial carcasses were placed outside of the search areas but within otherwise similar agricultural areas which could not be searched due to the presence of aggressive dogs. However, in Quarter 3 and Quarter 4 FY 2023, we conducted comparative trials to evaluate differences in carcass persistence and to determine if the initial concern was warranted. Within supplemental agricultural search areas, an additional 70, 28-day carcass persistence trials were conducted in FY 2023. The probability that a carcass persisted until the next search used in the fatality analysis (Quarter 1 – Quarter 2 data with trial carcasses placed outside of the search areas and Quarter 3 – Quarter 4 data with trial carcasses placed within the search areas) is reported in Table 1. Comparative results of Quarter 3 – Quarter 4 carcass persistence trials within search areas and outside of search areas are reported in Table 2. Results of the comparative study suggest that carcass persistence times may differ among plots and temporally and that with appropriate canine handling, the risks of crop damage can be minimized. Therefore, to most accurately reflect conditions within the searched areas, NPMPP plans to continue carcass persistence testing within the supplemental agricultural search areas.

2.4 Searcher Efficiency Trials

Within systematic search areas, a total of 104 searcher efficiency trials over 13 trial days were administered during FY 2023. Similar to the carcass persistence trials, black rats were used as surrogates for bats, and chukars, wedge-tailed shearwaters, or cattle egrets (*Bulbulcus ibis*) were used as surrogates for avian Covered Species. Searcher efficiency trials occurred approximately monthly throughout the year. Most trials tested canine search teams in FY 2023; however, in Quarter 4 FY 2023 un-aided human searches occurred during 13 searches to cover a small area adjacent to a warehouse near Turbine 7 due to dog concerns. Therefore, 20 of these 104 searcher efficiency trials were administered to test human-only searcher efficiency. This warehouse area routinely had aggressive loose dogs in the vicinity, making it unsafe to perform searches with the search dog. Of the 113 trials placed, 7 bat surrogates and 2 bird carcasses were not available for detection.³ Within supplemental search areas, an additional 83 searcher efficiency trial carcasses

³ Carcasses not available for detection are those that were not detected by the search team, and upon investigation by the testing proctor, could not be found, indicating the carcass had likely been scavenged prior to the search.

were placed over 13 trial days. Of these, 11 bat surrogates and 6 bird carcasses were not available for detection. The probability that an available carcass would be detected is reported in Table 1.

Table 1. Cumulative Searcher Efficiency and Carcass Persistence Trial Results FY 2023

Size	Search Area	Total Trials		Mean (95% Confidence Interval)	
		Searcher Efficiency ¹	Carcass Persistence	Searcher Efficiency (Proportion Detected) ²	Probability of Persistence to the Next Search (r) ³
Bat Surrogate	Systematic	42	40	1.00 (0.94 – 1.00)	0.78 (0.66 – 0.87)
	Systematic (human only) ⁴	10		0.60 (0.30 – 0.85)	
Medium Bird	Systematic	42	40	1.00 (0.94 – 1.00)	0.74 (0.61 – 0.85)
	Systematic (human only) ⁴	10		0.90 (0.62 – 0.99)	
Bat Surrogate	Supplemental (analysis) ⁵	41	25	0.93 (0.82 – 0.98)	0.47 (0.34 – 0.61)
Medium Bird	Supplemental (analysis) ⁵	42	25	0.88 (0.76 – 0.95)	0.59 (0.43 – 0.74)

1. Available for detection.

2. Estimates and 95 percent confidence interval calculated using Dalthorp et al. (2017) single year module.

3. The estimate of r is reported in lieu of carcass persistence time, as r provides a more informative portrayal of the effect of carcass persistence on fatality estimates, incorporating information from the carcass persistence distribution and the search interval in a single variable. Estimates and confidence interval for r calculated using Dalthorp et al. (2017) single year module. We report the probability of persistence based on a 7-day search interval for the supplemental agricultural search areas, but the actual measure varies based on the frequency of searches.

4. In Quarter 4 a small area around a warehouse in the vicinity of turbine 7 routinely had loose dogs in the vicinity. The canine handler could not safely search this small discrete area. Testing of searcher efficiency performed by the canine handler without their dog was performed to incorporate this information into the analysis.

5. In Quarter 1 – Quarter 2 carcass persistence trials were only done within agricultural areas where canine searches could not take place (areas where the regular presence of aggressive dogs made the safe performance of searches impossible), but with otherwise similar conditions to those where searches occurred. In Quarter 3 – Quarter 4 parallel carcass persistence trials were performed in searched agricultural areas and unsearched agricultural areas. The data used in the analysis include results from Quarter 1 – Quarter 2 (unsearched areas) and Quarter 3 – Quarter 4 (searched areas). Comparisons between the searched and unsearched areas in Quarter 3 – Quarter 4 are shown in Table 2.

Table 2. Supplemental Area Comparative Carcass Persistence Trial Results Quarter 3 – Quarter 4 FY 2023

Size	Search Area	Number of Trials	Probability of Persistence to the Next Search (r) Mean (95% Confidence Interval) ¹
Bat Surrogate	Supplemental (searched; Quarter 3 – Quarter 4) ²	10	0.63 (0.42 – 0.79)
	Supplemental (not searched; Quarter 3 – Quarter 4) ²	10	0.18 (0.08 – 0.34)
Medium Bird	Supplemental (searched; Quarter 3 – Quarter 4) ²	10	0.66 (0.36 – 0.89)
	Supplemental (not searched; Quarter 3 – Quarter 4) ²	10	0.92 (0.79 – 0.97)

1. The estimate of r is reported in lieu of carcass persistence time, as r provides a more informative portrayal of the effect of carcass persistence on fatality estimates, incorporating information from the carcass persistence distribution and the search interval in a single variable. Estimates and confidence interval for r calculated using Dalthorp et al. (2017) single year module. We report the probability of persistence based on a 7-day search interval for the supplemental agricultural search areas, but the actual measure varies based on the frequency of searches.

2. In Quarter 1 – Quarter 2 carcass persistence trials were only done within agricultural areas where canine searches could not take place (areas where the regular presence of aggressive dogs made the safe performance of searches impossible), but with otherwise similar conditions to those where searches occurred. In Quarter 3 – Quarter 4 parallel carcass persistence trials were performed in searched agricultural areas and unsearched agricultural areas.

2.5 Vegetation Management

Mowing within each of the eight search plots currently occurs every other week, on average; staff evaluate and perform necessary vegetation management around turbines weekly following the completion of scheduled fatality monitoring searches. This effort maintains vegetation at heights below approximately 8 inches within the systematic search areas at each turbine.

2.6 Scavenger Trapping

Nā Pua Makani Power Partners has contracted scavenger control for the site. Traps are checked approximately every two weeks. Active trapping occurred at all eight turbines and connecting roadways throughout the Project area using 90 DOC250 and 10 Steve Allan traps. Trap distribution has remained consistent throughout the implementation of this program. The scavenger control program documented the removal of 278 mongooses (*Herpestes auropunctatus*), 121 rats (*Rattus* spp.), 16 feral cats (*Felis catus*), six house mice (*Mus musculus*), and 39 non-target species (spotted dove [*Spilopelia chinensis*], common myna [*Acridotheres tristis*], cane toad [*Rhinella marina*], red junglefowl [*Gallus gallus*], giant African snail [*Lissachatina fulica*]) in FY 2023. Trapping rates were relatively stable over time and are reported in Table 3.

Table 3. Scavenger Trapping Results at the Project in FY 2023

Trap Check Date	Mongoose per Trap	Rats per Trap	Cats per Trap	Mice per Trap	Non-Target Species per Trap	Active Traps per Check ¹
7/9/2022	0.15	0.00	0.02	0.00	0.07	91
7/23/2022	0.08	0.04	0.05	0.00	0.01	91
8/7/2022	0.17	0.05	0.03	0.04	0.04	92
8/20/2022	0.11	0.05	0.00	0.00	0.00	88
9/5/2022	0.14	0.07	0.00	0.00	0.02	99
9/17/2022	0.12	0.02	0.01	0.00	0.00	99
10/2/2022	0.13	0.13	0.01	0.00	0.02	96
10/15/2022	0.16	0.04	0.00	0.00	0.01	90
10/30/2022	0.17	0.11	0.01	0.00	0.02	90
11/11/2022	0.10	0.03	0.00	0.00	0.00	88
11/25/2022	0.09	0.06	0.00	0.00	0.00	89
12/10/2022	0.09	0.06	0.01	0.00	0.00	93
12/24/2022	0.08	0.02	0.01	0.00	0.02	89
1/8/2023	0.10	0.09	0.00	0.00	0.01	88
1/21/2023	0.16	0.04	0.00	0.01	0.01	92
2/4/2023	0.10	0.01	0.00	0.00	0.00	89
3/4/2023	0.07	0.05	0.00	0.00	0.01	95
3/19/2023	0.15	0.04	0.00	0.00	0.02	94
4/2/2023	0.16	0.03	0.00	0.00	0.03	93
4/23/2023	0.12	0.06	0.00	0.00	0.06	95
4/30/2023	0.09	0.03	0.00	0.00	0.02	95
5/13/2023	0.12	0.08	0.00	0.00	0.00	91
5/27/2023	0.14	0.06	0.01	0.01	0.01	94
6/09/2023	0.14	0.03	0.00	0.00	0.01	87
Mean (SD)	0.12 (0.03)	0.05 (0.03)	0.01 (0.01)	0.00 (0.01)	0.02 (0.02)	92.0 (3.2)
1. Traps were less than 100 when trap(s) were damaged, lost, or malfunctioned.						

2.7 Documented Fatalities and Monitoring Results

All observed downed wildlife were handled and reported in accordance with the USFWS and DOFAW Downed Wildlife Protocol (DOFAW and USFWS 2020). NPMPP documented 33 wildlife incidents in FY 2023 (Appendix 1). No Covered Species injuries or fatalities were found in FY 2023. Eight Migratory Bird Treaty Act (MBTA) species fatalities were documented: three cattle egrets, two house finches (*Haemorrhous mexicanus*), one Pacific golden-plover (*Pluvialis fulva*), one great frigatebird (*Fregata minor*), and one Bulwer's petrel (*Bulweria bulwerii*). The other wildlife

incidents included 15 spotted doves, six zebra doves (*Geopelia striata*), three common mynas, and one common waxbill (*Estrilda astrild*).

Various factors affect how the number of observed fatalities is scaled to estimate the direct take of Covered Species at the Project. Unobserved fatalities are due to three primary factors:

- Carcasses may be scavenged before searchers can find them,
- Carcasses may be present and not detected by searchers, and
- Carcasses may fall outside of the search area.

Sections 2.3 and 2.4 describe methods that are used to estimate the effect of the first two factors. To evaluate the contribution of the proportion of the search area searched to the estimate, we used an agency recommended ballistics model (Hull and Muir 2010) and GIS-delineated search area spatial data to estimate the proportion of the carcass distribution searched.

2.7.1 Hawaiian Hoary Bat

Estimated Take

One Hawaiian hoary bat fatality has been observed at the Project since the Project began testing turbine operations (commissioning) in August 2020. The single documented Hawaiian hoary bat fatality was found on September 22, 2021, during a regular search. The carcass was detected 14 meters from the base of Turbine 6 and was collected and transferred to the U.S. Geological Survey (USGS) for genetic sexing. The results of the testing identified the individual as a female (Pinzari and Bonaccorso 2018). The observed Hawaiian hoary bat fatalities by fiscal year are listed in Table 4.

Table 4. Observed Hawaiian Hoary Bat Fatalities at the Project through FY 2023

Fiscal Year	Hawaiian Hoary Bat Observed Direct Take	Hawaiian Hoary Bat Incidental Fatality Observations	Total
2021	0	0	0
2022	1	0	1
2023	0	0	0
Total	1	0	1

Cumulative take is estimated from three components: (1) observed direct take (ODT) during protocol (standardized) fatality monitoring, (2) unobserved direct take (UDT), and (3) indirect take. The Evidence of Absence software program (EoA; Dalthrop et al. 2017), an agency-approved analysis tool for analyzing direct take, uses results from bias correction trials and ODT to generate an upper credible limit (UCL) of direct take (i.e., ODT + UDT). USFWS and DOFAW have requested that estimates of direct take be reported at the 80 percent UCL. Direct take values from this analysis can be interpreted as: there is an 80 percent probability that actual direct take at the Project over

the analysis period was less than or equal to the 80 percent UCL. Associated indirect take is estimated based on the sex and age characteristics of bat fatalities found at the Project, and the life history characteristics of (assumed to be representative of) the Hawaiian hoary bat, as described in the Project's approved HCP and current agency guidance (USFWS 2016).

The total cumulative estimated bat take (including indirect take) from the start of Project commissioning (when periodic turbine operation began) through FY 2023 is summarized in Table 5. Input values used in the EoA multi-year analysis are provided in Table 6.

Table 5. Cumulative Take Estimation for Hawaiian Hoary Bat through FY 2023

A: Observed Direct Take Used in Analysis	B: Incidental Observed Take	C: 80% Upper Credible Limit of Estimated Direct Take ¹	D: UDT (C – A – B)	E: Estimated Indirect Take (Adult Equivalents) ²	Total Estimated Adult Take (C + E)
1	0	3	2	1	4
1. Multi-year EoA analysis (Dalthorp et al. 2017) based on FY 2021 –FY 2023 data. 2. Overall indirect take for the Project is the rounded-up value calculated using the USFWS (2016) methodology as described in the text.					

Table 6. Input Values for Multi-Year Analysis of Hawaiian Hoary Bat Take

Modelling Period	Weight	Search Fatalities	Ba ¹	Bb ¹	\hat{g}	\hat{g} 95% CI
FY 2021	0.87	0	81.18	74.92	0.520	0.442 – 0.598
FY 2022 ²	1.00	1	144.3	115.2	0.556	0.492 – 0.616
FY 2023 ²	1.00	0	152.9	134.2	0.533	0.475 – 0.590
1. EoA stores the parameters of the beta distribution to 4 significant digits; however, model imprecision suggests these results should be reported to a maximum of 3 digits (Dan Dalthorp, USGS, pers. comm. January 2020). 2. Results from FY 2022 – FY 2023 include results from searches within the systematic search areas and consistently searched supplemental search areas combined into a single estimate through the multi-class module in EoA (Dalthorp et al. 2017).						

The estimated direct take (ODT + UDT) for the one Hawaiian hoary bat fatality found between the start of operation and end of FY 2023 (June 30, 2022) is less than or equal to 3 bats (80 percent UCL). Details of the estimated direct take parameters are in Appendix 2.

Indirect take is estimated to account for the potential loss of future individuals (offspring) that may occur as the result of the loss of an adult female through direct take during the breeding period when females may be pregnant or supporting dependent young. Indirect take for the Project is calculated using the USFWS (2016) guidance as follows:

- **Total Juvenile Take Calculated from Observed Female Take (April 1 – September 15)**

- 0 (observed females) * 1.8 (pups per female) = 0 juveniles⁴
- **Total Juvenile Take Calculated from Observed Unknown Sex Take (April 1 – September 15)**
 - 0 (observed unknown sex) * 0.5 (assumed sex ratio) * 1.8 (pups per female) = 0 juveniles
- **Total Juvenile Take Calculated from Unobserved Take**
 - 2 (unobserved direct take) * 0.5 (assumed sex ratio) * 0.25 (proportion of calendar year females could be pregnant or have dependent pups) * 1.8 (pups per female) = 0.45 juveniles
- **Total Calculated Juvenile Indirect Take = 0.45**
- **Total Adult Equivalent Indirect Take = 0.3 (juvenile to adult conversion factor) * 0.45 = 0.135**

The UCL for cumulative Project take of the Hawaiian hoary bat at the 80 percent credibility level is 4 adult bats (3 [estimated direct take] + 1 [estimated indirect take]). That is, there is an approximately 80 percent probability that actual take at the Project at the end of FY 2023 is less than or equal to 4 bats.

Projected Take

Evidence of Absence (EoA) includes a module that allows users to project future estimates of mortality based on results of past fatality monitoring. Due to the inherent uncertainty of these projections (including the potential future contribution of indirect take) and the amplification of this uncertainty resulting from the use of the 80 percent UCL as the estimate of take for regulatory compliance, long term projections have limited utility. Nevertheless, they do help gauge the likelihood of permitted take exceedance, and may help operators in their mitigation planning, assuming future management and monitoring conditions can be reasonably estimated.

NPMPP projected take through the end of the permit term using the fatality monitoring data collected through FY 2023. The objective of this analysis was to evaluate the potential for the Project to exceed the permitted take limit at the 80 percent UCL prior to the end of the permit term (Appendix 2). For this analysis, the detection probability for future years is assumed to be constant at 0.533 (95 percent CI = [0.475, 0.590]). As future indirect take is unknown and will potentially vary based on the timing of ODT, we assumed total indirect take for the Project over the permit term would be a maximum of 3 adult equivalents (10 juveniles based on assumed Hawaiian hoary bat survival rates; USFWS 2016), or 5.8 percent of the permitted take. Currently, the proportion of total take that is attributable to indirect take is 4.3 percent (0.135 [adult indirect take]/3.135 [adult direct and indirect take] = 0.043). Assuming 3 adult bat equivalents are attributed to the Project as indirect take, the permitted direct take under the Project's ITP and ITL would be 48 bats (i.e., 51 permitted take – 3 indirect take = 48 direct take). Based on the analysis described above and

⁴ As the observed fatality in FY 2022 occurred outside the period when females have dependent young, no indirect take is associated with that individual.

presented in Appendix 2, there is a 92.9 percent chance that the 80 percent UCL of cumulative take will not be exceeded during the permit term.

2.8 Invasive Species Management Surveys

In FY 2019 NPMPP developed an invasive species management plan to limit the potential impacts of invasive species (Tetra Tech 2019b). Consistent with HCP requirements, NPMPP coordinated with the O'ahu Invasive Species Committee (OISC) to identify and implement measures to minimize the risk of introducing devil weed (*Chromolaena odorata*) to the Project area. Approaches to minimize risk include periodic site inspections by qualified personnel to search for the presence of plants and cleaning of equipment used in the Project area. Surveys covering the Project's disturbance footprint are conducted annually in the fall.

During an invasive plant species survey of the Project in Quarter 2 FY 2023, biologists detected devil weed in the approximately the same distribution as the Quarter 2 FY 2022 surveys (turbines 3, 4, and 6, as well as near Kamehameha Highway, along the road between the Mālaekahana and Department of Land and Natural Resources-owned portions of the Project, and on the road between turbines 6 and 7). New detections in FY 2023 were documented along the northern boundary of the laydown area and on the Project road between Turbine 8 and the meteorological tower road. Following initial detection of devil weed at the site, NPMPP coordinated with the OISC to verify appropriate control measures for this species within the Project's disturbance footprint and has continued to implement this approach in FY 2023.

Field observations suggest devil weed is established beyond the Project's disturbance footprint. The OISC has reported the presence of a known infestation in the vicinity of the Project prior to Project construction. Based on current data, OISC does not believe eradication of devil weed is possible and requested that NPMPP manage the species to the extent practicable, using best practices identified in the Project's invasive species management plan. NPMPP manages the devil weed within the Project footprint through a combination of hand removal, herbicide, and mowing. Herbicide cannot be used within the systematic search areas to protect the health and safety of the canine search team. Hand pulled specimens are bagged and incinerated. NPMPP continues to monitor and manage known infestations and monitor for the presence of devil weed in new locations. The canine search team and project biologist follow decontamination protocols to clean field gear following potential exposure to devil weed seed sources. This approach should reduce the risk of further expansion of the colony. To date regular mowing of affected areas within the systematic search areas have kept the plants from forming flowers or seeds.

2.9 Wildlife Education and Incidental Reporting System

NPMPP implemented a Wildlife Education and Incidental Reporting Program for Project staff working at the Project. This training enables staff to identify the Covered Species that may occur at the Project site by providing staff with printed reference materials that include photographs of each of the Covered Species, information on their biology and habitat requirements, threats to the species onsite, and avoidance and minimization measures of the HCP. Project staff are responsible

for awareness of wildlife activity onsite, responding to and treating wildlife appropriately, documenting any Project-related wildlife incidents, and reporting any downed wildlife to the on-site manager.

Eight Project personnel, subcontractors, and visitors were trained through this program in FY 2023. Downed wildlife observations found during standardized searches were supplemented by 22 incidental downed wildlife observations reported in FY 2023 by Project personnel trained through the Wildlife Education and Incidental Reporting Program (Appendix 1).

3.0 Mitigation and Related Activities

The Project's mitigation requirements are described in Section 6.0 of the HCP (Tetra Tech 2016).

3.1 Hawaiian Hoary Bat

3.1.1 Poamoho Management Area Research and Management Plans

The mitigation plan for the Hawaiian hoary bat in the HCP includes preparation and implementation of research and management plans targeting actions that will improve and protect bat habitat in the Poamoho Management Area and study the effectiveness of habitat restoration activities on improving the availability of bat food resources, increasing bat activity, or other appropriate variables. In FY 2023 (Quarter 2) revised drafts of the associated research and management plans were submitted and reviewed by DOFAW and USFWS in Quarter 4 (DOFAW) and Quarter 3 (USFWS). NPMPP and Tetra Tech are working with the Ko'olau Mountain Watershed to address agency comments and submit revised versions for approval by USFWS, DOFAW, and the Endangered Species Recovery Committee (ESRC).

3.1.2 Bat Deterrent Research Plan

The ITL includes a special condition requiring NPMPP to perform research focused on bat deterrence measures with the goal of reducing the bat take at wind turbines. NPMPP and Tetra Tech have consulted with DOFAW on their priorities for this research, potential challenges, and possible research approaches. In Quarter 1 FY 2023, NPMPP and Tetra Tech submitted a research plan for review and received input from DOFAW and USFWS in Quarter 4. Following additional discussion with DOFAW in FY 2024, NPMPP will submit a revised research plan for review by the ESRC. Results of the research plan will be reported in the HCP annual reports for the duration of the approved research project.

3.1.3 On-Site Acoustic Surveys

The Project commenced commercial operation on December 11, 2020. As part of the HCP the Project commits to performing acoustic monitoring for Hawaiian hoary bat activity for an undefined period during operation (Section 4.2.2 of the HCP, Tetra Tech 2016). Post construction

monitoring for bat activity began in September 2020 and is currently in the second monitoring year. Monitoring was conducted at four locations (turbines 1, 4, 6, and 9; Figure 1) using ground-based recording units. Recording units consisted of a Song Meter SM4BAT-FS ultrasonic acoustic recorder equipped with high frequency microphones (SMM-U2; Wildlife Acoustics, Inc., Maynard, Massachusetts), elevated 3 meters above the ground on poles and powered by 12 v/18 amp-h batteries connected to 10 w/12 v solar panels (ACOPower, Walnut, California). All units were set to record nightly bat activity beginning 1 hour before sunset and end 1 hour after sunrise. Monitoring site locations were selected to provide the best spatial distribution across the Project and representation of the habitats (e.g., mature forest, agriculture, and gulch).

The objective of acoustic monitoring is to better understand the annual, seasonal, and site variation in bat activity at the Project. Analysis of variance (ANOVA) and Tukey's honest significance difference (Tukey's HSD) were used to test for differences in annual detection rates between the FY2021 and FY 2023 monitoring years. A linear model (LM) was used to test for a change in detection rates across all monitoring years and for differences in mean detection rates between sites. Data were normalized with an Ordered Quantile Normalization transformation using the 'bestNormalize' package in R (Peterson 2021). The distribution of residuals from the LM were examined to check for violations of model assumptions. All tests were two-tailed, employed an alpha value of 0.05, and were conducted in R version 4.2.3 (R Core Team 2023). The characterization of Hawaiian hoary bat seasons corresponds approximately to Gorresen et al. (2013).

Bat activity at the Project was generally low. Across the four turbines monitored during FY 2023 (June 2022 – May 2023), Hawaiian hoary bats were detected on 130 nights out of the 1351 (9.6 percent) detector-nights sampled. Detection rates were highest from July through November during the lactation and post-lactation reproductive periods, with a peak (0.23) occurring in the month of August (Figure 2). Following November, bat activity continued to decline throughout the pre-pregnancy reproductive period, with a lowest detection rate (0.01) observed in the month of February. Detection rates increased again in April and May of the pregnancy reproductive period (Figure 2).

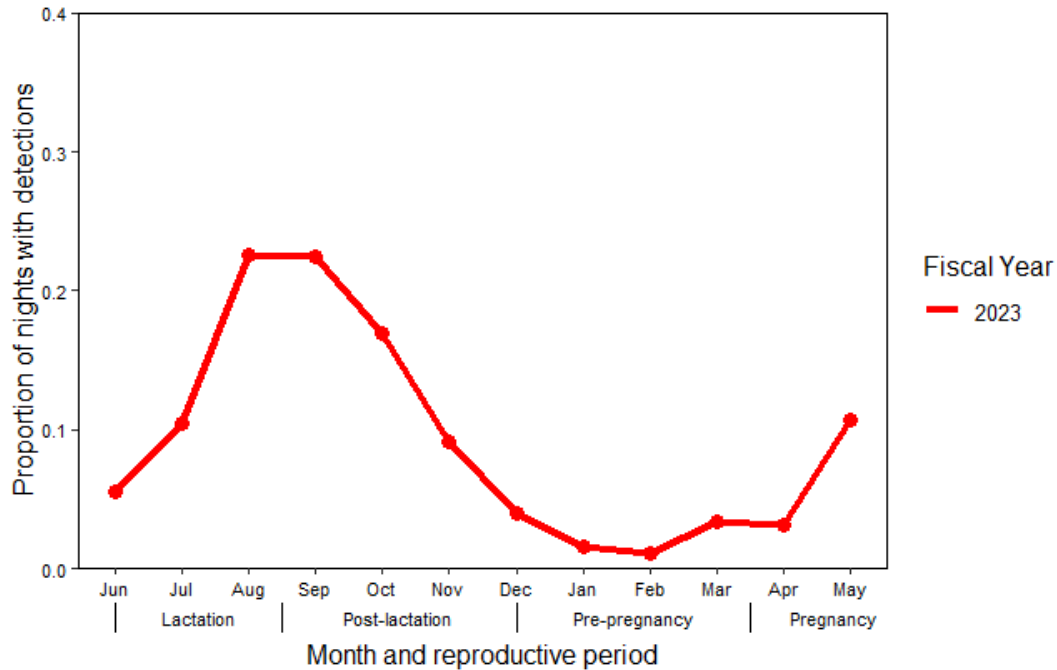


Figure 2. Monthly Bat Acoustic Activity at Nā Pua Makani for FY 2023 with Corresponding Reproductive Periods

The annual detection rate during the FY 2023 monitoring period (9.6 percent) was higher than the observed annual detection rate (6.1 percent) for the previous FY 2022 monitoring period (Table 7), although not significantly different (Tukey's HSD: $P = 0.406$). A significant difference in the annual detection rate between the three sampling years was only observed between 2021 and 2023 (ANOVA: $F_{2,30} = 3.48$, $P < 0.044$; Tukey's HSD: $P < 0.034$). The seasonal trend observed in FY 2023 was similar to the seasonal trend observed in previous sampling years (Figure 3), and across the three monitoring years there is a significant increase in the annual detection rates (LM: $R^2 = 18.79$ percent; $F_{1,31} = 7.17$, $P < 0.012$; Figure 4).

Table 7. Number of Nights Sampled, Number of Nights with Detections, and Proportion of Nights with Bat Detections at Four Ground-based Detectors Sampled from FY 2021 through FY 2023.

Sampling Period	No. of Nights Sampled	No. of Nights with Detections	Proportion of Nights with Detections
FY 2021 (September 2020 – May 2021)	969	26	0.027
FY2022 (June 2021 – May 2022)	1,357	83	0.061
FY 2023 (June 2022 – May 2023)	1,351	130	0.096

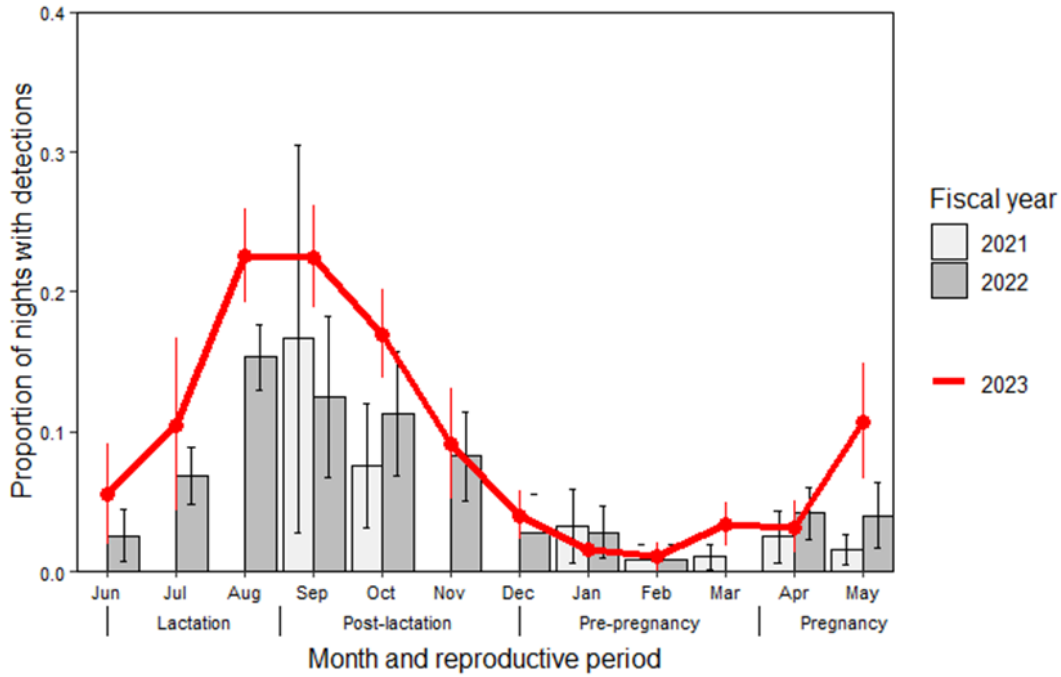


Figure 3. Monthly Bat Acoustic Activity at Nā Pua Makani for FY 2021 and FY2023 with Corresponding Reproductive Periods

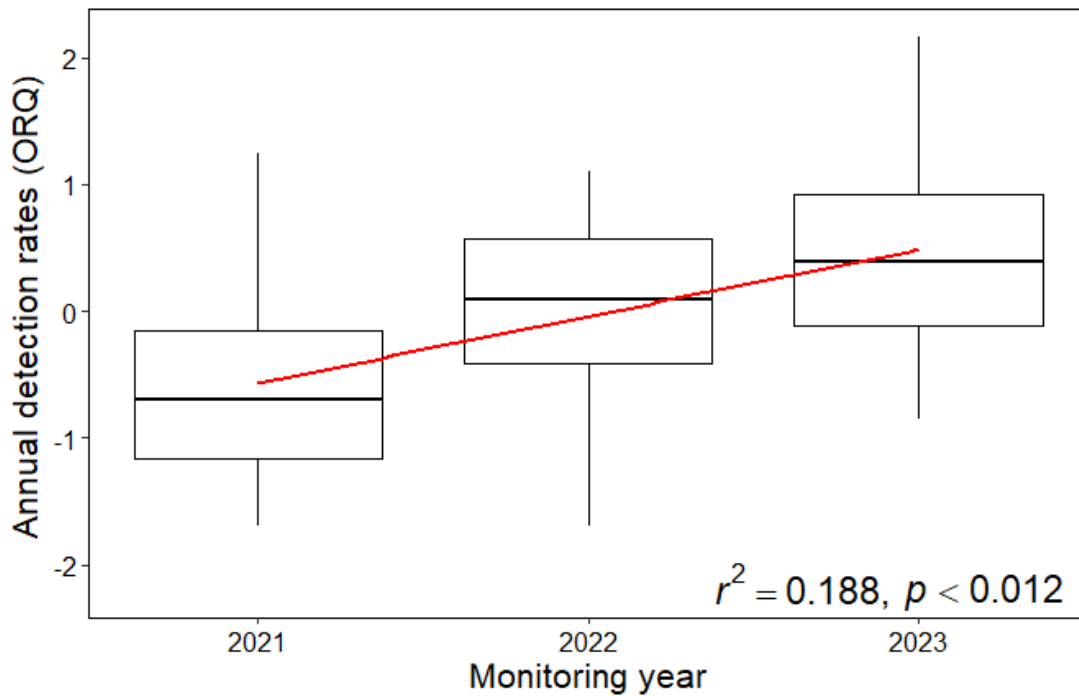


Figure 4. Box-plot with Linear Regression Showing the Increasing Trend in the Annual Detection Rate at the Project between FY 2021 and FY 2023

The seasonal pattern in mean detection rates was similar across all monitoring locations. Significant site level differences in detection rates occurred during the lactation and post-lactation reproductive periods (July through October) when bat activity was higher (LM: $R^2 = 67.78$ percent; $F_{47,83} = 3.71$, $P < 0$; Figure 5). During the lactation reproductive period, detection rates were significantly higher in July at WTG-6 (LM: $t = 2.06$, $P < 0.043$), and in August at WTG-4 (LM: $t = 2.65$, $P < 0.01$) and WTG-6 (LM: $t = 2.97$, $P < 0.004$). During the post lactation reproductive period detection rates were significantly higher in September at WTG-1 (LM: $t = 2.73$, $P < 0.008$) and WTG-6 (LM: $t = 4.05$, $P < 0$) and in October at WTG-4 (LM: $t = 2.68$, $P < 0.009$; Figure 5).

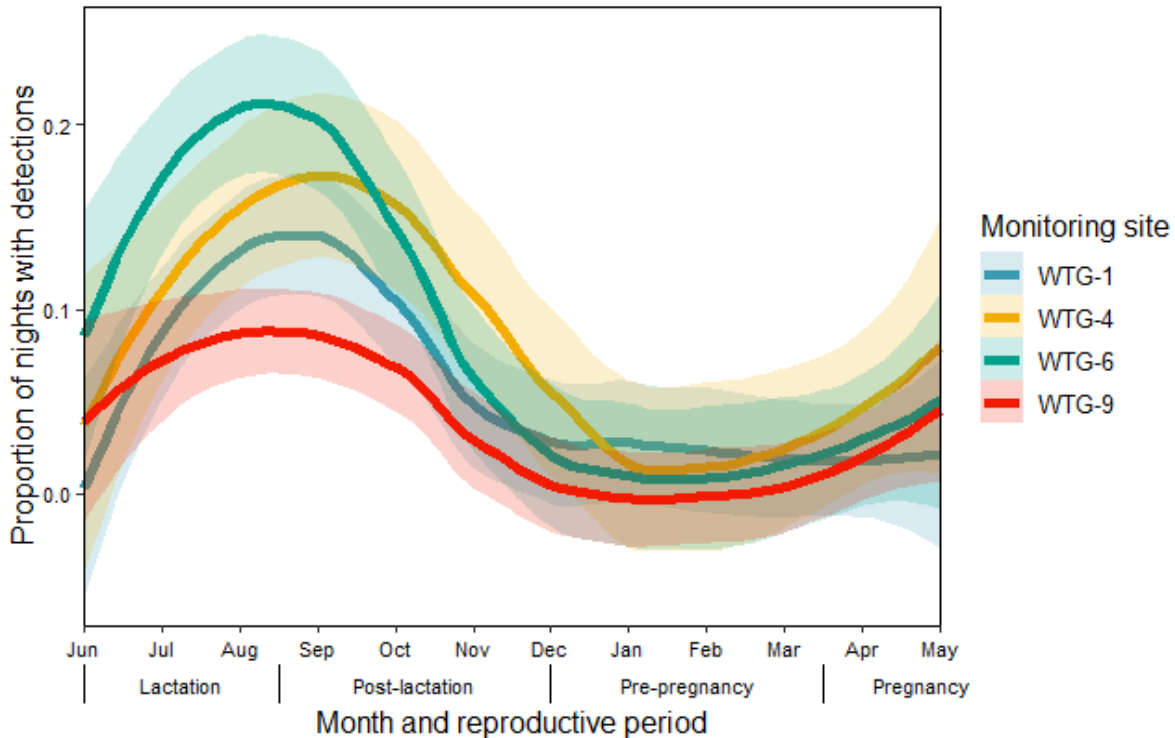


Figure 5. Site-Specific Variation in Mean Detection Rates for Each Month with Corresponding Reproductive Periods. Trend Lines are fitted with a Loess Smoothing Curve.

Note: Trend Lines are fitted with Loess smoothing curve; see Figure 1 for spatial context.

3.2 Newell's Shearwater

NPMPP provided required mitigation funds to the National Fish and Wildlife Foundation (NFWF) on September 22, 2020. USFWS will share updates on the status of the NFWF program when available (pers. comm. E. Gosliner, July 2023). At the end of FY 2022 USFWS reported that NFWF had not yet funded programs using the NPMPP funds. USFWS and DOFAW are coordinating on mitigation project selection. NPMPP will report results from the Newell's shearwater mitigation efforts once NFWF identifies and funds an appropriate mitigation project.

3.3 Hawaiian Goose

Based on NPMPP's consultation with DOFAW and USFWS regarding the extirpation of the Hawaiian goose from O'ahu prior to the construction and operation of the Project, NPMPP will address new information associated with this species in the HCP major amendment (see Section 4.0).

3.4 Hawaiian Waterbirds

Adaptive management of the Hawaiian waterbird mitigation program is required (see Section 4.0). Based on this need, NPMPP has submitted and received agency comments on multiple drafts of an updated Hawaiian waterbird mitigation plan, including two in FY 2023 (Quarter 1 and Quarter 4). NPMPP and Tetra Tech are working with DOFAW and USFWS to approve final edits and initiate implementation in FY 2024.

3.5 Hawaiian Short-eared Owl

NPMPP provided required mitigation funds to the Endangered Species Trust Fund on September 18, 2020, and an MOU for use of the funds and reporting requirements was finalized with DOFAW on February 18, 2021. DOFAW used the funds provided by NPMPP to fund a graduate research project on Hawaiian short-eared owl breeding ecology. Appendix 3 is the final report from that study (Price and Wang 2023). To minimize the risk of impacts, we have redacted specific nest location information in the report.

4.0 Adaptive Management

NPMPP has identified several adaptive management actions for the Project and has coordinated closely with USFWS and DOFAW to document needs and ensure agency support for the identified actions. Adaptive management actions identified by NPMPP include:

- Limited deployment of ultrasonic acoustic bat deterrents to test their efficacy at the Project;
- Modifications to the waterbird mitigation plan described in the HCP to address changed conditions at Hāmākua Marsh (the proposed mitigation site); and
- Addressing changed conditions relating to the status of the Hawaiian goose on O'ahu.

In consultation with USFWS and DOFAW, NPMPP installed ultrasonic acoustic bat deterrents on four Project turbines based on available scientific research and preliminary results from the Kawaiiloa Wind Farm on O'ahu (Tetra Tech 2019c, Weaver et al. 2019). Deterrents became operational between September 17 and 28, 2020.

The deterrent system is monitored to ensure components are operating according to the manufacturer's recommendations. The effective area covered by each of the 6 deterrent units overlap, ensuring redundancy in the system in the event of a component failure. Components are replaced as soon as practicable after they fall below the manufacturer's standards, and replacement

components are stored on site to ensure availability. During FY 2023, the deterrent units operated within manufacturer’s recommendations 96.3 percent of the time.

USFWS and DOFAW have agreed that a modified waterbird mitigation program implemented at Hāmākua Marsh that reduces fatalities and/or increases productivity of the resident waterbird species is appropriate, as the fencing, public outreach, and staffing program identified in the HCP is no longer viable due to changed site conditions and development plans.

USFWS, DOFAW, and NPMPP have agreed that because the Hawaiian goose was extirpated from O’ahu prior to the construction and operation of the Project, the Project currently poses no risk to the Hawaiian goose. NPMPP continues to work with USFWS and DOFAW to address this changed circumstance in the Project’s HCP major amendment.

5.0 Agency Meetings, Consultations, and Site Visits

NPMPP and Tetra Tech communicated actively with USFWS, and DOFAW throughout FY 2023 through in-person meetings, conference calls, and e-mail communications related to the Project’s HCP. The purposes of these communications included required semi-annual meetings, and planning associated with avoidance and minimization measures, monitoring, and mitigation. A summary of agency coordination is provided in Table 8.

Table 8. Summary of Key Agency Coordination and Communication in FY 2023

Date	Description	Participants/Recipients
07/30/2022	FY 2022 Annual Report Submittal	DOFAW, USFWS, NPMPP, Tetra Tech
09/30/2022	Waterbird Adaptive Management Plan Submittal	DOFAW, USFWS, NPMPP, Tetra Tech
11/07/2022	Bat Deterrent Study Submittal	DOFAW, USFWS, NPMPP, Tetra Tech
11/09/2022	Semi-annual HCP Implementation Meeting	DOFAW, USFWS, NPMPP, Tetra Tech
11/18/2022	PCMM Plan DOFAW Comments Received	DOFAW, USFWS, NPMPP, Tetra Tech
11/23/2022	Waterbird Adaptive Management Plan DOFAW Comments Received	DOFAW, USFWS, NPMPP, Tetra Tech
11/29/2022	PCMM Plan USFWS Comments Received	DOFAW, USFWS, NPMPP, Tetra Tech
12/09/2022	Draft HCP Amendment Submittal	DOFAW, USFWS, NPMPP, Tetra Tech
12/09/2022	HCP Amendment Meeting ¹	DOFAW, NPMPP, Tetra Tech
12/15/2022	HCP Amendment Meeting ¹	DOFAW, USFWS, NPMPP, Tetra Tech
12/30/2022	Hawaiian Hoary Bat Habitat Management and Research Plans Submittals	DOFAW, USFWS, NPMPP, Tetra Tech
01/09/2023	HCP Implementation ESRC Annual Review	DOFAW, USFWS, NPMPP, Tetra Tech
03/03/2023	Site Visit and PCMM Plan Discussion	DOFAW, USFWS, NPMPP, Tetra Tech
03/30/2023	Waterbird Adaptive Management Plan Meeting	DOFAW O’ahu, DOFAW HCP, USFWS, NPMPP, Tetra Tech

Date	Description	Participants/Recipients
03/31/2023	Hawaiian Hoary Bat Habitat Management and Research Plans USFWS Comments Received	DOFAW, USFWS, NPMPP, Tetra Tech
04/06/2023	Bat Deterrent Study Submittal USFWS Comments Received	DOFAW, USFWS, NPMPP, Tetra Tech
05/03/2023	HCP Amendment USFWS Comments Received	DOFAW, USFWS, NPMPP, Tetra Tech
05/16/2023	Waterbird Adaptive Management Plan Submittal	DOFAW, USFWS, NPMPP, Tetra Tech
05/19/2023	Bat Deterrent Study DOFAW Comments Received	DOFAW, USFWS, NPMPP, Tetra Tech
05/26/2023	Hawaiian Hoary Bat Habitat Management and Research Plans DOFAW Comments Received	DOFAW, USFWS, NPMPP, Tetra Tech
06/06/2023	PCMM Plan Submittal	DOFAW, USFWS, NPMPP, Tetra Tech
06/08/2023	HCP Implementation Meeting	DOFAW, USFWS, NPMPP, Tetra Tech
06/15/2023	Semi-annual HCP Implementation Review	DOFAW, USFWS, NPMPP, Tetra Tech
1. Based on initial consultation with USFWS and DOFAW, the HCP Amendment is anticipated to include two primary changes: adding the Hawaiian petrel (<i>Pterodroma sandwichensis</i>) as a Covered Species and addressing the changed circumstances regarding the Hawaiian goose's extirpation from O'ahu (see Section 4.0).		

6.0 Expenditures

Total HCP-related expenditures for the Project in FY 2023 were \$296,827. A summary of expenditures by category is provided in Table 9.

Table 9. HCP-related Expenditures at the Project in FY 2023

Category	Amount
Permit Compliance	\$19,618
Fatality Monitoring	\$111,197
Acoustic Monitoring for Bats	\$12,934
Vegetation Management	\$75,000
Scavenger Trapping	\$22,710
Bat Mitigation Planning	\$1,591
Other Mitigation Planning and Coordination	\$5,095
HCP Amendment Planning	\$30,982
Miscellaneous Costs	\$17,701
Total Cost for FY 2023	\$296,827

7.0 FY 2023 HCP Implementation Work Plan

NPMPP's FY 2023 HCP implementation work plan is provided as Table 10.

Table 10. FY 2024 HCP Implementation Work Plan

Program	Component	FY 2024			
		Quarter 1	Quarter 2	Quarter 3	Quarter 4
PCMM	Fatality Searches	Weekly searches throughout FY			
	Bias Correction Trials	Searcher efficiency and carcass persistence trials	Searcher efficiency and carcass persistence trials	Searcher efficiency and carcass persistence trials	Searcher efficiency and carcass persistence trials
	Scavenger Control	Trap checks every ~2 weeks, quarterly evaluation to assess changes in schedule			
	Vegetation Management	Occurs shortly after completion of searches, search areas evaluated weekly and managed as needed			
	Invasive Species Surveys		Survey Project area		
		Manage devil weed consistent with protocols			
Bat Acoustic Monitoring	Data downloads and Equipment Checks	Download data and equipment check monthly			
Bat Deterrents	Maintenance	Maintain operational deterrents on 4 turbines			
	Research Study	Revise and submit research plan for ESRC review and DOFAW approval		Implementation	
Mitigation	Hawaiian Goose	To be addressed in HCP major amendment			
	Waterbirds	Revise and submit mitigation plan for approval	Implementation		
	Newell’s Shearwater	Coordinate with USFWS regarding mitigation progress and reporting			
	Hawaiian Hoary Bat	Revise and submit research and management plans for ESRC review and USFWS and DOFAW approval		Implementation	
	Hawaiian Short-eared Owl	Coordinate with DOFAW regarding mitigation progress and reporting			
Reporting	Wildlife Incidentst	As required per DOFAW and USFWS 2020 protocol			
	Regular Reporting	FY 2023 annual report	Semi-annual agency meeting	ESRC annual review	Semi-annual agency meeting

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APPENDIX 1. OBSERVED FATALITIES, LOCATIONS, AND DETECTION METHOD IN FY 2023 AT THE PROJECT

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Species	Date	Turbine Number or Location ¹	Distance to the Turbine (meters)	Detection Method ²
<i>Spilopelia chinensis</i> (spotted dove)	07/18/2022	2	2	Incidental
<i>Spilopelia chinensis</i> (spotted dove)	07/29/2022	4	1	Incidental
<i>Haemorhous mexicanus</i> (house finch)	08/10/2022	2	10	Search
<i>Spilopelia chinensis</i> (spotted dove)	08/14/2022	9	3	Incidental
<i>Geopelia striata</i> (zebra dove)	09/03/2022	Meteorological Tower	31	Incidental
<i>Spilopelia chinensis</i> (spotted dove)	09/10/2022	3	1	Incidental
<i>Pluvialis fulva</i> (Pacific golden-plover)	09/17/2022	Project Road	1,000	Incidental
<i>Spilopelia chinensis</i> (spotted dove)	09/27/2022	8	1	Incidental
<i>Spilopelia chinensis</i> (spotted dove)	11/05/2022	8	1	Incidental
<i>Spilopelia chinensis</i> (spotted dove)	12/28/2022	7	165	Search
<i>Estrilda astrild</i> (common waxbill)	12/28/2022	2	1	Search
<i>Bulbulcus ibis</i> (cattle egret)	12/28/2022	8	15	Incidental
<i>Acridotheres tristis</i> (common myna)	01/04/2023	8	115	Search
<i>Acridotheres tristis</i> (common myna)	01/11/2023	3	16	Search
<i>Haemorhous mexicanus</i> (house finch)	01/11/2023	3	24	Search
<i>Spilopelia chinensis</i> (spotted dove)	01/15/2023	9	6	Incidental
<i>Geopelia striata</i> (zebra dove)	01/18/2023	6	1	Search
<i>Geopelia striata</i> (zebra dove)	01/18/2023	7	1	Search
<i>Acridotheres tristis</i> (common myna)	01/25/2023	1	24	Search
<i>Spilopelia chinensis</i> (spotted dove)	02/01/2023	7	3	Search
<i>Spilopelia chinensis</i> (spotted dove)	02/13/2023	8	3	Incidental
<i>Geopelia striata</i> (zebra dove)	02/15/2023	2	2	Search
<i>Spilopelia chinensis</i> (spotted dove)	04/03/2023	8	3	Incidental
<i>Spilopelia chinensis</i> (spotted dove)	04/10/2023	4	1	Incidental
<i>Geopelia striata</i> (zebra dove)	05/10/2023	2	1	Incidental
<i>Bulbulcus ibis</i> (cattle egret)	05/12/2023	7	12	Incidental

Species	Date	Turbine Number or Location ¹	Distance to the Turbine (meters)	Detection Method ²
<i>Spilopelia chinensis</i> (spotted dove)	05/15/2023	8	1	Incidental
<i>Bulbulcus ibis</i> (cattle egret)	06/04/2023	7	7	Incidental
<i>Spilopelia chinensis</i> (spotted dove)	06/04/2023	2	2	Incidental
<i>Fregata minor</i> (great frigatebird)	06/05/2023	9	21	Incidental
<i>Bulweria bulwerii</i> (Bulwer's petrel)	06/09/2023	2	86	Incidental
<i>Spilopelia chinensis</i> (spotted dove)	06/13/2023	2	1	Incidental
<i>Geopelia striata</i> (zebra dove)	06/16/2023	2	3	Incidental
1. Weekly systematic searches by a trained canine search team were conducted throughout FY 2023. Incidental detections are downed wildlife incidents detected outside of the systematic search effort, including detections outside of the defined search areas used in the statistical estimation of take but found during a search effort.				

**APPENDIX 2. DALTHORP ET AL. (2017) FATALITY ESTIMATION
DATA FOR HAWAIIAN HOARY BATS THROUGH FY 2023 AT THE
PROJECT**

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Figure 1. Dalthorp et al. (2017) Multi-year Analysis Input

Past monitoring and operations data

Year	ρ	X	Ba	Bb	\hat{g}	95% CI
2021	0.871	0	81.18	74.92	0.5201	[0.442, 0.598]
2022	1	1	144.3	115.2	0.5561	[0.495, 0.616]
2023	1	0	152.9	134.2	0.5326	[0.475, 0.59]

Future monitoring and operations parameters

Year	ρ	\hat{g}	g_{lwr}	g_{upr}
1	1	0.533	0.4748	0.5899
2	1	0.533	0.4748	0.5899
3	1	0.533	0.4748	0.5899
4	1	0.533	0.4748	0.5899
5	1	0.533	0.4748	0.5899
6	1	0.533	0.4748	0.5899
7	1	0.533	0.4748	0.5899
8	1	0.533	0.4748	0.5899
9	1	0.533	0.4748	0.5899
10	1	0.533	0.4748	0.5899
11	1	0.533	0.4748	0.5899
12	1	0.533	0.4748	0.5899
13	1	0.533	0.4748	0.5899
14	1	0.533	0.4748	0.5899
15	1	0.533	0.4748	0.5899
16	1	0.533	0.4748	0.5899
17	1	0.533	0.4748	0.5899

Options

Fatalities

☒ Estimate M Credibility level (1 - α)

☐ Total mortality ☒ One-sided CI (M*)

☐ Two-sided CI

Project parameters

Total years in project

Mortality threshold (T)

☐ Track past mortality

☒ Projection of future mortality and estimates

Future monitoring and operations

☒ g and ρ unchanged from most recent year

☐ g and ρ constant, different from most recent year

g 95% CI: ρ

☐ g and ρ vary among future years

Average Rate

☐ Estimate average annual fatality rate (λ)

Annual rate threshold (τ)

☐ Credibility level for CI (1 - α)

☒ Short-term rate ($\lambda > \tau$) Term: α

☐ Reversion test ($\lambda < \rho \tau$) ρ α

Actions

Figure 2. Dalthorp et al. (2017) Projection Results Figure Output

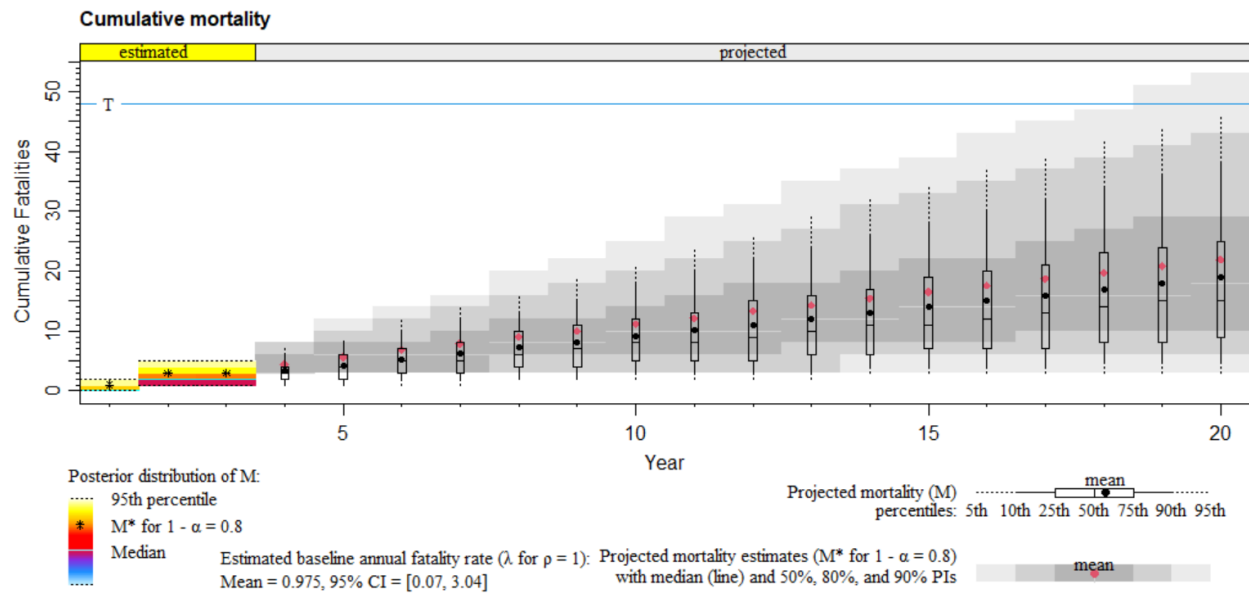


Figure 3. Dalthorp et al. (2017) Projection Text Results Output Page 1 of 2

Projected fatalities and fatality estimates...

$p(M > \text{Tau within 20 years}) = 0.0428$ [exceedance]

$p(M^* > \text{Tau within 20 years}) = 0.0708$ [triggering]

M^* based on credibility level $1 - \alpha = 0.8$

Among projects with triggering (7.08%), $\text{mean}(M) = 42.46$ at time of triggering, with median = 42 and IQR = [38, 46]

Among projects with no triggering (92.92%), $\text{mean}(M) = 16.30$ at end of 20 years, with median = 14 and IQR = [8, 23]

Years of operations without triggering:

Mean = 19.77, with median = 20 and IQR = [20, 20]

Summary statistics for projection years

Yr	Mean		quantiles of M							quantiles of M^*						
	M	M^*	0.05	0.10	0.25	0.50	0.75	0.90	0.95	0.05	0.10	0.25	0.50	0.75	0.90	0.95
1	3.3	4.4	1	1	2	3	4	6	7	3	3	3	3	6	8	8
2	4.3	5.6	1	1	2	4	6	8	9	3	3	3	6	8	10	12
3	5.2	6.8	1	2	3	5	7	10	12	3	3	3	6	8	12	14
4	6.2	7.9	1	2	3	5	8	12	14	3	3	3	6	10	14	16
5	7.2	9.0	2	2	4	6	10	13	16	3	3	6	8	12	16	20
6	8.2	10.0	2	2	4	7	11	15	19	3	3	6	8	12	18	22
7	9.1	11.1	2	3	5	8	12	18	21	3	3	6	10	14	20	25
8	10.1	12.2	2	3	5	8	13	20	24	3	3	6	10	16	22	29
9	11.1	13.3	2	3	5	9	15	22	26	3	3	6	10	18	25	31
10	12.1	14.4	2	3	6	10	16	24	29	3	3	8	12	18	27	35
11	13.0	15.4	3	4	6	11	17	26	32	3	6	8	12	20	31	37
12	14.0	16.5	3	4	7	11	19	28	34	3	6	8	14	22	33	39
13	15.0	17.6	3	4	7	12	20	30	37	3	6	8	14	22	35	43
14	16.0	18.7	3	4	7	13	21	32	39	3	6	10	16	25	37	45
15	16.9	19.8	3	5	8	14	23	34	42	3	6	10	16	27	39	47
16	17.9	20.8	3	5	8	15	24	36	44	3	6	10	16	29	41	51
17	18.9	21.9	3	5	9	15	25	38	46	3	6	10	18	29	43	53

=====

Figure 3 (continued). Dalthorp et al. (2017) Projection Text Results Output Page 2 of 2

Governing parameters: Tau = 48, alpha = 0.2

Data for 3 years of monitoring:

yr	x	g	glwr	gupr	rho	M*
2021	0	0.5201	0.4403	0.5998	0.871	1
2022	1	0.5561	0.4945	0.6176	1	3
2023	0	0.5326	0.4738	0.5914	1	3

Parameters for future monitoring and operations:
 Number of years: 17
 g = 0.5326, 95% CI [0.4738, 0.5914]
 Relative weight (rho): 1

Summary statistics for mortality estimates through 3 years

Results

Totals through 3 years

M* = 3 for 1 - alpha = 0.8, i.e., $P(M \leq 3) \geq 80\%$
 Estimated overall detection probability: g = 0.537, 95% CI = [0.499, 0.574]
 Ba = 364.21, Bb = 314.07
 Estimated baseline fatality rate (for rho = 1): lambda = 0.9748, 95% CI = [0.07, 3.04]

Cumulative Mortality Estimates

Year	M*	median	95% CI	mean(lambda)	95% CI
2021	1	0	[0, 2]	0.9699	[0.0009283, 4.888]
2022	3	2	[1, 5]	2.7900	[0.2002, 8.714]
2023	3	2	[1, 5]	2.7990	[0.201, 8.733]

Annual Mortality Estimates

Year	M*	median	95% CI	mean(lambda)	95% CI
2021	1	0	[0, 2]	0.9699	[0.0009283, 4.888]
2022	3	2	[1, 5]	2.7100	[0.1942, 8.473]
2023	1	0	[0, 2]	0.9430	[0.0009389, 4.745]

Test of assumed relative weights (rho) and potential bias

Assumed rho	95% CI	Fitted rho
0.871	[0.004, 2.059]	
1	[0.255, 2.811]	
1	[0.004, 2.174]	

p = 0.36109 for likelihood ratio test of H0: assumed rho = true rho
 Quick test of relative bias: 1.012

=====

Input

Year (or period)	rel_wt	X	Ba	Bb	ghat	95% CI
2021	0.871	0	81.18	74.92	0.520	[0.442, 0.598]
2022	1.000	1	144.3	115.2	0.556	[0.495, 0.616]
2023	1.000	0	152.9	134.2	0.533	[0.475, 0.590]

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**APPENDIX 3. BREEDING ECOLOGY OF HAWAIIAN SHORT-EARED
OWLS (*ASIO FLAMMEUS SANDWICHENSIS*). FINAL REPORT JUNE
2023 (PROJECT DATES: MAY 1, 2021 – JUNE 30, 2023).**

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Breeding Ecology of Hawaiian Short-eared Owls (*Asio flammeus sandwichensis*)

Final Report

June 2023

Project dates: May 1, 2021 – June 30, 2023

Submitted by

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ABSTRACT

Short-eared Owls (*Asio flammeus*) are an appropriate study species for understanding intraspecific variations in life-history traits in raptors due to their global distribution across continental and island systems at a variety of latitudes. In Hawai‘i, little is known about the ecology of Pueo (Hawaiian Short-eared Owls, *A. f. sandwichensis*), but populations are thought to be in decline and are state-listed as endangered on O‘ahu. While studies of other Short-eared Owl subspecies serve as a starting point for creating conservation plans for Pueo, initial research has indicated differences in diet, habitat use, and movement ecology of Pueo versus continental Short-eared Owls. Given these differences, further regional studies from Hawai‘i are necessary to ensure management actions adequately address the needs of Pueo. In Chapter 2 of this study, I investigated the breeding ecology of Pueo using a collaborative approach to combine results from targeted nest-searching at two focal study sites on O‘ahu with incidental reports of Pueo nests across the Hawaiian Islands. In Chapter 3 I used these results to draft management recommendations to minimize disturbance to breeding Pueo. At our focal study sites, I found that Pueo select sites with greater vegetation height and density than the surrounding environment for nesting, but that these same vegetation characteristics do not necessarily correlate to increased nest survival. The diet of breeding Pueo was relatively diverse and contained more bird prey when compared to that of North American and European Short-eared Owls. However, diet did not differ significantly among breeding Pueo pairs. Across both focal study sites and incidental observations, Pueo nest initiation spanned November through July, with a peak in February and March. Pueo breeding habitat ranged from non-native dry grasslands at low-elevation to high-elevation native wet forest, showing a marked increase in breeding habitat diversity compared to North American and European Short-eared Owls. Our results establish a basis for informing Pueo conservation in Hawai‘i, including recommendations towards reducing different types of nest disturbance and data to inform spatial and temporal nest buffers. State-wide management actions must account for the expanded breeding season and diversity of breeding habitat types of Pueo.

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INTRODUCTION

As top predators and “charismatic megafauna”, raptors serve as biological indicators of ecosystem health and biodiversity (Bildstein, 2001; Sergio et al., 2006). Despite their ecological and cultural importance, 52% of raptor species globally are experiencing population declines, and even for species listed as “Least Concern” by the IUCN, 38% are in decline (McClure et al., 2018). World-wide, raptors are threatened by habitat fragmentation and loss, environmental contaminants, and direct mortality caused by anthropogenic factors (Bildstein et al., 1998; Grande et al., 2018). Assessments of factors that impact reproductive success and breeding ecology are necessary to understand population trajectories and ultimately to mitigate threats to raptors, especially given that their lower fecundity and longer generation time makes them more susceptible to anthropogenic impacts, such as habitat loss or human persecution, relative to other bird species (Bennett & Owens, 1997; Owens & Bennett, 2000).

However, raptors tend to be difficult to study and conserve due to their relatively low densities and large home ranges and often elusive behavior and breeding locations (Donazar et al., 2016; Newton, 2010). These challenges sometimes result in a lack of basic life history understanding for certain species. Indeed, current research on raptors is biased towards a few species, with only 10 species accounting for one-third of all research worldwide (Buechley et al., 2019). Raptors with small geographic ranges, such as tropical and island endemics, are particularly underrepresented in research efforts despite having higher risks of extinction due to their restricted ranges and vulnerability on islands (Buechley et al., 2019; Ferrer-Sanchez & Rodriguez-Estrella, 2015). Given the increased threats and heightened vulnerability for island and tropical raptor species, studies that fill basic knowledge gaps of their life history and ecology are necessary to address global raptor conservation needs and to investigate how biogeographic variation may influence various aspects of life history.

Some aspects of life history are likely to differ for raptors in island versus continental systems or across a latitudinal gradient, necessitating focused regional studies (Wiggins et al., 1998). For example, the globally distributed Barn Owl (*Tyto alba*) diet varies across their range with the proportion of rodents in their diet varying significantly with latitude, elevation, and island versus mainland geographies (Romano et al., 2020). However, this is one of the few examples of global biogeographical patterns in raptor niche variation due to both the low number

of raptors with a global distribution, and the abundance of data required to look at trends from all areas of their range. For species that are found on both continental and island systems, altered climatic conditions, differences in the timing of food abundance, and island size and distance from the continent are all potential factors that would result in island populations displaying a different breeding ecology than continental populations (Blondel, 1985; Lambrechts & Dias, 1993; Wiggins et al., 1998). For example, Common Kestrel (*Falco tinnunculus*) mean egg laying date and clutch size varied across a latitudinal gradient and between island and continental populations; clutch size increasing along with latitude is a commonly documented phenomenon thought to be driven by increased photoperiods at more northerly latitudes during the breeding season (Carrillo & González-Dávila, 2009; Lack, 1947). Given the potential for variance in breeding ecology based on biogeography and increased extinction risk for island-restricted species, regional studies are necessary to ensure that conservation and management actions reflect the ecology of each population (Buechley et al., 2019).

Investigating the differences in life history parameters across populations not only provides critical region-specific ecological knowledge to inform local management of threatened species, but also provides data to investigate the relationship between intraspecific niche expansions in widely distributed species. The Niche Variation Hypothesis suggests that populations with wider niches are more variable than populations with narrower niches, and has been used to explain why bird populations on oceanic islands tend to display more morphological variance than their mainland counterparts (Bolnick et al., 2007; Van Valen, 1965). This niche widening in populations may result from increased niche width of all individuals within that population, or from increased distances between each individual's niche, which remains relatively narrow (Van Valen, 1965). This theory has often been investigated by looking at the morphology of a species as a proxy for niche expansion, even though variation in behaviors and resource use may not necessarily correlate to variation in morphology (Araújo et al., 2011; Bolnick et al., 2007). Thus, studies seeking to understand individual versus population niche expansion should look at actual measures of resource use, such as comparing diet or habitat use data (Araújo et al., 2011; Bolnick et al., 2007). For example, Montagu's Harriers (*Circus pygargus*) are broadly considered a diet generalist, but studies of individual diet composition and foraging behavior showed individual specialization of breeding birds (Terraube et al., 2014). As individual variation in resource use may affect population and community

ecology dynamics, this is an important aspect of a species' ecology to understand as it can impact conservation and management decisions (Araújo et al., 2011; Terraube & Arroyo, 2011).

Short-eared Owls (*Asio flammeus*) are one of the few raptors with a global distribution inhabiting every continent except for Australia and Antarctica (Wiggins et al., 2020). Ten subspecies occur globally, including three different subspecies found across South America, six endemic island subspecies found in the Greater Antilles, the Galapagos, the Falklands, and the Hawaiian Islands, and the nominate subspecies *A. f. flammeus* found across North America, Europe, and Asia (Wiggins et al., 2020). Despite this global distribution, the bulk of our understanding of Short-eared Owl ecology stems from research of *A. f. flammeus* in North America and Europe (Booms et al., 2014; Wiggins et al., 2020). One of the main research objectives for *A. f. flammeus* in North America is identifying critical habitat, especially within their breeding range, to inform conservation planning and management (Booms et al., 2014). This objective holds true for other Short-eared Owl populations, where their breeding ecology and critical habitat is even less well understood. As a globally distributed species with both continental and island populations, Short-eared Owls provide an interesting opportunity to investigate intraspecific variations in life-history traits driven by latitudinal and geographical variation, but regional studies are needed to draw global comparisons.

In the Hawaiian Islands, the Pueo (*A.f. sandwichensis*) is the only native raptor that breeds on all the main islands yet their population dynamics, habitat use, and even basic breeding parameters remain poorly understood (Hawai'i Department of Land and Natural Resources, 2005). On O'ahu they are thought to be in decline and are state-listed as endangered, and recent efforts have been made to petition the state Department of Land and Natural Resources to request the listing of Pueo as endangered at the federal level (Hawai'i State Legislature, 2021). Pueo are thought to be threatened by habitat loss, the effects of which are exacerbated by the already restricted land area of the island system, as well as introduced mammalian predators (i.e. feral cats (*Felis domesticus*), feral dogs (*Canis lupus familiaris*) and Indian mongoose (*Herpestes auropunctatus*)), and direct anthropogenic causes such as collisions with heavy machinery, cars, or barbed wired fences (Bell et al., 2021; Hawai'i Department of Land and Natural Resources, 2005). Addressing these knowledge gaps in Pueo nest site characteristics, breeding phenology,

and breeding parameters will allow for a better understanding of their population trends and conservation needs. In this study, we addressed two main research objectives:

1. Describe the breeding ecology of Hawaiian Short-eared Owls, including nest-site selection characteristics and nesting success, and,
2. Describe the timing of courtship and nesting, based on all confirmed nesting records for Hawaiian Short-eared Owls.

METHODS

Data collection

Focal study sites

Focal studies of nesting ecology took place at two study sites on O‘ahu. Marine Corps Base Hawai‘i - Kaneohe Bay is located on east/windward O‘ahu (21.43272, -157.75211) on the Mōkapu Peninsula and primarily consists of urban and developed land cover in addition to the 482 acre Nu‘upia Ponds Wildlife Management Area (hereafter, Nu‘upia WMA). The Nu‘upia WMA contains mostly brackish wetlands in addition to small patches of wooded kiawe (*Prosopis pallida*) and haole koa (*Leucaena leucocephala*) forest (Figure 2.1). Surveys for Pueo nests primarily occurred within the Nu‘upia WMA. The other site, Joint Base Pearl Harbor Hickam Lualualei VLF Transmitter Annex (hereafter, Lualualei Valley), is an approximately 1,700 acre field located on west/leeward O‘ahu (21.42463, -158.15368) and is dominated by patches of grasslands and wooded kiawe savanna (Figure 2.2). These two study sites were selected because preliminary surveys confirmed Pueo use and breeding activity at these sites in the past and because funding for Pueo research was provided by the U.S. Navy (Federal Grant Number W9126G-20-2-0017) and U.S. Marine Corps (Federal Grant Number W9126G-19-2-0063), with an expectation that core study activities would take place at the funded locations. All activities were conducted under appropriate federal, state, and institutional permits (Bird Banding Lab permit no. 24137 and 23395; Hawai‘i Department of Forestry and Wildlife Scientific Collecting Permit no. WL18-10 and WL20-05; University of Hawai‘i Institutional Animal Care and Use Committee protocol no. 18-2752).



Figure 0.1. Map of the Nu'upia Ponds Wildlife Management Area located within Marine Corps Base Hawai'i - Kaneohe Bay (Nu'upia Ponds WMA) on O'ahu, Hawai'i.



Figure 0.2. Map of the Joint Base Pearl Harbor Hickam Lualualei VLF Transmitter Annex (Lualualei Valley) on O‘ahu, Hawai‘i.

Nest discovery

Surveys were conducted at both focal study sites from March 2020 through June 2022. Surveys began with observers scanning from roads and lookout points to look for Pueo breeding behaviors such as courtship displays and calls, territorial displays and prey carrying (Wiggins et al., 2020). When breeding behaviors were observed in a particular area, it was revisited at least twice a week in the weeks following to confirm establishment of a nesting territory and whether a female had begun incubating. Within a month of observing breeding behaviors and identifying an area suspected of containing a nest, the exact location of the nest was ascertained by observing prey deliveries to the nest or by observing the incubating female leaving or returning to the nest. If observations from a distance were not enough to reveal the location of the nest, the approximate area was searched by observers spaced out approximately 1.5 meters apart walking transects through the area in order to flush the incubating female Pueo from the nest so that the exact location of the nest was revealed (Holt & Larson, 2018; Leasure & Holt, 1991). Once a nest was located and confirmed to be active (containing either eggs or chicks), observers retreated to a distance and observed to be sure the female returned to the nest and both parents resumed normal nesting behaviors. The exact GPS location of the nest was recorded at the time of nest discovery.

Breeding parameters

Nests were monitored approximately every other day from a distance of at least 200 meters away and then checked directly by observers on a weekly basis to determine clutch size, nesting success and productivity. Though the use of nest cameras to document breeding parameters has been used successfully in many avian breeding studies, nest camera use has been documented to increase predation risk and nest failure for Short-eared owls in North American study systems (Holt pers. comm). We chose not to use nest cameras for this study based on this information, along with the fact that Pueo are state-listed as endangered on O‘ahu, no prior research existed on their breeding ecology and response to nest disturbance, and that mammalian predators (i.e. feral cats, dogs, mongoose, and rats) were all present at both study sites, increasing predation risk from olfactory and visual cues. Nest checks during the egg incubation stage were used to inform estimates of first-egg lay date and first-egg hatching date. Nest checks after chicks hatched were used to further refine the lay date, hatch date, and first-fledge date estimates.

We defined “nest initiation” as the date of first-egg laying. The incubation period for Short-eared Owls ranges from 21-42 days, with most studies reporting an incubation period of 28 days (Wiggins et al., 2020). Thus, nest initiation dates were estimated by subtracting 28 days from the first-egg hatch date, which in turn was either directly observed during nest checks or estimated from nestling age if a nest was discovered after hatching. Nestling age was determined based on size, plumage characteristics, and other physical characteristics following a Short-eared owl aging guide (Wiggins et al., 2020). In some cases, we were able to collect biometrics (i.e. tarsus length, tarsus width, wing chord, and weight) of chicks and compared these measurements to Short-eared owl growth curves (Arroyo et al., 2000; Holt et al., 1992). We were not able to determine lay date from nests that were abandoned before eggs hatched; however, we estimated an earliest possible nest initiation date by backdating from the date of nest discovery.

Clutch size was defined as the maximum number of eggs laid. Nest success was defined as whether at least one young was raised to 14 days old, the approximate age of dispersal from the nest. While this is technically not fledgling age (approximately 28 days old), once the chicks disperse from the nest on foot they are extremely difficult to find and thus I quantified nest success as survival of a chick to the dispersal stage (Clark, 1975; Fondell & Ball, 2004; Holt, 1992); a similar definition of “fledgling” has been used in other studies quantifying Short-eared owl nest success (Fondell & Ball, 2004). Nests were monitored regularly until all chicks dispersed from the nest or the nest was abandoned, predated, or otherwise failed. Once chicks began dispersing, we searched the general area of the nest (up to 500 meters away from the nest) to relocate chicks, confirm the outcome of the nest, and document dispersal distance. Dispersed chick locations were also determined by observing parent Pueo delivering prey to chicks away from the nest or by listening for chick begging calls. Final nest fate was recorded as successful (at least one chick disperses), failed (with specific sources of nest failure such as predation or abandonment), or unknown. Probable causes of abandonment were noted for each abandoned nest, including but not limited to predator presence, anthropogenic disturbance, or extreme weather. The stage at which the nest failed (egg stage or chick stage) was also noted.

Biometric measurements

When possible, we took biometric measurements of nestlings at approximately 13-15 days old, including mass, wing, tarsus, tail, and culmen lengths. At this age, nestlings can

thermoregulate by themselves and were large enough to be banded with metal U.S. Geological Survey Bird Banding Lab (USGS BBL) aluminum butt-end bands and VID aluminum rivet bands, which allowed for future re-sightings of individuals and will assist in future studies investigating survival and dispersal.

Nest site selection

Pueo nest site selection characteristics were determined using a paired design in which site data were collected both for nests and for four randomly selected points within 100m of each nest site (Fondell & Ball, 2004; Keyes et al., 2016). All nest site characteristic data and random point data were collected as soon as possible after discovery of the nest. At the nest site and the four random points, we collected a mean high and low visual obstruction reading (VOR) (method modified Robel et al., 1970 and USDA Agricultural Research Service, n.d.), percent vegetation cover within a 0.5-meter radius of the point, tallest vegetation height, and the top three dominant vascular plant species within a 0.5-meter radius of the point, ranked 1-3 in order from most (1) to least (3) abundant (Fondell & Ball, 2004; Monroe et al., 2019). Distance to nearest human-made structure, road, and body of water was also recorded for each nest and random point using either a rangefinder or satellite imagery and in ArcGIS.

Diet

Pellet and prey remains were collected from both study sites during weekly nest checks and during searches of each nesting area for dispersed chicks. Observers also searched known perch locations of the breeding adults and collected pellets as we came across them incidentally around the site, even if they could not be associated with a particular nest or breeding Pueo. Each pellet or prey remain was dried in a fume hood and then stored individually. Once dried, pellets were dissected to extract parts, such as bones, feathers, and insect exoskeleton components, that could be used to identify prey items to lowest possible taxa.

State-wide data collection

To obtain a broad overview of Pueo breeding phenology and nesting habitats, we reached out to federal, state, non-profit, and private partners across the Hawaiian Islands and asked them to report any observations of Pueo breeding behaviors, nests, or chicks and juveniles that they encountered incidentally during their fieldwork. Along with this request for information was sent an informational document showing how to identify Pueo breeding behaviors, nests, and chicks;

this information was also made available on the project website, pueoproject.com. Data requested included the date of observation, location of observation (GPS points), type of observation (breeding behavior or nest with eggs or chicks), and as much detail about the behavior, nest site characteristics, and eggs or chick as possible, including photos. An email, online form, and physical datasheet were sent to help guide data collection (Appendix A). We followed up on each reported observation to confirm observations and obtain additional details as necessary. We also reviewed journal articles and project reports to look for historical records of Pueo breeding phenology and nesting habitats.

Data analysis

Pueo breeding parameters and nest site characteristics

All statistical analyses were conducted using program R (version 4.2.0). Breeding parameters (nest initiation date, clutch size, nesting success, and nest productivity) were combined across all breeding seasons, and the means, standard errors, and ranges of all parameters calculated. The mean, standard errors, and range of dispersal distance of the fledged chicks were also calculated. The means, standard errors, and ranges of all the quantitative nest site characteristics were also calculated, and the top three most abundant plant species across all nest sites summarized.

Effect of nest site characteristics on nest site selection

We used a conditional logistic exposure model to estimate the relative probability of use of a site for nesting. We built a fully parameterized model with terms for tallest vegetation height, mean high and low VOR, ratio of high to low VOR, and percent vegetation cover fitted as predictor variables and use of site (1 for Pueo nests, 0 for random points) as the response variable (package “lmer4”). Due to the small sample size of nests overall, we constrained models to one covariate at a time and only looked at vegetation characteristic covariates, excluding the distance to nearest human structure, road, and body of water covariates from the fully parameterized model. We then generated a model selection table that dredged the fully parameterized model to look for the combination of covariates in the best fit model based on AICc values (using an Δ AICc value cutoff of 2) and a Hosmer and Lemeshow goodness-of-fit test with R packages “MuMin” and “ResourceSelection”.

Effect of nest site characteristics on nesting success

We used a logistic exposure model, a form of logistic regression model that includes a custom logit link function to account for exposure days, to examine the Nest Survival (NS) and Daily Nest Survival Rate (DSR) of all Pueo nests (Schwarz & Rivers, 2018; Shaffer, 2004). Exposure days were calculated as the number of days between the date the nest was found to the date the nest failed or was successful in fledging at least one Pueo chick. To investigate the influence of nest site characteristics and nest timing on DSR, we created a fully parameterized model with covariate terms for tallest vegetation height, mean high and low VOR, ratio of high to low VOR, percent vegetation cover, and relative day of nesting season that the nest was initiated. Relative day of nesting season was calculated as the number of days between the beginning of the Pueo breeding season, which we set as November 1st based on the earliest date that Pueo breeding behaviors such as courtship displays have been observed (Cotín et al., 2018), and each nest's initiation date (i.e. November 1st is relative day of nesting season 0, November 2nd is day 1, etc.). We then generated a model selection table that dredged the fully parameterized model to look for the combination of covariates in the best fit model based on AICc values (using an Δ AICc value cutoff of 2) and a Hosmer-Lemeshow goodness-of-fit test. Due to the small sample size of nests overall, we constrained models to one covariate at a time and only looked at vegetation characteristic covariates, excluding the distance to nearest human structure, road, and body of water covariates from the fully parameterized model.

Diet

All prey items were identified to lowest possible taxa by consulting reference collections and scientists at the Bernice Pauahi Bishop Museum. For rodents, the lowest possible taxonomic delineation was to species for House Mouse (*Mus musculus*) or genera for rats (*Rattus sp.*). Differentiation between the three rat species found in Hawai'i - Norway Rat (*Rattus norvegicus*), Black Rat (*Rattus rattus*), and Pacific Rat (*Rattus exulans*) – requires comparing whole skulls from specimens, which are often not intact in owl pellets and prey remains (Mostello, 1996). However, differentiation between House Mice and *Rattus sp.* can be done by examining the incisor shape, molar occlusion pattern, and mandible size, which are all bones that are more frequently retained in owl pellets. Measurements of the bird bones most frequently retained in the pellets (tarsometatarsus, tibiotarsus, femur, humerus, ulna, radius, and coracoid) were taken from all available skeletal specimens of likely prey species from the Bishop museum reference

collection. These bird bone measurements were used to create a set of classification trees in R (package “rpart”) that could classify to taxonomic family (Appendix B). These classification trees were used alongside other identifiable parts, such as skull shape and feather characteristics to identify bird remains to lowest possible taxa. Insect remains were cleaned and separated out and identified to lowest possible taxa by Bishop Museum entomologists.

Diet comparison studies often utilize contingency tables or analysis of variance, but the data does not meet the assumptions of independence to be able to use these techniques (Bilder et al., 2000; Lemons et al., 2010; Loughin & Scherer, 1998). Thus, to compare diet composition among Pueo nests, we followed an approach that treats each sample (i.e. each pellet or prey remain) as a multinomial vector representing the presence or absence of each prey type within a pellet (i.e. a 1 for present and 0 for absent, and a vector in the form “0100” for which there are 4 potential prey types available). As there is often more than a single prey item within each pellet, establishing each sample as a multinomial vector thus accounts for dependence of the different prey items within one sample. Approaching the data in this way is similar to how data are analyzed in capture-mark-recapture studies that investigate the probability of recapturing an individual given different variables, and thus we can use the same analytical methods to determine if nest served as a predictor for the presence of different prey items (Lemons et al., 2010; Morin et al., 2019). We used package “RMark” to build a closed population capture-recapture model (Huggins, 1989). In building the models, we constrained p (initial encounter probability in a traditional capture-recapture model) to equal c (reencounter probability), since traditionally a different p and c value is used to account for behavioral responses of an animal to recapture, which is not relevant for my data structure or analysis. Due to a low sample size, the fully parameterized model only included nest ID and year as covariates. We also calculated the overdispersion parameter, \hat{c} , from the global model to control for correlation among the different prey items. Use of \hat{c} allows for a conservative estimate of model performance. We incorporated this parameter into the model selection process, and thus quasi-AICc (QAICc) values are used to compare model fit.

State-wide incidental data summary

Reported breeding parameters were summarized in the same manner as breeding parameter data from focal study sites. To standardize reported information of Pueo nesting

habitats, we mapped each observation location over a 30-meter resolution land-cover map from the U.S. Geological Survey Carbon Assessment of Hawaii Land Cover Map and identified the General Land Cover class for each observation (Jacobi et al., 2017). To standardize observations with regards to breeding phenology, we looked at the photos and descriptions of Pueo chicks to age them and estimated the date of nest initiation for each observation by back-dating and assuming a 28-day egg incubation period.

RESULTS

Pueo breeding parameters

A total of 34 nesting observations were collected; 13 observations were from focal study sites and 21 incidental observations were from across the Hawaiian Islands (Figure 2.3). Due to the variety of sources from which data were compiled, the level of detail of each observation varied greatly, and sample sizes varied depending on the parameter reported. Maximum clutch size across all observations ranged between one and seven eggs ($\bar{x} = 3.63 \pm 0.39$ SE, $n=19$). The maximum number of chicks per nest across all observations ranged between one and five ($\bar{x} = 2.67 \pm 0.44$ SE, $n=9$). Many incidental chick observations were of fledglings that had dispersed from the nest and thus we could not reliably judge the maximum number of chicks observed from that nesting instance; thus, only incidental observations of chicks pre-fledging were included in this calculation as they provided a more reliable estimate of the actual number of chicks that hatched from a nest. Nests or fledglings were observed between November and July (Figure 2.4), across seven different vegetation cover types (Figure 2.5).

At the two focal study sites, a total of 13 nests were discovered from the 2020-2022 breeding seasons, all between mid-December and mid-June of the respective years (Table 2.1). The maximum clutch sizes observed ranged between one and seven eggs ($\bar{x} = 3.5 \pm 0.58$ SE, $n = 10$). The maximum number of chicks observed ranged between one and five ($\bar{x} = 2.57 \pm 0.61$ SE, $n=7$). Six of the 13 nests (46%) had at least one nestling successfully disperse from the nest. Morphometrics for Pueo chicks from four different nests are reported in Appendix C. Pueo chicks were observed dispersing from the nest as early as 12 days old. I was able to document chick dispersal distances from four of the six successful nests; one chick was found twice on two different days, in two different locations. Dispersal distances range from 9 to 198 meters from the nest ($\bar{x} = 91.84 \pm 35.67$ SE, $n=5$). All dispersed chicks found were between approximately 12 and 24 days old. At the remaining two successful nests, I confirmed chick dispersal and thus nest success by hearing the begging calls of dispersed chick or witnessing prey deliveries by the parents to areas away from the nest but within the general nesting territory. However, I was unable to locate these chicks directly and obtain exact dispersal distances.

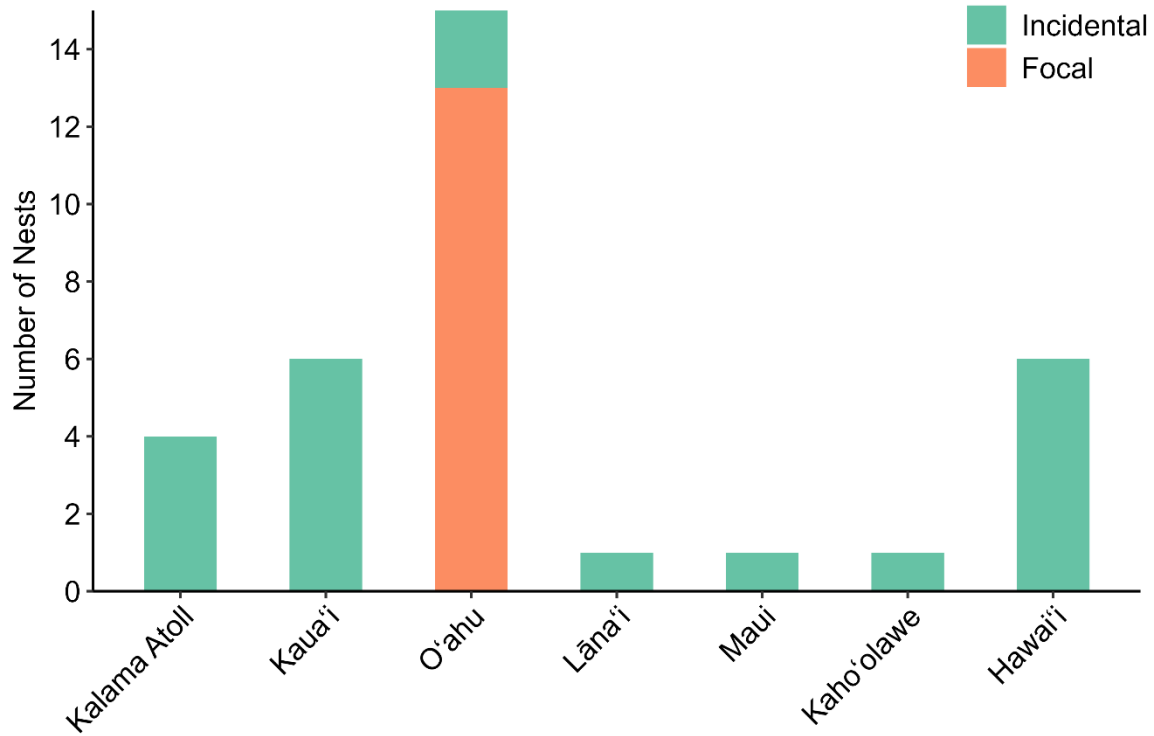


Figure 0.3. Number of Pueo nests found at both the focal study sites and incidentally, broken down by island.

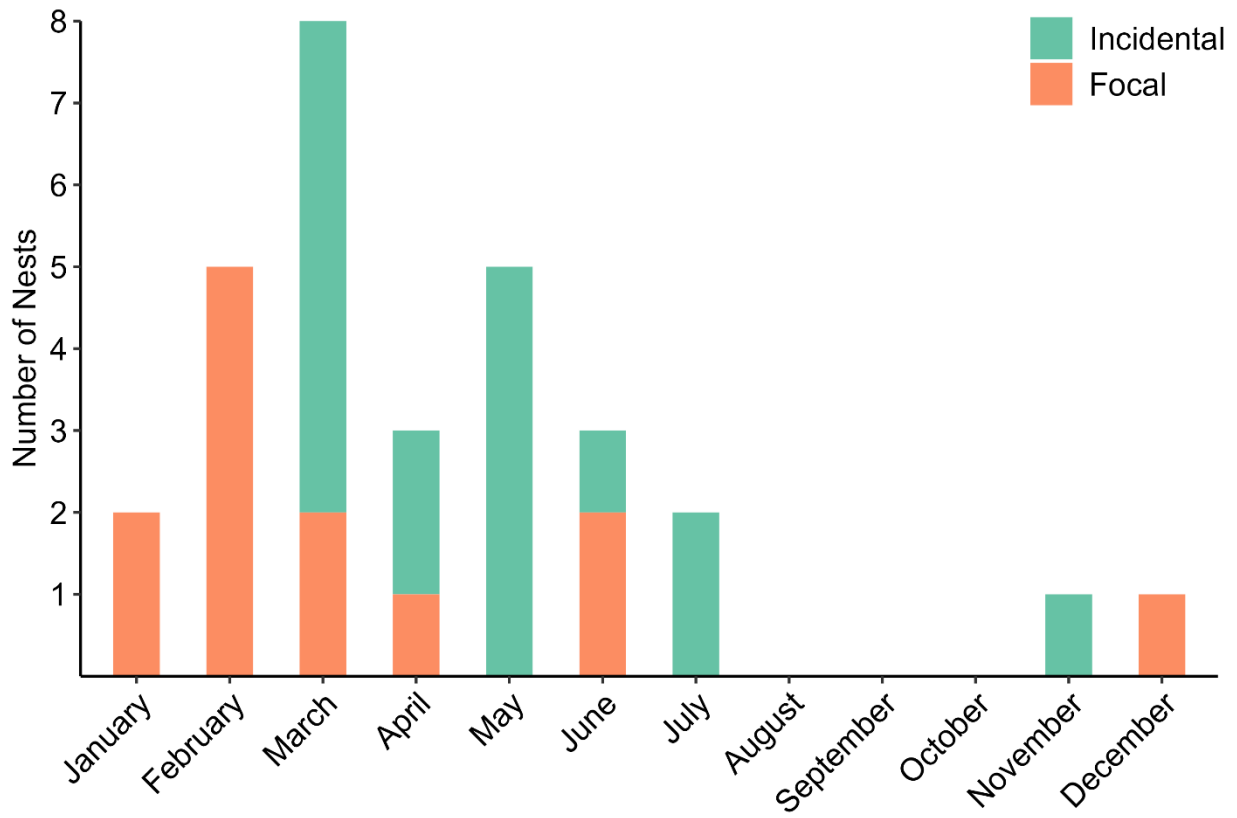


Figure 0.4. Number of Pueo nests found at both the focal study sites and incidentally, broken down by month of discovery.

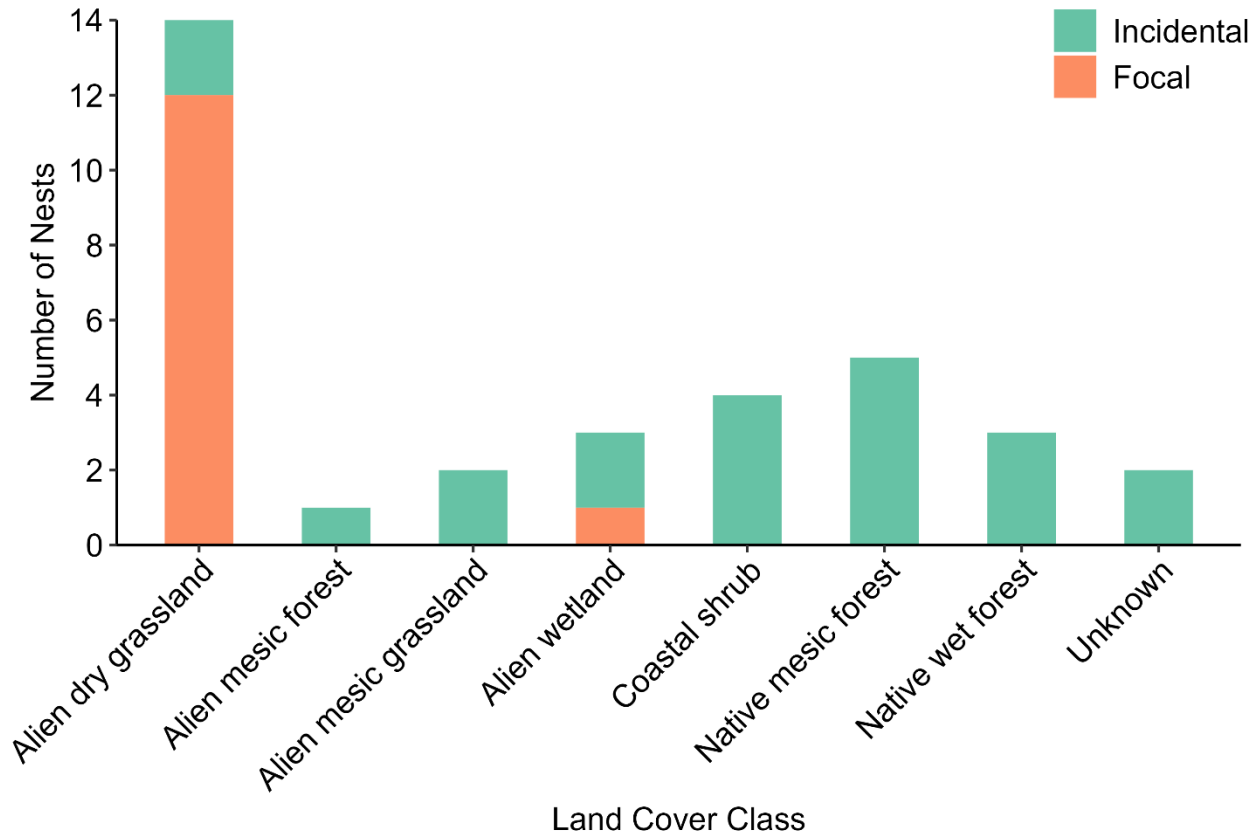


Figure 0.5. Number of Pueo nests found at both the focal study sites and incidentally, broken down by habitat type. Note that numbers are biased towards one of the two focal study habitat types – alien dry grassland. Habitat types derived from the General Land Cover class from the U.S. Geological Survey Carbon Assessment of Hawaii Land Cover Map (Jacobi et al., 2017).

Table 0.1. Summary of Pueo nest breeding parameters, from focal study sites on O‘ahu (Nu‘upia WMA and Lualualei Valley).

Nest ID	Date discovered	Latitude	Longitude	Estimated initiation date ¹	Estimated hatch date ¹	Number of eggs ²	Number of chicks ³	Nest fate
01	12/18/2019	██████	██████	2019-12-16	2020-01-11	2	0	Fail - unknown cause
02	1/7/2020	██████	██████	2020-01-02	2020-01-31	5	0	Fail - predated
03	1/28/2020	██████	██████	2020-01-24	2020-02-21	NA	1	Success
04	2/13/2020	██████	██████	2020-02-09	2020-02-26	2	1	Fail - predated
05	2/14/2020	██████	██████	2020-02-10	2020-03-09	4	0	Fail - unknown cause
06	2/18/2020	██████	██████	2020-02-13	2020-03-13	NA	NA	Fail - unknown cause
07	3/25/2020	██████	██████	2020-02-11	2020-03-10	NA	1	Success
08	6/3/2020	██████	██████	2020-04-29	NA	2	0	Fail - unknown cause
09	2/5/2021	██████	██████	2021-01-31	2021-03-06	7	3	Success
10	2/16/2021	██████	██████	2021-01-16	2021-02-13	NA	5	Success
11	3/31/2021	██████	██████	2021-03-01	2021-03-28	NA	3	Success
12	6/8/2021	██████	██████	2021-05-27	NA	1	0	Fail - unknown cause
13	4/26/2022	██████	██████	2022-04-20	2022-05-13	4	4	Success

¹Based on status of nest at time of finding, using a 28-day incubation period, or from direct observation.

²Maximum number of eggs observed at the nest.

³Maximum number of chicks observed at the nest.

Nest site characteristics and site selection

We collected vegetation characteristic data from 11 nests found between March 2020 and June 2022. Two of the 13 nests included in the other analyses were discovered prior to the development of the nest characteristics protocol, and thus these data types were not collected for those nests. Tallest vegetation height ranged from 38-67 cm ($\bar{x} = 48.82 \pm 3.15$ cm SE, n=11). VOR ranged from 3.25-42 cm ($\bar{x} = 15.43 \pm 3.467$ cm SE, n=11). Percent cover ranged between 62-98 % ($\bar{x} = 83.82 \pm 3.77$ % SE, n=11).

For nest site selection, the best fit models as determined by AICc values and goodness-of-fit tests included mean high VOR and mean low VOR as predictor variables; Table 2.2 summarizes the AICc values of the top 3 models. The top models (Figures 2.6a and 2.6b) indicates that as the mean high VOR and mean low VOR at a given site increases, the probability of use of that site by a Pueo for nesting also increases. However, given the small sample size, there was high model uncertainty among these top models.

Nests were generally in small, bowl-shaped depressions in the ground surrounded by vegetation that was tall enough that incubating females were fully obscured by vegetation cover (on average 40 cm in height). The most common vegetation at nests in the grassland were buffelgrass (*Cenchrus ciliaris*), haole koa (*Leucaena leucocephala*) shrubs (less than 1 meter tall), and yellow bluestem (*Bothriochloa ischaemum*), while the nest in the wetland was surrounded by pickleweed (*Batis maritima*). The terrain of both the grassland and wetland sites was naturally quite uneven, and therefore it is unknown whether the Pueo were choosing pre-existing depressions in the ground or creating their own as the female incubated and brooded. While some nests were sparsely lined with some vegetation and a few Pueo feathers, most of the eggs sat directly on bare ground. The carrying of nest material or nest building was never observed.

Table 0.2. Model selection table for relative probability of use of a site for nesting by a Pueo in response to vegetation characteristics.

Model Predictor Variables	AICc	ΔAICc	Model Weight (w_i)	Negative log Likelihood (-2(L))
Tallest	52.7	0.00	0.37	-24.22
VOR high	53.1	0.42	0.30	-24.32
VOR low	54.2	1.49	0.18	-24.97

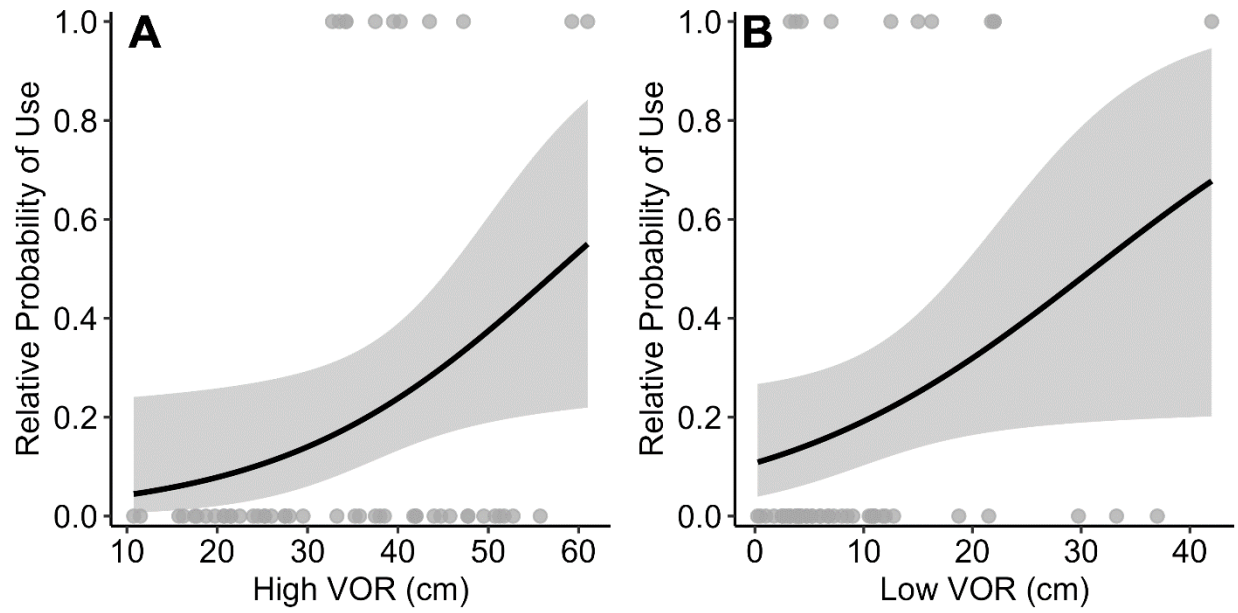


Figure 0.6. Plot of the relative likelihood of use of a site for Pueo nesting versus (A) mean High VOR (Visual Obstruction Reading) and (B) mean Low VOR. Gray dots are the VOR at each site. Solid line indicates the predicted likelihood of use, grey areas are the 95% confidence intervals.

Nest success

All 13 nests were included in calculating the estimate of Nest Survival (NS), but the two nests discovered prior to the development of the nest characteristics collection were excluded from the analysis investigating the relationship between predictive covariates and Daily Nest Survival Rate (DSR). DSR was $0.97 (\pm 0.01 \text{ SE}, n=13)$, while NS (DSR^{number of days to success}) was $0.24 (\pm 0.12 \text{ SE}, n=13)$. The null model, (i.e. constant nest survival) was the top model, with separate models including relative day of nesting season and percent cover as the second and third best model, respectively (Table 2.3). Given the high model uncertainty among the top models due to the small sample sizes, and that the second and third models had an ΔAICc value of less than one, we examined the effect of covariates in the second and third best models on DSR. Relative day of nesting season was negatively correlated with DSR, while percent cover was positively correlated with DSR (Figures 2.7a and 2.7b).

For five of the seven failed nests we were unable to definitively determine the causes of nest failure, but confirmed predation to be the cause of at least two nest failures. At one nest, feral dogs were seen within 150 meters of the nest on the last day that the nest was known to be active (i.e. female Pueo was seen incubating the nest). At the next nest check, no eggs were present in the nest, though there had been 5 eggs upon initial discovery of the nest, and the remains of an adult Pueo were found nearby. The remains looked consistent with tearing by a large animal, likely a feral dog. In another failed nest the eggs were damaged, likely by a mongoose or rat, and a fully intact dead Pueo nestling was found a couple meters outside the nest bowl. In one nest that succeeded, prior to egg laying but after the establishment of the nesting territory, observers watched one Pueo chase and dive at a feral cat encroaching on its territory.

Table 0.3. Model selection table for the effect of nest site characteristics on Daily Nest Survival.

Model Predictor Variables	AICc	ΔAICc	Model Weight (w_i)	Negative log Likelihood (-2(L))
Null (Constant survival)	28.4	0.00	0.28	-11.12
Relative day of nesting season	29.0	0.60	0.21	-10.36
Percent cover	29.1	0.71	0.20	-10.42
VOR low	30.2	1.85	0.11	-10.99

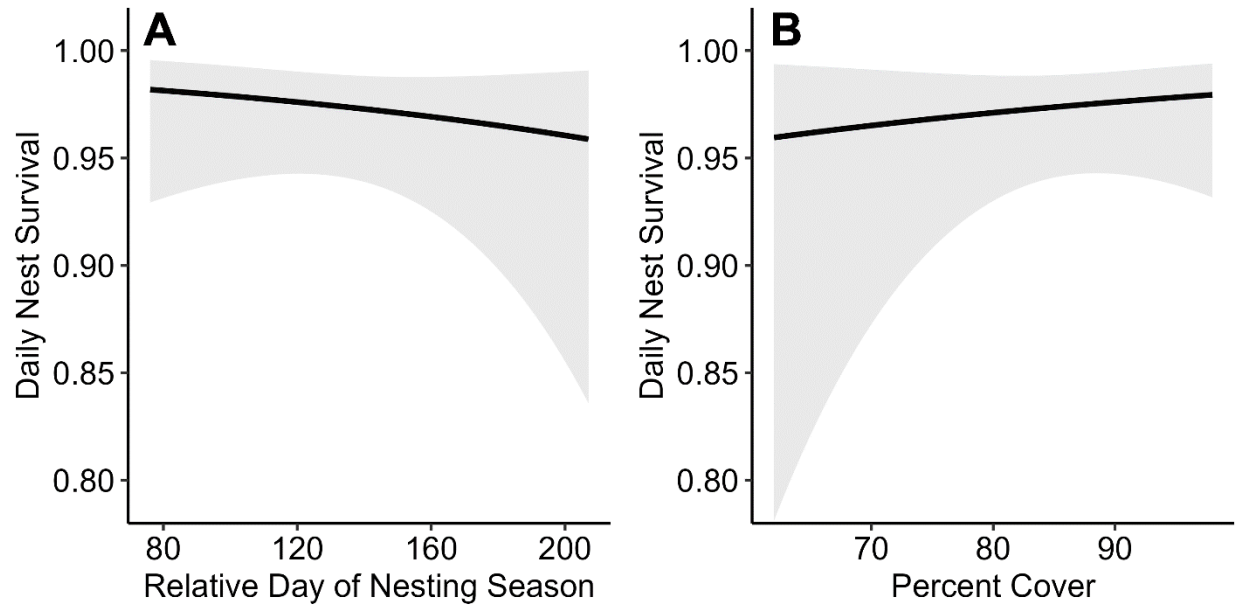


Figure 0.7. Plot of the estimated Daily Nest Survival Rate in relation to (A) Relative day of nesting season and (B) Percent cover of vegetation at the nest. Solid line indicates the predicted DSR, grey area is the 95% confidence interval.

Nesting Pueo diet

A total of 71 pellets and prey remains were collected from six different Pueo nests (Table 2.4). House Mice (*Mus musculus*) were the most frequently occurring prey type, occurring in 69.01% of the samples. Birds were the next most frequently occurring prey type, occurring in 38.03% of the samples, followed by *Rattus* species and insect species occurring in 14.1% and 11.3% of samples, respectively (Figure 2.8). Figure 2.9 summarizes the frequency of occurrence of different prey items by nest. Before accounting for overdispersion, my top model predicting the occurrence of different prey items included only Nest ID as a covariate, suggesting that there is a difference in diet composition of each nesting Pueo pair (Table 2.5). However, once accounting for overdispersion, the null model is the top model, ranking higher than any combination of Nest ID and year as covariates, lending little support to the hypothesis that Pueo diet may vary from nest to nest (Table 2.6).

Table 0.4. Number of Pueo pellets in which each prey type occurred. Numbers in parenthesis are percentages representing the overall frequency of occurrence of each prey taxa.

PREY TYPE	NUMBER OF PELLETS (PERCENTAGE)
MAMMALS	58 (81.7)
	<i>Mus musculus</i> 49 (69.0)
	Unidentified species of genus <i>Rattus</i> 10 (14.1)
BIRDS	27 (38.0)
	<i>Geopelia striata</i> (Zebra Dove) 12 (16.9)
	<i>Zosterops japonicus</i> (Warbling White-eye) 1 (1.4)
	<i>Estrilda astriid</i> (Common Waxbill) 1 (1.4)
	Unidentified species of genus <i>Lonchura</i> 2 (2.8)
	Unidentified species of family Fringillidae 3 (4.2)
	Unidentified bird species 14 (19.7)
INSECTS	8 (11.3)
	Unidentified species of family Carabidae 1 (1.4)
	Unidentified species of family Tenebridae 1 (1.4)
	Unidentified species of family Elateridae 1 (1.4)
	Unidentified species of family Curculonidae 1 (1.4)
	Unidentified insect species 8 (11.3)

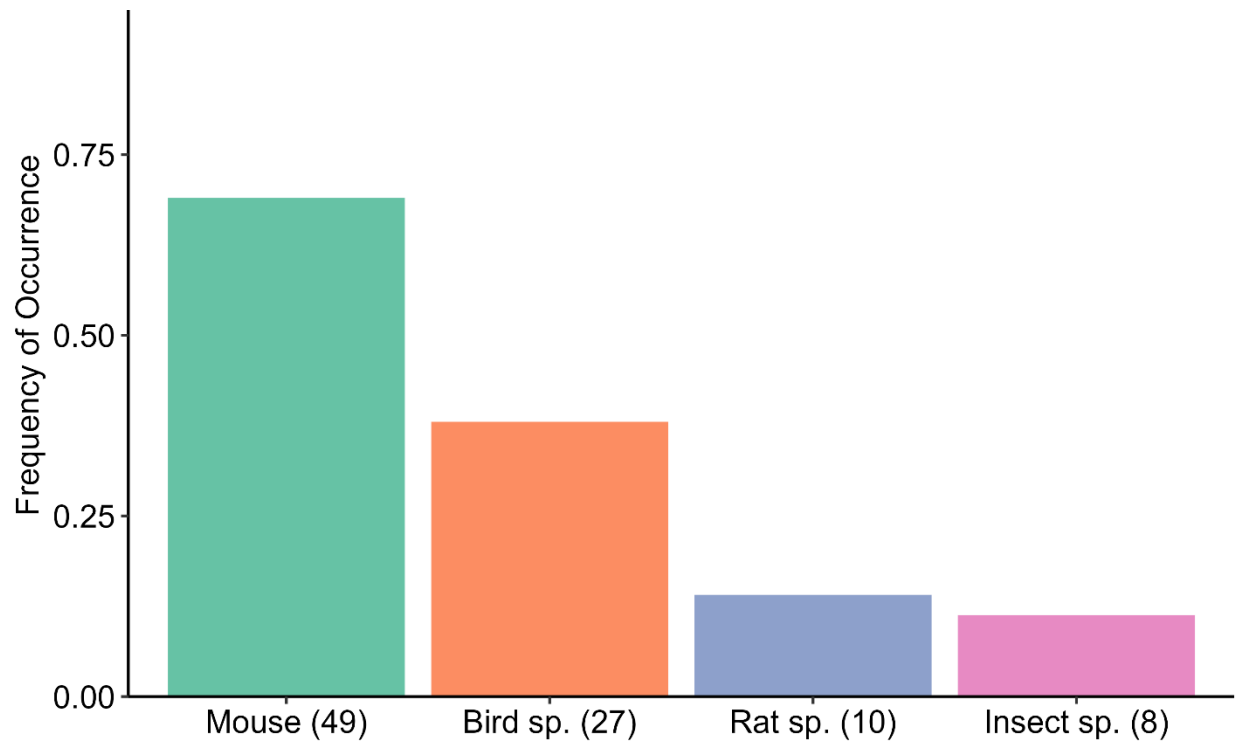


Figure 0.8. Frequency of occurrence of each prey type across all samples. Numbers in parentheses represent the number of occurrences of that prey type in pellets and prey remains.

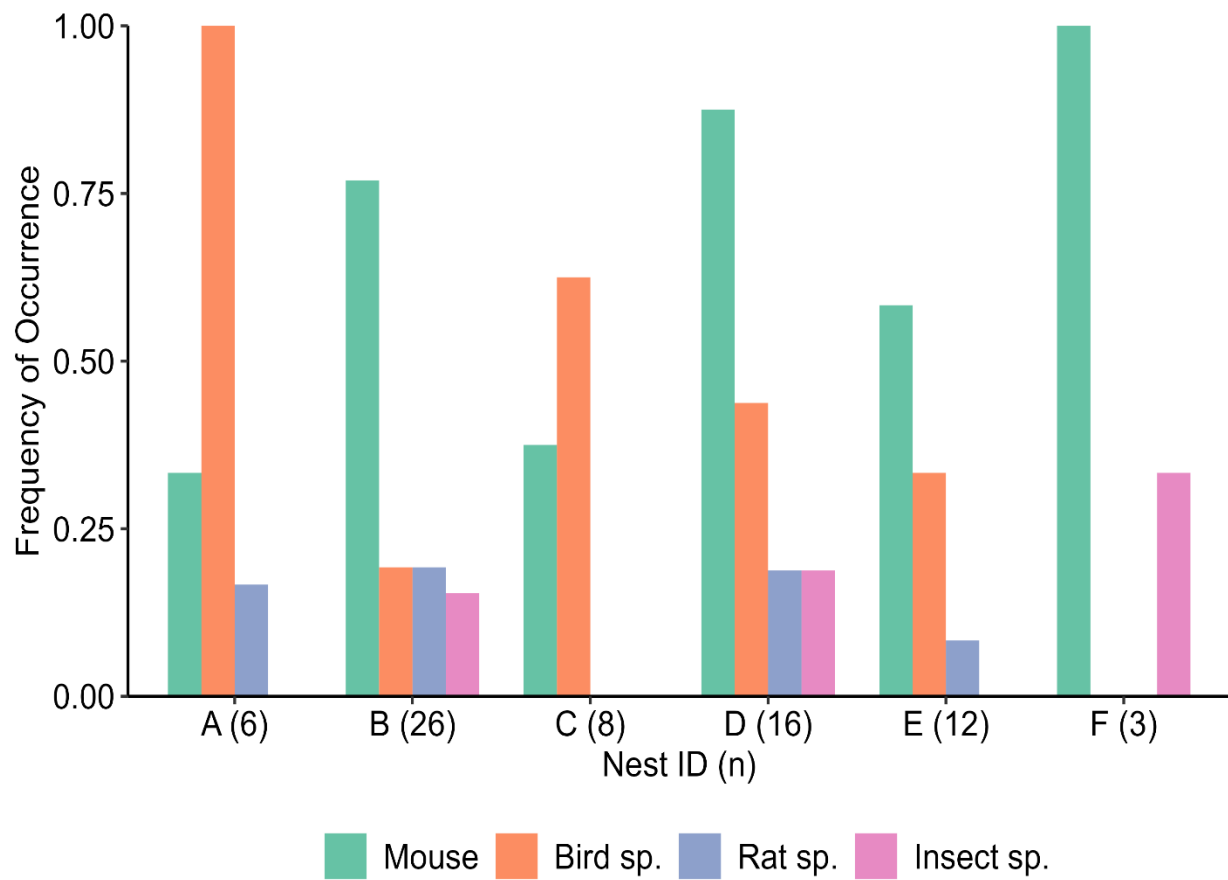


Figure 0.9. Frequency of occurrence of each prey type across all samples, broken down by individual nests. Numbers in parentheses represent the number of samples (pellets or prey remains) from each nest.

Table 0.5. Model selection table for models used to predict diet of nesting Pueo without incorporating overdispersion parameter.

Model Predictor Variables	AICc	ΔAICc	Model Weight (w_i)	Number of model parameters
Nest	339.10	0.00	0.75	6
Nest + Year	341.99	2.89	0.18	8
Year	344.19	5.09	0.06	3
Null model	347.99	8.89	0.01	1

Table 0.6. Model selection table for models used to predict diet of nesting Pueo, with overdispersion parameter. \hat{C} equals 18.916.

Model Predictor Variables	QAICc	ΔQAICc	Model Weight (w_i)	Number of model parameters
Null model	20.30	0.00	0.85	1
Year	23.95	3.65	0.14	3
Nest	29.54	9.23	0.01	6
Nest + Year	33.65	13.35	0.001	8

State-wide incidental data summary

A total of 21 separate incidental breeding observations from across the Hawaiian Islands were collected. Incidental breeding observations were defined as a nest with eggs or chicks inside, or a recently dispersed chick found outside of its nest. Observations were reported from Hawai‘i island, Maui, Lāna‘i, O‘ahu, Kaua‘i, and Kalama Atoll (also known as Johnston Atoll). Thirteen of the observations were reported as a response to requests for data during the 2020-2022 breeding seasons; these observations were reported by staff from Hawai‘i Department of Forestry and Wildlife, U.S. Fish and Wildlife Service, U.S. Forest Service, Archipelago Research and Conservation, Pūlama Lāna‘i, and Kaho‘olawe Island Reserve Commission. The remaining eight observations were from prior project reports or the single publication on Pueo nests by Thomas Snetsinger (Snetsinger, 1995).

Table 2.7 summarizes the locations, breeding dates, habitat types, and nest contents or number of dispersed chicks observed per observation across all the incidental reports; Table 2.8 breaks the number of observations down by island and month. Pueo breeding was discovered between the months of March and November. Of the 17 observations that noted specific nest contents (i.e., eggs or chicks), 12 were discovered after at least one chick had hatched and five were discovered during the egg stage. Nine observations were of Pueo chicks that had already dispersed from the nest but were not yet fully fledged (between 14 and 28 days old). Of the 15 observations that could be mapped for comparison with the U.S. Geological Survey Carbon Assessment of Hawaii Land Cover Map for habitat standardization, three were found in native wet forest, five were found in native mesic forest, three in alien mesic grassland, one in alien mesic forest, and three in areas categorized as “very sparse vegetation to unvegetated” (Table 2.6). Based on habitat descriptions and photos associated with these observations, we determined that two of these nests were in a wetland and one in sparse nonnative mesic grassland. Reported clutch sizes ranged from two to seven eggs ($\bar{x} = 4.6 \pm 0.8$ SE, $n = 5$). Because most of the reports were one-time visits to a nest or a single observation of a Pueo chick or fledgling, nesting success and productivity could not be determined in most cases. However, eight of the observations were of fledged chicks who had already dispersed from their nests, indicating successful nesting.

On Kalama Atoll, all four observations were made by U.S. Fish and Wildlife staff between March 1st and 19th of 2020. Land cover class data for Kalama Atoll was not available but all four observations were of nests found in small depressions on the ground within bushes of *Pluchea spp* and therefore considered coastal shrub. Pueo nests were found during routine surveys for seabird nests. In one of these nests, three dead downy Koa'e'ula (Red-tailed Tropicbird, *Phaethon rubricauda*) chicks and the remains of one adult 'Ewa'ewa (Sooty Tern, *Onychoprion fuscatus*) were found alongside three young (less than 10 days old) Pueo chicks and one Pueo egg. Upon revisiting the same nest a few days later, the observers found one of the Pueo chicks 3.5 meters away in a different *Pluchea spp.* bush next to another dead Red-tailed Tropicbird chick.

On Hawai'i island, three observations from March through May of 1993 reported in Snetsinger (1995), two observations were reported to my team in May of 2021, and one observation was reported to my team in April of 2022. Snetsinger reported finding Pueo nests in the Mauna Kea area between March and May, while the new observations were all from or around the Hakalau Forest National Wildlife Refuge around the eastern slope of Mauna Kea. In both 2021 and 2022, fledgling Pueo were reported within areas fenced to exclude predators and protect Nēnē (Hawaiian Goose, *Branta sandvicensis*) nest sites. The predator exclusion fencing in that area protects nesting birds from mongoose, feral cats, feral dogs, and pigs, and live traps and A24 rodent traps were also present at the site in case of incursions into the fenced area. The April 2022 observation was of two Pueo fledglings found approximately 152 meters from each other and assumed to be from the same nest. The observer returned to the same area a few days later and found one dead Pueo fledgling, presumed to be one of the two fledglings seen prior. The observer said the carcass looked intact with no visible wounds and noted that it was found within the predator-proof fenced area, making predation an unlikely cause of death. The observer did note that it had been raining for the past few days and that inclement weather such as heavy rain in the area was common, suggesting that exposure was the likely cause of death for the Pueo fledgling. Snetsinger (1995) also observed a Pueo nest failure after a period of heavy rainfall, first finding the nest on May 5 1993 with four owlets and returning a week later to find three dead owlets near the nest.

On Kaua‘i, six observations were submitted by staff from Archipelago Research and Conservation (ARC) during their field work monitoring endangered seabirds in montane wet forests on Kaua‘i; one found in 2022 and the other 5 of unknown date. These six observations included stage of nesting as well as general location of the observations, but the observer noted that Pueo are seen regularly at all of their main study sites near seabird colonies. In Maui Nui, three observations, one each from Lāna‘i, Maui, and Kaho‘olawe were reported in 2011, 2019, and 2021, respectively. The two incidental observations from O‘ahu were found within the Nu‘upia WMA in 2017 and 2018.

We also obtained Pueo patient records from 2012-2022 from the Hawai‘i Wildlife Center (HWC), a state-wide non-profit that provides medical and rehabilitative care to native wildlife. Many Pueo were not aged in their records or did not have photos that would allow me to age the birds. Thus, only patients that were clearly indicated as juveniles on their records were included in my count of juvenile birds. Due to a lack of photos, patients could not be aged and therefore we could not estimate nest initiation dates, but a summary of the HWC data is in Appendix D. Given the uncertainty around these data, we did not include it in the broad summary of nesting phenology and habitat types above.

Table 0.7. Incidental reports of Pueo nests or chick observations across the Hawaiian Islands and nearby atolls. A request for observations was sent out to organizations and individuals working in natural resources and wildlife fields on a regular basis from 2020 to 2022. Historic observations were also found through literature review.

<i>Island</i>	<i>GPS Coordinates</i>	<i>General Location Description</i>	<i>Discovery Date</i>	<i>Estimated Initiation Date¹</i>	<i>General Habitat Type²</i>	<i>Nest Contents</i>	<i>Nest / Chick Location Site Description</i>
Kaho'olawe	██████	Pu'u Moaulaiki	5/26/2019	4/16/2019	Alien dry grassland	One fledgling	-
Kalama Atoll	██████	Johnston Atoll	3/6/2020	2/7/2020	Coastal shrub	One chick, 3 eggs	Directly on ground, within <i>Pluchea</i> bush
Kalama Atoll	██████	Johnston Atoll	3/1/2020	2/27/2020	Coastal shrub	Four eggs	Directly on ground, within <i>Pluchea</i> bush
Kalama Atoll	██████	Johnston Atoll	3/1/2020	1/24/2020	Coastal shrub	Three chicks, 1 egg	Directly on ground, within <i>Pluchea</i> bush
Kalama Atoll	██████	Johnston Atoll	3/19/2020	3/14/2020	Coastal shrub	Five eggs	Directly on ground, within <i>Pluchea</i> bush
Lanai	██████	-	6/8/2021	5/1/2021	Native wet forest	One fledgling	Found approximately one meter from base of O'hia tree, in Uhule understory
Hawai'i	██████	Hakalau Forest National Wildlife Refuge	7/14/2021	5/26/2021	Alien mesic grassland	One fledgling	Found in field with kikuyu grass and uluhe
Hawai'i	██████	Hakalau Forest National Wildlife Refuge	7/6/2021	5/15/2021	Native mesic forest	One fledgling	Found approximately 10 meters from the base of a Koa tree, in tall, green, kikuyu grass
Hawai'i	██████	Hakalau Forest National Wildlife Refuge	4/7/2022	2/8/2022	Alien mesic grassland	Two fledglings	Found in field with kikuyu grass and uluhe, near
Kaua'i	██████	Upper Manoa	3/2/2022	1/9/2022	Native wet forest	One fledgling and one egg	Small divot within Uluhe understory
Kaua'i	██████	Pihea	-	-	Native mesic forest	Nest	-
Kaua'i	██████	Upper Manoa	-	-	Native wet forest	Fledgling	-
Kaua'i	██████	Pohakea	-	-	Native mesic forest	Eggs	-
Kaua'i	██████	Sleeping Giant	-	-	Alien mesic forest	Nest	-
Hawai'i*	██████	Kanakaleonui, Mauna Kea	3/22/1993	-	Native mesic forest	7 Eggs	Found approximately 30 cm from a dead Māmane snag, in grass about 30 cm tall
Hawai'i*	██████	Kanakaleonui, Mauna Kea	4/3/1995	-	Native mesic forest	2 Chicks	Found perched in Pukiawe bush
Hawai'i*	██████	Pu'u La'au, Mauna Kea	5/5/1993	-	Alien dry grassland	4 Eggs	Found near base of a small Māmane tree
O'ahu	-	Mōkapu Peninsula	5/30/2018	-	Alien wetland	Fledgling	-
O'ahu	-	Mōkapu Peninsula	5/18/2017	-	Alien wetland	Chick	-
Maui	-	-	11/1/2011	-	Unknown	Nest	-
Kaua'i	-	-	5/1/2017	-	Unknown	Nest	-

¹If photos or detailed descriptions of the chicks or eggs were provided, an estimated initiation date (i.e. date of first egg laying) was calculated in order to standardize observation timing. ²General habitat type was ascertained by mapping observations over the U.S. Geological Survey Carbon Assessment of Hawaii Land Cover Map and using their General Land Cover categories (Jacobi et al., 2017). *Indicates observations from Snetsinger 1995, "Observations of Pueo Nests on the Slopes of Mauna Kea".

Table 0.8. Number of breeding observations found across the Hawaiian Islands and nearby Atolls, separated by island and month. Numbers include both incidental observations (from data request and literature review) and observations from our main study areas on O‘ahu.

	Kaua'i	O'ahu	Maui	Hawai'i	Lanai	Kaho'olawe	Kalama Atoll
January	0	2	0	0	0	0	0
February	0	5	0	0	0	0	0
March	1	2	0	1	0	0	4
April	0	1	0	2	0	0	0
May	1	2	0	0	1	1	0
June	0	2	0	0	0	0	0
July	0	0	0	3	0	0	0
August	0	0	0	0	0	0	0
September	0	0	0	0	0	0	0
October	0	0	0	0	0	0	0
November	0	0	1	0	0	0	0
December	0	1	0	0	0	0	0
Total	2	15	1	6	1	1	4

DISCUSSION

This study is one of the first to document Pueo nests across the state of Hawaii and investigate the factors influencing Pueo breeding ecology, filling an important geographical gap in our understanding of the basic life history traits of a globally distributed raptor. By using a combination of systematic nest searching and incidental observations reported from partners across the region, we were able to obtain insights on specific vegetation characteristics influencing nest site selection and nesting success, as well as provide evidence that Pueo are selecting a wider variety of habitat types for breeding than their continental counterparts. Understanding the variety of habitats and the specific site characteristics that are important to Pueo reproduction and nestling survival is directly relevant to the conservation of this endemic raptor. When compared to results from Short-eared Owl breeding ecology studies in other regions, these results suggest that the global population of Short-eared Owls may be a generalist species, with island and tropical subspecies displaying more variation among individuals than continental and higher latitude subspecies.

In grassland systems, Pueo are selecting nesting areas with taller (40 to 50 cm) and denser vegetation compared to unselected sites, which is expected based on results from similar systems on North American Short-eared Owls (Fondell & Ball, 2004; Keyes et al., 2016). North American Short-eared Owls are also thought to have an upper limit in terms of tallest vegetation heights at nesting sites; Herkert et al. (1999) found that Short-eared Owl nests were nesting primarily in managed grasslands that had been mowed in the year prior and thus only had a maximum vegetation height of 50 cm, compared to Northern Harriers (*Circus hudsonius*), another ground nesting raptor, which nested primarily in undisturbed areas with taller vegetation. Other studies have indicated that some level of habitat management and disturbance is beneficial for Short-eared Owl nesting, as grasslands that are periodically mowed, hayed, or grazed results in a mid-range vegetation height that they seem to prefer (Dechant et al., 1998). In Hawaii, The Lualualei Valley site is regularly mowed due to fire risk concerns; this management action may provide more suitable nesting habitat for Pueo, but also presents an additional threat for Pueo nests to be disturbed or destroyed using heavy machinery.

While the null model assuming constant nest survival was the top model selected, likely due to a low sample size of nests, the other top models ($\Delta AICc < 1$) suggest some environmental

factors may be significant in determining Pueo nest success. The second-best model selected included relative day of nesting season as the only covariate, with nests initiated earlier in the nesting season having a higher Daily Survival Rate. This is similar to seasonal nest success patterns observed in the Hawaiian Stilt (Harmon et al., 2021), and is likely an effect of higher precipitation during that time period (i.e. November through March) on O‘ahu, thus resulting in both rapid plant growth and higher prey abundance (Giambelluca et al., 2013). The third-best model selected included percent vegetation cover, with nests with higher percent vegetation cover having a higher Daily Survival Rate; these results are in line with a study from North America that found greater Short-eared Owl nest success in fields with taller and denser vegetation (Fondell & Ball, 2004). Additionally, my study did not look at survival after dispersal from the nest, which would provide a more complete understanding of juvenile survival and population trends overall. Rivest (1998) examined post-fledging dispersal of Short-eared Owls in Idaho with radio-tagged individuals and found a high mortality rate (88.2%) in the period between dispersal from the nest and first flight. Given the low survival rates found in my study and Rivest 1998, future studies should look at both pre- and post-dispersal survival of chicks to fully understand factors that influence juvenile survival and population dynamics.

Pueo diet composition did not vary significantly among nests. Pellets and prey remains associated with nests were only found at the Lualualei grassland site. Mostello and Conant (2018) also analyzed Pueo pellets collected from the Lualualei Valley site between 1993 and 1995 and found that birds and mice were the most frequently occurring prey items, occurring 70% and approximately 45% of the time, respectively. I observed slightly different proportions, with mice occurring more frequently than birds despite including prey remains, which were entirely avian prey, in my analyses while Mostello and Conant only looked at pellets. The differences in these frequencies may not be statistically significant, and both mice and small passerines can be subject to irruptive population dynamics depending on environmental conditions, so I cannot draw conclusions regarding changes in Pueo diet from this area between 1993 and 2020. However, it is interesting to note that birds have remained a significant contributor to Pueo diet at this site. Furthermore, Mounce (2008) and Tweed (2006) documented Pueo eating native passerines such as Kiwīkiu (*Pseudonestor xanthophrys*), ‘Apapane (*Himatione sanguinea*), and Puaiohi (*Myadestes palmeri*), and one of our incidental nest observations noted Koa‘e‘ula and ‘Ewa‘ewa remains in Pueo nests. That Pueo predate on other

native and threatened bird species poses a potential conservation challenge, but further research is necessary to determine the magnitude of effect of Pueo predation on other native bird species, given their archipelago-wide distribution.

This study contributes to global indications that Short-eared Owl diets vary geographically. Thus, though globally the species appears to be a foraging generalist, there are strong regional dietary preferences, suggesting potential specialization at this level. In the Galapagos, seabirds in the genera *Oceanodroma*, *Phaeton*, *Sula*, and *Puffinus* are thought to be major elements in the Short-eared Owl diet, and in North America, coastal populations of Short-eared owls are thought to take a greater proportion of avian prey than inland populations (Grant et al., 1975; Holt, 1994). In contrast, multiple studies from inland North America and Europe found that small mammals, especially *Microtus* voles, make up at least 80% of the breeding season diet (Evrard et al., 1991; Glue, 1977; Holt, 1992; Korpimäki & Norrdahl, 1991; Roberts & Bowman, 1986). Thus, my study more closely follows expected patterns for island and coastal species, despite substantial rodent contributions to diet.

Table 2.9 summarizes the breeding parameters, phenology, and nesting habitat found in this study compared to what is known about the breeding parameters, phenology, and nesting habitat of other Short-eared Owl subspecies. Though there are far fewer studies from regions in latitudes closer to the equator (i.e. tropical regions between 23.5° North and 23.5° South, there seems to be greater variation in breeding phenology and nesting habitat in Short-eared Owls in tropical regions and in island systems compared to Short-eared Owls in continental systems. A previous study suggested that island populations may have later breeding seasons compared to their continental counterparts (Lambrechts & Dias, 1993; Wiggins et al., 1998). I did not find evidence of a later breeding season but instead a prolonged breeding season, perhaps driven more by different seasonal patterns in tropical climates resulting in broader periods of net productivity and prey availability (Wagner, 1957). Similar to this study, Greater Antillean Short-eared Owls (*A.f.domingensis* and *A.f.portoicensis*) were observed nesting as early as November and as late as June, with activity peaking in February (Garrido, 1984; Guerrero, 2005; Rodríguez Castañeda, 1998; Thorstrom & Gallardo, 2017). Similarly, Galapagos Short-eared Owls (*A.f.galapagoensis*) also have an expanded breeding season, with active nests found between September and May (de Groot, 1983).

We did not find a reduced clutch or brood size relative to continental Short-eared Owls. In contrast, Galapagos Short-eared Owls had smaller clutch sizes (2-5 eggs), fewer number of fledglings, and slower development of chicks (de Groot, 1983). Both the Galapagos and Hawaiian Islands have a similar suite of invasive mammalian predators, but Galapagos Short-eared Owls are thought to have diverged from *A.f. flammeus* between 890,000 and 1.7 million years ago, a much longer evolutionary period compared to that of Pueo which were thought to establish in the Hawaiian Islands between 1000 and 1200 A.D. ((Pyle, n.d.; Schulwitz et al., 2018). Given their longer existence in an island system without mammalian predators, Galapagos Short-eared Owls may have lost defenses to mammalian predators, allowing them to evolve smaller clutch sizes and a longer chick developmental period, while Pueo never lost their defenses to mammalian predators due to their relatively shorter evolutionary history.

Within the Hawaiian Islands, nests were found across a wide range of habitat types and elevation ranges. Although my focal study sites were composed of grasslands and wetlands, similar to those of studies from North America and Europe, we also received reports of nests and chicks in high elevation wet and mesic forests of Hawai'i. Pueo are known to reside in these habitats and a previous study suggested that Pueo utilize forested areas for roosting more often than their continental counterparts (Hawai'i Department of Land and Natural Resources, 2005; Wilhite, 2021). Though the small sample size and nature of incidental observations collated in this study preclude population-wide conclusions about Pueo nest site selection across different habitat types, my study suggests that vegetation structure may be more important than the broader habitat type in identifying potential Pueo nesting sites. All Pueo nests or young were found in spots with relatively dense ground plant cover, whether it be of non-native grasses such as kikuyu grass (*Pennisetum clandestinum*) and buffleggrass (*Cenchrus ciliaris*) in grasslands, 'uluhe (False staghorn ferns, *Dicranopteris linearis*) understory in native wet forests, or *Pluchea* bushes in coastal vegetation. Successful Pueo nesting in these areas further supports the fact that there are a variety of habitat types that are critical to their life history. This diversity in habitat use, especially for nesting, must be accounted for when determining what constitutes critical habitat for Pueo. Roberts and Bowman (1986) also suggested a broad spectrum of breeding ecology strategies based on their five-year study of breeding and diet of Short-eared Owls in heather moor in Wales; they noted that Short-eared Owls in heather moor had a narrower breeding season, smaller and more consistent clutch sizes, and a different diet than Short-eared

Owls in grasslands in Great Britain. Future research in the Hawaiian Islands should focus on nest searching and monitoring across all potential Pueo breeding habitats to examine if clutch size, brood size, diet, and nesting success differ based on vegetation type, as differences in breeding parameters could have important consequences for conservation and management actions.

Our nesting habitat results, along with prior studies of Pueo movement and habitat use with GPS-VHF tracked individuals, suggest decreased habitat specialization and expanded habitat use of Pueo compared to continental Short-eared Owl (Garcia-Heras et al., 2022; Wilhite, 2021). Antillean and Galapagos Short-eared Owl nests have also been documented closer to forested and wooded areas at the bases of trees or in bushes, tentatively suggesting that the variation seen in these subspecies (including Pueo) are driven by island biogeography (Garrido, 1984; Guerrero, 2005; Rodríguez Castañeda, 1998; Thorstrom & Gallardo, 2017). Niche expansion with regards to diversified habitat use in island systems may result from the simultaneous decrease in interspecific competition and increase in intraspecific competition relative to the continental system (Blondel, 1985; Sayol et al., 2018; Van Valen, 1965). These simultaneous pressures on the population can result in increases in among-individual niche variation along with population niche breadth (Bolnick et al., 2003). Movement and habitat use data from GPS-VHF tagged Pueo suggest that they can travel relatively large distances, such as exploratory movements across and between different islands (Garcia-Heras et al., 2022). While we documented nesting at the Lualualei Valley site in consecutive years, adults were not marked, and we could not confirm if the same individuals were returning to the site to breed. Future research focused on tracking breeding birds over multiple years could shed light on whether individual Pueo are moving between among nesting areas in different habitat types each breeding season and thus displaying individual niche width widening (Bolnick et al., 2007).

The expanded breeding habitat use and diet of Pueo is especially interesting when considering that globally, Short-eared Owls are generally thought to be foraging and habitat specialists. The movement patterns and breeding habitat use of *A. f. flammeus* are strongly tied to fluctuating small mammal populations in grassland systems, and population-wide management recommendations stem heavily from this predator-prey dynamic (Booms et al., 2014). These Short-eared Owls display low breeding site fidelity, which is thought to stem from small rodent population irruptions and breeding wherever preferred prey is abundant (Johnson et al., 2017;

Korpimäki & Norrdahl, 1991). However, though the ability of a species to specialize is often thought to be relatively static, short-term changes in habitat degradation, population density, and source-sink dynamics caused by rapid environmental change can result in a species quickly becoming less specialized (Barnagaud et al., 2011). This relationship between prey population dynamics and Short-eared Owl breeding habitat use may be weaker in tropical and island regions such as the Hawaiian Islands, where various biogeographical dynamics have allowed for the species to become less specialized in their diet and habitat use and therefore less reliant on nomadic movements to obtain necessary resources. Indeed, studies of Short-eared Owl site colonization and extinction rates in both North America and the Hawaiian Islands have provided evidence that Pueo are indeed less nomadic than those on the continent (Miller et al., 2022; Wilhite, 2021).

Overall, this study provides insight into factors affecting the nest site selection and nesting success of Pueo, while also providing evidence of diverse resource use across the Hawaiian Islands. Pueo selected sites for nesting that had greater vegetation density than the surrounding areas and had greater nest survival for nests initiated earlier in their breeding season and at nests with greater percent vegetation cover. Across the Hawaiian Islands, Pueo utilized a variety of habitats ranging from native wet forests to alien mesic grasslands for breeding and utilized a variety of different prey types including insects and birds throughout their breeding period. Though it is difficult to draw population-wide conclusions due to my small sample size and incidental state-wide data collection methodology, these results illuminate the fact that habitat conservation and management plans for Short-eared Owls in one region may not be applicable across their global populations, nor even across a single state with as much habitat diversity as Hawai'i. Thus, regional studies are crucial in forming relevant and effective regional management plans.

Table 0.9. Summary of current knowledge of the breeding parameters of the nominate subspecies *Asio flammeus flammeus* and four of the island endemic subspecies. Notes on the sample sizes for each subspecies provided in the footnotes.

Subspecies	Location	Latitude	Breeding season	Number of eggs	Number of chicks	Nest habitat types	References
<i>A.f.flammeus</i>	North America (Canada and the contiguous United States.) and Europe	65 - 26° N	February - May	4-10 eggs	2-5 chicks	Natural grasslands, agricultural fields, and marshes	Urner 1925, Clark 1975, Hammerstrom 1961, Mikkola 1983, Saunders 1913, Arroyo et al. 2000, Holt et al. 1992
<i>A.f. domingensis</i> & <i>A.f. portoricensis</i> ¹	Greater Antilles	23 - 17° N	November – June	3-4 eggs	2 chicks	Natural grasslands, agricultural fields (pineapple fields), bases of Agave sp. trees	Garrido, 1984; Guerrero, 2005; Rodríguez Castañeda 1998, Thorstrom & Gallardo, 2017
<i>A.f. galapagoensis</i> ²	Galapagos	0.9538° S	September – May	2-5 eggs	2 chicks	Natural grasslands, transition forests, and vegetated lava fields	de Groot, 1983
<i>A.f. Sandwichensis</i>	Hawaiian Archipelago ³	28 - 16° N	November – June	1-7 eggs	1-5 chicks	Natural grasslands, wetlands, high-elevation wet and mesic forests	This study

¹*A.f. domingensis* & *A.f. portoricensis*: Garrido 1984 and Guerrero 2005 each reported metrics from 1 nest (total n=2). Rodríguez Castañeda 1998 and Thorstrom & Gallardo, 2017 report nesting habitat types and breeding season dates but no specific numbers for eggs or chicks.

²*A.f. galapagoensis*: De Groot 1983 reports number of eggs and chicks from 7 nests, and breeding season dates comes from a total of 22 nest observations.

³Includes nearby atolls

RECCOMENDATIONS FOR THE MANAGEMENT OF BREEDING PUEO IN HAWAI‘I

This section serves to synthesize the results of the study into management recommendations specific to Pueo. First, we present recommendations for state guidelines regarding spatial and temporal Pueo nest buffers. Second, we present specific recommendations for land and natural resource managers who may have Pueo breeding in their lands. These recommendations are informed by the many hours of observation and targeted nest searching conducted at the two O‘ahu focal study sites, but these recommendations are general enough that they should apply across all islands and habitat types.

STATE-LEVEL RECOMMENDATIONS

Overview

Direct and indirect effects of human disturbance are known to negatively impact breeding raptors, and establishment of spatial and temporal buffer zones are an effective way to protect raptor nests from disturbance (Richardson & Miller, 1997; White & Thurow, 1985). Buffer zones are defined as a minimum area or time frame around a nest/nesting event where human activity should be avoided in order to prevent negative effects to the nest (Richardson & Miller, 1997; White & Thurow, 1985). Currently, there is no official guideline set by Hawai'i Division of Land and Natural Resources (hereafter, DLNR) or Hawai'i Division of Forestry and Wildlife (hereafter, DOFAW) for buffers around Pueo nests, despite their endangered species status on the island of O'ahu (Hawai'i Department of Land and Natural Resources, 2015). Different projects across the state have been recommended various Pueo nest buffer distances, ranging from 20 meters to 100 meters (Raine et al., 2018, DOFAW pers. comm.). Temporal buffers are nonexistent as no research existed on the timing of Pueo nest establishment and chick development (Hawai'i Department of Land and Natural Resources, 2005). Based on the findings of this study, we advise that the state adopt and enforces a set guideline of a 200-meter minimum spatial buffer and a three-month minimum temporal buffer for Pueo nests.

Spatial buffer

A buffer of at least 200 meters should be maintained around the Pueo nest from the time that the nest is discovered until chicks are capable of flight. We found that the average Pueo chick dispersal distance was 98 meters, with chicks being found up to 200 meters away from their nest. These dispersal distances are comparable to observations of chick dispersal distances in North America and Europe (Arroyo & Bretagnolle, 1999; Clark, 1975). Chicks begin dispersing at around 12 days old and are not capable of flight until they are at minimum 28 days old. During this dispersal period, chicks are still dependent on their parents to feed them and cannot fly. The inability of chicks to flush when disturbed is especially concerning; adult Pueo will flush when approached by humans or when habitat is disturbed (i.e. grass mowing, heavy machinery use) and thus escape the area and alert observers of their presence, while chicks cannot. Pueo nests are also sensitive to disturbance at the incubation stage, and repeated disturbance in the area surrounding the nest may cause the Pueo to abandon their nest.

Temporal buffer

If a Pueo nest with eggs or chicks is discovered, a two-month temporal buffer, starting from the estimated nest initiation date, should be observed. If Pueo breeding behaviors are observed over repeat surveys of an area, then a conservative approach would be to observe a three-month temporal buffer of the area. We found that the time that the first egg is laid to the time that the first chick fledges takes approximately 47 to 56 days; this timing is comparable to the observations of the timing of Pueo nests in North America and Europe (Wiggins et al., 2020). We also observed that breeding behaviors (i.e. courtship displays, vocalizations, etc.) associated with each nest were observed in the nesting area up to three weeks before the first egg was laid. In order to be effective, temporal buffers should encompass the entire span of nesting activities, beginning with the presence of adult birds in the area displaying breeding behaviors until nesting is complete (Fyfe & Olendorff, 1976; Richardson & Miller, 1997). The total span of nesting activities for Pueo amounts to approximately 77 days or approximately 2.5 months. However, Pueo breeding behaviors are often difficult to observe without repeat surveys of an area, and all the incidental observations of Pueo breeding collated in this study were of nests that already had eggs or chicks.

LAND MANAGER-LEVEL RECOMMENDATIONS

Overview

Site-specific Pueo management actions should follow official Hawai'i DLNR and DOFAW guidelines, but may vary depending on the specific region (i.e. habitat type), physical characteristics of each site, and the potentially disturbing activities that may occur at the site. The following recommendations are general enough to be tailored to site-specific situations. Management recommendations are listed below in brief, with further contextualization and detail in the text that follows.

- I. Minimize habitat alterations and disturbance during Pueo breeding season. Before any potentially disturbing activity, especially ground-based disturbance, conduct surveys during crepuscular hours and walk line transects through the area to detect any active Pueo nests.
- II. If a Pueo nest is discovered, minimize time spent at the nest and establish a minimum buffer distance of 200 meters from the nest until chicks are capable of flight, approximately 2 months after nest is discovered.
- III. Reduce anthropogenic threats: use non-toxic methods of pest control and lower traffic speed limits.
- IV. Remove and exclude non-native mammals such as mongoose, cats, dogs, and ungulates from the nesting area.

I. Minimize habitat alterations and disturbance during Pueo breeding season

Actions such as vegetation mowing, clearing, construction, or harvesting in agricultural areas alters important Pueo nesting habitat and directly threatens Pueo adults and nests through crushing by heavy machinery and trampling by personnel walking through the area. Prolonged, intensive human activity (i.e. mowing grass, constructing structures) can also cause Pueo to abandon nests. Importantly, grassland nests are often in tall and dense vegetation that is difficult to see, even when standing as close as a meter to the nest. If habitat altering actions must be conducted during the Pueo breeding season, the target areas should be surveyed for Pueo nests prior to the start of the activity.

Initial surveys should check for Pueo activity in the general area, which includes point counts and targeted searches for other signs of Pueo activity such as looking for pellets. Because adults may be sitting on nests and are not visible, surveys should take place during the time when Pueo are most active (i.e. when they make a prey delivery to the nest or take an incubation break where they may perch elsewhere for a small period of time), which occurs between dawn and sunrise and between sunset and dusk. Observing either of these behaviors can confirm nesting in the area without having to access the nest directly and create additional disturbance towards the Pueo. Surveys should take place from a favorable vantage point and last for at least 90 minutes (Larson & Holt, 2016). Surveys should begin at least a week before the habitat altering activity takes place; conduct as many surveys as possible within that time frame in order to maximize the probability of detecting Pueo breeding behaviors.

If Pueo display defensive behaviors towards an observer, the observer should try to leave the area immediately to minimize disturbance. In a few instances, adult Pueo would emerge from areas other than the nest, such as a nearby perch, and begin displaying defensive behaviors such as swooping, beak snapping, and other vocalizations in response to observers entering a nesting area (Wiggins et al., 2020). Defensive behaviors towards observers strongly suggests the presence of a nest nearby and thus can also be used to confirm breeding activity in the area. These behaviors were also observed when checking known nests or searching for dispersed chicks in a nesting area.

If breeding behaviors are observed, a conservative approach would be to avoid any activities in the area until Pueo are no longer observed using the area or until 2.5 months from the first day that breeding behaviors are observed. If the habitat altering activity cannot be delayed, an exact nest location will be necessary to obtain, and a buffer established around the nest that activities cannot be conducted in until the nest is no longer active. Transect searches should be used to flush the incubating Pueo off the nest and thus discern the exact location of the nest. This method is described in depth in Chapter 2 (See Chapter 2 Methods: Nest Discovery), but essentially entails multiple observers spaced approximately 1 meter apart walking through an area of interest to search for a nest. During nest searching I found that incubating Pueo varied greatly in their flight initiation distance when approached. Some Pueo flushed when observers were roughly 10 meters away while others did not flush until observers were less than a meter

away. Thus, thoroughly searching through the vegetation and doing multiple sweeps may be necessary to flush the Pueo off its nest (Larson & Holt, 2016). The section below (“If a Pueo nest is discovered...”) details the next steps to take after discovery of a Pueo nest.

This study documented Pueo nests in grasslands yet failed to detect Pueo nests in agricultural areas. Nonetheless, studies of Short-eared Owls elsewhere have described breeding in croplands, cattle grazed fields, and other intensively managed grassland-type systems (Arroyo & Bretagnolle, 1999; Clark, 1975; Fondell & Ball, 2004; Herkert et al., 1999; Sviridova et al., 2020). Therefore, particular care should be taken to survey for Pueo and search for nests in both agricultural areas and managed grasslands.

II. If a Pueo nest is discovered, minimize time spent at the nest and establish a minimum buffer distance of 200 meters from the nest until chicks are capable of flight

Upon discovery of a nest, observers should take note of the location and quickly leave to minimize disturbance and allow the parent Pueo to return to the nest as soon as possible. To avoid attraction of predators to discovered nests, observers should check if vegetation surrounding the nest was moved or trampled and re-cover the vegetation so that no obvious gap or opening to the nest remains. We observed that nests were more likely to be abandoned during the early egg laying and incubation stages compared to once chicks had hatched and were older. (i.e. at least 5 days old). If a nest is discovered at the incubation stage, extra care should be taken to leave the area as soon as possible.

We found that Pueo chicks dispersed up to approximately 200 meters from the nest, beginning at about 12 days old, which is comparable to observations of chick dispersal in North America and Europe (Arroyo & Bretagnolle, 1999; Clark, 1975). At this dispersal stage, chicks are still dependent on their parents to feed them and cannot fly. Thus, a buffer of at least 200 meters should be maintained around the nest until chicks are capable of flight. We found that the time that the first egg is laid to the time that the first chick fledges takes approximately 47 to 56 days, so a temporal buffer of approximately 2 months from the estimated nest initiation date should be observed before resuming ground-disturbance activities in the nest area.

III. Reduce anthropogenic threats: eliminate usage of rodenticides and lower speed limits

Eliminating use of toxicants, such as replacing anticoagulant rodenticides with non-toxic Goodnature A24 rodent traps, in Pueo breeding areas will be crucial for nest survival. Across all

stages of their life cycle Pueo are vulnerable to secondary poisoning from pesticides such as rat poison (Nakayama et al., 2019; Siers et al., 2019). Siers (2019) found that 47% of Hawaiian raptor carcasses analyzed contained secondary-generation anticoagulant rodenticides. We found that both insects and rodents, common targets of toxicants, were regularly occurring prey items for breeding Pueo, with rodents representing a significant proportion of Pueo diet.

Additionally, speed limits should be reduced on high traffic roads in areas where Pueo are nesting when possible and erecting signage that alerts drivers to be aware of Pueo in and around the road. At our focal study sites, we regularly observed both adult and recently fledged juvenile Pueo hunting on and alongside roads; likely because the reduced vegetation cover along roads may create optimal hunting conditions. We found one dead adult Pueo off the side of the road, presumably killed by a vehicle collision. Vehicle collisions also pose a threat to Pueo chicks as multiple nests were found approximately 100 meters from roads. Although we did not observe any instances of this occurring, dispersing chicks could be hit by passing vehicles.

III. Remove and exclude non-native mammals such as mongoose, cats, dogs, and ungulates from the nesting area

Thirty percent of the nests we monitored failed due to predation – one likely due to feral dog predation on the adult and chicks, and another due to egg predation likely from a mongoose or rat. Other mammals such as feral cats and wild boars were often observed at my study sites in the vicinity of Pueo nesting areas, and in one instance we observed a Pueo chasing a cat away from its nest. Predator traps were set once Pueo nests were discovered, but given that the longer a nest is established the more likely it is to be discovered, it is unknown how many nests may have been initiated but abandoned or otherwise failed early on due to the presence of a predator. If Pueo appear to be repeatedly breeding at a given site, ongoing predator removal should be considered in order to minimize predation probability. Some incidental observations of Pueo nesting on Hawai'i Island and Kaua'i were located in areas that had predator-exclusion fencing installed for the purposes of protecting other endangered ground-nesting birds (i.e. Nēnē and seabirds), further supporting that removing mammalian predators from an area increases Pueo nest survival.

APPENDIX A: STATE-WIDE INCIDENTAL PUEO BREEDING OBSERVATION DATA COLLECTION FORMS

<i>Pueo Project Breeding/Nest Observation Data Sheet</i>				General habitat type (circle): <ul style="list-style-type: none"> • Grassland • Savanna • Forest • Urban/developed • Agricultural • Wetland/Marsh • Beach/Coast 		Please email completed form and photos to Olivia Wang at owang@hawaii.edu
Observer Name:		Date:		Time:		
Latitude: (please use decimal degrees for locations)		Longitude: (please use decimal degrees for locations)				

ADULT PUEO BEHAVIOR	Number of pueo	Circle breeding behaviors observed	Behavior notes
		<ul style="list-style-type: none"> • Courtship display / wing clap • Nest incubation • Prey delivery to nest • Other (describe in notes) 	

NEST CONTENTS/CHICKS	Number of eggs	Egg description (shape: spherical (golf-ball like) or more oblong (chicken egg))	Number of chicks	Chick description (color: white or tan? feather texture: downy and soft or larger, pin-like feathers also present?)	General notes	PHOTOS: 1. Photo of the eggs in nest (do NOT touch eggs) 2. Photo of each individual chick (do NOT touch chicks)

NEST SITE (0.5 radius area from the center of the nest)	Height of tallest vegetation (cm)	Most abundant plant species (rank 1-3; 1 being the most abundant)	Distance to nearest tree (m)	General Habitat Description	PHOTOS: 1. One photo of an aerial view of the nest from 1m high 2. One photo from each of the four cardinal directions from 1m above the ground, while standing 1m away

Figure A.1. Paper version of the datasheet that will be sent to federal, state, non-profit, and private partners.

The online version is accessible at <https://airtable.com/shriqVYZY3z7eDBBr>

APPENDIX B: CLASSIFICATION TREES FOR DETERMINING SPECIES OF AVIAN PREY

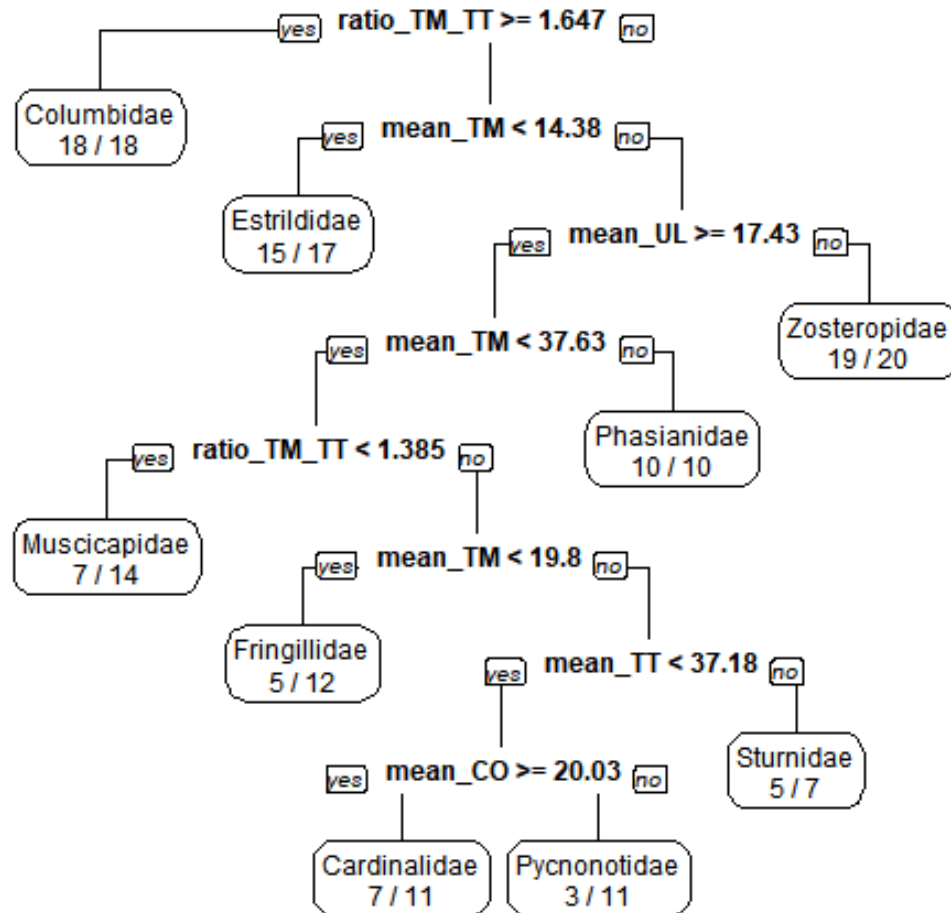


Figure B.1. Classification tree categorizing likely avian prey families based on select bone measurements. Numbers underneath the avian family name at each node are the number of correct classifications / the number of total observations within the node.

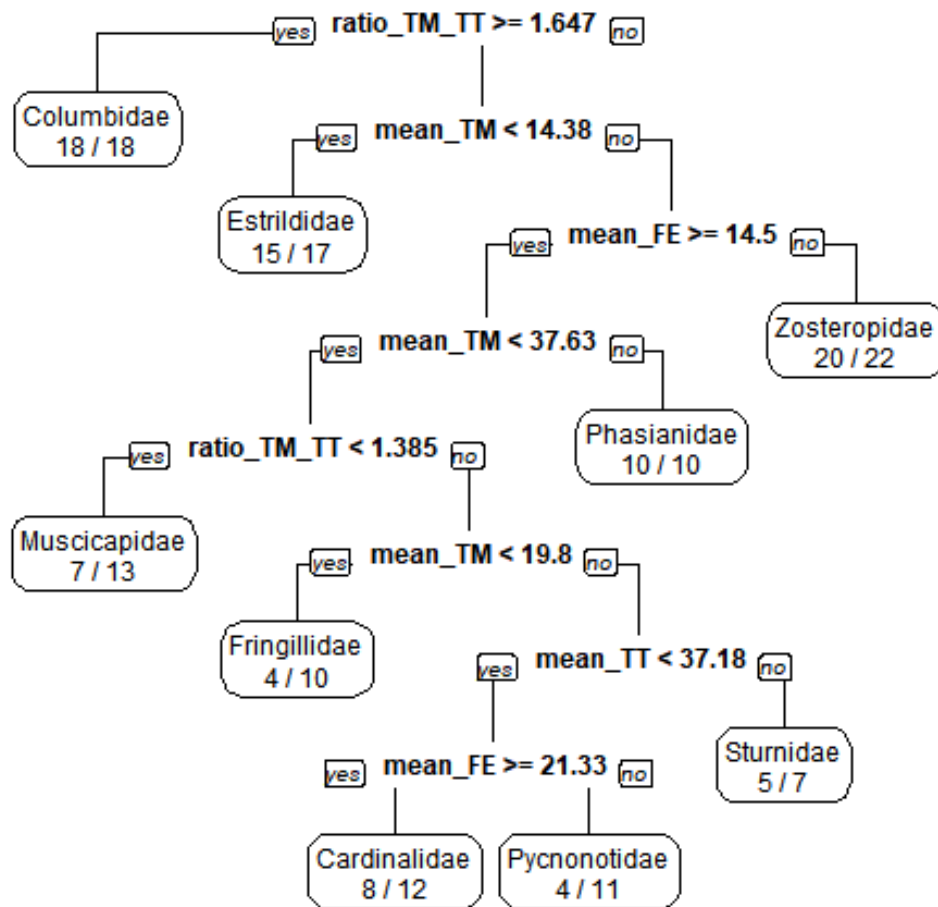


Figure B.2. Classification tree categorizing likely avian prey families based only on leg bone measurements. Numbers underneath the avian family name at each node are the number of correct classifications / the number of total observations within the node.

APPENDIX C: PUEO NESTLING MORPHOMETRICS AND PHOTOS

Table C.1. Pueo nestling morphometrics. Age estimates were based on both morphometrics by comparing with other studies of Short-eared Owl nestling morphometrics (Arroyo et al. 2000, Holt et al. 1992) and based on the age of nest through repeated nest checks.

Nest ID	Chick ID	Estimated Age (days)	Weight (g)	Metatarsus Length (mm)	Culmen Length (mm)	Unflattened Wing Chord (mm)	Tail Length (mm)
03	03_01	15	362	47.5	26.7	NA	NA
07	07_01	15	307	46	26.6	148	NA
09	09_01	12	245	37.1	NA	85	15
09	09_02	11	245	36.5	NA	79	<10
09	09_03	10	214	30.82	NA	68	<10
10	10_01	16	308	40.98	14.7	105	20
10	10_02	15	253	36.07	13.45	78	<10
10	10_03	13	178	30.53	12.34	45	0
10	10_04	11	173	29.05	11.89	52	0

Photos for some chicks documenting plumage and primary feather development can be found at https://github.com/oliviawang115/Pueo_Breeding_Ecology_Photos?raw=true

APPENDIX D: HAWAI'I WILDLIFE CENTER JUVENILE PUEO PATIENT DATA

Table D.1. Juvenile Pueo patient records from the Hawai'i Wildlife Center. Island and general location where the Pueo was found are reported along with intake date and the status of the patient.

Island	Discovery Location	Intake Date	Status
O'ahu	NA	2014-10-21	Released
Hawai'i	Parker Ranch, Old Saddle Rd	2014-08-26	Released
Maui	Kihei	2018-07-05	Released
Hawai'i	Waimea HS	2019-05-28	Died
Hawai'i	Hakalau Forest NWR	2021-7-06	Released*
Lana'i	Manele Rd	2020-07-28	Released
Hawai'i	Hawi	2019-06-04	Died

*Discovery of this juvenile Pueo was also reported to our online data collection form and is included in the state-wide incidental observation summary.

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