The Pueo Project

Final Report April 2017 – March 2018

Population size, distribution and habitat use
of the Hawaiian Short-eared Owl
(*Asio flammeus sandwichensis*) on O'ahu

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Abstract

The Pueo (*Asio flammeus sandwichensis*), once common across the Hawaiian Islands, is currently state-listed as Endangered on O'ahu. The Pueo provides important ecosystem services by controlling population sizes of introduced rodents and preying on other introduced and native species, including birds and invertebrates. As the only native raptor that breeds on the main Hawaiian Islands, the Pueo plays an important role in top-down ecological regulation and is also valued by native Hawaiians and other Hawai'i residents. Although the Pueo has been recorded in a variety of vegetation types in the Hawaiian archipelago, key habitat selection variables are still unknown. In this study, we optimized a survey methodology to improve population estimates and define vegetation types important to population stability and we compared distribution among vegetation types and overall population densities of Pueo with other Short-eared Owl populations across the globe. Three different approaches were used: (a) standardized surveys by trained personnel; (b) citizen science reports of Pueo sightings submitted to an online portal www.pueoproject.com; and (c) citizen science reports to eBird www.ebird.org, a publicly available, well-established, and curated international online portal for submitting bird sighting reports. We collected more than 50 Pueo sightings in one year through the Pueo project online portal, while the eBird portal collected 43 reports in three decades. Information gathered through the citizen science portal was highly valuable for obtaining phenology and breeding event observations (nests, owlet locations, display flights), however, data collected in this manner were biased due to the lack of standard distribution of the observers, which hampered their usefulness for running distribution models or other population analyses. During the standardized surveys Pueo were observed on agricultural lands, wetlands, short grasslands and open native vegetation. Pueo were detected, on average, 23 minutes before twilight. Estimated densities ranged from 0 to 3.3 Pueo per 100 ha across vegetation types, with most detections occurring in open vegetation types, such as agricultural lands, grasslands, and wetlands. Based on observed densities, the population of Pueo inhabiting O'ahu was estimated at 807 individuals, with 95% confidence intervals of 8 to 2199. Densities obtained from standardized, randomized surveys are aligned with those studies targeting known Short-eared Owl populations with a high rate of occupancy, which does not seem to be the situation on O'ahu, especially if we consider the high level of threats that this species faces in Hawai'i and the observations of declining populations that local inhabitants have reported in person or submitted to the Pueo Project portal. Densities on O'ahu are probably similar to the ones reported in non-targeted, randomized and standardized studies, where owls occupy territories with high prey availability, but leave unoccupied low-prey-density territories. Based on this information, we consider the most likely population number to be on the lower end of the estimated range of possibilities.

Acknowledgments

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We wish to express our appreciation to the land owners that provided access to their properties, as well as to the citizen scientists that submitted their reports of Pueo sightings to our website.

We would like to thank the photographers that allowed us using their photographs on the report and website. Darcy Fiero and Tom Kualii for the Pueo photographs and Stefan Hage and Ron Dudley for the continental Short-eared Owls photographs.

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Photo: Darcy Fiero

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Introduction

The Hawaiian Short-eared Owl or Pueo (*Asio flammeus sandwichensis*), endemic to the Hawaiian Islands, is a subspecies of the Short-eared Owl (Strigidae; Berger 1981). The species is thought to have colonized the Hawaiian Islands sometime after the arrival of Polynesians. The Pueo provides important ecosystem services by controlling population sizes of introduced rodents and preying on other introduced and native species, including birds and invertebrates (Work and Hale 1996). As the only native raptor that breeds on all the main Hawaiian Islands, the Pueo plays an important role in top-down ecological regulation. The species is also valued by Hawai'i residents and native Hawaiians as an 'aumakua, or incarnation of an ancestor.

Once common across the islands, the Pueo is currently state-listed as Endangered on O'ahu (DLNR 2005). Short-eared Owl declines have similarly been observed in Europe and North America (Booms et al. 2014). Despite their cultural and ecological importance, relatively little is known about the biology of the Pueo in the Hawaiian Islands, with most information originating from research on North American Short-eared Owls (Booms et al. 2014, Morales and Traba 2016).

In North America, two characteristics that make this owl particularly vulnerable to disturbance are its reliance on intact grasslands and its preference for a diet of small mammals, a food source that tends to fluctuate (Wiggins et al. 2006). When environmental conditions result in a high density of prey items, Short-eared Owls breed at high densities (Pitelka et al. 1955). Conversely, in years when prey items are scarce, Short-eared Owls either do not breed or move to other areas (Clark 1975, Korpimäki and Norrdahl 1991, Johnson et al. 2013). On the North American continent, Short-eared Owls also appear to have little or no site fidelity and vary their movements between seasons and years, leading to challenges in monitoring population size (Booms et al. 2014). However, adults may roost communally outside of the breeding season (Keyes et al. 2016), allowing for one means of assessing numbers.

The relatively recent establishment of Short-eared Owls in Hawai'i may have been linked to the introduction of rats (*Rattus exulans*) by Polynesians (which colonized the Hawaiian Island approximately around 800 CE), as suggested by fossil evidence (Olson and James 1982). However, it is possible that flightless rails and other birds provided a sufficient prey base prior to rodent introductions. Unlike most owls, Pueo are active during the day (i.e., diurnal) and are commonly seen hovering or soaring over open areas (Berger 1981, Tomich 1971, Mostello 1996). Pueo tend to be more active during crepuscular periods on O'ahu, likely associated with prey availability (Mostello 1996). Like Short-eared Owls in continental environments, at least one study suggests Pueo primarily consume small mammals (Tomich 1971). However, other studies show that Pueo are not solely dependent on small mammals, but also include birds and invertebrates in their diet, sometimes at high rates (Mostello 1996).

Compared to other widely distributed raptors, documentation is limited for basic life history characteristics of Short-eared Owls. The knowledge gap is especially noticeable on their breeding ecology, perhaps due to the difficulty in observing their well-concealed nests and their inconspicuous behavior from egg laying through fledging of young (Clark 1975, Wiggins et al. 2006, Booms et al. 2014). Most of the existing knowledge of breeding behavior comes from studies in North America. Males perform aerial displays, known as *sky dancing*, to prospective females (Wiggins et al. 2006). Nests are constructed by females and are comprised of simple scrapes in the ground lined with grasses and feather down. Females lay eggs on the ground and prefer dry locations within open habitats such as

grasslands, marshlands and dunes proximate to an adequate food base (Clark 1975, Mikkola 1983). Females perform all incubating and brooding (Holt and Leasure 1993), while males feed females and defend the nests (Holt and Leasure 1993). Chicks hatch asynchronously and are fed by the female with food delivered by the male (Holt and Leasure 1993). Young may fledge from the nest on foot before they are able to fly and depend on their parents for approximately two months (Holt and Leasure 1993).

Continental nest sites tend to be surrounded by taller vegetation (Keyes et al. 2016) and are associated with patches of grass (Keyes et al. 2016). Continental Short-eared Owls are also known to prefer territories with wooden fence posts, rather than metal fence posts (Martinez et al. 1998, Keyes et al. 2016). Breeding success of continental Short-eared Owls ranges from 2.1 to 3.2 fledged chicks per active nest (Clark 1975, Holt 1992, Keyes et al. 2016), with a high occurrence of juvenile mortality due to avian and mammalian predators, disease, as well as anthropogenic causes such as heavy machinery, car strikes, or barbed-wire fences (Lockie 1955, Clark 1975, Bluhm and Ward 1979, Holt 1992, Work and Hale 1996, Wiggins et al. 2006, Weir 2008, Keyes et al. 2016).

Today, the Pueo is not the only owl species present in the Hawaiian archipelago. The Barn Owl (*Tyto alba*) was introduced to Hawai'i in 1958 to control rodents. A total of 15 birds were imported from California by the state Department of Agriculture and released at Kukuihaele on Hawai'i Island. Over the next five years, an additional 71 Barn Owls were introduced on the islands of Kaua'i, O'ahu, and Moloka'i. Currently, the Barn Owl is found throughout the main Hawaiian Islands, including offshore islets such as Lehua near Kaua'i (Tomich 1962). Barn Owls likely compete with the native Pueo for introduced rats and mice and could potentially be limiting their population size (Mostello 1996).

In this study we: (1) designed and tested an effective survey protocol for Pueo; (2) defined habitats important to population stability for this species and compared distribution among vegetation types; and (3) used standardized survey data to estimate the population size of Pueo on Oʻahu, and compared estimates based on density with studies of other Short-eared Owl populations across the globe. To define habitats important to the population stability of Pueo, three different approaches were used: (a) standardized surveys by trained personnel; (b) citizen science reports of Pueo sightings submitted to an online portal www.pueoproject.com; and (c) citizen science reports to eBird www.ebird.org, a publicly available, well-established, and curated international online portal for submitting bird sighting reports.

Materials and Methods

Study area and site selection

The island of O'ahu, the third largest island in the Hawaiian archipelago, is home to roughly two-thirds of the human population of the state of Hawai'i. Including small associated islands, such as Ford Island and the islands off the eastern (windward) coast, O'ahu is 597 square miles (1,545 km^2), making it the 20th largest island in the United States (State of Hawai'i 2004). The island is composed of two separate shield volcanoes: the Waianae and Ko'olau Ranges, with a broad "valley" or saddle (the central O'ahu Plain) between them. The highest point is Mount Ka'ala in the Waianae Range, rising to 4,003 feet (1,220 m) above sea level (State of Hawai'i 2004).

Survey locations were determined using a random stratified design across six vegetation types: wetlands, agricultural lands, grasslands, shrubland, alien forest and native vegetation (Figure 1). Urban and developed areas were excluded from study site selection, as they are not known to be used by continental species (Booms et al. 2014).

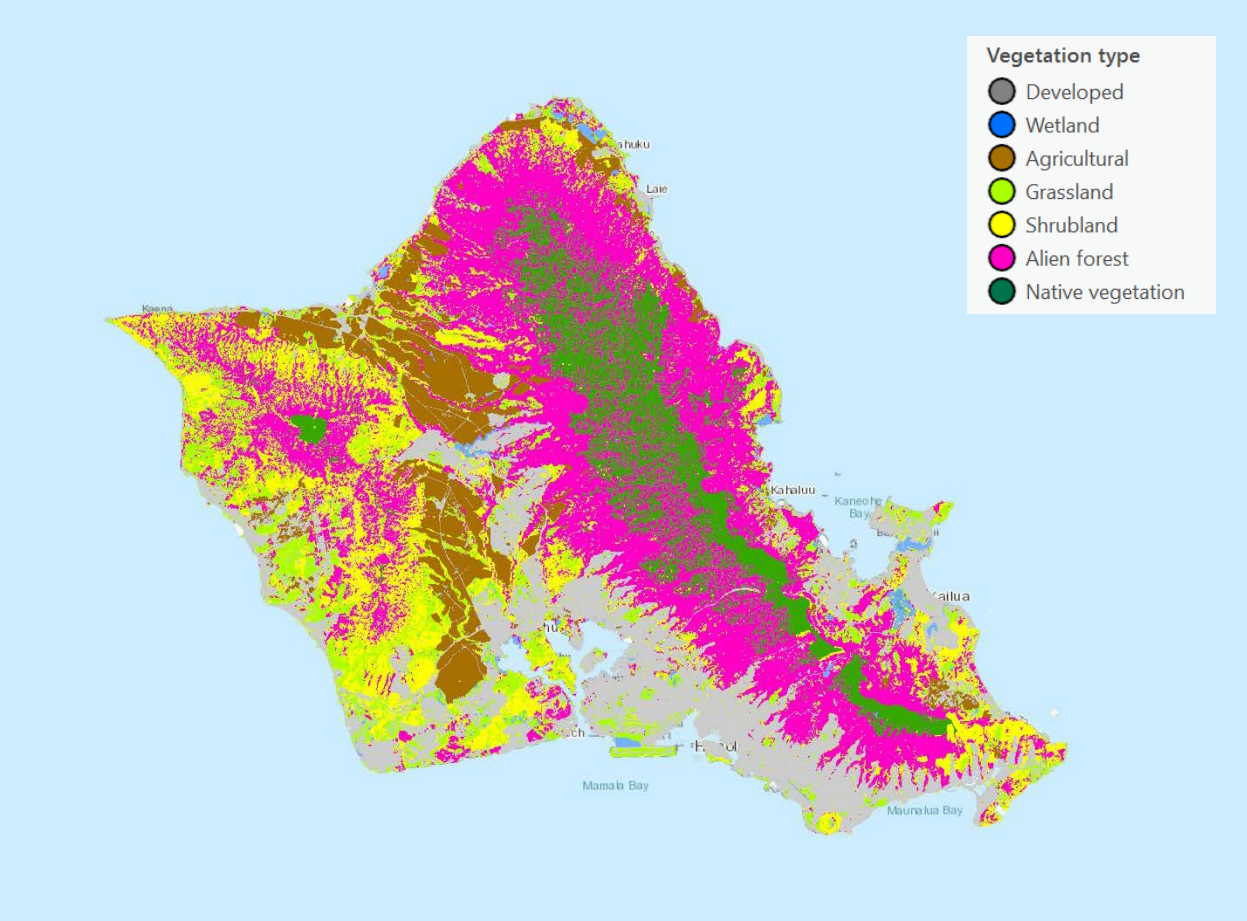

Fig. 1. In this study, Pueo distribution among six vegetation types was evaluated on the island of O'ahu.

Vegetation classification followed the GIS vegetation layers provided by the State of Hawai'i's Office of Planning http://planning.hawaii.gov/gis/download-gis-data/, and sub-vegetation information was noted according to the following classification:

(1) **Developed,** land that is predominantly built-up or developed and vegetation associated with these land covers. This includes road surfaces, buildings and paved surfaces, and farmsteads; (2) **Wetlands,** land with a water table near/at/above soil surface for enough time to promote wetland or aquatic processes (semi-permanent or permanent wetland vegetation, including swamps, sloughs, marshes etc.); (3) **Agricultural lands,** annually cultivated cropland; lands that generally change from bare cover to green/vegetated cover during the growing season, (4) **Grasslands,** may include a few shrubs, but there should not be many and should not be regular on the landscape. Grasslands were subdivided in (a) short grassland; (b) grazed grassland, land used to pasture livestock (cattle, sheep and horses); (c) mowed lawn; (d) grasslands/fallow, formerly grazed grassland, crop or hay, but has not been used for such uses in at least the previous growing season, and which has not yet reached the stage of shrubland; (e) tall grassland: california grass or grass >75 cm tall; (5) **Shrubland,** Predominantly woody vegetation of relatively low height (generally 2 m). Also includes grass or grassland wetlands with woody vegetation and regenerating forest; (6) **Alien forest,** predominantly forested or treed areas, including at least 10-25% crown closure of coniferous, broadleaf and mixed wood; (7) **Native vegetation,** predominantly forested or treed areas, including at least 10-25% crown closure of coniferous, broadleaf and mixed wood.

Standardized owl surveys

Thirty-five survey sites were randomly selected from the six vegetation types using ArcGIS Pro. Five sites were selected from each vegetation type, except for grassland, in which ten sites were selected, as this vegetation type is the main habitat for the species in its worldwide distribution (Figure 2). Grassland vegetation types were subdivided into mowed (140 ha), short >30 cm (123 ha), and long >75 cm (70 ha), based on visual observations during surveys. Ground-truthing of vegetation type was carried out at the time of surveys by visually categorizing the proportion of each vegetation type within a study area.

Surveys were carried out from vantage viewpoints within 500 m of the randomly selected sites. Areas observed from viewpoints did not overlap at any point. Minor variation in distance between vantage viewpoints was due to terrain and roadside safety concerns. Each point was documented using a hand-held GPS Garmin GPSMAP® 64st. Vantage viewpoints had at least a 180° field of view of the surrounding area, which extended at least 300 m from the viewpoint.

Surveys were carried out in the late evening, between 75 and 60 minutes before sunset, and finished at civil twilight, around 30 minutes after sunset (defined as when the sun is six degrees below the horizon www.timeanddate.com). Observations of both Short-eared Owls and Barn Owls were recorded during the survey period (see Appendix 2 for distinguishing characteristics between these two species). Surveys were repeated three times at each site to increase the likelihood of detecting Pueo, and were spaced, when possible, at least three weeks apart.

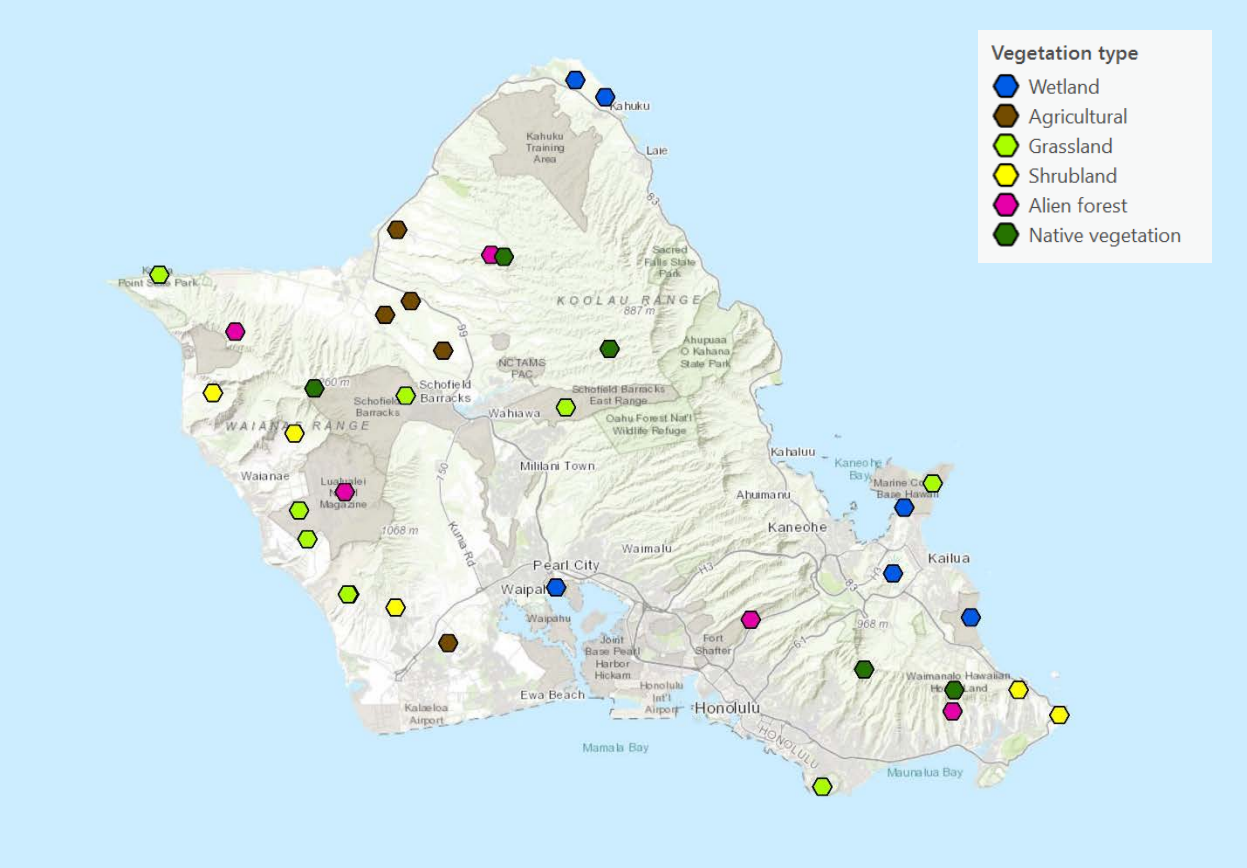

Figure 2. Thirty-five survey sites were randomly selected from the six vegetation types using ArcGIS Pro.

Citizen Science and web reporting

Citizen science data was gathered both through the Pueo Project online portal (www.pueoproject.com), a website created for this project in 2017, and eBird (www.ebird.org), a globally recognized reporting system for bird sightings. Pueo sightings were reported to the Pueo Project website by filling in an online form or by providing localization information into an embedded ESRI GIS web app. Sightings were gathered from March 15, 2017 to March 15, 2018. All available eBird data on Pueo sightings in Hawai'i were downloaded on March 15, 2018. By overlaying a GIS layer of data points with the vegetation layer, we identified the vegetation type where each observation took place.

Literature comparison

Short-eared Owl population metrics were compared between studies, following a literature search of Google Scholar and OneSearch Mānoa to obtain all studies globally available of Short-eared Owls. From these websites, 24 published papers or reports were identified that contained population counts, estimates, densities or home ranges for Short-eared Owl populations across the globe.

Analyses

***Population densities* on O'ahu.** Densities were calculated for each vegetation type by dividing the sum of the maximum number of Pueo observed in a single survey for each site, by the total number of hectares surveyed for that vegetation type.

***Population estimates* on O'ahu.** The Pueo population size was estimated from the standardized survey data. The population size on O'ahu was estimated by multiplying the density of pueo per vegetation type by the total number of hectares of that vegetation type available on Oʻahu. Population estimates and densities were calculated with Microsoft Excel. Total hectares of each vegetation type on O'ahu were calculated with ArcGIS Pro 2.1.1., based on the GIS vegetation layers provided by the State of Hawai'i's Office of Planning http://planning.hawaii.gov/gis/download-gis-data/. Confidence limits were obtained by bootstrapping in IBM SPSS Statistics v.25. The confidence limits were derived by adding the 999 unsorted bootstrapped estimates for the populations, sorting them into numerical order and taking the 25th and 975th values. The final O'ahu population estimate was reached by summing the total estimated number of Pueo in each vegetation type.

Global comparison of densities of Short-eared Owls. Densities of Short-eared Owls were compared between studies that utilized targeted (studying known populations or breeding sites for the species) and non-targeted (which surveyed the whole range of possible habitats and included areas not occupied by owls) approaches with an independent samples *t*-test in IBM SPSS Statistics v.25.

Results

Standardized surveys: Pueo distribution among vegetation types on O'ahu

We carried out 105 surveys at 35 sites, across a total of 1030 hectares (0.66% of the total area of O'ahu). The total time spent surveying all vegetation types was 158 hours. Survey effort was approximately equal across vegetation types (100–172 ha per vegetation type), except for grassland, the preferred habitat for Short-eared Owls in North America (333 ha; see Table 1).

Vegetation type	Hectares on O'ahu	Hectares surveyed	Pueo Detected	Density (Pueo/100 hectare)	Estimated Pueo
Wetland area	1,540	145	1	0.7	11 (1-32)
Agricultural land	13,160	119	4	3.3	441 (4-1102)
Grassland	17,405	333	1	0.3	52 (1-157)
Shrubland	22,203	156	1	0.6	142 (1-427)
Alien forest	54,782	172	0	0.0	0
Native vegetation	16,116	100	1	1.0	161 (1-482)
Total	155,120	1030	8		807 (8-2199)

Table 1. Results of Pueo surveys on O'ahu in 2017. Numbers in brackets are the 95% confidence limits.

We detected Pueo at six different sites out of thirty-five, including one wetland site, two agricultural sites, one grassland site, one shrubland site, and one native vegetation site.

Population size and density. Densities were highest in agricultural lands (3.3 Pueo per 100 ha), followed by native vegetation (1.0), wetland areas (0.7) and shrublands (0.6). Grasslands (0.3) and alien forest (0.0) vegetation types had the lowest densities of detected Pueo (see figure 3). Pueo were observed during survey hours at mowed areas, and outside survey time at short grasslands, but never in sites classified as tall grasslands. Density estimates were not adjusted for detectability, as detection rates of Pueo among vegetation types have not been identified. Based on observed densities, the number of Pueo inhabiting O'ahu was estimated at between 8 and 2199 individuals, with a mean likely population size of 807 individuals (95% CI; Table 1).

Densities of Pueo were in the mid-range, compared to Short-eared Owl studies globally (Table 2). Studies in Europe targeting known breeding sites for the species report significantly higher densities (1.8 ± 1.81) than studies in North America which surveyed the whole range of possible habitats and included areas not occupied by owls (0.15 ± 0.27; $P = 0.049$, $t_{6.378}$=-2.427).

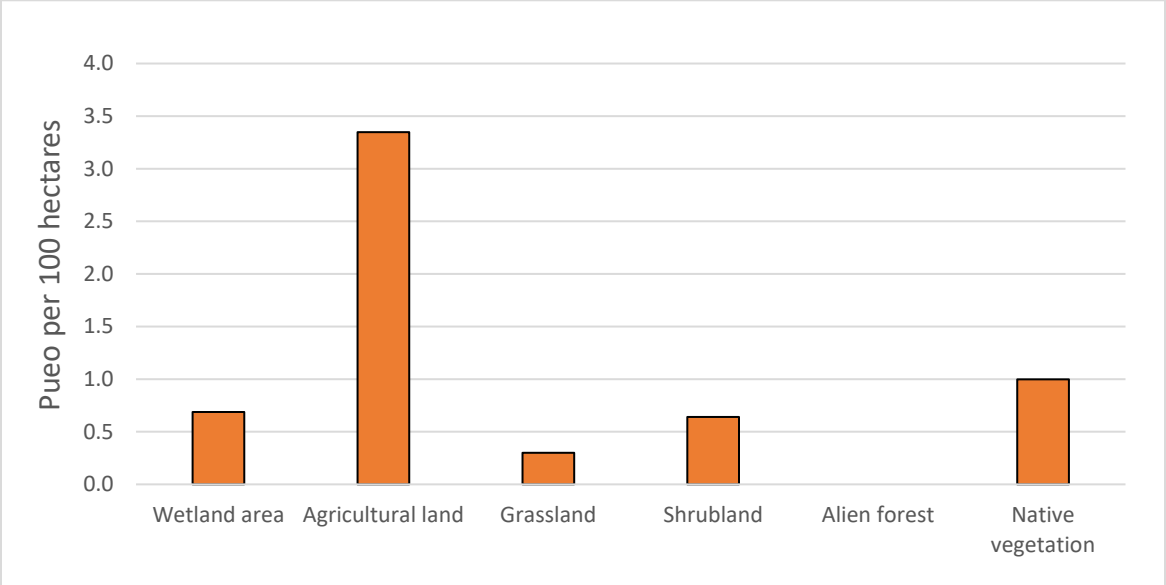

Figure 3. Pueo density per 100 hectares varied among vegetation types on O'ahu, with the highest densities observed on agricultural lands and in native forests.

Timing of first observation in relation to twilight. Surveys began approximately 90 minutes before twilight. During surveys where Pueo were sighted, they were first seen, on average, 23 minutes before twilight. Four of the eight Pueo sightings were first observed just before twilight, but during the other four surveys Pueo were observed up to 68 minutes before twilight. In comparison, Barn Owls were first detected an average of two minutes before twilight (N = 5, see Figure 4).

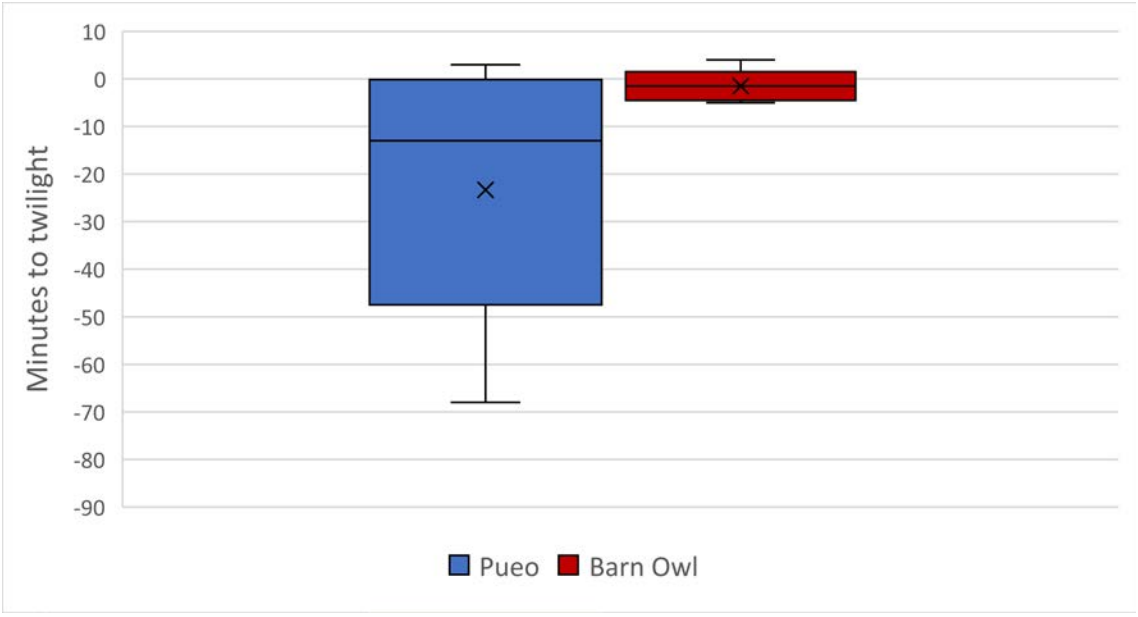

Figure 4. Time of first Pueo and Barn Owl observation during standardized surveys.

Habitat	Owls per 100 hectares	Population on O'ahu?	Study area (Km^2)	Location	Year	Reference
Grassland, shrubland, marshland and agriculture land	0.016 (0.009 - 0.027)	20 (12-34)	77,600	Utah, USA	2016	Miller et al. 2017
Grassland, shrubland, marshland and agriculture land	0.023 (0.015 - 0.035)	29 (19-44)	94,600	Idaho, USA	2016	Miller et al. 2017
Grassland, shrubland, marshland and agriculture land	0.041 (0.03 - 0.055)	52 (38-69)	62,800	Idaho, USA	2015	Miller et al. 2016
Shrubsteppe	0.043	54	1,604	Idaho, USA	1991-94	Lehman et al. 1988
Moorland	0.229	287	35	Wales	1971-84	Roberts & Bowman 1986
Farmland	0.479	600	17	Finland	1977-87	Korpimäki & Nordahl 1991
Moorland & plantation	0.599	751	70	Scotland	1985-2004	M. Ogilvie pers comm. Calladine et al. 2005
wetlands, agricultural lands, grasslands, shrubland, alien forest and native vegetation	**0.645 (0.006 – 1.756)**	**807 (8-2199)**	**1,550**	**O'ahu, HI, USA**	**2017**	**This study**
Young plantation	0.67 - 0.871	838 - 1090	15	Scotland	1934	Goddard 1935
Young plantation	1.759 - 3.194	2203 - 4000	100	Scotland	1976-78	Village 1987
Young plantation	3.299	4131	200	Scotland	1991	Shaw 1995
Young plantation	5	6260	14	Scotland	1954	Lockie 1955

Table 2. A comparison of all published densities for breeding Short-eared Owls globally. Studies in Europe targeting known breeding sites for the species report significantly higher densities (1.8 ± 1.81) than studies in North America which included surveys across the whole range of possible habitats and included areas not occupied by owls (0.15 ± 0.27; $P = 0.049$, $t_{6.378} = -2.427$)..

Foraging observations. Pueo were observed foraging in three vegetation types: grasslands, wetlands, and low-growth agricultural lands. More than 80 percent of the foraging habitat in these areas was in open vegetation type.

Nest observations. We gathered information from seven nests on three different islands: O'ahu (N = 4), Maui (N = 2) and Kauai (N = 1). Nest information was provided from other non Pueo research projects. Nests were found in spring (April through June) and autumn (November), and from sea-level up to 2000 meters of altitude. Vegetation types included wetlands, open grasslands and wet montane forests (uluhe fern, *Dicranopteris linearis,* understory with ‘ōhi‘a trees, *Metrosideros polymorpha,* as primary canopy cover).

Pueo Project citizen science

Fifty-five citizen science reports of Pueo sightings were gathered (see Figure 5), during a one year period (March 15, 2017 – March 15, 2018). The highest number of reports came from developed areas (22%), followed by alien forest (20%) and grasslands (20%), agricultural lands (16%), shrubland (11%). The lowest number of reports were from wetlands (7%) and native vegetation (4%; Figure 7).

Ten additional reports submitted as Pueo were identified as Barn Owls after further descriptions were elicited from the citizen scientists.

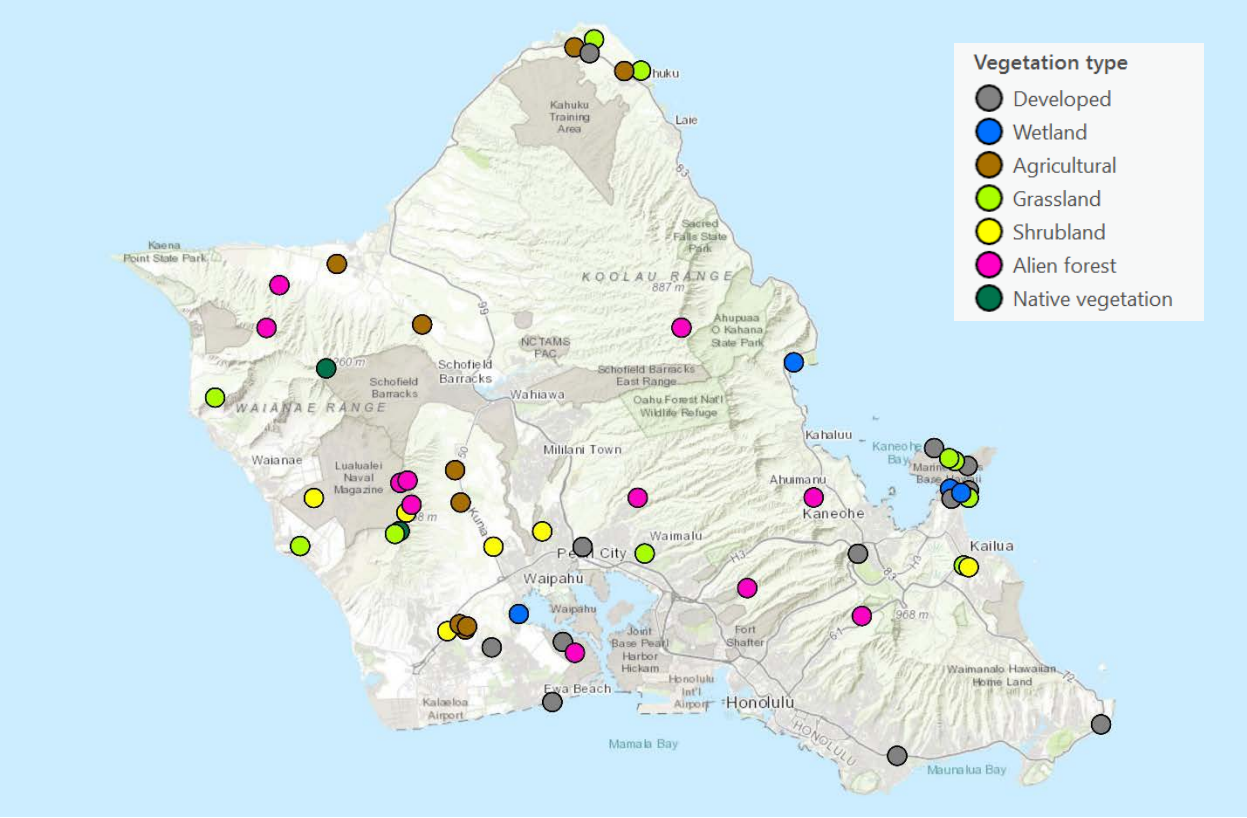

Figure 5. Pueo sightings (N = 55) reported to the Pueo Project online portal, by vegetation type.

eBird citizen science

From the eBird portal, 43 reports were obtained across 32 years (1986-2018) for O'ahu (Figure 6). The first recorded sighting was in 1986, with 50% of the sightings occurring from 2011-2015. Only four reports were from 2017 and 2018. Developed areas had the highest number of eBird Pueo reports (37%), followed by wetlands (26%), and shrubland (16%). The least number of sightings were in alien forest and native vegetation (7%), grasslands (5%) and agricultural lands (2%) (Figure 7).

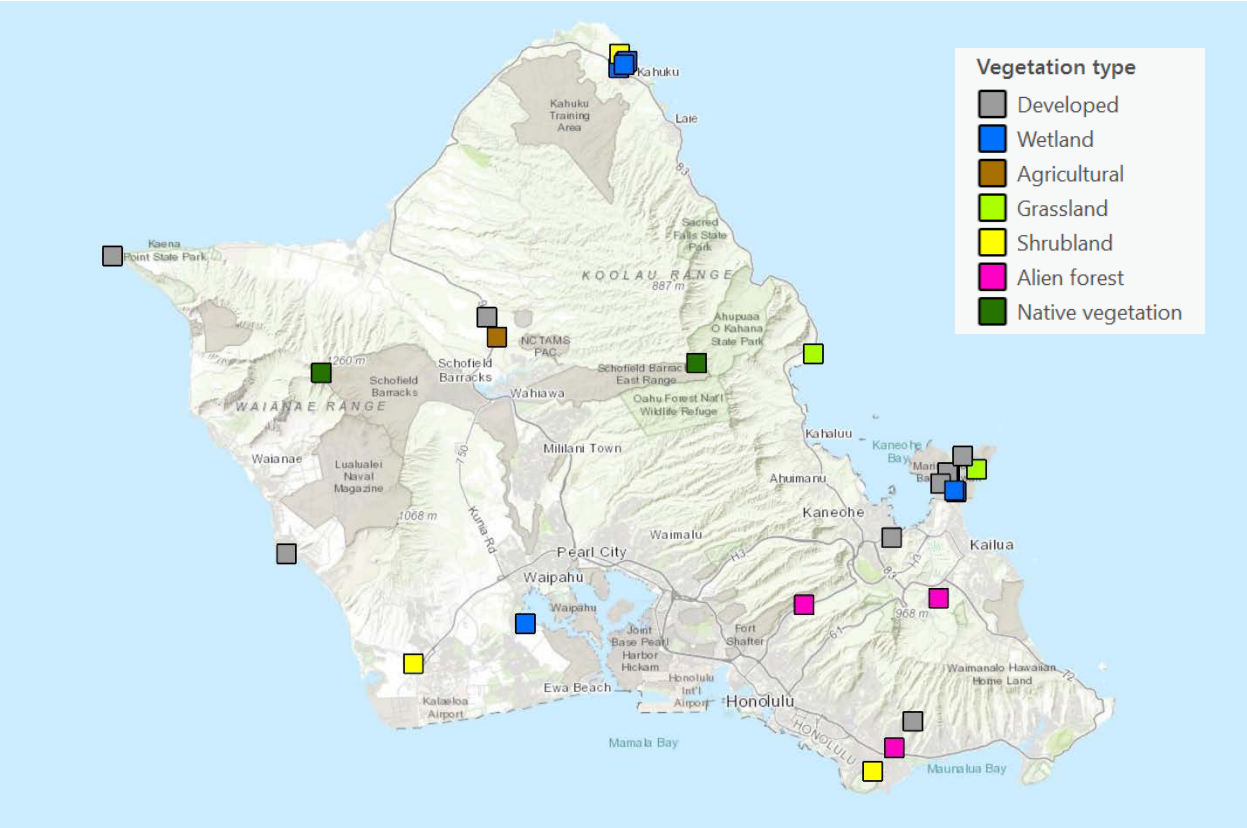

Fig 6. Pueo sightings (N=43) reported to the eBird online portal between 1986–2018, by vegetation type.

Comparison of data sources

The highest number of observations was in developed areas for the Pueo portal and eBird datasets, but in agricultural areas for standardized surveys (Figure 7). Conversely, vegetation types with the lowest number of observations were alien forest for the standardized surveys, native vegetation for Pueo portal, and agricultural lands for eBird data.

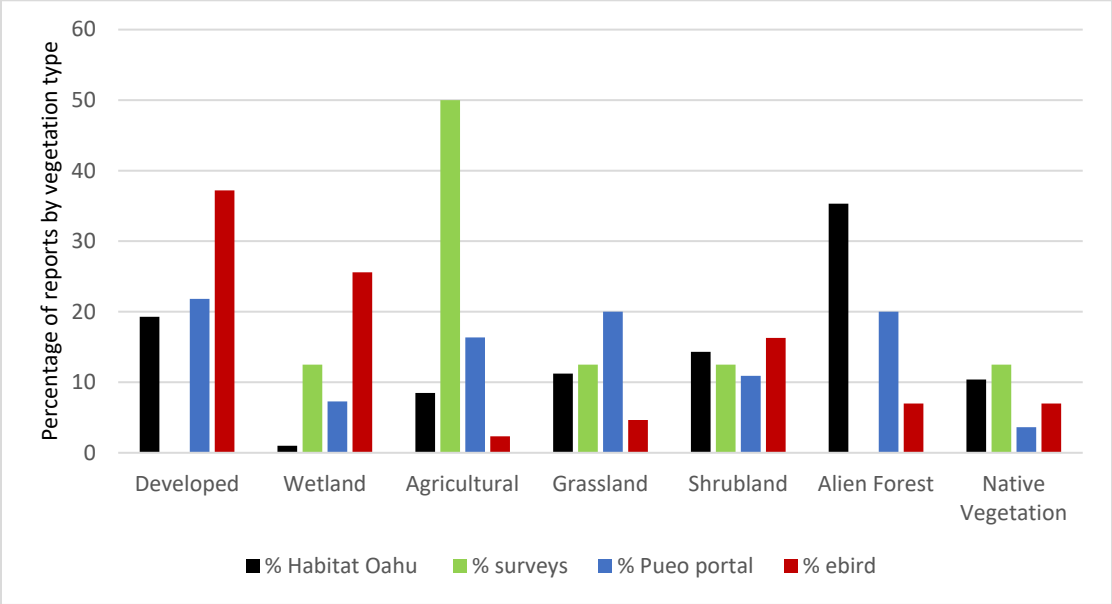

Figure 7. Comparison among Pueo records datasets, with percentages of reports by vegetation types.

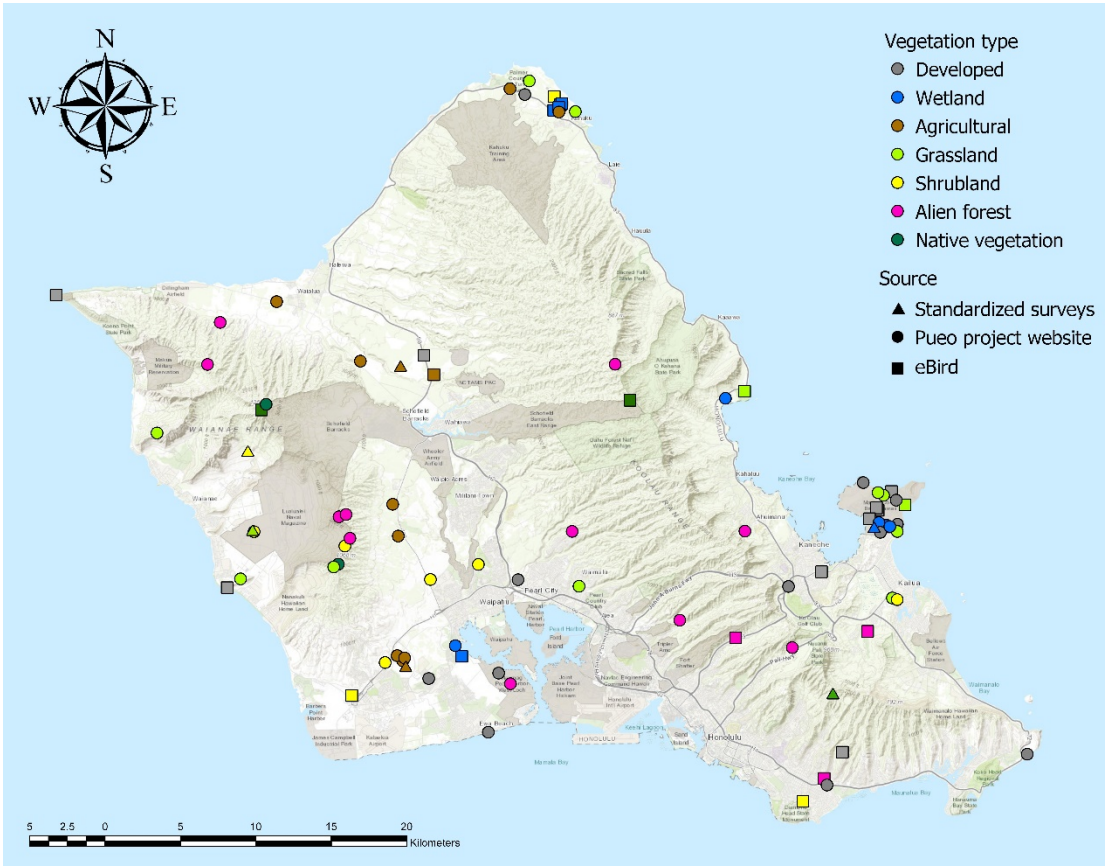

Figure 8. Pueo sightings obtained for O'ahu through the surveys (triangles), Pueo Project online portal (circles) and eBird (squares).

Discussion

Globally, Short-eared Owls tend toward the irruptive end of the migration strategy continuum (Newton 2006), with an ability to shift distribution and establish breeding territories within suitable habitats wherever there is a sufficient abundance of small mammal prey, particularly voles (Village 1987, Korpimäki & Norrdahl 1991, Korpimäki 1994, Poulin et al. 2001). Accordingly, breeding densities and territory sizes can vary depending on local prey abundance (Mikkola 1983, Village 1987, Korpimäki & Norrdahl 1991, Arroyo & Bretagnolle 1999, Poulin et al. 2001).

Movements and breeding phenology of the Pueo, a subspecies of the Short-eared owl, are still poorly known, but this study has expanded the known vegetation types that are utilized by this species. Our standardized surveys show that on O'ahu, Pueo densities are highest in agricultural lands, but given the low numbers of Pueo detected (a maximum of four individuals at one site), and the limited land surface surveyed in the study (less than 1%), further studies are needed to determine preferred habitats, and those habitats most important to survival and reproduction. Agricultural lands may provide higher prey densities (Moulton et al. 2006), attracting owls to occupy these areas. Although this species does not maintain territories in its worldwide distribution, low habitat availability on O'ahu may increase site fidelity.

Pueo sightings obtained through citizen science efforts were highly biased toward developed and urbanized areas, which are not suitable habitat for the species (Booms et al. 2014). This is consistent with expected biases of citizen science datasets (Robinson et al. 2018). Since human populations are most dense in urban areas, the abundance of people increases the likelihood of detecting Pueo that pass through these areas. On O'ahu, urban areas are often adjacent to suitable foraging habitat, such as urban wetlands, agricultural lands, or open parks, so residents are likely to observe Pueo as they pass through.

Despite the small proportion of wetlands on O'ahu (around 1% of the total surface), all datasets show a relatively high proportion of Pueo observations in wetland vegetation. This could be explained by: (1) owls favoring this kind of habitat, as they do in other parts of the world (Booms et al. 2010); (2) predator control programs in these areas, which lower the risk of predation on eggs, chicks, and adults; (3) and the regular occurrence of waterbird surveys throughout the year, which increases the number of birdwatchers in these areas. Additionally, Pueo nests have been reported in this habitat on the Hawaiian Islands, indicating the importance of wetlands for this species. In contrast, despite occupying 35% of the whole island surface, there was a low percentage of observations in alien forests. Owl detectability is expected to be lower in closed canopy vegetation, even if they are present, and this might explain the lower number of observations.

Overall, in our surveys, Pueo were most often detected in open vegetation types, including agricultural lands, grasslands, and wetlands. Pueo densities in native vegetation, wetlands and shrubland were above 0.5 Pueo per hectare. Surprisingly, grasslands, which are the preferred habitat of this species in other parts of the world (Booms et al. 2014), had lower densities than other vegetation types. When divided into subtypes, densities were closer to expected values in grasslands of low height. Invasive California Grass (*Brachiaria mutica*) can grow up to 2.5 meters (8 feet), and Sugar Cane (*Saccharum sp.*) up to 6 meters (20 feet), creating fields that are probably too dense or tall for breeding or foraging Pueo. Further study is needed to elucidate why distribution among vegetation types differs from continental systems.

Several factors limited survey effort and should be addressed in future studies. Due to very low detection rates, survey sites were visited three times in order to accurately assess the presence of the species. In future studies, if the intent is to develop distribution models or evaluate distribution among vegetation types, we recommend conducting only one survey per site, and increasing the number of sites surveyed, to increase statistical power across the study area. However, if the intent is to determine presence/absence at specific sites, an approach that includes three surveys per site, conducted according to the developed protocol, appears to be adequate.

Pueo on O'ahu appear to be mostly crepuscular-nocturnal, limiting observation time for visual surveys. Our first sightings during surveys averaged 23 minutes to twilight, which is past sunset, limiting observation time for visual surveys. Outside of the standardized survey time frames, Pueo were detected just before total darkness. This behavior is consistent with Larson and Holt (2016), which noted that nearly three-quarters of visual survey detections occurred between 30 minutes and 70 minutes before the end of civil twilight. We note that reports from other islands in the archipelago, such as Kaua'i or Hawai'i, suggest that Pueo can be more diurnal in higher elevations. Nevertheless, this limited observational time frame means that surveys may only be carried out near twilight on O'ahu. For our study, this limited the number of surveys to one per day. With additional personnel skilled in distinguishing Barn Owls from Pueo, survey effort (number of surveys) could be increased during the study period. On the other hand, Barn Owls are specialized nocturnal hunters particularly because of their auditory acuity which enables location of prey in darkness (del Hoyo et al. 1994), which corresponds with our findings (Barn Owls were only detected 2 minutes before twilight) and with other global studies (Pavey et al. 2008).

Due to the cryptic nature of the Pueo and the above-mentioned challenges in conducting the surveys, we surveyed approximately 1,000 hectares on O'ahu, which is less than 1% of the total area of the island. This relatively small area might not be representative of the whole island, and results in a high degree of uncertainty in our estimated population size for O'ahu (i.e. a large range between low and high estimates).

Due to the highly variable nature of this species' worldwide distribution, which depends mostly on prey availability, territory size cannot be used for assessing the population size on O'ahu, especially since breeding seasons are not well defined. The breeding density of Short-eared Owls is widely reported to vary temporally with high densities associated with years of high vole abundance (Korpimäki & Norrdahl 1991, Arroyo & Bretagnolle 1999, Poulin et al. 2001). Village (1987) found that mean territory sizes varied from 42 hectares in winter to 112 hectares in summer (an approximately three-fold difference). Variation in the size of individual territories was greater, with a ten-fold difference between the smallest (25 hectares) and the largest (242 hectares). Lockie (1955) had territories that varied from 16 hectares in good vole conditions to 137 hectares after the voles had declined. Clark (1975) recorded one territory of 121 hectares in 1968 in Manitoba, and a mean of 73 hectares for five ranges in 1969, when voles were increasing. Short-eared Owls in Europe showed high variation, with ranges from 40 to 900 hectares (Goddard 1935, Lockie 1955, Village 1987, Shaw 1995, Roberts & Bowman 1986, Korpimäki & Norrdahl 1991). With observed fluctuations in breeding densities, low tenacity to some breeding sites and their migratory behavior, it is generally accepted that Short-eared Owls can range widely to find breeding sites with high numbers of voles (Korpimäki & Norrdahl 1991, Korpimäki 1994).

Conclusions

Information gathered through the citizen science portal is highly valuable for obtaining phenology and breeding event observations (nests, owlet locations, display flights) or to give insight into areas or sites not accessible to the researchers or general public. However, data collected in this manner tend to be biased due to the lack of standard distribution of the observers, which hampers their usefulness for running distribution models or other population analyses.

In order to properly assess the population size of the Pueo in the Hawaiian Islands, the species' movements, prey availability and breeding seasons need to be determined. Increased survey efforts, carried out annually, are needed to narrow down the variability in the population estimates. Pueo, as a subspecies of the Short-eared Owl, might be subject to the short-term variability in population size related to prey abundance for which this species is known (Clark 1975, Korpimäki and Noordahl 1991, Johnson et al. 2013). Wiggins et al. (2006) and Johnson et al. (2013) each suggest that consistent surveying over a time span exceeding multiple prey cycles is required before trend estimation should be performed.

Pueo were mostly detected in open vegetation types. Agricultural lands had higher densities of Pueo, but nesting activities detected on wetlands indicate the importance of this habitat for the species. Densities obtained with our surveys are aligned with those studies targeting known Short-eared Owl populations with a high rate of occupancy (Goddard 1935, Lockie 1955, Shaw 1995, Village 1987). That does not seem to be the situation on O'ahu, especially if we consider the high level of threats that this species faces (Work and Hale 1996) and the observations of declining populations that local inhabitants have reported in person or submitted to the Pueo Project portal. Densities on O'ahu are probably similar to the ones in non-targeted, randomized and standardized studies carried out in Idaho and Utah (Miller et al. 2016, Miller et al. 2017, Lehman et al. 1988), where owls occupy territories with high prey availability, but leave unoccupied low-prey-density territories, even if they contain adequate vegetation requirements. Based on this information, we expect the true number of Pueo on Oʻahu to be closer to the lower end of the estimated range.

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Appendices

Pueo Project

Survey Protocol 2017

Materials

- **GPS** unit or Smartphone.
- Datasheet and map, clipboard (or hard surface to write on) and writing utensil (pen preferred).
- Civil twilight times (refer to www.timeanddate.com).
- Binoculars (+ spotting scope).
- Range finder.
- Stopwatch or clock to keep track of minute-by-minute intervals of the survey.
- This survey protocol (for reference).
- Flashlight for reading datasheet when dark.
- Survey partner (optional… but it's easier and more fun with two people; record # of observers).
- Good sense of humor and tons of patience.

Methods

Survey points (vantage viewpoints) will be selected from the randomized selection of sites/area.

Vantage viewpoints: Vantage viewpoints observation areas should not overlap and should be spaced roughly 1 kilometer apart when possible. Minor variation in distance between points is expected due to terrain and roadside safety concerns. If an observer believes they are seeing the same bird on multiple points, this should be noted. Each point should be documented by GPS. The goal for each point is to have a minimum of 180° field of view of the surrounding area, up to at least 300m distance.

Survey frequency: Survey points should be visited at least 2 times (3 times optimum) to increase detectability.

Survey timing: Surveys can be carried out during morning** or evenings***.

***Morning surveys:* Surveys begin at civil twilight (around 30 min before sunrise, defined to be when the sun is 6 degrees below the horizon) and finished between 75 and 60 minutes after sunrise. Refer to www.timeanddate.com.

****Evening surveys:* Surveys begin between 75 and 60 minutes before sunset, and finish at civil twilight (around 30 min after sunset, defined to be when the sun is 6 degrees below the horizon). Refer to www.timeanddate.com.

Weather: Your survey should be completed during periods of good or fair weather. Clouds are fine, but you should avoid any steady rain. Breezy conditions are also ok, but strong winds should be avoided.

Pueo search: Begin scanning surrounding area, including ground and sky for Pueo presence. Surveys should be done using a combination of binoculars and naked-eye observation (and listening). All Pueo observations should be recorded on the data sheet. Best efforts should be made to avoid double-counting of birds.

Data collection

The following data fields will be collected:

General:

- Date
- Observer(s)
- Site Location
- GPS point and coordinates. "Decimal degrees" should be used for all coordinates (e.g., *UH Manoa is located at 21.302015°, -157.814769*°). Please record at least 5 digits to the right of the decimal point. This may require a settings change on your GPS or Smart Phone. Some units may report the longitude as 157.814769 W instead of -157.814769. If this is the case, drop the "W" and add the "-" later.
- Survey "start" time
- Survey "stop" time

Environmental:

- Cloud Cover Classification – measured at start point only. Classified as cloudy (100% cloud cover), mostly cloudy (50-99% cloud cover), partly cloudy (1-49% cloud cover), and clear (0% cloud cover).
- Wind speed based on Beaufort Scale (see appendix 1).
- Temperature.
- Precipitation (none, light fog or mist, light drizzle, scattered showers; no surveys should be attempted in heavy fog or steady rain).
- Surveyed area (describe max length of surveyed distance in a N, S, W and E basis using a range finder).
- **Habitat / Vegetation Cover Classification** (see appendix 2) with a % estimate within surveyed area. Radius should not exceed 400 meters.

Bird observations:

- Detection time start:
- Detection time end:
- Detection type documented per forest bird survey protocols (e.g., 2-bird seen; 1-bird heard only; 4-bird heard and then seen etc.)
- **Owl Behavior Classification** – recorded at initial detection of each individual owl (i.e. if same individual owl is re-sighted, do not change the behavioral classification) classified as **perched, foraging, direct flight, agonistic, or courtship** (Holt and Leasure 1993). If courtship behavior is suspected, the behavior should be described in more detail. See appendix 3.
- Owl Vocalizations/Sounds – any sound produced by Short-eared Owls should be classified as hoots, barks, screams, wing clapping, bill clapping (Holt and Leasure 1993).
- Distance from observer in meters.
- Direction from observer (cardinal directions - N, NE, E, etc.)
- **Habitat where owl is observed** – The general classification of habitat where the owl was initially observed. For example, the point habitat might be 90% shrubland and 10% wetland, but the owl was observed in the wetland vegetation. If the bird is flying, *what habitat was it flying over when initially observed?*
- Courtship/Breeding behavior.

Appendix 1. Beaufort Scale:

Beaufort Scale for measuring wind speed:

- 0 = Calm: smoke rises vertically
- 1 = Light Air: Smoke drift indicates wind direction, still wind vanes
- 2 = Light Breeze: Wind felt on face, leaves rustle, vanes begin to move
- 3 = Gentle Breeze: Leaves and small twigs constantly moving, light flags extended
- 4 = Moderate Breeze: Dust, leaves, and loose paper lifted, small tree branches move

Do not survey if:

- 5 = Fresh Breeze: Small trees in leaf begin to sway
- 6 = Strong Breeze: Larger tree branches moving, whistling in wires
- 7 = Near Gale: Whole trees moving, resistance felt walking against wind
- 8-12 = Gale – Hurricane: generally impedes progress.

Appendix 2. Habitat / Vegetation Cover Classification – measured at *each survey* point.

Record values to the nearest **10%**. Recorded as percentage of various land types within approximately 400 meters/yards (1/4 mile) of each survey point. Values should total to 100%.

- **Developed** Land that is predominantly built-up or developed and vegetation associated with these land covers. This includes road surfaces, buildings and paved surfaces, and farmsteads.

- **Wetlands:** Land with a water table near/at/above soil surface for enough time to promote wetland or aquatic processes (semi-permanent or permanent wetland vegetation, including swamps, sloughs, marshes etc.).
- **Agricultural lands:** Annually cultivated cropland; lands that generally change from bare cover to green/vegetated cover during the growing season.
    - Crops.
    - Dirt: ground has been tilled to bare dirt or very short stubble, not high enough to provide shelter for mice or voles.
- **Grasslands:** may include a few shrubs, but there should not be many and should not be regular on the landscape.
    - Short grassland.
    - Grazed grassland: Land used to pasture livestock (cattle, sheep and horses).
    - Mowed lawn.
    - Grasslands/Fallow: Formerly grazed grassland, crop or hay, but has not been used for such uses in at least the previous growing season, and which has not yet reached the stage of shrubland.
    - Tall Grassland: California grass or grass >75 cm tall.
- **Shrubland:** Predominantly woody vegetation of relatively low height (generally 2 m). Also includes grass or grassland wetlands with woody vegetation and regenerating forest.
- **Alien forest:** Predominantly forested or treed areas, including at least 10-25% crown closure of coniferous, broadleaf and mixed wood.
- **Native vegetation:** Predominantly forested or treed areas, including at least 10-25% crown closure of coniferous, broadleaf and mixed wood.

Appendix 3. Owl behavior – breeding?

The following categories of behavior should be noted, in generally ascending order of evidence for a breeding attempt or holding territory (modified after Shaw, 1995):

POSSIBLE BREEDING

- Owl(s) carrying prey
- Courtship display (wing clapping)
- Owl(s) giving alarm calls or mobbing potential predators

CONFIRMED BREEDING

- Owl(s) repeatedly carrying prey to an area (feeding an incubating female or young)
- Recently fledged young owl(s) seen

If breeding is designated as probable or if pairs of owls are observed, surveyors will make a special note to follow up.

Pueo Project Survey Datasheet 2017

Site : _____ GPS point: _____ GPS coordinates: (D.dddddd, -D.dddddd) _____

Date: _____ Visit # (1, 2 or 3):___ Survey Start Time: _____ Survey Stop Time:_____ Observers: _____

Temperature: _____ Cloud cover (Clear, PC, MC, Cloudy):_____ Rain:_____ Wind (0-7):_____

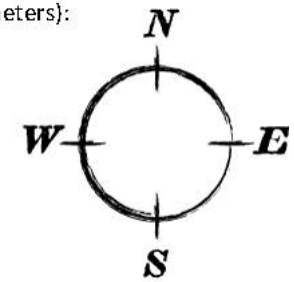
Detection start time	Detection end time	Number	Initial distance	Initial direction	Sounds	Behavior	Habitat

% Habitat w/in 400 m or surveyed area (must be 100%):

Developed	Wetland	Agricultural Crops	Agricultural Dirt	Grasslshort Grazed	Grasslshort Golf	Grasslshort Mowed
Grassland Fallow	Grasslands Tall >75cm	Shrublands	Non Native Forest	Native Forest	Other	Total

Surveyed area (max visible meters):

N:	S:
NE:	SW:
E:	W:
SE:	NW

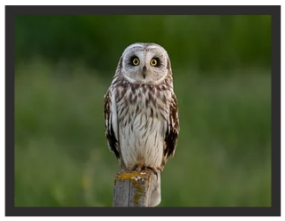
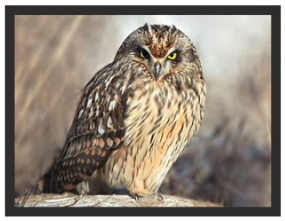


Observations:_____

Identifying tips: Pueo vs Barn owl

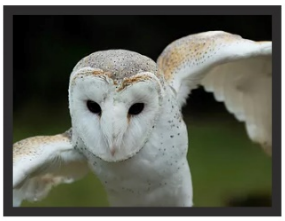
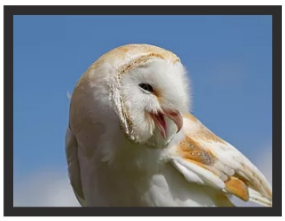
The Pueo can be distinguished from the introduced Barn Owl by appearance as well as hunting behavior.



Pueo *(Asio flammeus sandwichensis)*



Barn Owl (*Tyto alba*)

Smaller & slender body
with relatively longer wings and tail than Barn owl.

Heavier body
with relatively shorter wings and tail than Pueo.

Brownish
Mottled pale brown underparts with upper breast streaked dark brown.
Mottled pale and dark brown upperparts.
Overall impression in flight of a large brown bird (but underparts can look almost white).

White and gold
Largely white underparts.
Golden buff upperparts with grey markings.
Overall impression in flight of a large white bird.

Round face
Rounded brown face

Heart-shaped face
White, heart-shaped face.

Yellow eyes

Dark eyes

Small ears
often indiscernible ear tufts

No ears

Often diurnal
Both nocturnal and diurnal, they can be seen hunting in daylight in suitable habitat.

Nocturnal
Often seen at night whilst driving but dawn and dusk sightings are most common.

Hoots
A male's rarely heard song is a low 'boo-boo-boo-boo-boo', whilst females give a 'ree-yow' call.

Shrieks and hisses
Barn Owls don't hoot! They shriek, hiss and snore.
Lives mainly in open farmland habitat (not woodland).
Seen but not heard, they call rarely.

Pueo Project Website and citizen science participation

One of the main activities realized towards citizen science participation was the creation of a website about the project www.pueoproject.com

Figure 9. Pueo Project website www.pueoproject.com

The website has information about the project, the two species of owls present in the Hawaiian Islands, which are the introduced Barn Owl (*Tyto alba*) and the native Hawaiian Short-eared Owl or Pueo (*Asio flammeus sandwichensis*). The key feature of the website is a web application for reporting Pueo sightings.

Figure 10. WebApp for reporting Pueo sightings.

We have received more than 50 Pueo reports during the last year, which are more than the records registered in eBird (the main tool for reporting bird sightings in USA) since 1986. We also have received several dozens of emails from people interested in the project. Now, we have a list of 40 citizen scientist interested in the project and that will submit reports if they encounter a Pueo on the wild.

To update the volunteers and the general public, a blog within the website is frequently updated.

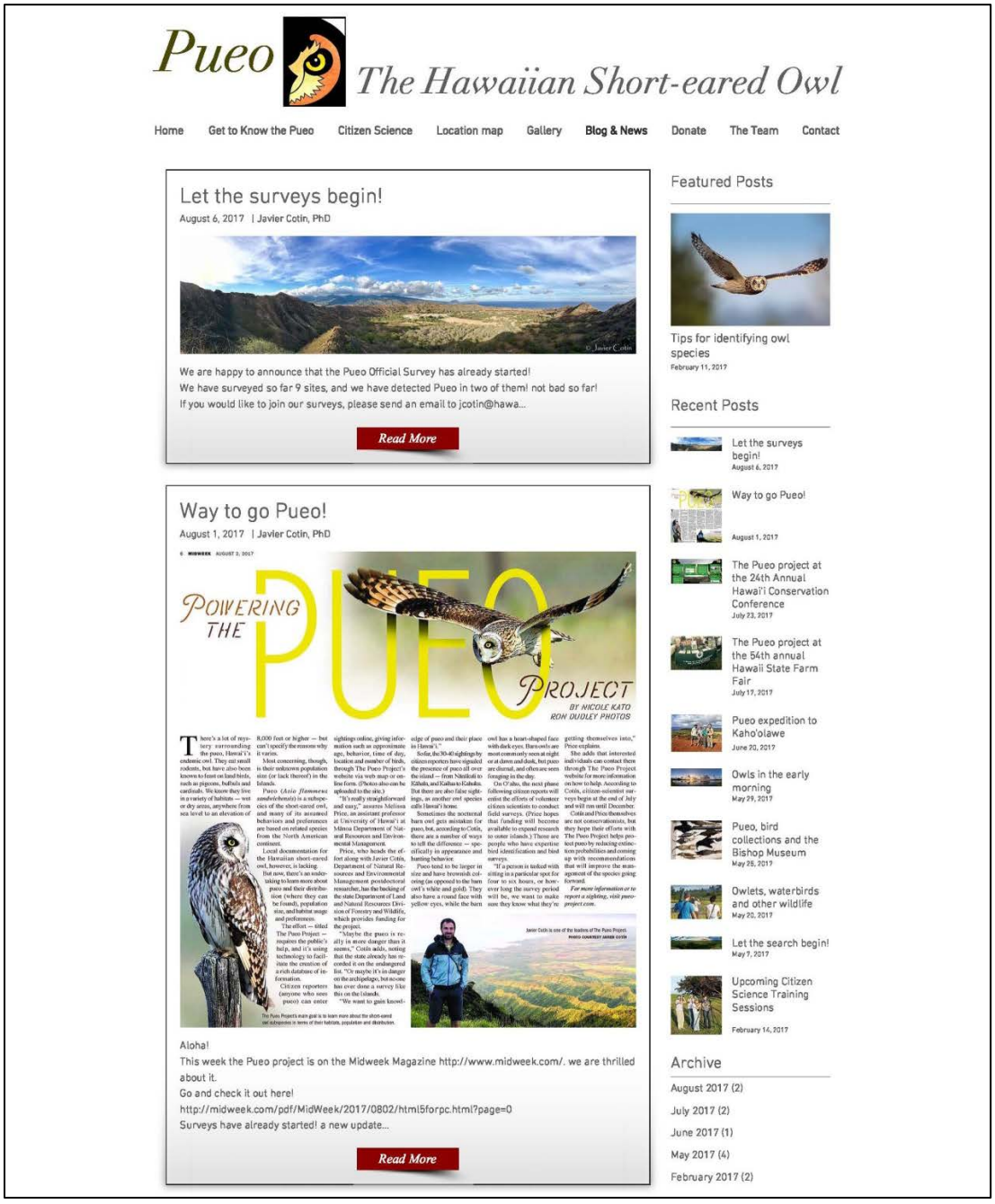


Figure 11. Example of two posts of the blog within the Pueo Project website www.pueoproject.com

The website has been received **4,123 visitors (with 11,070 page visits)**. 55% of the visitors were from Hawai'i (see Figure 12), although there have been visits from all over the world (see Figure 13), including countries such as Canada, New Zealand, Indonesia, Colombia, Brazil, Bolivia, Argentina, Chile, Uganda, Philippines, India, China, Russia, Iran, Saudi Arabia and Tunisia!

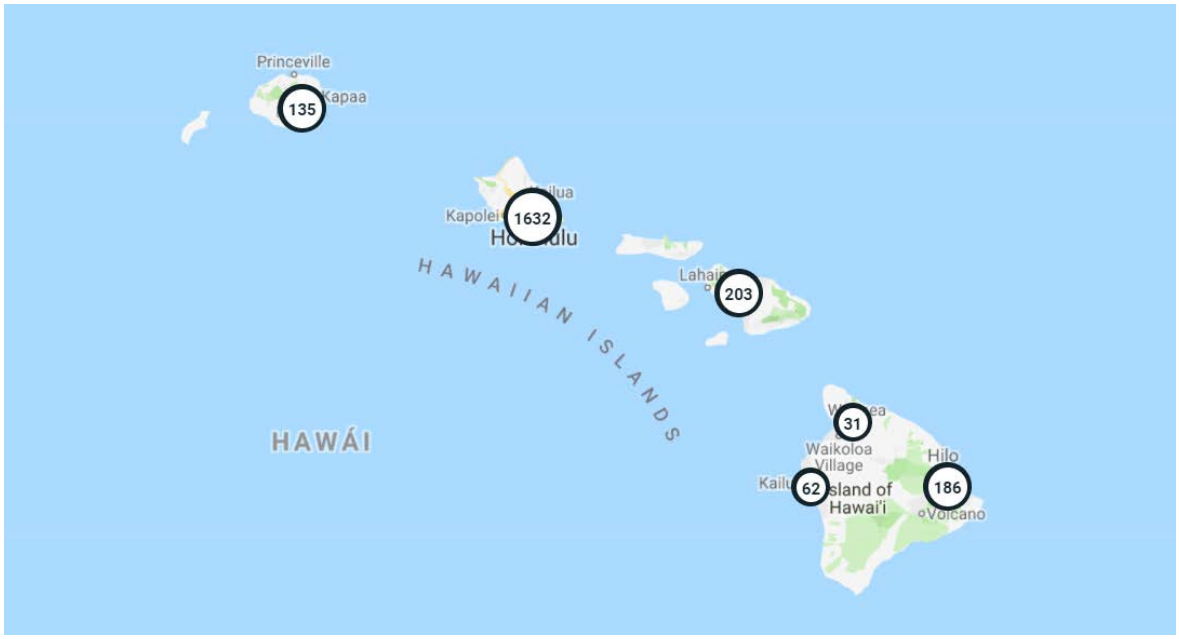


Figure 12. Number of visitors to the Pueo Project website from the state of Hawai'i.

Figure 13. World map with countries (in light green) that visited the Pueo Project website. In dark green, the country with highest number of visits (USA).

In order to reach an even broader audience, a Facebook website https://www.facebook.com/Pueoproject and a twitter account https://twitter.com/pueoproject were also created.

Finally, leaflets and informative sheets were designed for sharing with the general public.

Figure 14. Example of leaflet used during the citizen science project and outreach activities.

The Pueo Project was presented at two different international conferences (see Figure 19 and 20):

24th Hawai'i Conservation Conference

Presentation of the Poster "Distribution of the Pueo or Hawaiian Short-eared Owl: Utilizing Citizen Science to Aid Monitoring Surveys" at the 24th Hawai'i Conservation Conference - Hawai'i Conservation Alliance. July 18 to 20 2017. http://www.hawaiiconservation.org/conference

Figure 15. iPoster presented at the HCC conference.

World Owl Congress 2017

Oral presentation about the results of the Pueo Project at the **World Owl Congress 2017** (Évora, Portugal), September 26 to 30, 2017. http://www.woc2017.uevora.pt

Figure 16. World Owl Conference Website

Outreach activities

The main outreach activities that have taken place in the last year are:

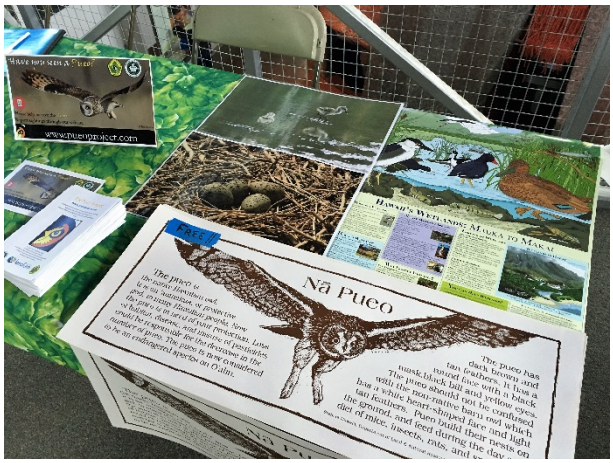
- Thirty-four volunteers participated in our surveys during the 105 surveys that we carried out between July and December 2017.
- Presentation about the Pueo Project for the O'ahu Army Natural Resource Program (OANRP) – May 4, 2017 http://manoa.hawaii.edu/hpicesu/dpw.htm
- Presentation about the Pueo Project for the Hawaiian VINE Project – June 1, 2017 https://www.facebook.com/hawaii.vine.project/
- Representation of the Pueo Project at the College of Tropical Agriculture and Human Resources table at the Hawai'i State Farm Fair, July 15th and 16th. http://www.hawaiistatefarmfair.org

Figure 17. Stand of the Pueo Project at the Education Pavilion of the Hawai'i State Farm Fair.

- Talk about the Pueo Project at Mid-Pacific institute, with the coordination of Liz King - 11th of September 2017.
- Talk story about the Pueo Project at KCC STEM Center, in collaboration with Hawai'i Conservation Alliance, Hawai'i Audubon Society, Bishop Museum and Kapiolani Community College – October 12, 2018 (see Figure 18).
- Pueo surveys at Mount Ka'ala with students from the Mid-Pacific Institute – 18th November 2017.

Figure 18. Poster about the Pueo Project talk at Kapi'olani Community College.

- Representation of the Pueo Project at the World Wetlands Day at Keawawa Wetland. February 3, 2018.
- Representation of the Pueo Project at the Fall in Love with Science at the Bishop Museum (see pictures below), March 18, 2018. www.bishopmuseum.org Special thanks to Molly Hagemann (Collections Manager Bishop Museum) for providing the museum specimens and some of the materials.



Figures 19 and 20. Stand of the Pueo Project and Vertebrate Collection at the Fall in Love with Science event at the Bishop Museum.

Figure 21 and 22. Stand of the Pueo Project and Vertebrate Collection at the Fall in Love with Science event at the Bishop Museum.

Future outreach activities

- Seminar about the Pueo Project at UH Manoa, NREM department seminar series –March 21, 2018.
- Talk about the Pueo Project for Teacher Planning Conferences in collaboration with Hawai'i Nature Center – April 5, 2018.
- Pueo workshop at University of Hawai'i West O'ahu –April 6, 2018 (Figure 23).
- Collaboration with the Boys Scouts of America. Caleb Turner, District Executive, will include participation and collaboration with the Pueo Project and its fieldwork in the process of obtaining the Bird Study merit badge. http://www.scoutinghawaii.org

Figure 23. Flier of the Aha Pueo or Pueo workshop at UHWO.

The Pueo Project has been cited and promoted on the following media and news:

- College of Tropical Agriculture and Human Resources (CTAHR) news. Article titled "Way to go Pueo!" Issue 309. April 26, 2017.
- University of Hawai'i news http://www.hawaii.edu/news/2017/05/23/pueo-project
- Star Advertiser. Article titled "Yearlong project to study habitats of Hawaiian owl". May 23, 2017.
- Midweek Magazine. Article titled "Powering the Pueo Project" by Nicole Kato. August 2, 2017.
- And we are currently working on an article for the Elepaio journal, from the Hawai'i Audubon Society. http://www.hawaiiaudubon.org/elepaio-journal

From the Pueo Project we have also collaborated with other researchers, to extend our efforts:

- Trapping, banding and transmitter attachment of Pueo with USFWS and DOFAW partners, during a Kaho'olawe field trip. The expedition team was formed by Jamie Bruch (KIRK), Emily Bjerre (USFWS), Jenny Hoskins (USFWS), Jay Penniman (Maui Nui Seabird Recovery Project) and Javier Cotin (University of Hawai'i).
  https://www.pueoproject.com/single-post/2017/06/20/Pueo-expedition-to-Kahoolawe

Figure 24. Kaho'olawe expedition Team.

- Collaboration with the Panaewa Zoo in order to test different Pueo solar GPS tags. Special thanks to Pam Mizumo.
- Collaboration with the Bishop Museum to collate data on Pueo from museum skins, and continue the study of Pueo diet analysis with the Collections Manager Molly Hagemann

Figure 25. Pueo at the Bishop Museum collection.

- Collaboration with the **National Geographic Photographer, Erika Larsen.** Photographic expedition in O'ahu and to Kaho'olawe during November 2017. Erika joined the project for two weeks, in order to promote our study and photograph the research and cultural aspects of it. http://www.erikalarsenphoto.com

Figure 26. Photo of Francisco Roman (cultural expert and practitioner, part of the National Geographic team), at Kaho'olawe

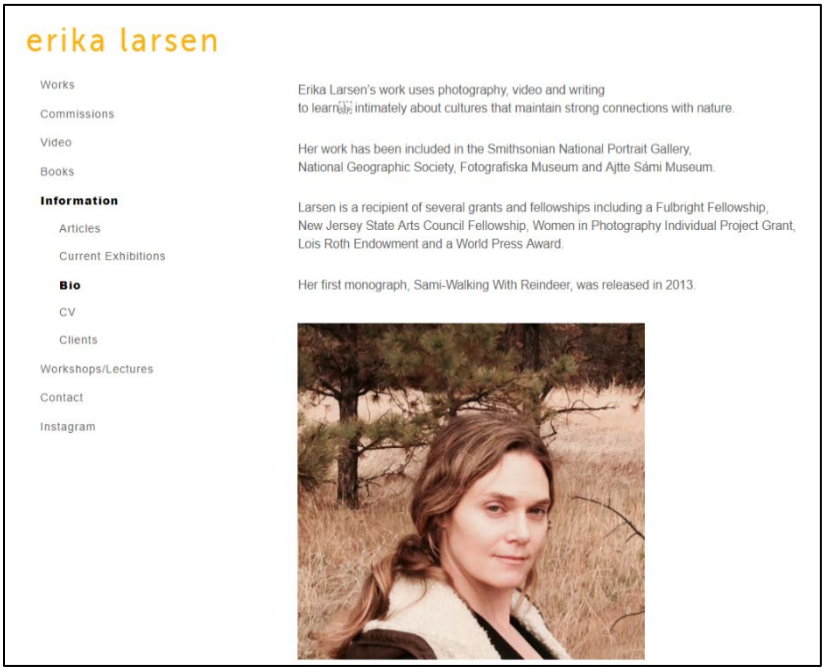


Figure 27. Erika Larsen website, National Geographic Photographer

- Collaboration and partnership with the book's author Hooked by the Stars, Aline LaForge http://www.hookedbythestars.com http://www.wisebirdbooks.com a story about the Pueo's Voyage to Hawai'i.

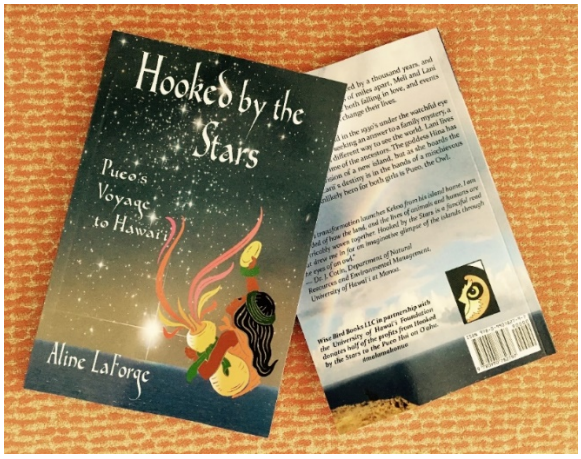


Figure 28. Cover of the book Hooked by the Stars, with the Pueo project logo.

- Collaboration with the photographers Darcy Fiero (www.darcyfiero.com) and Tom Kualii (www.facebook.com/tomkualiiphotography and https://500px.com/tomkualii). They have allowed using some of their images in this report, and in the future we hope to develop outreach materials with them.

Figures 29. Pueo photo by Darcy Fiero www.darcyfiero.com and by Tom Kualii www.facebook.com/tomkualiiphotography

Future Studies

We strongly recommend further studies to be conducted on distribution, biological threats and life history traits for this species. The IUCN status of the Pueo should be assessed, and for that, population estimates through the year are needed to infer trends.

- Coordinated survey efforts for each of the main Hawaiian Islands. Pueo are known to exist throughout the state with very little information on habitat needs and occupancy. Such effort could be conducted over a one year time span with temporary field assistants coordinated to conduct Pueo surveys on each island during the same time period along with data analysis and distribution modeling.
- Breeding ecology studies to identify needs and preferences of breeding habitat, nest site characteristics and reproductive success to inform improved habitat management specific to Pueo.
- Foraging ecology studies to evaluate Pueo diet in different habitat types during the breeding and non-breeding seasons. Results from previous studies suggest Pueo might be a great source of biocontrol for bird pest species impacting crops, such as bulbuls, as well as rodent pests.
- Cultural/indigenous knowledge studies to include in-depth analysis of Hawaiian newspapers and interviews with cultural practitioners regarding Pueo habitat use, breeding ecology, and diet in the past, as well as an enriched understanding of what Pueo mean to Hawaiian people and culture.