

# Roost Culling as an Effective Management Strategy for Reducing Invasive Rose-Ringed Parakeet (*Psittacula krameri*) Populations

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## Research Article

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# Abstract

Rose-ringed parakeets (*Psittacula krameri*) are one of the most widespread invasive avian species worldwide. This species was introduced to the island of Kaua'i, Hawai'i, USA, in the 1960s. Depredation of crops by this species causes extensive economic losses. Large congregations in evening roosts damage trees and lead to excessive noise and droppings in public areas. We evaluated the efficacy of a roost culling program conducted by an independent contractor from March 2020 – March 2021. We estimated island-wide minimum abundance was 10,512 parakeets in January 2020 and 7,372 in April 2021. Over 30 nights of culling, approximately 6,030 parakeets were removed via air rifles with 4,415 (73%) confirmed via carcasses retrieval. An estimated average of 45 parakeets were removed per hour of shooter effort. The ratio of culled juveniles to adults was approximately 1.6:1.0. Age and sex structure of animals removed varied seasonally; the proportion of adult females removed in 2020 was 1.9× greater when culled outside of the estimated nesting season. Of the four roosts where culling occurred, the parakeets fully abandoned three and partially abandoned one site; of the three fully abandoned roosts, an estimated average of 29.6% of birds were culled prior to roost abandonment. This study was conducted during the COVID-19 pandemic, when tourist numbers and foot traffic were greatly reduced; it is unknown how public perception of roost culling in public areas may impact future efforts. Findings can be used to inform implementation of roost culling for management of nonnative rose-ringed parakeet populations.

## Introduction

Rose-ringed parakeets (*Psittacula krameri*) are one of most widespread and detrimental invasive avian species (Jackson 2021). The popularity of this species in the pet trade has led to introductions worldwide (Menchetti et al. 2016). Escape from the pet trade, combined with its ability to survive in human-modified habitats and tolerance of a wide range of environmental conditions, has led to established populations of rose-ringed parakeets on every continent except Antarctica (Menchetti et al. 2016; ISSC 2021). Throughout much of their introduced range, populations are increasing; Balmer et al. (2013) estimated the global rose-ringed parakeet breeding range increased over 440-fold from the late 1960s to mid-2010s, making it one of the most rapidly spreading avian species worldwide.

Introduced populations of rose-ringed parakeets have led to negative impacts on native natural resources, economies, and human health and safety. Ecological impacts of invasive rose-ringed parakeets include potential habitat alteration, invasive seed spread, resource competition, and injury and death of native wildlife from the parakeet's highly antagonistic behavior (Shiels and Kalodimos 2019). In Australia, invasive rose-ringed parakeets strip tree bark which has led to tree death (Fletcher and Askew 2007). Shiels et al. (2018) determined 97% of invasive rose-ringed parakeets evaluated in Hawai'i, USA, had consumed yellow guava (*Psidium guajava*), potentially leading to seed dispersal of this invasive plant. In Europe, native birds responded to rose-ringed parakeet presence by reducing feeding rates and increasing vigilance (Peck et al. 2014). Perhaps the greatest impact on native species stem from rose-ringed parakeets' nesting behavior. Rose-ringed parakeets are secondary cavity nesters, utilizing cavities that are naturally occurring or created by other species. In Israel, cavity enlargement by rose-ringed parakeets

appears to facilitate breeding success of invasive common mynas (*Acridotheres tristis*; Orchan et al. 2012). In Spain, invasive rose-ringed parakeets maim and kill imperiled greater noctules (*Nyctalus lasiopterus*) to claim cavities, which has led to decreased abundance of the bats (Hernandez-Brito et al. 2018).

Beyond ecological impacts, invasive populations of rose-ringed parakeets pose human health and safety threats. They are noted agricultural pests in their native and introduced ranges, as they frequently depredate fruit, grain, and seed crops (Khan 1983, Khan et al. 2011, Klug et al. 2019). Rose-ringed parakeets congregate nightly in roosts, which are often in urban, peri-urban, or agricultural areas. Excessive droppings at roost sites potentially expose humans to zoonotic pathogens such as psittacosis and avian flu (Klug et al. 2019). Furthermore, aircraft have struck rose-ringed parakeets at London's Heathrow Airport on three documented occasions, which posed a threat to human safety and cost >£20,000 British pounds each (Fletcher and Askew 2007).

Given the rapidly increasing distribution of rose-ringed parakeets and the pervasive negative impacts of this species, natural resource managers throughout the world are seeking effective population reduction strategies. In parts of their native range, rose-ringed parakeet populations are thought to be reduced by capture for the pet trade (Menchetti 2016). To date there have been two documented eradications of invasive rose-ringed parakeet populations, both on islands. A culling program on Mahe Island (157 km<sup>2</sup>) in the Seychelles included the removal of 548 rose-ringed parakeets; the majority of these individuals were removed via shotgun culling along flight lines, with remaining individuals located via a public bounty program (Bunbury et al. 2019). The second documented eradication occurred on La Palma Island Biosphere Reserve (728 km<sup>2</sup>) in the Canary Islands, where 175 individuals were removed over three years; the majority were removed via live trapping, and the final 34 individuals were removed via shooting with air rifles (Saavedra and Medina 2020).

Rose-ringed parakeets were introduced to the island of Kaua'i, Hawai'i, USA, in the 1960s. The population remained relatively low for the following four decades, demonstrating a lag period that is common among introduced parrot populations (Aagard and Lockwood 2014; Menchetti and Mori 2014). Population management began in 2005, predominately through use of shotguns at corn (*Zea mays*) fields in the southern part of the island (W. Bukoski, unpublished data). Despite control efforts, the population reached an estimated 2,000 individuals in 2011 (Gaudioso et al. 2012) and 6,800 individuals in 2018 (Shiels and Kalodimos 2019).

Rose-ringed parakeets on Kaua'i are voracious crop predators of corn, lychee (*Litchi chinensis*), mango (*Mangifera indica*), papaya (*Carica papaya*), longan (*Dimocarpus longan*), and citrus crops, among others. While no formal economic assessment has been conducted, one hybrid seed production company estimated losses at over US\$1 million for commercial hybrid seed corn crops (J. Young, Kani Wildlife Control, personal communication). The other pronounced impact of rose-ringed parakeets on Kaua'i results from their roosts, which occur in urban or peri-urban areas. The nightly congregations lead to

excessive droppings, causing property damage and threatening human health, as well as complaints about excessive noise and tree damage (Klug et al. 2019).

Beginning in 2020, a new management effort was implemented to control the rose-ringed parakeet population on Kaua'i by culling birds at their roosts; this effort was conducted by an independent wildlife control company and funded by the County of Kaua'i. Prior to this effort, roost culling had been generally avoided on Kaua'i for ecological and social purposes. Primarily, there was concern culling would lead to roost abandonment, which would be problematic because roosts are the primary method of monitoring the abundance of this species. Further, because the roosts were in developed areas, managers were concerned roost abandonment would lead to new roosts in natural areas; this could increase impacts on native wildlife species, which are largely restricted to central portions of the island. Second, two of the three known roosts were adjacent to tourist resorts, and there was concern of how the public would perceive culling efforts. In this regard, reduced tourist activity due to the COVID-19 pandemic provided a unique and optimal timeframe to trial roost culling as a rose-ringed parakeet population management strategy. Only ~331,000 tourists traveled to Kaua'i in 2020, compared to 1.37 million in 2019 (Hawai'i Tourism Authority 2021). Further, Kaua'i implemented a 21:00–05:00 curfew from March 20 - May 6, 2020, as a COVID-19 safety precaution (County of Kaua'i 2020). The reduced human activity allowed nighttime roost culling to be conducted in public areas with relatively few public observers.

We evaluated overall impact of roost culling on estimated island-wide minimum rose-ringed parakeet abundance. We further evaluated take per hour of shooter effort, estimated the age and sex ratio of animals removed, and monitored whether the parakeets abandoned their roosts in response to culling efforts. Findings can be used to inform implementation and best practices of roost culling for management of nonnative rose-ringed parakeet populations.

## Methods

### Study Species

Rose-ringed parakeets are considered a medium-size parrot, with adult body mass ranging from 131–180 g (Butler 2003, Mentil et al. 2019). Adults measure around 40 cm in length, about half of which is their long tail. The native range of the four subspecies includes two geographically disjoint regions, with subspecies *P. k. krameri* and *P. k. parvirostris* native to equatorial Africa, and subspecies *P. k. borealis* and *P. k. manillensis* native to the Indian subcontinent (Cardador et al. 2016, Menchetti et al. 2016). Rose-ringed parakeets are one of the few parrot species successfully adapted to living in human-modified environments including urban parks, cultivated areas, and woodlands (Menchetti et al. 2016). Clutch size ranges from two to six eggs, most often with three or four (Braun and Wink 2013). Rose-ringed parakeets are sexually dimorphic; adult males are distinguished by black and rose-colored neck rings that develop around three years of age. Although some efforts have been made to distinguish juveniles from adult females by size and plumage (Butler and Gosler 2004; Mentil et al. 2019), they are largely monomorphic (Senar et al. 2019).

# Study Area

The Hawaiian island archipelago is among the most remote in the world. It consists of eight major islands and dozens of smaller islets. Kaua'i is the northernmost and fourth largest of the major islands (Figure 1). It has an area of 1,430 km<sup>2</sup> and ranges in elevation from sea level to 1,598 m. Kaua'i has a tropical climate, with average daily temperatures of 26° C in February and 29° C in August. January–March is regarded as the wet season, although precipitation is high year-round; mean annual rainfall ranged from 440 mm in the lowlands to nearly 10,000 mm at the highest peak (Giambelluca et al. 2013). Agriculture impacted by rose-ringed parakeets on Kaua'i includes large hybrid seed corn farms on the southwestern portion of the island (converted from previous sugar cane fields) and tropical produce farms throughout the lowlands including lychee, mango, papaya, avocados, longan, and citrus, among others.

## Study Design

We estimated the island-wide minimum abundance of rose-ringed parakeets on Kaua'i prior to, during, and post roost culling through roost counts, the method most commonly used to estimate rose-ringed parakeet population size (Butler 2003, Pithon and Dytham 1999, Shiels and Kalodimos 2019; Figure 1). Roost counts were conducted by counting rose-ringed parakeets as they departed the roost at sunrise. When flocks were too large to count by individual, parakeets were counted by increments of five or ten individuals (Shiels and Kalodimos 2019). Each roost count was conducted two to four times within a two-week period, and counts were averaged to represent the respective estimate (Table 1; Figure 1). This technique should be considered a conservative population estimate, or minimum number of known individuals, as it is possible there were unknown roosts during any given time; thus, we refer to cumulative estimates from roost counts as island-wide minimum abundance.

Prior to roost culling we estimated island-wide minimum abundance in January 2020, at which time there were three known roosts: Po'ipū, Lihue\_1, and Kapa'a (Figure 1). There was a pause in roost culling from November 2020 to February 2021; we estimated island-wide minimum abundance twice during this period, once immediately after culling cessation in November 2020 and once immediately before culling was resumed in February 2021. In November 2020 there were four known roosts: Po'ipū, Lihue\_2, Koloa, and Kapa'a. In February 2021 there were four known roosts: Po'ipū, Koloa, Lihue\_3, and Kapa'a. In April 2021, we estimated minimum island-wide abundance after the completion of culling at which time there were four known roosts: Po'ipū, Lihue\_2, Kapa'a, and Princeville (Figure 1).

Figure 1. a) Rose-ringed parakeet (*Psittacula krameri*) roosts observed on Kaua'i, Hawai'i, in 2020 and 2021, and b) timeline of roost counts (ellipses), culling phases (grey shading), and observed roost establishment and abandonment dates (white shading). Brackets are used to indicate roost abandonment or establishment when the exact date was not known. Months in bold (January – April) represent estimated reproductive season. Reported roost counts represent estimated island-wide minimum abundance (Table 1).

Thirty nights of roost culling were conducted from March 2020 – March 2021; these were divided over three phases (Figure 1). Phases were differentiated by whether they included the estimated nesting season, number of roosts culled, and culling frequency (see below). For each night of culling, we documented the estimated number of parakeets lethally removed, the total number of carcasses retrieved, the number of shooters, and the number of hours culling was conducted. Not all carcasses were retrieved, as some birds flew away with injuries and some carcasses were inaccessible when caught in vegetation or scavenged by feral cats (J. Young, Kani Wildlife Control, personal communication); thus, the discrepancy in removal estimates and total carcass retrieval. All data – estimates of parakeets removed nightly, number of carcasses retrieved, number of shooters, and number of hours worked - were provided by the private company that implemented the culling effort, Kani Wildlife Control (Kekaha, HI, USA). Culling was conducted by one or two shooters each night using sound-suppressed 22-caliber air rifles with telescopic sights. Each shooter had a partner using a white spotlight to locate parakeets perched in palm trees. We calculated the total shooter hours for each night as the number of hours worked per shooter (i.e., two shooters working for three hours = six shooter hours). We calculated the estimated number of birds culled and total number of carcasses retrieved per shooter hour. We calculated the means ( $\pm$  standard deviations) of these values for each phase.

## Roosts subjected to culling:

The roosts of rose-ringed parakeets on Kauaʻi were in urban to peri-urban habitats. We measured the approximate size of each roost by documenting the coordinates of the two furthest points of the roost and measuring the distance between them using ArcMap (version 10.6.1, ESRI, Redlands, CA, USA). The Poʻiipū roost included >100 ornamental trees over approximately 1 km; trees used for roosting by the rose-ringed parakeets included royal palms (*Roystonea regia*) and king palms (*Archontophoenis alexandrea*). Within this area were four tourist resorts, the edge of a golf course, a public park, and >50 private residential properties. The Lihue\_1 roost included 46 royal palms and two coconut palms (*Cocos nucifera*) concentrated in the parking lot of a shopping center; total length of the roost was ~190 m. The Lihue\_3 roost was not occupied at the beginning of the study; it had historically been a roost site less than six months prior to the study (CJ Anderson, personal observation) and was repopulated by the parakeets between November 2020 – February 2021. This roost was spatially the smallest of all evaluated, with a total length around 60 m. In this site, the parakeets were using ~20 royal palms in a lawn surrounding a convention center. The Koloa roost was not occupied at the beginning of the study but was also historically a roost site, with documented use in 2011 (Gaudioso et al. 2012). The parakeets re-established the Koloa roost around June 2020 (WP Bukoski, personal observation) in a row of ~50 palm trees along a road between a residential street and a golf course. The length of the roost was approximately 237 m (Figure 1).

## Phase 1: March – May 2020

Twenty-one nights of culling were conducted from March 27 – May 29, 2020, between two roosts, Lihue\_1 and Poʻiipū (Figure 1). No culling was conducted at the third known roost at the time, the Kapaʻa

roost. The Lihue\_1 roost was markedly smaller in estimated number of birds occupying the roost and spatial length than the Poʻiipū roost (see above). There were four nights of culling (10.68 shooter hours) at the Lihue\_1 roost, (March 27 – April 17, 2020), implemented at a rate of once per week. There were 17 nights of culling (64.67 shooter hours) at the Poʻiipū roost (April 1 – May 29); this included five nights of culling (15.13 shooter hours) in April 2020 implemented at a rate of once per week and 12 nights of culling (49.53 shooter hours reported for nine nights; data were not provided for three) in May 2020 implemented at an average rate of every 2.5 days (min = 1, max = 6).

We obtained 2,993 carcasses from the parakeets culled in Phase 1. We documented the total number of adult males, as noted by their black and rose-colored neck collars. Birds lacking neck rings were initially classified as unknown age and sex. From the sample of unknown birds, we conducted 601 necropsies to determine age and sex in three classes: sexually mature females, immature females, and immature males. We determined sex by presence of testes or ovaries. Immature males were classified as those with testes but lacking neck rings. We determined female age by follicular development; females in which all follicles were undeveloped were designated as sexually immature, and those with active follicles were designated as sexually mature (J. Heatley, Texas A&M University, personal communication; Figure S1 in Supplementary Information). Of the 601, 16 carcasses had too much internal damage to accurately assess age and sex, leading to a usable sample of 585 carcasses (32% from the Lihue roost; 68% from the Poʻiipū roost). We assumed the age and sex ratio of the unknown birds we did not necropsy ( $n = 1,755$ ) was the same as those we necropsied. We therefore used the proportion of each age and sex class among necropsied birds to estimate the proportion of the respective age and sex class in the total sample ( $n = 2,993$ ). Using these findings, we estimated the proportion and 95% confidence interval of each age and sex class of parakeets removed during the entire study period.

## **Phase 2: June – November 2020**

Phase 2 was a continuation of culling efforts at the Poʻiipū roost (Figure 1). We evaluated this time period separately as it did not include the predicted nesting season and differed in culling frequency. There were six nights of culling between June 5 – November 12, 2020 (27 shooter hours). Frequency of culling effort was less consistent during this time as compared to Phase 1, with an average of 32 nights between culling efforts (min = 1, max = 85). The largest lag between culling events was from August to November 2020 (85 days).

## **Phase 3: February & March 2021**

Two nights of culling were implemented at the Lihue\_3 roost on consecutive nights, February 23 and 24, 2021 (17.5 shooter hours; Figure 1). To evaluate the impact of successive disturbance on roost abandonment, we conducted roosts counts at the Lihue\_3 roost on February 22, 24, and 26, 2021. For all carcasses collected at the Lihue\_3 roost, we recorded the number of adult males and number of unknown age and sex birds. From the first of the two nights of culling, we necropsied 52 of the unknown birds to estimate the age and sex ratio of the parakeets removed. We assumed the age and sex ratio of carcasses we did not necropsy ( $n = 165$ ) were the same as those we did.

The final night of roost culling was conducted at the Koloa roost (Figure 1) in March 2021 (9.32 shooter hours). The company conducting the culling reported the estimated number of parakeets removed ( $n = 214$ ) and reported total number of carcasses retrieved ( $n = 165$ ) but did not obtain carcasses to evaluate age and sex.

## Comparison of age/sex culled by season

We compared age and sex ratio of rose-ringed parakeets culled by season. During the nesting season, nesting female rose-ringed parakeets remain on their nests rather than returning to the roost at night - beginning when the first egg is laid (Braun and Wink 2013) - and are therefore not expected to be available for roost culling. Nesting season of rose-ringed parakeets on Kaua'i has not been documented. However, nesting season of rose-ringed parakeets on the neighboring island O'ahu has been observed as late January – mid April (Shiels and Kalodimos 2019). We therefore evaluated whether age and sex ratio differed between birds removed in March and April 2020 ( $n = 1,140$ ) with those in May 2020 ( $n = 1,853$ ) during Phase 1. While February is within the predicted nesting season, post-hoc observation indicated a higher proportion of adult females was culled in February 2021 ( $n = 402$ ). We performed a multinomial logistic regression using the *nnet* package in R (version 4.0.5) with age/sex as the response variable (mature female, mature male, immature female, and immature male) and culling season as the independent variable (March/April 2020, May 2020, February 2021) to evaluate whether age and sex ratio of parakeets culled varied significantly by season (code provided in Supplementary Information).

## Results

We estimated an island-wide minimum abundance of 10,512 rose-ringed parakeets in January 2020 (prior to roost culling) among the three known roosts (Lihue\_1, Po'ipū, and Kapa'a; Table 1). An estimated 6,030 parakeets were removed via roost culling with 4,415 carcasses retrieved from March 2020 – March 2021. Among all culling efforts, there was an estimated mean of 44.7 (SD = 28.4) parakeets removed per shooter hour. An average of 36.7 (SD = 22.9) carcasses were retrieved per shooter hour (Table 2). Island-wide minimum abundance estimates were 4,963 individuals in November 2020, 6,883 in February 2021, and 7,372 in April 2021 (Table 1). The number, location, and estimated abundance of roosts changed throughout the study.

Table 1

Estimates of island-wide minimum abundance of rose-ringed parakeets (*Psittacula krameri*) on Kaua'i, Hawai'i, USA, estimated via roost counts. Roost counts were conducted two to four times at each site within a two-week period; reported estimates represent averages from the respective time period. Periods indicate the roost was not occupied during the study period.

Roost	January 2020	November 2020	February 2021	April 2021
Kapa'a	1,501	1,911	1,657	1,358
Lihue_1	2,559	.	.	.
Lihue_2	.	880	.	1,317
Lihue_3	.	.	1,031*	.
Po'ipū	6,452	1,325	3,043	4,650
Koloa	.	847	1,152	.
Princeville	.	.	.	47
Total	10,512	4,963	6,883	7,372
*estimate prior to February 2021 roost culling at the Lihue_3 roost; an estimated 725 birds were located at Lihue_2 after roost culling.				

Table 2

Estimated number of rose-ringed parakeets (*Psittacula krameri*) culled and carcasses retrieved from roost culling efforts on Kaua'i, Hawai'i, USA.

	Total	Phase 1		Phase 2	Phase 3
		March – April 2020 (Lihue_1 & Po'ipū)	May 2020 (Po'ipū)	June – November 2020 (Po'ipū)	February - March 2021 (Lihue_3 & Koloa)
Nights of culling	30	9	12	6	3
Estimated parakeets culled	6,030	1,511	3,415	392	712
Carcasses retrieved	4,415	1,277	2,333	238	567
Mean estimated take per shooter hour (SD)	44.7 (28.4)	53.8 (25.9)	56.25 (23.7)	22.2 (29.6)	28.1 (16.6)
Mean carcasses retrieved per shooter hour (SD)	36.7 (22.9)	49.6 (19.9)	39.4 (17.1)	19.5 (29.1)	22.6 (15.3)

### Phase 1: March – May 2020

Over 21 nights of culling, an estimated 4,926 rose-ringed parakeets were removed from the Lihue\_1 and Po'ipū roosts, a confirmed 3,619 carcasses were retrieved, and average take per shooter hour was 55.0

(SD = 23.5). At the Lihue\_1 roost, an estimated 561 parakeets were removed (530 carcasses retrieved) over four nights of culling, approximately 22% of the pre-culling roost abundance (n = 2,559; Table 1). During the fourth night of culling, the number of birds removed per shooter hour decreased substantially (13.1) from the average of the first three nights (59.8), as the parakeets had partially abandoned the roost (J. Young, Kani Wildlife Control, personal communication). After the fourth night of culling, the parakeets fully abandoned the roost.

An estimated 4,365 parakeets were removed from the Poʻiipū roost - approximately 68% of the pre-culling roost abundance (6,452; Table 1) - and 3,089 carcasses were retrieved. Average take per shooter hour was 57.0 (SD = 18.6). Over the 17 nights of culling, the parakeets did not fully abandon the roost. While we did not measure the number of birds per tree or per individual property, we noted that the extent and composition of the roost changed. For example, during this period, the parakeets shifted approximately 175 m west onto a different property. In many areas, the parakeets shifted to private properties where culling was not permitted (J. Young, Kani Wildlife Control, personal communication).

Of the 2,993 carcasses evaluated, 653 (21.8%) were sexually mature males. Of the 585 carcasses necropsied, 142 were immature males, 123 were mature females, and 320 were immature females (Table 3). Using these findings to estimate the total sample size, we estimated the 4,926 parakeets removed during Phase 1 included  $21.8 \pm 3.4\%$  mature males,  $19.0 \pm 3.2\%$  immature males,  $16.4 \pm 3.0\%$  mature females, and  $42.7 \pm 4.0\%$  immature females (Figure 2).

Figure 2. Estimated number and percent (95% CI) of rose-ringed parakeets (*Psittacula krameri*) by age and sex removed via roost culling from March - April 2020 (n = 1,511 from Lihue\_1 and Poʻiipū roosts), May 2020 (n = 3,415 from Poʻiipū roost), and February 2021 (n = 498 from Lihue\_3 roost) on Kauaʻi, Hawaiʻi, in 2020 and 2021. We identified all mature males by plumage, whereas we identified a sample of mature females, immature females, and immature males via necropsy during Phase 1 (n = 337 from March - April; n = 248 from May) and Phase 3 (n = 52). Carcasses were not evaluated during Phase 2 due to COVID-19 travel restrictions.

### *Phase 2: June - November 2020*

An estimated 392 rose-ringed parakeets were culled (238 retrieved carcasses) at the Poʻiipū roost. The average number of parakeets removed per shooter hour in Phase 2 (22.2 [SD = 29.6]; Table 2) was lower than Phase 1 and ranged from 7.8 to 13.7 in June-August. After an 85-day hiatus in culling, the number of birds removed per shooter hour increased in November to 82.3 (Figure 3). We were unable to evaluate age and sex of carcasses retrieved during this time due to COVID-19 travel restrictions.

We estimated the island-wide minimum abundance was 4,963 individuals among four roosts in November 2020 after the conclusion of Phase 2 roost culling. Given the Lihue\_1 roost was abandoned during roost culling, there were no birds in this location. The Poʻiipū roost was greatly reduced in size due to culling and partial roost abandonment. The Kapaʻa roost, where no culling occurred, had increased by approximately 27%. Two roosts had established, Lihue\_2 and Koloa; it was unknown when the Lihue\_2

roost established, but the Koloa roost was first documented in June 2020 (Figure 1; Table 1; W. Bukoski, personal observation). While neither roost was present in January 2020, both were historic roost locations that had previously been abandoned for unknown reasons.

Figure 3. Estimated number of rose-ringed parakeets (*Psittacula krameri*) culled per shooter hour (black dots) and total number of carcasses retrieved per shooter hour (gray dots) at the Poʻiipū roost in 2020 (Phases 1 and 2) on Kauaʻi, Hawaiʻi, USA, in 2020 and 2021. Data were not reported by the independent wildlife control company for three of the 23 nights included in this time period (May 21, 22, and 29).

### *Phase 3: February & March 2021*

Between November 2020 and February 2021, the Lihue\_2 roost abandoned for unknown reasons and the Lihue\_3 roost became established (Figure 1). Among the four known roosts in February 2021, we estimated island-wide minimum abundance to include 6,883 rose-ringed parakeets (Poʻiipū, Lihue\_3, Kapaʻa, and Koloa; Table 1).

We estimated the Lihue\_3 roost had 1,031 birds prior to culling. On 23 February 2021, an estimated 350 rose-ringed parakeets were culled (298 retrieved carcasses). We estimated 680 parakeets were occupying the Lihue\_3 roost on the morning of 24 February. On 24 February an estimated 148 parakeets were culled (103 retrieved carcasses). We counted only 14 parakeets at the roost on the morning of 26 February, indicating the site had been abandoned. Between the two nights of culling, an estimated 48.3% of the roost was culled prior to abandonment.

Of the 402 carcasses retrieved, 185 (46.0%) were mature males. Of the 52 birds of unknown age and sex necropsied, we identified 28 mature females, nine immature females, and 15 immature males (Table 3). Using these observations, we estimated take from the Lihue\_3 roost during this period included  $29.1 \pm 3.7\%$  sexually mature females,  $15.6 \pm 2.9\%$  immature males, and  $9.3 \pm 2.4\%$  immature females (Figure 2). Qualitatively, we observed that follicles were more developed among females in February 2021 than March–May 2020, including one female with an intact egg.

During the single night of culling at the Koloa roost, an estimated 214 individuals were removed (165 retrieved carcasses). The parakeets did not return the following evening, indicating they abandoned the site after only one night of culling. An estimated 18.6% of the roost was removed prior to abandonment.

Table 3

Observed age and sex of rose-ringed parakeets (*Psittacula krameri*) removed via roost culling on Kaua'i, Hawai'i, USA, in March - May 2020 (n = 2,993, Phase 1) and February 2021 (n = 402, Phase 3). We identified all mature males by plumage, whereas we identified a sample (n = 585, Phase 1; n = 52, Phase 3) of mature females, immature females, and immature males via necropsy. Carcasses were not evaluated during Phase 2 due to COVID-19 travel restrictions.

	Phase 1		Phase 3
	March – April 2020	May 2020	February 2021*
Mature Males	313	340	185
Unknown Age/Sex (Not Necropsied)	490	1,265	165
Immature Males	68	74	15
Mature Females	55	68	28
Immature Females	214	106	9
Total	1,140	1,853	402
*includes only individuals culled at the Lihue_3 roost			

*Comparison of age/sex culled by season*

The age and sex ratio of rose-ringed parakeets culled varied between the March–April 2020 (n = 1,140), May 2020 (n = 1,853), and February 2021 (n = 498) sampling periods (Table 3; Figure 2). The likelihood of harvesting a mature female vs an immature female, immature male, or mature male was significantly higher in February compared with March/April or May (p <0.01; Table 4).

Table 4

Multinomial logistic regression predicting proportion of mature females compared with mature males, immature females, and immature males culled via roost culling on Kaua'i, Hawai'i, USA, over three time periods: March/April 2020 (n = 1,511), May 2020 (n = 3,416), and February 2021 (n = 499).

	Coefficient	Standard error	P-value
	March/April   May	March/April   May	March/April   May
Mature Males	0.38   -0.66	0.14   0.12	<0.01   <0.01
Immature Females	2.48   1.57	0.19   0.17	<0.01   <0.01
Immature Males	0.83   0.70	0.17   0.15	<0.01   <0.01

## Discussion

Roost culling appears to be an efficient mechanism to rapidly remove large numbers of rose-ringed parakeets with relatively little effort. In this study, an estimated >6,000 parakeets were removed in one

year at a cost of around \$30,000 US (J. Young, Kani Wildlife Control, personal communication). While the required effort and cost of this method were relatively low, roost culling appears to lead to full or partial roost abandonment, which can have negative consequences including compromising population monitoring (Bunbury et al. 2019) or potentially disturbing native species.

All roosts subjected to roost culling in this study were either fully or partially abandoned by rose-ringed parakeets. The likelihood and rate of abandonment appeared to be related to roost size as well as exposure of parakeets to previous roost culling. Two roosts were culled in Phase 1 and therefore included parakeets without prior exposure to roost culling. The Lihue\_1 roost was partially abandoned after three nights of weekly roost culling and fully abandoned after four nights. The Poʻipū roost was never fully abandoned; however, this roost was spatially restructured and partially abandoned by the parakeets. The lack of complete abandonment may have been due to the large size of the Poʻipū roost, which allowed shooters to operate in sections of the roosts (e.g., individual properties) rather than disturbing the entire roost simultaneously (J. Young, Kani Wildlife Control, personal communication). The two roosts culled in Phase 3 (Koloa and Lihue\_3) were both established after other roosts had been abandoned in response to roost culling. Thus, it is feasible the birds in these roosts came from the abandoned roosts and therefore had previous exposure to roost culling. Parakeets in these roosts fully abandoned after one and two nights, respectively. Collectively, these findings indicate roost culling is best used for roosts spatially large enough (~ 1 km) to cull in sections, or small enough in abundance to cull entirely in no more than two nights. The optimal frequency of roost culling implementation, including whether consecutive nights of culling should be utilized, is difficult to ascertain from this study. Future research should further investigate the impact on culling frequency on roost abandonment.

We found an average of ~45 rose-ringed parakeets can be culled per shooter hour via roost culling; managers can use this estimate to determine whether roosts are small enough and staff size is sufficient to successfully remove all birds from the roost prior to abandonment. While the Poʻipū roost was not fully abandoned despite culling throughout Phases 1 and 2, take per shooter hour substantially decreased during Phase 2 (Figure 3); this finding indicated that parakeet exposure to roost culling or decreased roost size may influence efficacy of this strategy. It is important to note that the shooters in this study were professional wildlife control agents with many years of experience; less experienced shooters would likely have a lower take rate.

The island-wide minimum abundance of rose-ringed parakeets on Kauaʻi decreased by an estimated >3,000 birds from between January 2020 – April 2021 (Table 1), marking the first documented annual population decrease. This was particularly noteworthy given there were two estimated reproductive seasons during this period and population growth had been consistently documented within this population (Gaudioso et al. 2012, Shiels and Kalodimos 2019). Roost culling in 2020 resulted in the removal of approximately 5,318 rose-ringed parakeets. Outside of roost culling, approximately 2,500 rose-ringed parakeets were removed on Kauaʻi in 2020 via shotgun culling at corn fields (J. Young, Kani Wildlife Control, personal communication; T. Kaiakapu, Hawaii Division of Forest and Wildlife, personal communication). Demographic parameters such as fecundity, survivorship, and annual growth rate are

unknown on Kaua'i. However, the finding of a minimum abundance of >7,000 individuals in April 2021 despite the removal of >7,800 individuals in the preceding year (between roost and shotgun culling) indicates the 2020 abundance estimate in this study was likely conservative. Continued research to locate rose-ringed parakeet roosts and more precisely estimate population size is merited.

The number, locations, and sizes of roosts varied during the study. Because roost counts are the primary method used to estimate parakeet abundance on the island, roost inconsistency complicates population monitoring. Rose-ringed parakeets will sometimes abandon roosts for unknown reasons in the absence of management (Peck 2013, Pyle and Pyle 2017). Roost abandonment and restructuring appeared to occur during this study both as a direct consequence of roost culling (i.e., Lihue\_1, Lihue\_3, and Koloa roosts) as well as for unknown reasons (i.e., Lihue\_2; Figure 1). Interestingly, three of the roosts that established during the study (Lihue\_2, Lihue\_3, and Koloa), were all previously documented roost sites prior to the study (Gaudioso et al. 2012; Shiels and Kalodimos 2019); therefore, it seems rose-ringed parakeets return to historic roost sites when contemporary roosts are disturbed. If managers in the future aim to identify movement of parakeets after roost abandonment, incorporating telemetry (Gaudioso et al. 2012) or aluminum neck collars with numbered tags (Senar et al. 2019) may be beneficial.

The number of rose-ringed parakeets occupying individual roosts on Kaua'i appears to be larger than others reported in the literature. Reported roost sizes in native habitats range from 498 to 1,111 individuals in Pakistan (Khan 2002) and 229 to 519 individuals in India (Shivaji et al. 2017). Roost size in invaded habitats appears to be more variable. In South Africa, four roosts were reported to include 20–100 individuals (Hart and Downs 2014). Maximum reported roost size in Portugal was 644 individuals (Luna et al. 2016). In Britain, roosts have been reported as small as four individuals (Pithon and Dynam 1999) and as large as 2,500 individuals (Butler 2003). The smaller documented sizes of roosts in other parts of the world may indicate roost culling would provide an impactful management strategy elsewhere.

This study was conducted during the COVID-19 pandemic; consequently, roost culling occurred with far fewer members of the public in view of culling activities than would have occurred during normal tourism and business operations. Public support can be critical to the success of environmental management programs (Jacobson 2009), and public opposition to invasive species management programs can lead to program termination (Bertolino and Genovesi 2003; Anderson et al. 2019). Public support of invasive species' lethal control programs is lower for birds and mammals than other taxa (Verbrugge et al. 2013). In Britain, management of nonnative parakeets was halted due to public response (Crowley et al. 2019). In this study, approximately 30% of rose-ringed parakeet carcasses were not retrieved during nightly culling efforts; there was at least one documented case of a member of the public reporting rose-ringed parakeet carcasses the morning after a culling operation (T. Keanini, Kaua'i Invasive Species Committee, personal communication). Unretrieved carcasses are unsightly and unsanitary, may be objectionable to the public, and may subsidize invasive scavengers (e.g., cats [*Felis catus*] and rodents). Future roost culling efforts should strive to remove all carcasses.

Understanding the biology and population dynamics of a target species is critical for population management. An effective management plan for invasive species population reduction requires an informed strategy including information on target numbers to be culled as well as the spatial distribution, duration, and timing of lethal removal (Garrock et al. 2014). It is unclear why the proportion of juvenile females removed in this study was higher than juvenile males. Little information exists on the influence of social structure or hierarchy on physical placement of rose-ringed parakeets within or among roosts; it is possible juvenile females are located in areas of the roost that are easier to target than other age or sex classes or that division among roosts is related to age and sex. It is also possible juvenile females represent a larger proportion in the population, perhaps due to higher survivorship, although to our knowledge this dynamic has also not been explored. With long-lived bird species, removing sexually mature individuals can have a greater impact on population suppression than removal of juveniles (Ellis and Elphick 2007). While many parrot species demonstrate monogamy (Spoon 2006), rose-ringed parakeets do not form life-long pair bonds; this may suggest culling adult females has a greater impact on survivorship and fecundity than culling adult males. In this study, we found a larger proportion of sexually mature females among birds culled at the roost in May 2020 and February 2021 as compared to March and April 2020; this may suggest future rose-ringed parakeet roost culling efforts on Kaua'i should be restricted to months outside of March and April. Further research is merited to identify the breeding season of rose-ringed parakeets on Kaua'i as well as at-nest metrics, such as clutch size and nest success rates. Population modeling could further evaluate the efficacy of culling each age and sex class and efficacy of roost culling versus management at the nest.

As the rose-ringed parakeet distribution spreads and populations increase, managers will continually need informed management strategies to control populations. While eradication has proven successful for small, incipient populations (Bunbury et al. 2019; Saavedra and Medina 2020), it may not be feasible for most invasive rose-ringed parakeet populations. Roost culling appears to be an efficient, albeit imperfect management strategy to reduce rose-ringed parakeet populations and perhaps suppress populations below target thresholds. Like other management tools, effective implementation of roost culling will need to be sustained, strategic, and implemented long-term. Culling should also be coupled with evaluations of population growth rate to determine efficacy. Future research of roost culling should more specifically evaluate the influence of culling frequency (e.g., culling on consecutive vs. non-consecutive nights at similar-size roosts) as well as using alternative options to white spotlighting (e.g., infrared). While further research is merited, it appears roost culling is a viable option to incorporate into integrated pest management programs for this invasive species.

## Declarations

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**Conflicts of interest/Competing interests** All authors declare they have no financial or non-financial interests.

**Author contributions** All authors contributed to the study conception and design. Material preparation was performed by C. Jane Anderson, Leonard Brennan, William Bukoski, Steven Hess, Clayton Hilton, and Page Klug. Data collection was performed by C. Jane Anderson and William Bukoski. Data analysis was performed by C. Jane Anderson. The first draft of the manuscript was written by C. Jane Anderson and all authors commented on previous versions of the manuscript. All authors read and approved of the final manuscript.

### **Data availability statement**

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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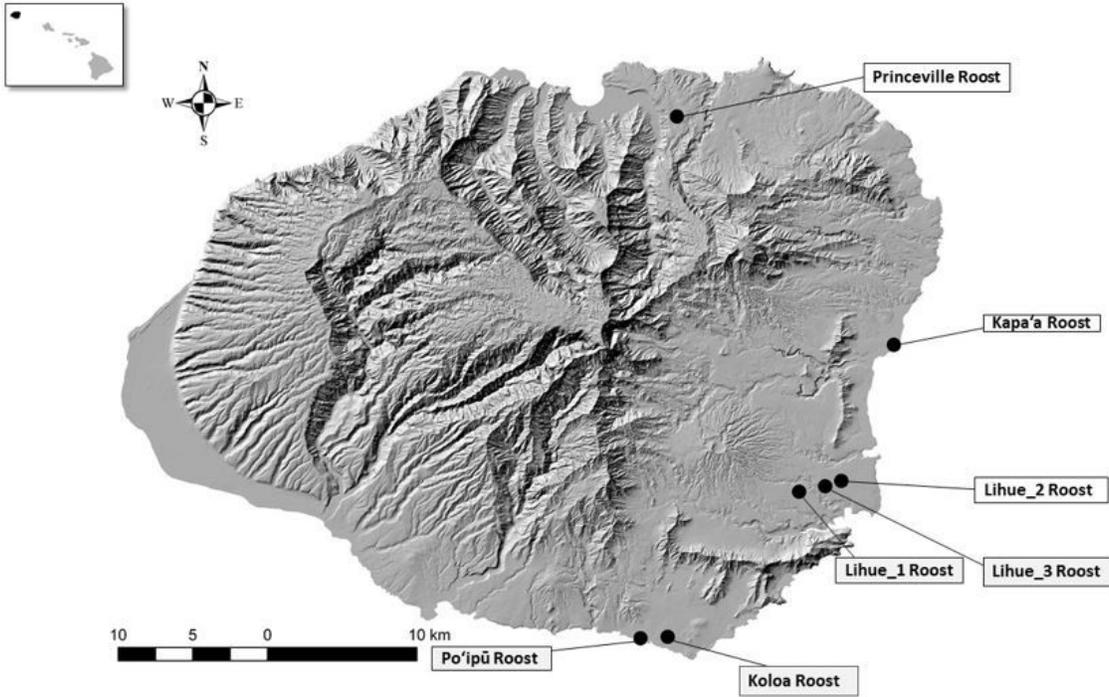
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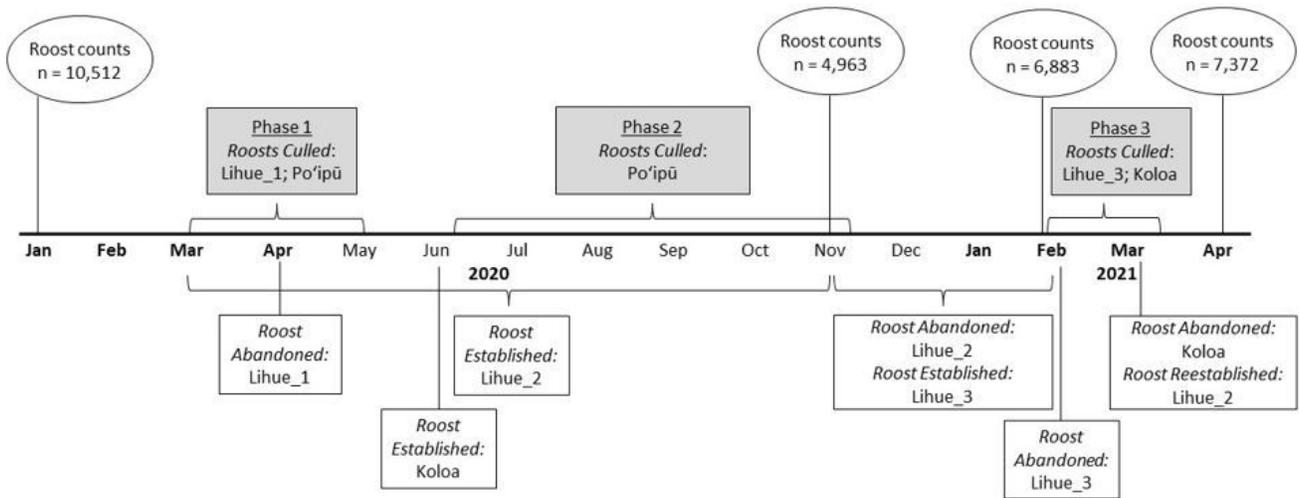
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## Figures

a.

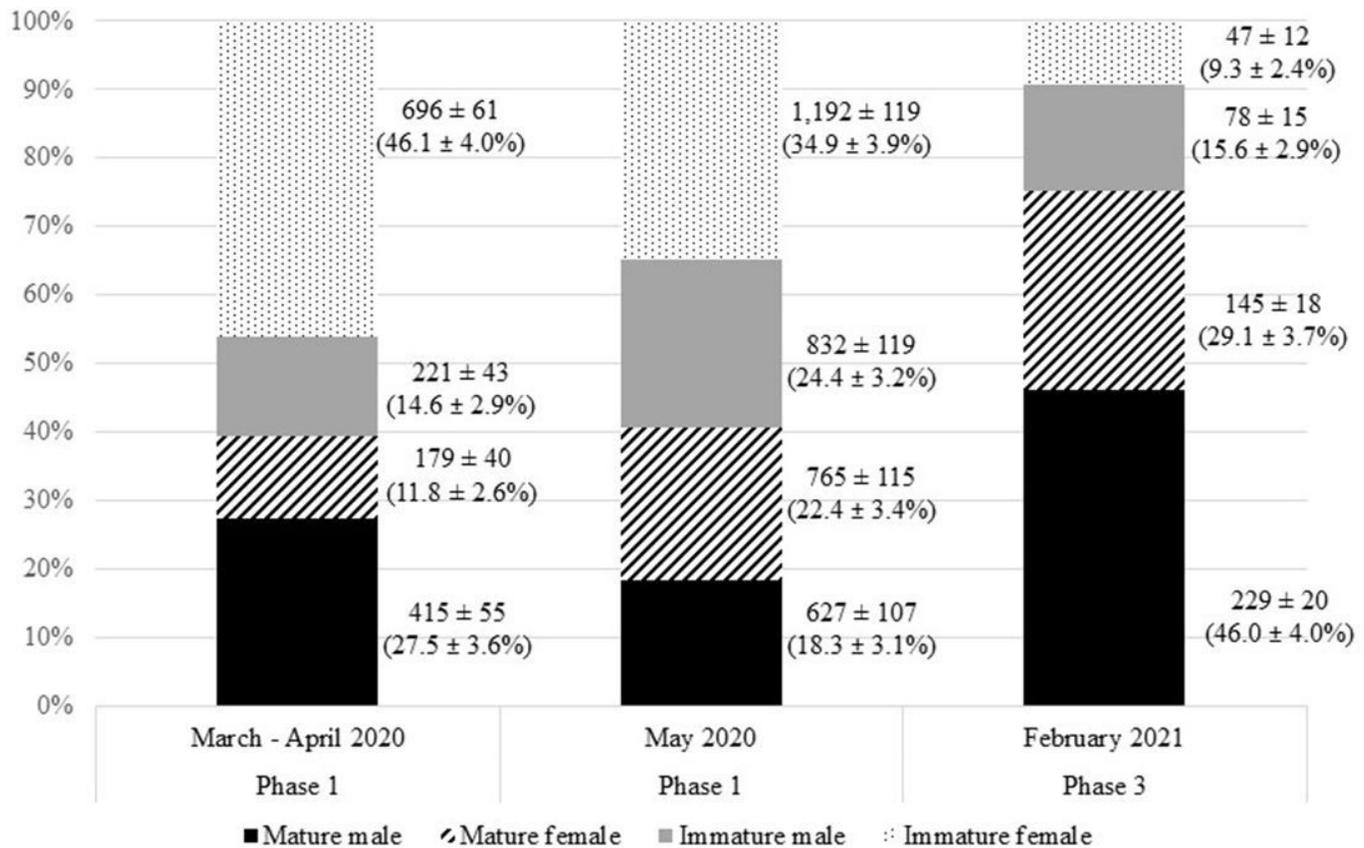


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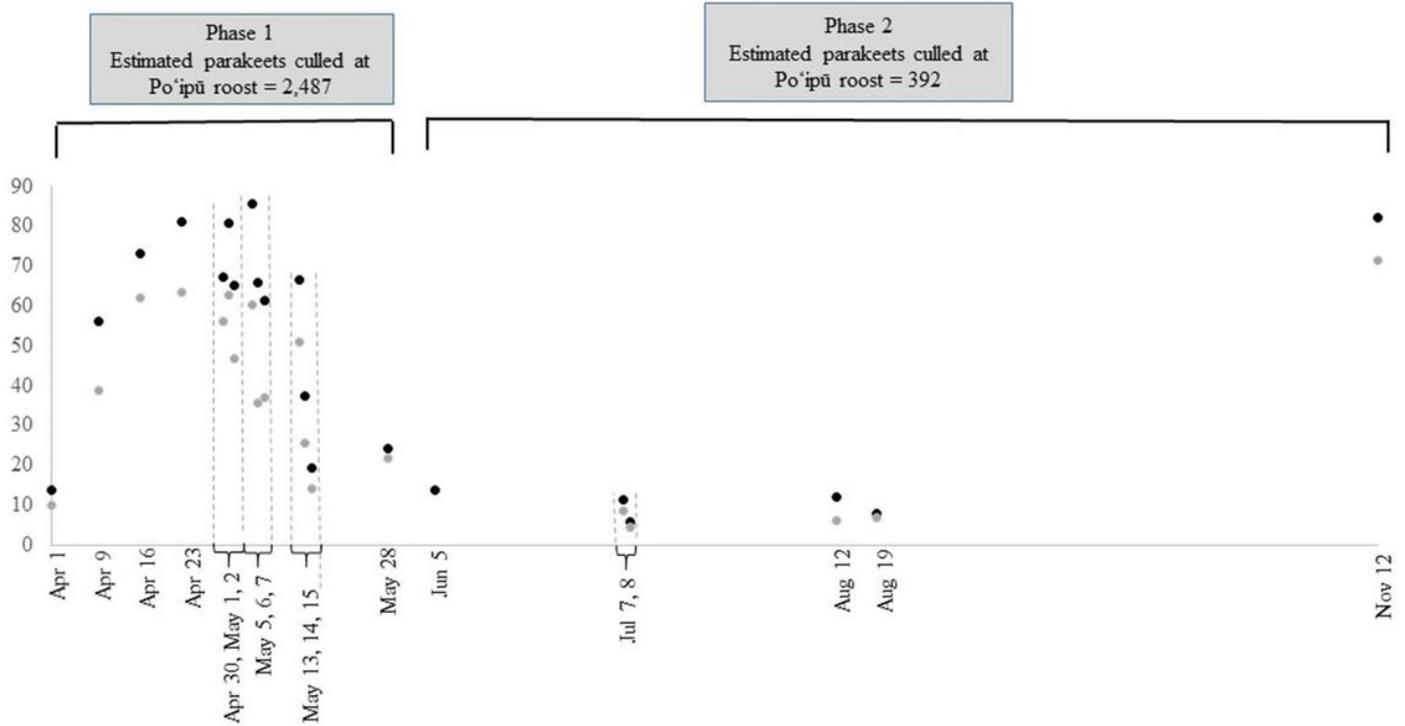
**Figure 1**

a) Rose-ringed parakeet (*Psittacula krameri*) roosts observed on Kaua'i, Hawai'i, in 2020 and 2021, and b) timeline of roost counts (ellipses), culling phases (grey shading), and observed roost establishment and abandonment dates (white shading). Brackets are used to indicate roost abandonment or establishment when the exact date was not known. Months in bold (January–April) represent estimated reproductive season. Reported roost counts represent estimated island-wide minimum abundance (Table 1).



**Figure 2**

Estimated number and percent (95% CI) of rose-ringed parakeets (*Psittacula krameri*) by age and sex removed via roost culling from March - April 2020 (n = 1,511 from Lihue\_1 and Poʻīpū roosts), May 2020 (n = 3,415 from Poʻīpū roost), and February 2021 (n = 498 from Lihue\_3 roost) on Kauaʻi, Hawaiʻi, in 2020 and 2021. We identified all mature males by plumage, whereas we identified a sample of mature females, immature females, and immature males via necropsy during Phase 1 (n = 337 from March - April; n = 248 from May) and Phase 3 (n = 52). Carcasses were not evaluated during Phase 2 due to COVID-19 travel restrictions.



**Figure 3**

Estimated number of rose-ringed parakeets (*Psittacula krameri*) culled per shooter hour (black dots) and total number of carcasses retrieved per shooter hour (gray dots) at the Po'ipū roost in 2020 (Phases 1 and 2) on Kaua'i, Hawai'i, USA, in 2020 and 2021. Data were not reported by the independent wildlife control company for three of the 23 nights included in this time period (May 21, 22, and 29).

## Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [AndersonetalRoostCullingSI.pdf](#)