Non-native Mammalian Predator Control to Benefit Endangered Hawaiian Waterbirds

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**ABSTRACT:** Hawai‘i’s wetlands are inhabited by 5 endangered endemic waterbird species: the Hawaiian stilt (ae‘o), Hawaiian coot (‘alae ke‘oke‘o), Hawaiian duck (koloa maoli), Hawaiian goose (nēnē), and Hawaiian gallinule/Moorhen (‘alae ‘ula). One of the biggest threats facing these waterbirds is predation by non-native mammalian predators. Non-native cats, rats, and mongooses all directly depredate either eggs, young, or adult birds. Control of these predators is a key component of the active management strategy employed to recover Hawaiian waterbirds. Predator control efforts have included live or kill traps, rodenticide bait stations, and fences in areas important for the waterbirds. To evaluate the success of these predator control efforts on key wetland national wildlife refuges in Hawai‘i, we explored 4 metrics: live trap capture history, rodent and mongoose presence/absence using track tunnels, waterbird population densities, and waterbird reproductive success. The track tunnel data documented lower predator density within the predator control areas. The live trapping capture history data showed strong spatial patterns of higher success along perimeter fence lines and limited success within the interior of the wetlands. We also found that areas receiving predator control had both higher reproductive success and, in most cases, greater waterbird population densities. These findings support mammalian predator control as a key management strategy to promote recovery of these endangered species.

**KEY WORDS:** endangered species, Felis catus, feral cats, Hawai‘i, Hawaiian waterbirds, Herpestes javanicus, mongoose, National Wildlife Refuges, predator control, rats, Rattus spp., rodents

**INTRODUCTION**

Hawaiian wetlands provide habitat to 5 endangered endemic waterbirds, the Hawaiian stilt (ae‘o; Himantopus mexicanus knudseni), Hawaiian coot (‘alae ke‘oke‘o; Fulica alai), Hawaiian duck (koloa maoli; Anas wyvilliana), Hawaiian goose (nēnē; Branta sandvicensis), and Hawaiian gallinule/Moorhen (‘alae ‘ula; Gallinula galeata sandvicensis). Endangerment of these 5 species has been attributed to a loss or modification of wetland habitats, introduced plants/predators, avian diseases, altered hydrology, hybridization, and historic overhunting (Englis and Pratt 1993, USFWS 2011a).

After a long decline, the last few decades have seen populations of endangered waterbird species remain stable or increase (Englis and Pratt 1993, Reed et al. 2011, Underwood et al. 2013). This positive trend is likely in response to the active management strategy currently being employed in Hawaiian wetlands (Reed et al. 2011, Underwood et al. 2013). The accepted active management strategy for these species has included 3 major components: control of invasive introduced plant species; manipulation of water levels to mimic natural hydrological processes and benefit waterbird life history needs; and control of introduced predators (Griffin et al. 1989, USFWS 2011a, Underwood et al. 2013).

Non-native vertebrate predators have often been cited as a major cause of native Hawaiian waterbird endangerment and extinction (Berger 1970, Berger 1972, Scott et al. 1988, Griffin et al. 1989, USFWS 2011a). Non-native predators of Hawaiian waterbirds include feral cats (Felis catus), rats (Rattus spp.), mongooses (Herpestes javanicus), dogs (Canis domesticus), wild pigs (Sus scrofa), and to a lesser extent, barn owls (Tyto alba), cattle egrets (Bubulcus ibis), predatory fish, and bullfrogs (Rana/Lithobates catesbeianus), all of which have been documented to directly depredate either eggs, young, or adult birds (USFWS 2011a). To control the mammalian predators that have the greatest negative impact, effective predator control in wetlands is believed to require a barrier of fences, rodenticide bait stations, and live or kill traps (Underwood et al. 2013). Rates of depredation and the population-level impacts of the non-mammalian predators mentioned are still being investigated.

Feral cats, rodents, and mongooses are believed to be the mammalian predators having the greatest impact on endangered waterbirds. Polynesian rats (Rattus exulans) were first brought to the Hawaiian Islands by Polynesian settlers (Atkinson 1977). European and other ships are thought to have introduced the house mouse (Mus musculus), the black/roof rat (R. rattus), the brown/Norway rat (R. norvegicus), and the domestic cat in the early to late 1800s (Atkinson 1977). The small Indian mongoose was introduced to Hawai‘i in the late 1800s to control rats in the cane fields (Atkinson 1977, Hays and Conant 2007). While all these species have been documented as predators of native avifauna in Hawai‘i (Berger 1970, Berger 1972, Scott et al. 1988, Griffin et al. 1989, USFWS 2011a), the degree to which...
each species has impacted native Hawaiian waterbirds is unknown.

Although non-native predator control has been identified as one of the major components of a successful active management strategy, there has been very little quantitative assessment of how these control activities have affected Hawaiian waterbirds. In our study, we quantify the effectiveness of mammalian predator control by evaluating data collected on predator and waterbird populations in areas with active predator management programs.

**METHODS**

To assess mammalian predator control efforts we evaluated data collected in association with predator control programs on 3 Hawaiian National Wildlife Refuges (NWRs): James Campbell NWR, Pearl Harbor NWR, and Keālia Pond NWR (Figure 1). All 3 refuges were created to preserve, restore, and manage essential wetland habitat for endangered waterbird species (USFWS 2010, USFWS 2011b,c). Mammalian predator control efforts on each refuge have varied in duration, control techniques, and spatial coverage. While various predator control activities have taken place on these refuges, we restricted our analysis to those efforts targeting mongooses, rodents, and feral cats. To evaluate effectiveness of these predator control activities, we assessed the status of waterbird and mammalian predator populations both in and adjacent to predator management areas. To assess the impact of mammalian predator control on endangered waterbird populations, we evaluated waterbird densities and reproductive success. If current predator control efforts are effective, we would expect higher bird densities and greater levels of reproductive success in areas with predator control. To evaluate the effectiveness of management activities in reducing the abundance of predators, we assessed the relative abundance of rodents and mongooses in and adjacent to control areas using footprint tracking tunnels (King and Edgar 1977, Gillies and Williams 2013). We also compared live trap capture history and rodenticide bait consumption of traps/bait stations located along the perimeters of controlled wetlands and their interiors. If current predator control efforts are effective, we would expect to see reduced levels of predator activity within control areas and fewer captures and less bait consumption within the interiors of controlled wetlands.

**Predator Control Methods**

Control of feral cats, rodents, and mongooses requires a variety of techniques. Feral cats and mongooses were controlled primarily through the use of live trapping and subsequent euthanasia. Feral cats and mongooses were also deterred to a smaller degree by fences located around the wetlands. Rats, mice, and to a lesser degree mongooses were controlled through the use of rodenticide bait stations. Control efforts for all species were focused along the perimeter of a controlled area. In most cases, perimeters of the controlled areas were delineated by a fence intended to exclude larger mammals (dogs, pigs, cows, horses, and humans). Control efforts are focused on the perimeters to create a barrier preventing predator incursion into the interiors of the wetlands. On James Campbell and Pearl Harbor NWRs, bait stations and live traps were generally paired at each control station. At Keālia Pond NWR, live traps and bait stations were not paired, but were located in close proximity to each other.

**Live Trapping**

We controlled feral cats and mongooses on refuges primarily with Tomahawk® live traps (Tomahawk Live Trap, Hazelhurst, WI) (dimensions: 81 × 25 × 25 cm, and 61 × 23 × 23 cm) and subsequent euthanasia. Live traps contained a water bottle and were sheltered for humane live capture. Each live trap was checked every 24–48 hrs to collect target species and release any incidental captures. Traps were closed when it was not possible to check them within a 48-hr time period.

Our analysis of trapping data was focused on James Campbell and Pearl Harbor NWRs for the time period spanning 2009-2012. On these refuges, we placed live traps at irregular intervals (25-150 m apart) so the limited number of traps could be deployed at the most likely predator entry points. On the Ki’i unit (47 ha; Figure 1) of James Campbell NWR, we placed 30 live traps along the perimeter fence and 9 on interior dikes. On the Honolulu unit (15 ha; Figure 1) of Pearl Harbor NWR, we placed 19 live traps along the perimeter fence and 3 on interior dikes. On the Waiauwa unit (10 ha; Figure 1) of Pearl Harbor NWR, we placed 13 live traps along the perimeter fence and 3 along the interior dikes.

**Rodenticide Bait Stations**

To control rats, mice, and mongooses on the refuges, we used rodenticide bait stations. Each station was baited with six 1-oz Ramik® Mini Bars (Neogen Corp., Lansing, MI), which contained 0.005% diphacinone rodenticide. Bait stations were checked weekly or every other week, at which time the number of baits consumed was recorded and if required, bait stations were replenished and moldy baits replaced. On the Ki’i unit of James Campbell NWR, we placed 40 bait stations along the perimeter fence and 4 bait stations in the wetland core along the dikes. At Pearl Harbor NWR, we placed 16 bait stations along the perimeter fence of the Waiauwa unit and 23 bait stations along the perimeter fence of the Honolulu unit. Our analysis of bait station consumption data focused on James Campbell NWR for the time period spanning 2009-2012, since bait stations at Pearl Harbor NWR were located exclusively along the perimeter.

**Evaluating Effectiveness**

To evaluate effectiveness of the predator control efforts, we assessed both response of waterbird populations and impacts to predator populations. The data required to assess both aspects of effectiveness were not available at any one refuge. To assess the effect on waterbird populations, we estimated bird densities using count data available for Hawaiian wetlands. We also used reproductive success data collected for Hawaiian Stilts at Keālia Pond NWR. To assess the effect on predator populations, we used track tunnel, rodenticide bait consumption, and live trap success data from James Campbell and Pearl Harbor NWRs.
**Waterbird Population Density**

To calculate population density we relied on the results of monthly (refuges) or semi-annual (other wetlands) waterbird counts. Both surveys have a similar methodology. All waterbirds observed or heard on each wetland are counted during a survey. The results are considered a minimum population estimate and underestimate the actual population because these surveys have not been corrected for detectability or observer bias. For the Hawaiian coot and Hawaiian stilt, these biases probably do not significantly impact the accuracy of the population estimate, as both species often use open water and mudflat areas and are considered to have detectability approaching 100% (USFWS 2011a). The Hawaiian gallinule and Hawaiian duck, however, are more secretive and often use densely vegetated wetlands resulting in low detection rates that lead to undercounting (Chang 1990, DesRochers et al. 2008, USFWS 2011a).

For this analysis, we selected representative wetlands from among those identified as high priority wetlands for the recovery of endangered waterbirds (USFWS 2011a). We compared bird densities from wetlands with predator control \((n = 6)\) and without \((n = 6)\). To calculate densities for a wetland, we averaged all bird counts by species for the time period \((2004-2008\) or \(2009-2012)\) and then divided the result by the number of hectares in the wetland. We compared the average densities of controlled and uncontrolled wetlands using the Wilcoxon rank sum test and Welch two sample t-test in R Stats version 2.12.1 (R Development Core Team 2010), selecting the most conservative result for our assessment. We did not include the Hawaiian goose or Hawaiian duck in this analysis, as these species are found in only a select few priority wetlands.

For some locations we included 2 time periods. This was done because our predator control datasets are available for a time period spanning either \(2004-2008\) or \(2009-2012\), and we wanted to evaluate density information that corresponded across the entire time frame of our data. When we did not include 2 time periods for a wetland, it is because the count data are only available through 2008. Additionally, having 2 time periods demonstrates the temporal variability in densities that can be observed even in the same wetland.

**Hawaiian Stilt Reproductive Success**

Of the 5 endangered waterbird species, we had the best reproductive success data for the Hawaiian stilt. The effects of predation on reproductive success can be difficult to isolate from other factors that might cause nest failure. Nevertheless, from 2005-2008 stilt nests in the vicinity of Kanuimanu Ponds (8 ha; Figure 1) at Keālia Pond NWR received predator control; whereas stilt nests in other suitable habitat interspersed across the remainder of the refuge did not (90 ha; Figure 1). This allowed us to gauge the effects of predator control on reproductive success in adjacent areas of similar habitat. Because these two areas were similar in habitat and experienced...
the same environmental conditions, differences in reproductive success were more likely to be the result of predator control. Within the predator controlled area (Kanuimanu Ponds), bait station and trap density ranged from 6-17 traps/stations per ha during the time period analyzed (2005-2008).

To evaluate reproductive success at Ke‘alia Pond NWR, we conducted weekly Hawaiian stilts nest searches each spring (March-June, 2005-2008). Once discovered, active nests were checked weekly. One egg at each active nest was floated and aged following the criteria developed by Alberico (1995). Clutch size was determined when the maximum egg count remained the same after 2 nest checks among nests that had an age index of 1 when first discovered (Alberico 1995). The presence of at least one chick at or near the nest, egg membranes, or egg chips without membrane determined a successful hatch. To evaluate reproductive success, we measured nest success by the Mayfield method (Mayfield 1961, Mayfield 1975) as modified by Klett et al. (1986) with nests containing all infertile/addled eggs excluded from the analysis. We also calculated apparent nest success using the number of nests where at least one egg hatched divided by the total number of active nests. Finally, we determined the cause of nest failure when possible. We evaluated the differences in nest success and depredation rates of the controlled and uncontrolled portions of the refuge using the Wilcoxon rank sum test and Welch two sample t-test in R Stats version 2.12.1 (R Development Core Team 2010), selecting the most conservative result for our assessment.

**Track Tunnels**

Footprint tracking tunnels have been used for more than 30 years as a method to monitor small mammal abundance (King and Edgar 1977, Gillies and Williams 2013). Track tunnels provide a coarse index of relative abundance and are best at detecting differences in areas that are simultaneously sampled, or in detecting change over time in the same area (Gillies and Williams 2013). We performed quarterly track tunnel monitoring from 2009-2012 to evaluate the effectiveness of the mongoose and rodent management program at reducing the density of these predators within the predator controlled area on James Campbell NWR. We deployed track tunnels simultaneously within the predator controlled Ki‘i unit and the Punamanō unit (15 ha; Figure 1), an area of similar habitat with no mongoose or rodent control on the refuge. This analysis allowed us to evaluate the abundance of rodents and mongooses in the predator control areas relative to the uncontrolled surroundings.

On James Campbell NWR, we permanently located a grid of track tunnels 50-100 m apart along the perimeter of the each wetland unit and across the interior dikes (Gillies and Williams 2013). Each track tunnel sampling period covered 4 days. Tracking cards were reviewed for footprints on the second and fourth days. On the first day of the sampling period, tracking cards were baited with peanut butter. If no track detections occurred, sardines were added the following day. If detections did occur on the second day, a new card was placed in the tunnel and baited with sardines. Although tracking cards were collected at the end of each sampling period, the track tunnels remained in place to allow target animals to become accustomed to their presence (Gillies and Williams 2013).

To compare relative activity levels of rodents and mongooses in the control and uncontrolled area, we summed the number of positive detections at each station across the 4-year sampling period. We then calculated the percent visitation rate for each track tunnel station by dividing the total detections at a station by the total possible detections (n = 18 for Punamanō; n = 17 for Ki‘i). Finally, we evaluated differences in percent visitation on controlled and uncontrolled portions of the refuge with the Wilcoxon rank sum test and Welch two sample t-test in R Stats version 2.12.1 (R Development Core Team 2010), selecting the most conservative result for our assessment.

**Capture History and Rodenticide Consumption**

The goal of live/kill trapping and rodenticide bait stations on refuges is to “stop predators at the gate.” For this reason, most predator control effort is focused along the perimeters of controlled wetlands. In addition to the activity information we obtained from track tunnels, we assessed our effectiveness at stopping predator ingress by evaluating the live trap capture history and bait consumption data for spatial patterns. For our evaluation, we summed the total number of captures in a trap across the time period or the total bait consumed from a bait station. We then averaged the results by location, either perimeter or interior. We compared the average total capture or consumption rates between perimeter traps and interior traps using the Wilcoxon rank sum test and Welch two sample t-test in R Stats version 2.12.1 (R Development Core Team 2010), selecting the most conservative result for our assessment. For these analyses, we used live trap capture history data and rodenticide consumption data for 2009-2012 from James Campbell and Pearl Harbor NWRs.

**RESULTS AND DISCUSSION**

**Waterbird Populations**

**Waterbird Population Density**

Waterbird population densities varied by species, location, and wetland size (Table 1). Across all species except the Hawaiian duck, the highest observed densities were on wetlands with predator control. Hawaiian coots (P < 0.03) and Hawaiian stilts (P < 0.01) had significantly higher densities on predator controlled wetlands, but we found no significant difference for the Hawaiian gallinule (P < 0.34). However, this metric is probably not a very good measure of the effectiveness of predator control. Many factors contribute to the number of birds at a given wetland. The type of wetland, resource availability, disturbance, depth of water, salinity, percent open water, type of wetland vegetation, time of year, time of day, level of recent precipitation, proximity to other wetlands, and many other factors can affect the species and number of individuals that use a wetland. Although we believe that predator control likely has a positive effect on waterbird population densities, we could not isolate its effect with the count data.
Table 1. Densities (birds/ha) of endangered Hawaiian waterbird populations on wetlands with and without non-native mammalian predator control. Densities based on average count data for the time period identified. All wetlands occur in Hawai‘i.

| Location and Time Period | Hectares | Hawaiian Stilt | Hawaiian Coot | Hawaiian Gallinule | Hawaiian Duck |
|--------------------------|----------|----------------|---------------|-------------------|--------------|
|                          |          | 2004-2008      | 2009-2012     |                   |              |
| James Campbell NWR: Ki‘i Unit | 28.3     | 5.45; 1.89     | 11.43; 7.29   | 2.48; 1.91        | NA           |
| Pearl Harbor NWR: Waiawa Unit | 8.3      | 9.91; 5.90     | 1.41; 3.33    | 0.01; 0.00        | NA           |
| Pearl Harbor NWR: Honouliuli Unit | 7.5      | 6.03; 6.94     | 18.64; 7.92   | 0.03; 0.86        | NA           |
| Hanalei NWR | 103.2    | 0.69; 1.97     | 0.42; 2.08    | 0.53; 3.32        | 1.30; 3.07   |
| Keālia Pond NWR | 101.2    | 3.40           | 1.77          | NA                | 0.04         |
| Hāmākua Marsh | 8.9      | 2.30           | 0.63          | 3.48              | NA           |

| Location and Time Period | Hectares | Hawaiian Stilt | Hawaiian Coot | Hawaiian Gallinule | Hawaiian Duck |
|--------------------------|----------|----------------|---------------|-------------------|--------------|
|                          |          | 2004-2008      | 2009-2012     |                   |              |
| James Campbell NWR: Punamanō | 15.2     | 0.33; 0.56     | 0.13; 0.47    | 0.04; 0.12        | NA           |
| Lumaha‘i Valley Wetlands | 51       | 0.00           | 0.10          | 0.00              | 0.02         |
| Ka‘elepulu Pond | 34.8     | 0.33           | 1.42          | 0.49              | NA           |
| Loko Waka Ponds | 10       | 0.00           | 1.53          | NA                | 0.03         |
| Hanapēpē Salt Ponds | 20       | 0.23           | 0.10          | 0.01              | 0.01         |

1 Two time periods are identified for some locations, as predator control data for our analyses spanned either 2004-2008 or 2009-2012.

2 National Wildlife Refuge (NWR)

3 Mongooses are currently not considered to be present at Hanalei and Hulē‘ia NWRs, Lumaha‘i Valley Wetlands, or Hanapēpē Salt Ponds.

Table 2. Hawaiian stilt (ae‘o; Himantopus mexicanus knudseni) reproductive success and nest depredation rates at Keālia Pond National Wildlife Refuge, Hi, 2005-2008.

| Year | Number of Nests Total (Viable) | Nest Success (Apparent) | Nest Success (Mayfield) | Depredation Rate |
|------|--------------------------------|-------------------------|-------------------------|-----------------|
|      |                                |                         |                         |                 |
|      | Predator Control Area           |                         |                         |                 |
| 2005 | 59 (53)                         | 54.2%                   | 44.8%                   | 39.0%           |
| 2006 | 25 (21)                         | 49.2%                   | 48.0%                   | 36.0%           |
| 2007 | 40 (31)                         | 40.0%                   | 38.7%                   | 37.5%           |
| 2008 | 44 (43)                         | 61.4%                   | 48.0%                   | 6.7%            |
|      | No Predator Control Area        |                         |                         |                 |
| 2005 | 88 (82)                         | 31.8%                   | 25.2%                   | 63.6%           |
| 2006 | 52 (48)                         | 44.2%                   | 39.7%                   | 53.8%           |
| 2007 | 40 (25)                         | 7.5%                    | 17.0%                   | 35.0%           |
| 2008 | 64 (38)                         | 26.6%                   | 34.0%                   | 54.9%           |

Reproductive Success

At Keālia Pond NWR, we found that areas with predator control had consistently higher rates of stilt nest success (Table 2). In some years, nest success was double or triple the rate in uncontrolled areas; however, we found only apparent nest success rates (P < 0.05) to be statistically significant (Mayfield methods (P < 0.06)). The rate of depredation in the controlled area was generally lower but was not significantly different (Table 2; P < 0.06). However, this result considers both avian and mammalian depredation. When we consider only mammalian depredation, feral cat, mongoose, and rat depredation events were noticeably reduced in the predator control areas. These findings demonstrate the importance of predator control during the nesting season. While our results are specific to the Hawaiian stilt, we believe that mammalian predator control also benefits other waterbird species. Even with mammalian predator
control, nest depredation was not eliminated, so future predator control efforts should also focus on avian nest predators.

**Predator Populations**

*Capture History and Rodenticide Consumption*

On the Honouliuli unit of Pearl Harbor NWR, the average total capture for perimeter live traps (n = 19) was 11.68 mongooses and 0.68 feral cats during the sampling frame. For the 3 interior traps, the rate of capture was 8.0 mongooses and 1.0 feral cats per trap. For both feral cats (P < 0.37) and mongooses (P < 0.06), there was no significant difference. On the Waiawa unit of Pearl Harbor NWR, the results showed no difference between the perimeter and the interior traps. However, there was a stark contrast between traps that abut the ocean and the rest of the traps, so we decided to modify our evaluation to reflect this situation. The 4 traps that border the ocean caught an average of 4.5 mongooses per trap and no feral cats. The rest of the traps (n = 12) caught an average of 42.91 mongooses and 1.08 feral cats during our sampling period. For both mongooses (P < 0.01) and feral cats (P < 0.01), the difference was significant. On the Ki’i unit of James Campbell NWR, the average total catch amongst the perimeter live traps (n = 30) was 16.67 mongooses and 0.73 feral cats during the sampling period. For the 9 interior traps, the rate of capture was 2.11 mongooses and 0.11 feral cats per trap. For both feral cats (P < 0.01) and mongooses (P < 0.01), the difference was significant.

At Pearl Harbor NWR, perimeter and interior traps had similar capture rates. However, the distance from the perimeter fence to these “interior” traps was always less than 50 m. While on James Campbell NWR, interior traps had an average distance of ~200 m from the perimeter and none were within 50 m. At the Waiawa unit of Pearl Harbor NWR, we found that traps bordering the ocean caught substantially fewer predators. Because it is unlikely that cats or mongooses swim into the refuge, these trapping sites represent the furthest locations from potential predator incursion points and can serve as a better indicator of predator invasion into the refuge than the interior traps.

On James Campbell NWR, feral cat and mongoose capture rates were substantially higher along the perimeter of the wetlands. These results would seem to indicate that the predator control program is effective at limiting mongoose and feral cat ingress into the more sensitive wetland interior, where the bulk of the endangered birds forage, roost, and raise their young. The smaller size of the Pearl Harbor NWR wetlands and higher rates of capture by interior traps suggest these wetlands face greater levels of predator incursion and have a reduced predator limited interior area. To combat this problem, a higher rate of trapping may be needed, and further study should be given to reproductive success on these two refuges.

For mongooses, we observed a large absolute difference between perimeter and interior trap success. This result indicates that the mongooses are being trapped along the perimeter and are likely found at low densities within the interior of the wetland. In contrast, the overall low capture rate for feral cats regardless of trap location does not clearly indicate that the program is effective at reducing the density of this predator. To more accurately determine the effectiveness of our feral cat control, we need alternative methods to evaluate feral cat abundance and program effectiveness.

Rodenticide bait consumption showed a far less dramatic difference. On the Ki’i unit of James Campbell NWR, the average number of bait blocks consumed was 87.29 for perimeter traps (n = 40) and 92.45 bait blocks at the 4 interior traps (P < 0.62). This suggests that rodents are likely found at similar densities across the Ki’i unit. Because we do not know which species are consuming the rodenticide bait, we cannot assess if the program is effective at controlling rats, the rodent that has the greatest impact on the waterbirds. In fact, anecdotal observations lead us to believe that mice are the main consumers of the rodenticide baits. To more accurately assess the impact of the rodenticide baiting, we could utilize a species-specific measure of abundance, such as track tunnels, and/or employ remote cameras to quantify species’ visitation rates.

**Track Tunnels**

Mongoose activity was significantly higher in the uncontrolled Punamanō unit (P < 0.01) (Figure 2). Levels of rodent activity were similar in both treated and untreated areas [rats (P < 0.10), mice (P < 0.16)], with mouse activity being higher than rat activity (Figure 2). The results demonstrate that the predator control program is significantly reducing the level of mongoose activity in the control area, but may not be as effective at controlling the rodent populations. These results are similar to what we would conclude based on analysis of the trap and bait station data.

We also combined the track tunnel data with our capture or baiting data to identify areas where our current capture or baiting program is less effective. For example, if we are catching very few individuals in the live traps of a certain area but track tunnels document high rates of activity, this should serve as an indicator to investigate control measures in the area. Adjustments could be made such as trap maintenance, adding traps or bait stations, or repositioning current assets. When we compared the capture history data with our track tunnel data for the Ki’i unit of James Campbell NWR, we found several such examples. Although mongoose trapping success was relatively low along the eastern boundary of the managed area, the track tunnel data documented the highest level of mongoose activity in this same area. Track tunnel data also identified the highest activity rate for rats to be around one structure in the interior of the managed area.

**CONCLUSION AND RECOMMENDATIONS**

Although labor intensive and potentially considered a controversial management activity, control of feral cats, rats, and mongooses can be effective at reducing predator abundance and increasing waterbird populations. However, our results raise some questions regarding the efficacy of the currently accepted mammalian predator management program for wetlands in Hawaii and suggest
the need to modify control efforts for both feral cats and rodents. To more effectively assess these conclusions about the current control paradigm, and to provide for future evaluations of success, we need to implement additional monitoring activities in association with each control effort. Additional monitoring activities needed include: a method to systematically assess feral cat abundance both in and around the control area; expansion of rodent abundance assessments such as track tunnels or remote cameras; and increased monitoring of waterbird reproductive success. With these monitoring activities in place, control of feral cats, rats, and mongooses can be better adapted and improved to promote recovery of Hawai’i’s endangered waterbirds.

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