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Special Issue: Effectiveness of Goodnature A24 self-resetting rat traps for invasive rodent control
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Research Article

Modifications to prevent non-target lethality of Goodnature A24 rat traps – effects on rodent kill rates

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Abstract

On Pacific islands, introduced rats (*Rattus* spp.) frequently drive extinction of endemic species. Since 2014, managers in Hawaii have frequently relied on Goodnature™ A24 self-resetting traps for rat control, but these traps can incur non-target mortality. After A24 traps killed several passerines in 2018–2019, we field tested trap modifications (lure type, lure flavor, blockers, and trap height) that might deter birds, but not rats. In 2019–2020, we assessed rat kill rates using digital counters on traps and counts of carcasses below modified and reference traps. We conducted trials at two sites with historic rat control on Kauai Island and two sites with no recent rat control on Oahu Island. At both Kauai sites, space and time variables more strongly affected kill rates than did experimental treatments; on Oahu, site and treatment both affected kill rates. Traps near streams had higher kill rates than upland areas or plateaus. Kill rates were highest in fall (Mohihi) and spring (Halepaakai), possibly reflecting scarce food resources that rendered lure more attractive to rodents or larger post-breeding rodent populations. Our results will improve configuration of trap grids and allocation of staff and hardware resources. On Kauai, there was no effect of trap height (12 cm vs 50 cm) on kill rates. Both black blockers and cinnamon lure (presumed to be distasteful to birds) slightly depressed kill rates versus unobstructed traps and chocolate lure. Automatic lure pumps had similar kill rates static lure, but sample sizes were small. On Oahu, traps with metal blockers had lower kill rates than traps with black or no blockers. We conclude that all tested lures except cinnamon, trap heights of 12 cm and 50 cm, and adding black blockers would not significantly affect rat control, so our next question becomes which modifications best deter birds. Additionally, future A24 trap deployments will focus on the seasonal timing and landscape positions to maximize rat kill rates.

Key words: blocker, excluder, Kauai, Oahu, bird, lure

Introduction

The Hawaiian archipelago, once a hotbed of biodiversity, is experiencing an extinction crisis. Many (63%) of Hawaii's endemic bird species known since European arrival in 1778 have gone extinct, and most of the

remaining species are declining rapidly (Leonard 2008). The situation on Kauai, the oldest of the main Hawaiian Islands, is particularly dire: five of Kauai's 13 forest bird species have disappeared in the last 40 years (U.S. Fish and Wildlife Service 2006). Introduced rats (*Rattus* spp.), which are pervasive drivers of extinction of island endemics (Harper and Bunbury 2015), have been implicated in reduced survival and reproductive success of the remaining eight bird species. In particular, rats are a primary impediment to the recovery of the endangered endemic Puaiohi (*Myadestes palmeri* Rothschild, 1893; Fantle-Lepczyk et al. 2018; Hammond et al. 2016; VanderWerf et al. 2014), which numbers only 487 individuals (95% CI: 405–579; Crampton et al. 2017). Rats prey on eggs, chicks, and females incubating eggs; and likely on recently fledged birds (Hammond et al. 2016; Tweed et al. 2006; VanderWerf et al. 2014). Rats also compete with forest birds by consuming seeds, fruits, and invertebrates.

The consensus in Hawaii is that rat control benefits forest birds by reducing predation on females and juveniles (e.g., Fantle-Lepczyck et al. 2018), although this assumption has rarely been tested (but see VanderWerf 2009; Banko et al. 2019). Since 2014, rodent control practitioners in Hawaii have increasingly relied on the self-resetting Goodnature™ A24 rat trap, which is less labor intensive than traditional snap traps and presents fewer regulatory and social obstacles than chemical methods to control rodents (Shiels et al. 2014; Warburton and Gormley 2015). Despite evidence that A24 traps provide effective suppression of rat populations in Hawaii (Shiels et al. 2019), no peer-reviewed studies have assessed benefits of rat trapping with A24s for Hawaiian forest birds. The benefits of rodent control with A24s are thought to outweigh the risk of inadvertent mortality of birds or other species during rodent control, yet there is little published information about non-target mortality. Because A24s only require maintenance every four months, animals may decay or be scavenged prior to trap checks, and non-target mortalities may go undetected (see Kreuser et al. 2020, 2022). However, Gronwald and Russell (2021, 2022) recorded no bird interactions at A24s in a seabird colony in 119 hours of footage spanning 2161 camera-days. Ryan (2021) recorded 1,312 bird observations on cameras at A-24s over two months; one bird (a juvenile Spotted Towhee *Pipilo maculatus* Swainson, 1827) poked its head in a trap, not far enough that it would have triggered the trap.

We concurrently used approximately 300 A24 traps to suppress rat populations 5–10 fold (depending on site and year) in critical bird habitat of the Alakai Plateau on Kauai since spring 2015. In fall 2018, for the first time, we found a dead Puaiohi below an A24 trap; and in spring 2019, we found four more birds, including at least one more Puaiohi (others were too degraded to identify) killed by A24 traps. Between 2015 and 2021 we have directly observed rat predation on females and nests at least 10 times (KFBRP *unpubl. data*). under the assumption that a) more birds are killed

by rats than by traps (Banko et al. 2019; Tweed et al. 2006; VanderWerf et al. 2014); and b) trapping with A24s can be made safe enough to ensure that we protect more birds (by killing rats) than are incidentally killed by A24s, we embarked on three experimental trials to assess trap modifications. Our primary objective was to identify A24 trap modifications to minimize mortality of non-target birds and maximize rat kill rates while controlling for effects of landscape position (e.g., stream vs. upland; headwaters vs. mainstem) and season.

We selected the following A24 trap modifications to test after reading the literature and consulting with experts in the field (including Goodnature™ trap company and predator control experts in Hawaii): 1) the type of lure dispenser, specifically static lure bottle vs. automatic lure pump type (both chocolate flavor); 2) the addition of cinnamon flavor as a bird deterrent to chocolate static lure (Udy and Pracy 1981; Hickling 1997); 3) trap height off the ground (50 cm vs. the standard 12 cm); and 4) presence of a blocker designed to prevent bird, but not rat, entry into the trap. These variables were examined singly or in combination in trials at three study sites. One trial combined an assessment of blockers with both lure flavor and lure dispensing mechanism, while the second trial examined height only, and the third trial compared two different types of blockers to reference traps without blockers. Below we have outlined our hypotheses for these trials.

Lure dispensing mechanism: We hypothesized that automatic lure pumps (ALPs)—which we began using at our Kauai forest sites in fall 2017 after using static lure bottles for 2.5 years—make traps more attractive to non-target birds. We had observed no bird kills until fall 2018. Both types of lure dispensers use the same chocolate lure flavor, but static lure remains in place at the trap opening, where it often molds. The ALPs constantly squeeze lure from a pouch so drops of lure pass through the trap entry and onto the ground, thereby ensuring fresh lure is always present. This pile of fresh lure may attract both rats and birds, thus we predicted that traps with ALPs would have higher rat (and bird) kill rates than traps with static lures.

Lure flavor: We hypothesized that birds would avoid traps with cinnamon lure, but rats would not. Puaiohi is a frugivore, and the frugivorous kaka (*Nestor meridionalis* Gmelin, 1788) does not like the smell or taste of cinnamon (Udy and Pracy 1981; Hickling 1997). Conversely, Clapperton et al. (2015) considered cinnamon to be a rat attractant, and Goodnature™ has been adding it to its lures for several years (R. van Dam *pers. comm.*). Therefore, we predicted no difference in rat kill rates between lure flavors (chocolate vs. cinnamon).

Trap height: We hypothesized that raising the bottom of traps ≥ 50 cm (vs. the standard set of 10–12 cm) would prevent entry by Kauai's native birds, as it does for wekas (*Gallirallus australis* Sparrman, 1786) in New Zealand (Carter et al. 2016). Birds would not be able to climb or fly into

high traps because their outstretched wings would not pass the narrow entrance (Shiels et al. 2022, this issue) Rats are strong climbers so this height should not deter them (Shiels et al. 2014); thus, we predicted no impact on rat kills for a trap configuration that might be safer for birds.

Blockers: We hypothesized that the black plastic blocker made by Goodnature™ to prevent kea (*Nestor notabilis* Gould, 1856) entry would also prevent entry by Kauai's forest birds (R. van Dam *pers. comm.*). Homemade blockers of metal mesh were also expected to prevent bird entry (J. Gaudioso *pers. comm.*). The material, length, and height from ground of these blockers may all affect rat kills. Blockers may deter rats or get jammed with carcasses that cannot fall away from the trap, thus preventing subsequent access to the trap. On the other hand, some blockers may enhance rat access by acting as ladders (K. Pias *pers. comm.*). We predicted that A24 traps without blockers would have higher rat kill rates than traps with blockers, but there would be no difference in rat kill rates between blocker types.

Materials and methods

Study areas

Our field trials occurred on two islands in Hawaii, Kauai, and Oahu. The sites on Kauai had received continuous rat trapping with A24 traps for six months (Mohihi) and four years (Halepaakai) prior to our trials, leading to lower rat densities and kill rates at Kauai sites than Oahu sites. Aside from a few small areas within the Oahu study sites where small populations of endangered plants were occasionally protected from rats with traps, the Oahu sites had no large-scale rat control prior to our study.

Kauai: On Kauai, we worked in two Goodnature™ A24 trap grids, Halepaakai and Mohihi on the eastern portion of Kauai's Alakai Plateau (22°7′18″N; 159°33′48″W,), an ~ 70 km^2 area of relatively pristine, wet (> 6,000 mm rain/year) montane forest dominated by ohia lehua (*Metrosideros polymorpha,* Gaudich). This area is remote, roadless, and drained by numerous deeply incised streams. We acquired high-resolution (1 m^2) LiDAR imagery for the Plateau in 2017, from which we derived habitat metrics (e.g., canopy height, tree density, slope) to describe the 10-m radius around each trap (Supplementary material Appendix A). On average, canopy height and density, and several measures of understory height, are greater in our two study sites than for the Alakai Plateau at large. However, considerable within-site variation exists that may describe variation in trap success. Therefore, within each study site, we examined correlations between these habitat metrics and landscape position.

In both grids, traps are spaced ~100 × 50 m apart (DOC 2006; Appendix B). The 84-ha trap grid at Halepaakai contains 164 traps and has operated continuously from March 2015 to the present. However, this grid has experienced periodic failures (due to CO_2 leakage) from individual traps

after they have been deployed for about 2.5 years, so the effective trap spacing is >100 × 50 m. We installed the 64-ha grid of 124 traps at Mohihi in fall 2018. Most A24 traps in both grids were installed 12–18 cm above ground (industry standard) and were outfitted with a "kill counter" that records the number of times the trap fires between checks. We check traps at both sites three times/year (every 4 months), record the counter tally on each trap, search for and record carcasses under and around the trap, and change out lure and CO_2 to maintain the traps, as needed. In March and June, we use track tunnels to monitor relative rodent abundance (i.e., % of tunnels tracked) on trapping grids and reference plots at both sites, following standard protocols (e.g., Carter et al., 2016). The track tunnel reference plots, where no rodent control occurs, are 44 ha at Halepaakai and 41 ha at Mohihi.

Oahu: On Oahu we chose two sites, Pahole and Kaluaa, where no rodent control was being conducted; we predicted these sites would have high rat kill rates once traps were installed thus greater power to test hypotheses about the effects of blockers. Both sites are mesic forest in the Waianae Mountains. Pahole is one of three major gulches within the Pahole Natural Area Reserve (NAR), and Kaluaa is located on the northern end of the Honouliuli Forest Preserve. The vegetation at Pahole consists mostly of invasive plants, however in certain areas, native plant communities exist (ANRP 2018a). At the Kaluaa site, the terrain is varied, ranging from gradual slopes to vertical cliffs. Like Pahole, at Kaluaa invasive plants dominate most of the forest with localized natives (ANRP 2018b). Parts of both sites are enclosed by ungulate-proof fences. In January 2020, we installed 120 Goodnature™ A24 traps (60 at each site) on previously cleared trails primarily following gulch bottoms. Each trap was spaced 35 m apart along transects that paralleled the gulch bottoms. Previous data from areas near these study sites suggest that black rat (*Rattus rattus* Linnaeus, 1758) density is 2–3 times higher than mouse density (Shiels 2010).

Trap height trial on Kauai

The A24 trap height trial was conducted at Halepaakai, at which all 164 traps have had static chocolate lure since April 2019. In April 2019, we randomly assigned half the traps to be set 12 cm above ground ("low") and the other half to be set 50 cm above ground ("high"; Appendix B). We ran this experiment through March 2020, checking the traps in July and November 2019 and March 2020 (Table 1). We used counters mounted on each trap to monitor this experiment, with physical observations of rat carcasses as a secondary measurement. Given the lack of ungulate scavenging at this fenced site, most rat corpses persist at least 120 days (Kreuser et al. 2022). At each visit, we recorded the counter tally and the number of corpses and replaced the CO_2 and lure if needed. We also noted if the trap

Table 1. Timing and details of three trap modification trials on Kauai and Oahu, including changes in lure type and freshness over time at the Mohihi field site, 2019–2020.

Site	Time Period	Experiment	Details
Halepaakai, Kauai	April 2019–April 2020	Trap Height Trial	12cm vs 50 cm
Mohihi, Kauai	April 2019–April 2020	Blocker * Lure Trial	
	Months	*Lure type*	*Lure freshness*
	April to July	Chocolate Static Lure	Fresh
	April to July	Chocolate Automatic Lure Pump	Fresh
	July to November	Chocolate Static Lure	Old
	July to November	Cinnamon Chocolate Static Lure	Fresh
	November to April	Chocolate Static Lure	Fresh
	November to April	Cinnamon Chocolate Static Lure	Old
Oahu	Jan–May 2020	Blocker Trial	Metal vs plastic vs none

Note: "Fresh" lure refers to lure that was installed at the beginning of that trapping interval, where as "old" lure is lure that remained from the previous trapping session

Table 2. Relative rat and mouse abundance (% tunnels with tracks) in trapping grids and reference plots at Mohihi and Halepaakai, Kauai, Spring 2019–Spring 2020.Until Spring 2019, no traps had blockers, all traps had ALPs, and trap height ranged between 10 and 50 cm, so relative abudance indicates trap effectiveness prior to the modifications made during this study. Between Spring 2019 and Spring 2020, we ran the 2 × 2 study at Mohihi, in which half of the traps had blockers set 0–4 cm off the ground (and half had no blocker) and half the traps had ALPs while the other half had static lures. At Halepaakai during this time, we ran the height experiment, in which half the traps were moved to 50 cm off the ground and the rest were 12 cm off the ground. Thus relative rat abundance in Summer 2019 and Spring 2020 measures the effectiveness of traps during the experimental period.

Site/species	Spring 2019		Summer 2019		Spring 2020	
	Trap grid	Reference	Trap grid	Reference	Trap grid	Reference
Mohihi-rats	4	42	6	52	2	36
Mohihi-mice	2	22	8	24	14	22
Halepaakai-rats	0	62	2	28	9	86
Halepaakai-mice	5	59	5	35	0	51

was in working condition or had failed in the period between checks. We removed any carcasses so they would not be counted at the next visit.

During analysis, we assigned each trap to one of three habitat categories: stream, terrace (above the flood plain but not on ridges or plateaus), and upland (ridges and plateaus). These variables were used as covariates in subsequent analyses. Many of these categorical variables were correlated with the LiDAR-derived habitat metrics around traps so we could not use both in statistical analyses (see Results). We chose to use the categorical variables because few other researchers would have likely described habitat at the fine scale offered by high resolution LiDAR, so these broader habitat categories would be more useful. Statistics for the LiDAR metrics by habitat type are summarized in Appendix C.

*Blocker * lure trial on Kauai*

At Mohihi, we implemented a 2 × 2 factorial experiment of blockers and lures across the entire grid from April 2019 to April 2020 (Table 2). Specifically, 31 traps were randomly assigned to each of four treatments: 1) lure A, no blocker; 2) lure A and blocker; 3) lure B, no blocker; and 4) lure B and blocker (Appendix B). At this site, which is topographically simpler than Halepaakai, we assigned each trap to one of two habitat categories—stream and upland—and stratified by these when assigning

treatment types. These variables were used as covariates in the analyses; their correlations with the LiDAR habitat metrics are summarized in Appendix D.

We used black plastic blockers manufactured by Goodnature™ that allow rat entry and deter bird entry; these blockers attach to the bracket that fastens the trap to its mount. The bottoms of blockers were 0–4 cm off the ground and the blockers stayed on the same traps for the whole year. Every four months we changed one of the lure types (Table 1). Lure age was not part of the experimental design but was introduced after the fact when new lure was unavailable for replacement, thus becoming a variable that we needed to assess statistically. Lure A was always static chocolate lure of variable freshness; Lure B was chocolate automatic lure pump (ALP), then static cinnamon chocolate of variable freshness. All traps had kill-counters. We recorded the counter tally and the number of corpses and replaced the CO_2 and lure if needed (Table 1; Coad et al. 2017). We also noted whether the trap was in working condition, had failed in the period between checks, or had been knocked off the mount (likely by a pig, based on unpublished camera data). Because the blocker stays with the mount and not with the trap, we could not use knocked-off traps in our analysis. We removed any carcasses so they would not be counted at the next visit. The Mohihi site is not fenced, so carcass tallies are unreliable due to pig scavenging, particularly in the stream beds (Kreuser et al. 2022).

Trial of two different blockers on Oahu

On Oahu, all 120 traps had counters and were baited with Chocolate ALPs with a low concentration slug deterrent added (Bogardus et al. 2020). Each trap was randomly assigned within sites to one of three blocker treatments, stratified by site and landscape position within the drainages as "headwaters" or "mainstem" based on whether it was above or below the fork in the drainages: 1) black blocker 0–2 cm off the ground; 2) 16-cm long metal mesh blocker 8 cm off the ground; 3) reference, where there was no blocker and the A24 was set at the standard height off the ground (~ 10 cm; Table 1; Appendix E). These blocker treatments, including set heights above ground and blocker length (for metal mesh) were based on observations of a captive Puaiohi at a conservation breeding facility that were obtained after the initial height study was conducted. The bird was able to access unobstructed traps at any height but did not access traps with black blockers <2 cm off the ground or with metal blockers either < 9 cm off the ground or 16 cm in blocker length at the time of our study (B. Masuda *pers. comm.*). At Pahole, nine traps were outside the fence, with the remainder inside the fence. At Kaluaa, 28 traps were outside the fence and 32 were inside the fence. Traps were checked after one month, in early February, and three months later (May), when they were removed.

Statistical Analysis

On Kauai we created two composite dependent variables for statistical analysis, because of low kill rates at both sites and issues with reliability of both counter tallies and carcass counts. The first was a binomial variable "KillYN"; if ≥ 1 carcass or counter tally was observed in a given 4–month interval, the trap was assigned a 1 (if not, then 0). KillYN was then summed over each of the three checks to create an index, so the range of values was 0–3. This variable, which can be thought of as the A24 trap's propensity to trigger during the study period, often underestimated the activity at the trap. The second variable, "NumKills", was the maximum of carcasses found or the counter tally at each trap check and can be considered a relative kill rate. We used this variable because sometimes (on 14 of 335 trap checks at Mohihi and 9 of 405 trap checks at Halepaakai) between one and three carcasses (both rats and mice) were found below traps with a 0-counter tally, which indicates that sometimes counters fail to record trap fires. These undercounts in our study were 16 and 12 carcasses at Mohihi and Halepaakai, respectively. Conversely, at Mohihi, where pigs are present, on 76 of 335 trap checks, the counter tally was positive (range 1–5) but no carcass was found (and likely scavenged by pigs, although the problem occurred both in streams and plateaus; see Kreuser et al. 2022). At Halepaakai, where no pigs occur, on 125 of 405 trap checks, counters registered between 1 and 10 kills where no corpse was found. These issues occurred at traps with and without blockers, at both trap heights, across multiple lure types, dates, and habitat types, so they did not seem to be biased to any of the variables that we were examining. Using the dependent variable NumKills had the advantage of a more normal distribution for statistical analyses and allowed us to include traps where carcass counts were available despite counters having failed. Nonetheless, in some instances NumKills likely overestimated kills due to counter malfunctions or other animals causing counters to record. Both the KillYN and NumKills variables were divided by the number of trap nights in each check interval, because check intervals were not exactly four months long. When traps failed to pass the test-fire at the four-month visit (usually because they were out of CO_2), we assigned them 2/3 of the trap nights for that period. Results were similar for both response variables, so we reported NumKills/TrapNight (which we abbreviated to "kill rate") in the text and KillYN/TrapNight in an appendix. These variables represent both mice and rat kills, which showed similar temporal and spatial patterns.

At Halepaakai, the fenced site where we conducted the height trial, we included 471 trap checks across 164 traps in the analysis. The raw minimum and maximum values for NumKills at a trap were 0 and 10, respectively, across all trap checks (mean = 1.18). Divided by trap nights, these values converted to kill rates of 0.00 and 0.084 (mean = 0.010), respectively.

At Mohihi, the unfenced site where we conducted the blocker * lure trial, we included 335 trap checks across 124 traps in the analysis. The raw minimum and maximum of NumKills across all trap checks for the year-long study were 0 and 8, respectively (mean = 0.74). The minimum and maximum value for kill rate were 0 and 0.057, respectively (mean = 0.0062).

On Oahu, scavenging was so pervasive that few carcasses were found, and we relied solely on the counter tally divided by the number of trap nights. Several traps were stolen or knocked down by pigs at Kaluaa, and some failed to pass test-fire, so some traps had fewer trap nights. Again, we assumed that traps that failed to pass test-fire had functioned for 2/3 of the trap nights for that period. On Oahu (Kaluaa and Pahole sites combined), the number of kills per trap ranged from 0–17 (mean = 1.76) over four months, with all but three traps having fewer than 10 kills; we ran models with and without the extreme values of 12 and 17 kills. Results of these models were similar, so we report models using all data. Divided by trap nights, these values were 0–0.59 (mean = 0.037) kills/trap night.

We assessed the factors of interest (height, blockers, and lure flavor and delivery mode) and controlled for spatial and temporal effects using Generalized Linear Models in R (Version 4.0.3). In all tests but those involving seasonal variation, we aggregated the data to the trap level by summing our response variables and dividing them by number of trap nights prior to analysis. We examined the distributions of the response variables and log-transformed all of them to improve normality and model fit. For each study area, we ran a null model, a full model, and models with subsets of the predictor variables and compared them using Akaike's Information Criterion (AIC). For the height trial, the full model included landscape position, season, and trap height. For the lure × blocker study, the full model included landscape position, blocker, lure type, season, and lure age, and the interaction between lure and lure age. For Oahu, the full model included blocker type, site, fence status, channel position, month, and interactions, but the interactions were uninformative, so we do not report them. Once we determined the best model fit by lowest AIC and using the principle of parsimony (fewest parameters modeled), we used the emmeans package in R to generate model adjusted parameter estimates and confidence intervals, and to perform significance tests (using $\alpha = 0.05$ as the level of significance). We used both information criteria and significance value to assess whether results corroborated each other in a weight of evidence approach. The degrees of freedom for multivariable models is cited in the AIC tables for each experiment; the degrees of freedom for all pairwise contrasts was infinite. We report adjusted means ± SE. Because we used logistic regression in GLM in our analysis, we cannot report a true R^2; instead we report McFadden's pseudo R^2, which quantifies the relationship between the deviance in the fitted model and the deviance explained by the null model (including the parameters in each of the individual models; https://bookdown.org/egarpor/SSS2-UC3M/logreg-deviance.html).

Table 3. AIC value of height trial models on the dependent variable NumKills/TrapNight at the Halepaakai field site, Kauai, 2019–2020.

Model	Hypothesis	DF	AIC	R^2
Landscape, Season	There are landscape effects on, and seasonal differences in, kill rate	464	1591	0.23
Landscape, Season, Height (Full)	There are differences in kill rate between low and high traps (controlling for both landscape and seasonal differences)	463	1592	0.23
Season	There are seasonal differences in kill rate	466	1593	0.22
Null	Intercept only	468	1704	0
Height	Only trap height affects kill rate	467	1704	0

Note: The smallest AIC value indicates highest likelihood of model fit to the data, with the best model listed first. We report McFadden's pseudo R^2, since this is a logistic regression.

Results

Relative rodent abundance on trapping grids vs. reference plots on Kauai

At Halepaakai in March 2016 (a year after the traps were first installed) relative rat abundance was 17% and 20% on the reference and trapping grids, respectively. By March 2019, when this study began, those figures were 62% and 0%, respectively and by March 2020, they were 86% and 9%, respectively, indicating effective rat suppression on the trapping plot (Table 2). At Mohihi in fall 2018 (before traps were installed), relative rat abundance was 21% (reference plot) and 31% (trapping plot); in March 2020, those figures were 36% and 2%, respectively (Table 2). Relative rat abundance is typically much greater than relative mouse abundance at Mohihi, whereas at Halepaakai they are more similar (except spring 2020; Table 2).

Trap height trial at Halepaakai on Kauai

Models including landscape position and season performed better than the model with only the test variable, trap height (Table 3). The full model including height was only 1 ΔAIC lower than the top model of landscape and season, indicating that height was not a strong predictor of kill rates, but cannot be completely discounted. Thus, we used the full model to generate model adjusted means.

Controlling for height and season, more kills per trap night occurred in terraces (i.e., midway between streams and uplands) than streams (0.0045 ± 0.00073 vs. 0.0037 ± 0.00055 kill rate), and in streams than uplands (0.0029 ± 0.00033 kill rate; Figure 1); the difference between terraces and uplands was not significant (z ratio = 2.29, $p = 0.057$). Track tunnel data support the greater relative abundance of rats on streams vs. uplands. The kill rate was greatest in spring 2020 (December–April 0.0089 ± 0.0011 kill rate), followed by fall 2019 (August–November; 0.0045 ± 0.00058 kill rate) then summer 2019 (May–July; 0.00086 ± 0.00020 kill rate; Figure 1). There were significant differences in kill rate between all pairwise combinations of season ($p < 0.0001$ for both combinations involving summer 2019 and $p = 0.0002$ for fall 2019 vs. spring 2020). However, track tunnels suggested that relative rodent abundance was greater on the trapping grid in July 2020 than in March

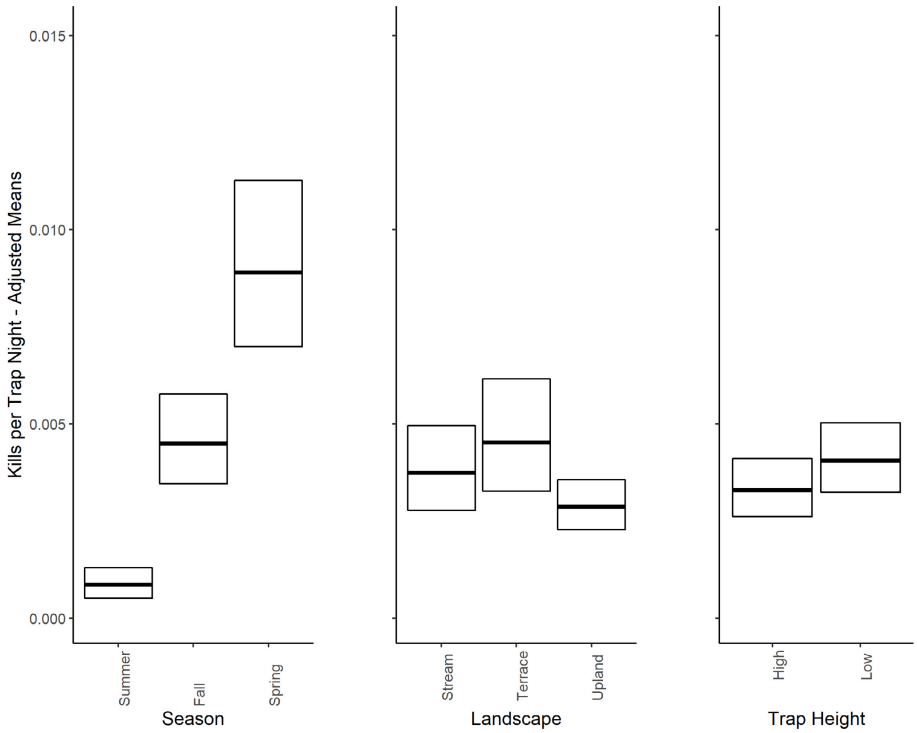

Figure 1. Effect of different variables on kill rate at Halepaakai, Kauai, 2019–2020. *Note:* From left to right: effect of season, landscape position, and trap height on NumKills/TrapNight. Shown are adjusted means (± 95% CI) from the full model, averaged over the levels of the other variables.

2020 (Table 2). Controlling for season and landscape position, kill rates did not differ at high vs. low traps (0.0033 ± 0.00038 vs. 0.0041 ± 0.00045 kill rate, z = −1.35, p = 0.18; Figure 1). Trends for KillYN were qualitatively similar, however only the seasonal differences were significant (Appendix F). Of 151 rodent corpses found at Halepaakai in 2019–2020, 72 were mice, 72 were rats, and the rest could not be identified. No non-target kills occurred during this period.

*Blocker * lure trial at Mohihi on Kauai*

In this trial, comparison of the generalized linear models by AIC favored the more complex models (the full model with all variables including lure age, the interaction model with all variables plus lure type × age interaction, and the design model with all variables but lure age; Table 4). Again, effects of landscape and season dominated. Because AIC is a likelihood penalized by the number of parameters tested, there is evidence that all variables we examined had some effect on kill rates. We used the design model to generate model adjusted means except for the variable Lure Age, which was not in the design model. Trends for Kill Y/N were similar but even the top model did not have much explanatory power (Appendix F).

The effects of landscape (stream vs. upland) and season overwhelmed the effects of our test variables (blocker and lure), which were marginally significant in most models. Controlling for other variables, kill rates were

Table 4. AIC value of lure * blocker trial models on the dependent variable NumKills/TrapNight at Mohihi, Kauai, 2019–2020.

Model	Hypothesis	DF	AIC	R^2
Landscape, Blocker, Lure, Season (Design model)	Both blocker presence and lure type affect kill rate (controlling for landscape and seasonal differences)	328	1124	0.11
Landscape, Blocker, Lure, Season, Lure_Age (Full model)	Lure type, lure age, and blocker presence all affect rate (controlling for seasonal and landscape effects)	327	1125	0.12
Landscape, Blocker, Lure, Season, Lure_Age, Lure Age*Lure (Interaction model)	In addition to the full model, there is an interaction between lure age and lure type that affects kill rate	327	1125	0.12
Landscape, Season	There are both landscape and seasonal differences in kill rate	331	1126	0.09
Lure, Season, Lure_Age	There are differences in kill rate among lure types (controlling for seasonal differences and lure age)	329	1139	0.07
Landscape Model	There are differences in kill rate between traps next to streams and traps on plateaus	333	1140	0.04
Blocker, Lure	Only lure type and blocker presence affect kill rate	331	1150	0.03
Null	Intercept only	334	1152	0

Note: The smallest AIC value indicates highest likelihood of model fit to the data, with the best model listed first. We report McFadden's pseudo R^2, since this is a logistic regression.

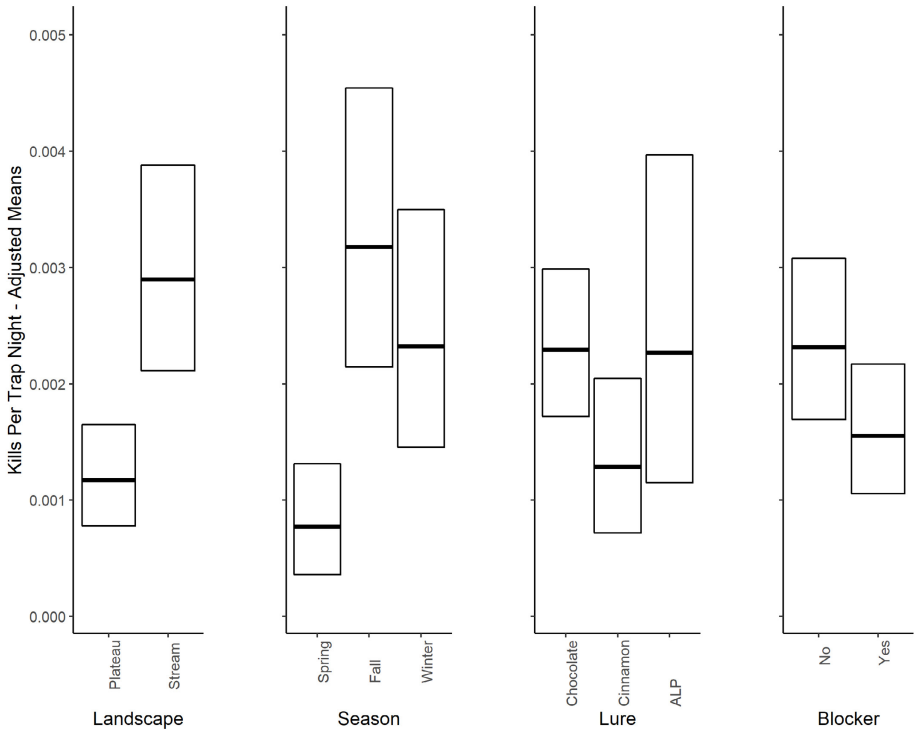

Figure 2. Effect of different variables on kill rate at Mohihi, Kauai, 2019–2020. *Note:* Effect of landscape position, season, lure type and presence of blocker on NumKills/TrapNight. Shown are adjusted means (± 95% CI) from the full model, averaged over the levels of the other variables. Lure types were chocolate static, cinnamon chocolate static, and chocolate automatic lure pump (ALP).

twice as high on streams (0.0029 ± 0.00044 kill rate) than uplands (0.0012 ± 0.0008 kill rate, z ratio = −4.1, $p < 0.0001$; Figure 2). As at Halepaakai, these results for Mohihi were supported by track tunnel data showing a higher likelihood of tracking in stream tunnels than upland tunnels. Kill rates were only slightly higher in fall 2019 (August–November, 0.0032 ± 0.00062 kill rate) than spring 2020 (December–April, 0.0023 ± 0.00051 kill rate, z = 1.29, p = 0.40), but significantly higher than summer 2019 (April–July, 0.00077 ± 0.00024, z = −3.92, p = 0.0003; Figure 2). Kill rates were higher

Table 5. AIC values of blocker trial models on Kills/TrapNight on Oahu, Spring 2020. The best model (smallest AIC) is listed first.

Model	Hypothesis	DF	AIC	R^2
Blocker, Fence, Site, Month, Channel Position (Full)	Blocker type, site, month, and channel position affect kill rate (controlling for differences in fence status)	198	833	0.15
Blocker	Blocker type alone affects kill rate	202	835	0.11
Blocker, Site, Month, Channel Position (Design)	Blocker type, site, month, and channel position affect kill rate	199	835	0.14
Design with Interactions	Blocker type, site, month, channel position, and interactions between main effects influence kill rate	198	836	0
Site	There are differences between sites in kill rate	203	853	0.024
Null	Intercept only	204	856	0
Month	There are seasonal differences in kill rate	203	856	0.0040
Channel Position	There are differences in kill rate between upstream and downstream traps	203	857	0.14

Note: The smallest AIC value indicates highest likelihood of model fit to the data, with the best model listed first. We report McFadden's pseudo R^2, since this is a logistic regression.

in spring 2020 than summer 2019 ($z = -2.81$, $p = 0.01$), but track tunnels in the trapping grid were more likely to be tracked in July than March.

Controlling for other variables, there was no evidence that kill rates were higher at traps with ALPs (0.0023 ± 0.00069 kill rate) than traps with static chocolate (0.0023 ± 0.00032 kill rate, $z = 0.033$, $p = 0.99$; Figure 2). Our inference regarding the ALPs was limited, however, by a short ALP deployment during a lower capture rate season. Kill rates were slightly higher at traps with chocolate static lure than cinnamon chocolate static lure (0.0013 ± 0.00033 kill rate), but the difference is not significant ($z = 2.07$, $p = 0.096$; Figure 2). There was no significant difference in kill rates between new and old lure ($z = -1.022$, $p = 0.31$), but this result should be interpreted cautiously as lures of different types and ages were compared across different seasons. Traps with blockers had slightly fewer kills than traps without (0.0015 ± 0.00028 vs. 0.0023 ± 0.00035 kill rate) but were not significantly different ($z = 1.85$ $p = 0.065$, Figure 2). At Mohihi, 27 of 70 rodent corpses were rats and no non-target kills occurred during this period.

Trial of two different blockers on Oahu

Models including the test variable Blocker performed best, and the blocker-only model was within 2 ΔAIC of the top model, which was the full model (Table 5). Inclusion of Site and Channel Position (and possibly Fence) into the models strengthened our inference about the system, especially through interactions with other variables. However, these variables were not statistically significant, and the principle of parsimony suggests they do not add much explanatory power. We used the full model to produce adjusted means (because you cannot adjust for factors that are not in the model).

Controlling for the other variables and compared to traps with no blockers (which had mean 0.022 ± 0.0059 Kills/TrapNight), rats strongly avoided metal blockers (0.0040 ± 0.0012 Kills/TrapNight, $z = 5.0$, $p < 0.0001$) but did not significantly avoid traps with black blockers (0.014 ± 0.0040 Kills/TrapNight, $z = 0.142$, $p < 0.33$; Figure 3). Metal blockers also performed

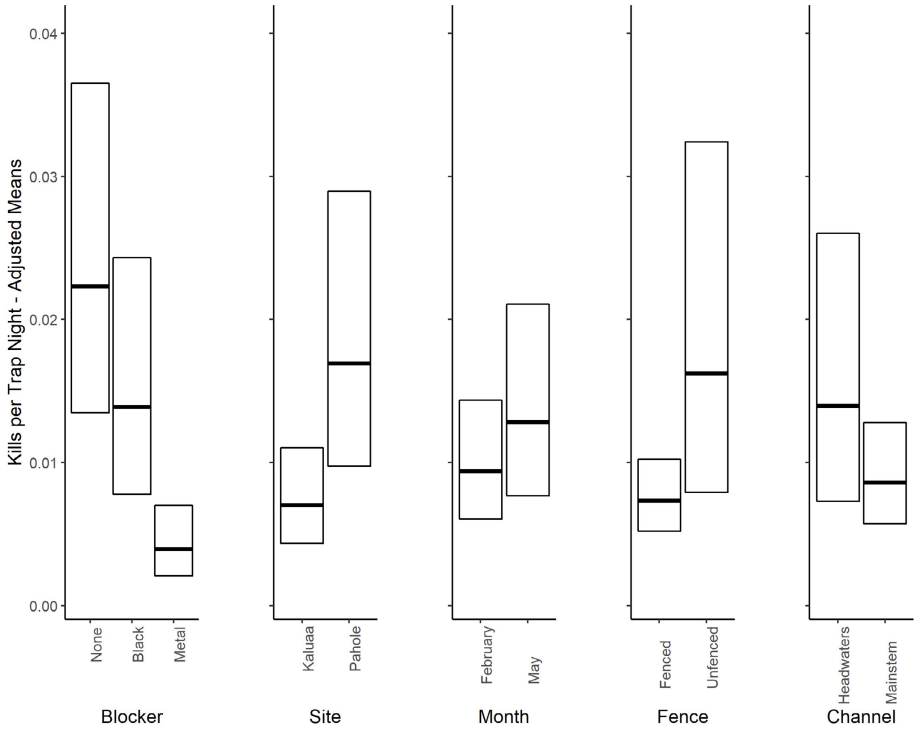

Figure 3. Effects of different variables on kill rate on Oahu, Spring 2020. *Note:* Effects of blocker type, site, date of trap check, fence status, and channel position on Kills/Trap Night on Oahu, Spring 2020. Shown are adjusted means (± 95% CI) from the full model, averaged over the levels of the other variables.

significantly worse than black blockers (z = 3.45, p = 0.0016). Kill rates were approximately an order of magnitude higher at traps with no blockers (0.015 kills per trap night, or one kill every 67 nights) than with metal blockers (0.0023 kills per trap night, or one kill every 386 nights). Most traps with metal blockers had no kills. Black blockers were intermediate with 0.009 kills per trap night or one kill per 111 nights.

There were more kills at Pahole (0.017± 0.0047 Kills/TrapNight) than Kaluaa (0.0070 ± 0.0016 Kills/TrapNight, z = −2.57, p = 0.01, Figure 3), with weak evidence that kills in unfenced areas in the mainstem of Pahole were even greater. The kill rate was apparently higher from mid-February to mid-May (0.013 ± 0.0033 Kills/TrapNight) than from mid-January to mid-February (0.0094 ± 0.0021 Kills/TrapNight), but with greater variance so this result was not significant (z = 1.085, p = 0.28). We lost several traps to pigs and theft in the latter part of the study, which might have influenced the uncertainty around this estimate. There was some evidence that unfenced areas (0.016 ± 0.006 Kills/TrapNight) had higher kill rates than fenced (0.0073 ± 0.001 Kills/TrapNight; z = −1.88, p = 0.06). Headwaters (0.014 ± 0.0044 Kills/TrapNight) had slightly higher kill rates than Mainstem (0.0086 ± 0.0017 Kills/TrapNight) traps, but this difference was also not significant (z = 1.25, p = 0.21).

Discussion

We investigated the impact on rodent kill rates of several modifications to traps that might prevent bird entry, including lure type and flavor, trap height, and addition of bird blockers. Changing trap height, lure type (ALP vs static bottles), or lure flavor had little impact on rodent kill rates, at least in areas already under rat control. However, blocker design was an important factor affecting rodent kills – the long (16 cm), hand-made metal mesh blockers employed during trials on Oahu caused a large reduction in kill rates relative to the plastic black blocker sold by Goodnature™ or no blocker at all. The blocker results are particularly robust in that they held over several study areas with different baseline levels of rodent control. As seen in other studies, including one using A24s in Hawaii (Shiels et al. 2019), trap effectiveness varied seasonally. An unexpected outcome of this study was that the landscape position of A24 traps and the habitat surrounding traps were among the most important variables influencing rodent kill rates. Although mice comprise almost half the carcasses and activity on Kauai, their seasonal and spatial patterns are similar to those of rats, so these results accurately describe trends among rats, which are the target species of control efforts due to their large impacts on forest birds. Similarly, rat and mouse activity were positively correlated on Oahu (ANRP 2014).

Raising traps to 50 cm instead of the standard 10–12 cm appeared to have little effect on kill rates. Black rats, the dominant rat in our study areas, are excellent climbers, and are most active on the ground and to an average of 3 m high in trees (Shiels 2010). Previous studies show that snap traps set in trees at 50 cm kill as many or more rats as snap traps set on the ground (ANRP 2013). However, recent observations of captive birds suggest that higher trap heights will not prevent birds from accessing Goodnature™ A24s (B. Masuda *pers. comm.*; Shiels et al. 2022, this issue). Therefore, we are unlikely to elevate A24 traps above 12 cm at our field sites because of the higher threat to killing birds with elevated traps.

There was no indication that lure type (static vs. ALP) affected rodent kill rates at our Mohihi study site. The cinnamon lure flavor slightly (but non-significantly) depressed rodent kill rates, which was unexpected as rats are not thought to find cinnamon distasteful and cinnamon lure has previously been promoted by Goodnature™ for rat control (R. Van Damm *pers. comm.*). We were surprised that ALPs did not have higher kill rates than static lure, given results of other studies in which ALPs enhance kill rates as measured by track tunnels (Bogardus and Shiels 2020). On the other hand, relative rodent abundance (track tunnel) data from Halepaakai, at which we previously have used both types of lure, remained consistent regardless of lure type (*unpubl. data*), which supports the present result. One possible explanation is that the Kauai study site at which ALPs were investigated has far lower densities of rats than the Oahu study sites

(almost six times fewer kills/trap night based on the A24 data presented here), including those sites in Bogardus and Shiels (T. Bogardus *pers. obs.*). The implication of this difference was that we had less power to detect differences on Kauai due to far fewer rat interactions with traps when compared to Oahu. The maximum number of kills on Oahu was almost twice as high as at Haleapaakai and three times greater than at Mohihi. Furthermore, the lure type comparison was run over four months when kill rates were particularly low, even for this study site, and at only 120 traps. We plan to further investigate the effectiveness of ALPs vs. static lures across more traps and over a longer period in 2021.

Alternatively, rather than our result being an issue of sample size, it is possible that ALPs are less effective in areas of low rat density (like Kauai) than they are in areas of high rat density (like Oahu). Simulations have shown multi-set or self-resetting traps (like A24s) to be more effective than single-set traps at high, but not low, rat densities (Warburton and Gormley 2015). At low rat density sites with lower trap visitation rates, single-set traps are effective at rat control. ALPs are designed to maximize the multi-set nature of A24s by continuously providing fresh lure, and thus according to this simulation be most effective in high rat-density areas. A24s equipped with static lure, which in some environments molds quickly or is eaten by slugs (Bogardus et al. 2020), may perform more like single-set traps, and work quite well in low rat-density areas. The performance of ALPs (and even self-resetting traps) over a variety of rat densities and other environmental conditions warrants further investigation, especially given their greater cost (~ $150 USD).

At Mohihi, Kauai and both sites on Oahu, the black plastic blockers manufactured by Goodnature™ and secured to the A24 mount caused a slight but not statistically significant reduction in rodent kill rates when set 2–6 cm off the ground, as compared to A24s without blockers. Biologically, this difference may be more significant: if the unobstructed traps that we deployed registered one kill every 67 trap-nights and the traps with black blockers only killed one rat per 111 trap-nights (in the high rat-density site on Oahu), it seems that rat suppression could be more difficult to achieve with plastic blockers in place. However, black blockers mounted close to the ground have been one of only two successful means of greatly reducing bird entry into traps (B. Masuda *pers. comm.*; Shiels et al. 2022, this issue). Further, rat densities and rat kill rates seem to be low throughout most of the range of endangered forest birds on Kauai, so use of black blockers on A24 traps warrants strong consideration for wide-scale deployment and subsequent monitoring at our field sites on Kauai. However, it needs further investigation across a wide range of rat densities. Another issue is that we do not know how low rat densities need to be before noticeable gains in bird survival are achieved. Rat control to benefit one sensitive bird species in New Zealand required rat activity from tracking tunnels to be < 10%

(Innes et al. 1995). It may be that we can kill slightly fewer rats at traps with blockers (vs. reference traps without blockers) while still increasing bird survival (due to fewer kills by both rats and traps). On the other hand, even slight reductions in trap performance may hamper recovery of these species. We have recently procured a grant to study bird survival as a function of rodent control at these sites.

The 16-cm long metal blockers set 8 cm off the ground performed poorly at both Oahu sites where they were tested, suggesting that something other than rat density was a factor. We chose this design because it was the other successful means of preventing entry of a single Puaiohi when tested in an aviary (B. Masuda *pers. comm.*), we did not think it would get occluded by dead rats, and it was inexpensive. The length of the metal tube was possibly too long, thus strongly deterring both rats and birds. However, another study with Hawaiian crow (*Corvus hawaiiensis*) compared the performance of black blockers to a shorter (10-cm long) metal mesh blockers 10-cm off the ground and found that the crow would not gain access to the A24 trigger area (Vickery et al. 2020). The height of the bottom of the blocker off the ground was possibly a factor, but rats readily access A24s set much higher (see above). Furthermore, while inexpensive, metal blockers proved time-consuming to make, difficult to attach, and hard to transport to field sites without damaging them, and Vickery et al. (2020) concluded for these reasons that metal mesh blockers were not worth pursuing. The black blockers, meanwhile, were costly ($25 USD) and difficult to fit to already-deployed traps because they attach to the back plate that mounts the trap to the tree. This black blocker attachment has proved problematic because pigs in the Mohihi study site frequently remove traps from the back plate, leaving the blocker still attached to the back plate and the trap unblocked on the ground where birds can gain access. We are experimenting with ways to secure the blocker to the traps so that they do not get separated.

Although we were not explicitly investigating environmental variables in these trials, we did control for their effects, and they provided some of the most interesting and statistically significant results. At Mohihi, where the initial trap layout comprised a line of traps down the banks of streams (where two endangered bird species build most of their nests) and "fences" of lines of traps on the uplands adjacent to the streams, the highest kill rates occurred in the streams. At Halepaakai, where traps were deployed at regular intervals without respect to landscape position, rat kills were highest on terraces adjacent to streams and lowest in uplands. Track tunnel data from both sites, which cover both streams and uplands, showed a higher relative abundance of rats in stream corridors at both reference and trapping plots, especially at Mohihi. Streams banks and terraces may be preferred by rats because they have greater food abundance, such as fruiting plants or birds' nests, and more fresh water (Feng and Himsworth 2014). Large trees favored for denning by *Rattus rattus* (Shiels 2010) also tend to

be more common in streams, where they are more protected from wind (mean canopy height was greater in streams; Fricker et al. 2021 and see Appendix D). Some of the upland areas at both Kauai sites consist of boggy soils with short, stunted trees. Similarly in Australia, *R. rattus* avoided heaths and areas of sparse understory (Cox et al. 2000). Rats may also avoid boggy areas because the soils do not allow for denning. Shiels (2010) found that most rodent activity occurred in areas where the space directly above the rodent movement was covered with vegetation, but at Halepaakai more rats were killed in terraces and streams where understory biomass was low.

On Oahu, unsurprisingly, kill rates were higher at the site with the greater rat density (Shiels 2010). All traps were near streams and there was no significant effect of Channel Position (headwater or mainstem) on kill rates. However, Channel Position was confounded with Fence Status, and kill rates appeared to be higher in mainstem unfenced areas where pigs occur. As described above, rats may favor streams for greater abundance of food or denning sites. It is also possible that occasionally pigs bumped traps, causing the counter to fire. Monitoring traps with cameras may answer some of these questions and will be incorporated in future studies.

Rodent kill rates on Kauai were always low on these established trapping grids, indicating the effectiveness of trapping. Nonetheless, they varied seasonally. They were lowest at both Mohihi and Halepaakai in in summer (May–July) and highest at Mohihi in fall (August–November) and Halepaakai in spring (December–April). However, track tunnel data suggested higher relative rat abundance in July vs. March/April. One possibility is that reproduction is higher in the spring, meaning higher rodent numbers and thus both more kills and more tracks by the end of spring. Another possibility (not mutually exclusive) is that food resources vary seasonally, potentially resulting in rats being less attracted to traps during periods of enhanced food abundance (e.g., April–July 2019 in this study; July–September in Shiels 2010). Our study covered just one year, but if such patterns were seen each year, and because rat predation disproportionately affects breeding birds, it would be particularly important to concentrate trapping efforts and resources in the fall and spring at our study sites if we could not trap all year.

Conclusions

The benefits of rat control to native forest bird species in Hawaii are thought be large enough to outweigh any inadvertent mortality of birds. Although the detrimental impacts of rat predation on native species have been well documented (e.g., Tweed et al. 2006; VanderWerf et al. 2014; Hammond et al. 2015 and 2016), studies of control are far fewer and have focused on benefits to the target species rather than environmental costs (e.g., VanderWerf 2009; Banko et al. 2019). Given this assumption and our

documentation of non-target take, an important outcome of this study will be recommendations for A24 trap modifications to reduce by-catch without greatly diminishing rat kills. We anticipate that this information can be widely implemented by A24 users across Hawaii and other areas where these traps are used and non-target take may occur. This study demonstrated that attaching black plastic blockers to A24s traps and securing the blockers 0–6 cm from the ground does not greatly reduce rat kills. Therefore, these black blockers seem to be a viable option for reducing bird entry and bird mortality when using A24 traps in areas where such bird entry into these traps is a concern. This study also suggests that comparing the effectiveness of ALPs vs. static lure warrants further study across a range of rodent densities, especially because ALPs were the lure dispenser present on A24 traps when birds were killed by A24s on Kauai. Seasonal differences in kill rates may indicate periods in which it is particularly important to focus trapping efforts and/or when studying different modifications may produce more robust results. Finally, the greater effectiveness of traps placed next to streams and on terraces vs. plateaus across several study sites and regardless of season or trap modification suggests that we can improve our trapping program by adding traps near streams and reducing the number of traps in upland areas.

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Authors' contribution

All authors contributed to the experimental design of the study. JMH, TAW, and TB took the lead on data collection, with help from EMG, LHC. Data management and analysis was primarily performed by EMG, JMH and MKR, with help from LHC. LHC wrote the manuscript, which was edited by ABS and MKR. All authors reviewed the manuscript.

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Supplementary material

The following supplementary material is available for this article:

Appendix A. Mean, minimum and maximum for topographic and forest structure variables extracted from LiDAR imagery for the Alakai Plateau as a whole and the Mohihi and Halepaakai field sites on Kauai, Hawaii.

Appendix B. Experimental Design at a) Halepaakai and b) Mohihi Study Areas on Kauai Island, Hawaii, Spring 2019–Spring 2020.

Appendix C. Association of LiDAR variables with Landscape Position of A24 Traps at Halepaakai, Kauai, 2019–2020.

Appendix D. Association of LiDAR variables with Landscape Position of A24 Traps at Mohihi, Kauai, 2019–2020.

Appendix E. Design of blocker experiment at two sites, a) Kaluaa and b) Pahole, on Oahu Island, Hawaii. January–May 2020.

Appendix F. AIC tables for models in which KillYN was the dependent variable in trap modification experiments at two sites on Kauai, Hawaii, 2019–2020.

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