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Effectiveness of snap and A24-automated traps and broadcast anticoagulant bait in suppressing commensal rodents in Hawaii

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Abstract: Commensal rodents (invasive rats, *Rattus* spp.; house mice, *Mus musculus*) are well established globally. They threaten human health by disease transfer and impact economies by causing agricultural damage. On island landscapes, they are frequent predators of native species and affect biodiversity. To provide managers with better information regarding methods to suppress commensal rodent populations in remote island forests, in 2016 we evaluated the effectiveness of continuous rat trapping using snap-traps, Goodnature® A24 self-resetting rat traps, and a 1-time (2-application) hand-broadcast of anticoagulant rodenticide bait pellets (Diphacinone-50) applied at 13.8 kg/ha per application in a 5-ha forest on Oahu, Hawaii, USA. We compared rat and mouse abundance at the rat trapping site to a reference site by monitoring rodent tracking tunnels, which are baited ink cards in tunnels that allow footprints of animal visitors to be identified. We found that trapping reduced rat, but not mouse, abundance. The rodenticide treatment did not further reduce rat populations (P = 0.139), but temporarily reduced the mouse populations (P < 0.001; from 33% tracking to 0% for 1.3 months). Our study highlighted the role of continuous trapping for rats and rodenticide baiting for mice as effective methods to suppress commensal rodent populations in remote island forests to protect native species biodiversity.

Key words: biodiversity, endangered species, Goodnature self-resetting traps, Hawaiian Islands, invasive pest species, *Mus musculus*, *Rattus exulans*, *R. rattus*, rodent management, rodenticides, tropical forest ecosystems

Commensal rodents have been implicated in affecting human health by disease transfer and impacting economies by causing agricultural damage (Pimentel et al. 2000). The most well-known commensal rodent species found worldwide include the Norway rat (*Rattus norvegicus*), black rat (*R. rattus*), and house mouse (*Mus musculus*). The Pacific rat (*R. exulans*) is restricted to southeast Asia and Pacific islands. These commensal rodent species may be locally abundant in urban, suburban, and agricultural areas, and they are among the most problematic invasive animals affecting natural resources (i.e., native species) on islands (Towns et al. 2006, Angel et al. 2009, Witmer and Shiels 2018). Through mostly unintentional introductions by humans, these rodents occupy >80% of the major islands worldwide (Atkinson 1985, Towns 2009, Witmer and Shiels 2018). On large islands, or those that are occupied by humans, complete removal of all such invasive rodents is not possible with available technology. Therefore, rodent control or suppression by trapping and/or poisoning within segments of islands is the most common form of protecting natural resources from the negative impacts of commensal rodents on islands (Duron et al. 2017).

In the Hawaiian Islands, USA, nonnative commensal rodents are now established from sea-level to near the peaks of the highest mountains (>3,000 m elevation) and occupy some of the most isolated forests (Shiels 2010, Shiels et al. 2014). In these areas, black rats and Pacific rats are most well-known for depredating native species (Shiels et al. 2013, 2014), including endangered birds (VanderWerf 2001), snails (Hadfield et al. 1993), and plants (Pender et al. 2013). Mesic forests are generally the most diverse ecosystems in Hawaii, and

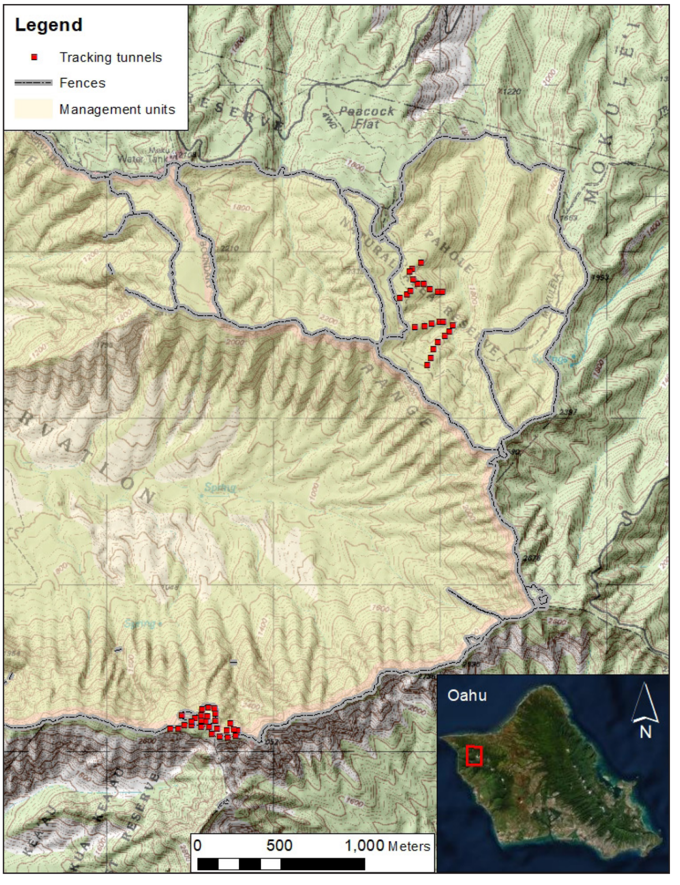

Figure 1. Map of the study locations in mesic forest in the Waianae Mountains, northwest Oahu, Hawaii, USA. The cluster of tracking tunnels (red squares) on the upper part of the map is the reference site (Kapuna) where no rodent control occurred, and the cluster of tracking tunnels on the lower (southern) site (Ohikilolo) is where rodent suppression occurred with continuous trapping and a 1-time hand-broadcast of rodenticide bait. The nearest human dwelling to either site is >3 km.

many rare, threatened, or endangered plants, snails, and birds reside in such forests and on U.S. Army-managed lands. The U.S. Army is required to stabilize populations of endangered species and their habitat as per Biological Opinions issued in 2007–2008 by the U.S. Fish and Wildlife Service (Oahu Army Natural Resources Program [OANRP] 2013).

The OANRP has been engaged in rodent control since 1995 using various techniques including snap traps, automatic traps, diphacinone rodenticide (the only approved rodenticide for use in conservation areas) applied in bait stations, and physical barriers. At the OANRP site called Ohikilolo, there is a stand of endangered palm (*Pritchardia kaalae*) that is the last remaining large stand (~85 adults) on Oahu, and it has seeds that are highly vulnerable to black rat predation (Shiels and Drake 2015). Furthermore, once goats (*Capra hircus*) were removed and rat suppression was in place at Ohikilolo, the juvenile palm numbers went from nearly zero to 1,600 individuals in just a few years (OANRP 2013). Several additional native plant species (Shiels and Drake 2011) and endangered tree snails (*Achatinella mustelina*; Hadfield et al. 1993) receive high rates of rat predation in mesic forests on Oahu, and this underscores the importance of implementing rodent control programs for protecting such natural resources. The OANRP rat control tools became more restricted in 2013 due to changes to the diphacinone Special Local Needs label that made bait station application unfeasible at most sites; label-specified bait station grid sizes and spacing were impossible to meet given the steep and rugged terrain and intrusion to adjacent land ownership at many sites (OANRP 2013). Therefore, rodenticide use was halted in 2013 at all the OANRP-managed sites (OANRP 2013).

Due to the high habitat quality and small sizes of Army-managed lands, grids of Victor® snap-traps were installed in 2009–2011 to protect native species from rats. These rat trapping grids were augmented with bait stations until 2012, and both were re-baited every 6 weeks (OANRP 2013). Snap-trapping and/or diphacinone rodenticide use results in an initial knock-down in the rat population (Pender et al. 2013, Shiels 2017) followed by a fluctuating rat population below pre-trapping levels (OANRP 2018). From 2013 to 2015, many of the rat snap-trap grids were supplemented or replaced by Goodnature® A24 rat + stoat traps (Goodnature Limited, Wellington, New Zealand; hereafter A24 traps or A24s), which are self-resetting traps that can fire 24 times with 1 CO_2 cartridge. The A24s and rat snap-traps were typically baited every 4 weeks.

Rat populations fluctuated during uses of

Figure 2. Ohikilolo treatment site (shown by arrow) within the western part of the Waianae Mountains, Oahu, Hawaii, USA. The Makua Valley military training area is in the central foreground and extends toward the Pacific Ocean.

both snap-traps and A24 grids, and the targeted levels of rat suppression were not always being met with the rat trapping grids; this resulted in noticeable losses of native and endangered seeds and predation of native snails by rats (OANRP 2018). Additionally, mouse populations often increased when rat trapping and suppression occurred (Witmer et al. 2007, OANRP 2018). Due to these shortcomings in rodent control using traps, there was interest but little experience in using broadcasted rodenticide baits to assist with rat and mouse suppression so that targeted natural resources were better protected.

An acceptable level of rat and mouse activity that promotes stable or increasing native or endangered species is unknown, but Innes et al. (1995) reported that reducing rat activity to 10% in tracking tunnels following treatment protected a native bird species in New Zealand. Pender et al. (2013) found that tracking tunnel activity of approximately 20% or less post-treatment was sufficient for increasing seed production of an endangered plant in mesic Hawaiian forests.

The objectives of our study were to determine if: (1) rat trapping using Victor® snap-traps and A24s was effective for suppressing commensal rat and mouse activity, and (2) if a 1-time (2-application) hand-broadcast of Diphacinone-50: Conservation rodenticide, applied according to label (Diphacinone 50: Conservation, EPA Reg. No.: 56228-35, State of Hawaii Lic. No. 8600.1) and during rat suppression through constant trapping with A24s and snap-traps, would reduce the commensal rodent populations in mesic remote forest in Hawaii. Based on previous research (Pender et al. 2013), we determined that effective rat and mouse suppression needed to reach tracking tunnel indices of ≤20%.

Study area

We conducted our experiment using 2 mesic forest sites located at 600–900 m elevation in the Waianae Mountains on Oahu Island, Hawaii. At the treatment site (Ohikilolo, within the Makua Military Reservation), we attempted to suppress rodent activity with a combined strategy of kill-traps and Diphacinone-50, and we compared the results to a reference site (Kapuna) where no rodent control occurred (Figure 1). The treatment area in Ohikilolo (158° 11′ 35.553″W, 21° 30′ 47.459″N) consisted of a steeply sloped 5-ha area that was fenced to exclude ungulates and is only accessible via helicopter or long hike (Figure 2).

Nonnative rodents are ubiquitous at Ohikilolo, including black rats, Pacific rats, and house mice. Norway rats are not typically found in forests in Hawaii, but they are established in urban, suburban, and agricultural areas (Shiels 2010, Shiels et al. 2014). Black rats numerically dominate these forests, outnumbering Pacific rats by ~10-fold (Shiels 2010). Negative impacts of each of these 3 rodent species in mesic forests near Ohikilolo have been reported for native plants, insects, snails, and birds (Shiels et al. 2013, OANRP 2018), and the dominant black rat is known as the most damaging rodent to island forests (Shiels et al. 2014).

Kapuna, our reference site, was 12 ha and approximately 2.4 km from Ohikilolo and has a similar mesic forest habitat but is less steep than Ohikilolo (Figure 1). There is only forest habitat near and between Ohikilolo and Kapuna, and the nearest human dwelling to either site is >3 km (Figure 2). Similar to Ohikilolo, Kapuna is fenced to keep out nonnative ungulates. This forest is also inhabited by native species vulnerable to rodents, including endangered plants (Pender et al. 2013, OANRP 2018). We were unable to add additional sites for our study because this would require additional

Figure 3. Rat traps used at Ohikilolo, Oahu, Hawaii, USA. Left image is a Victor snap-trap, and right image is a Goodnature A24 automatic trap. Bait lure is placed on the yellow treadle on the snap-trap and within the black reservoir on the upper right side of the A24 trap. Three yellow fruit of the invasive strawberry guava (*Psidium cattleianum*) had recently fallen and are visible beneath the A24 trap. The A24 is secured with screws to the guava tree.

areas where land managers would have to refrain from actively controlling rodents and thus leave natural resources unprotected that rodents (particularly rats) are known to depredate.

Methods

Treatments

Rat control at the treatment site had been conducted in a nearly continuous manner using snap-traps or diphacinone bait stations or the 2 methods in combination for >15 years before our study began, yet monitoring the effectiveness of these rat control efforts was absent until 2009. Since 2009, rat control was considered successful, and the rat population was maintained below 20% activity in tracking tunnels except for an 8-month period (April to November 2015) where there was no access to the site and rat control did not occur. Rat activity had risen to 33% by December 8, 2015, when site access was reinstated (OANRP 2018). On December 9, 2015, our year-long study began at our treatment site of Ohikilolo when we deployed 53 A24s (20 x 7 x 14 cm [length x width x height]; 6 cm diameter opening for rodent entry) and 127 Victor rat snap-traps (18 x 9 x 2 cm [length x width x height]; Figure 3) arranged in a grid within the 5-ha fenced area. A24s are self-resetting traps that are powered by CO_2 gas such that they fire 24 times before the CO_2 cartridge needs to be replaced. Each firing occurs when a rodent places its head up into the trap toward the lure, depressing the trigger that activates a bolt that rapidly slides forward and impacts the rodent in the head (http://goodnature.co.nz). The trapping grid was arranged so there were A24s every 25 m and snap-traps every 10 m within a transect, and there was approximately 25 m between each transect. Because rats were the species targeted for control at the site, there were no mouse-specific traps used. Although mice (10.7 ± 0.4 g, mean ± SE) are ~10 times smaller than black rats (111.1 ± 3.1 g) in these types of forests on Oahu (Shiels 2010) and may not always trigger rat traps, both rat snap-traps and A24s (Figure 3) have been found to occasionally kill mice (Shiels et al. 2017, OANRP 2018). We checked and serviced the traps every 4 weeks (e.g., re-armed, re-baited, gas cartridge replaced as needed for A24s).

We baited the rat snap-traps with peanut butter and the A24s with static Goodnature chocolate lure. Because rodent carcasses are often scavenged within 1–3 nights (Shiels 2010, Pender et al. 2013, Shiels et al. 2017), rodents were not present on snap-traps or beneath A24s during our checks, and only remnant rodent hair remained under the kill-bar on some snap-traps. Therefore, we did not calculate an index of rodents killed by these methods.

The Diphacinone-50 rodenticide treatment at Ohikilolo consisted of 2 bait applications by hand-broadcast, spaced 7 days apart (June 7 and 14, 2016; the Diphacinone-50 label states the second of the 2 bait applications must be within 5–7 days of the first application). We applied the bait at 13.8 kg/ha by walking the gridded trail system and evenly distributing (via hand-broadcast) rodenticide bait 10 m to each side of each trail and along the interior of the fenceline. We applied 138 kg of bait, 69 kg for each of the 2 applications in the 5-ha area. This resulted in approximately 1 bait pellet per m^2. Because each pellet was 1.1 g, there were approximately 62,727 pellets applied per application. Trapping with snap-traps and A24s was maintained throughout the rodenticide bait applications.

All bait applicators were certified in the Hawaii

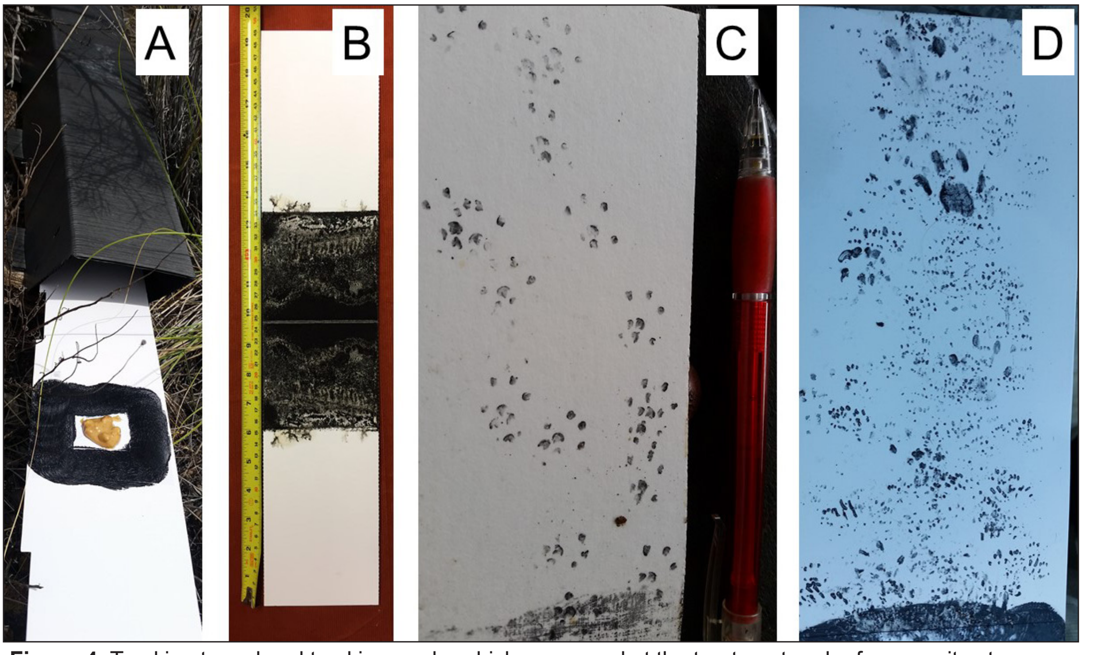

Figure 4. Tracking tunnel and tracking cards, which were used at the treatment and reference sites to monitor rodent populations on Oahu, Hawaii, USA. (A) A tracking tunnel (black) with a peanut butter baited and inked tracking card ready to be inserted into the tunnel. (B) A Gotcha Traps Ltd brand tracking card with pre-established ink; card is ready to be baited and placed into a tracking tunnel (ruler shows card is 49 cm long). (C) Rat (*Rattus* spp.) tracks on a tracking card (with pen for reference). (D) Mongoose (*Herpestes auropunctatus*; largest tracks, in center and upper), rat (medium tracks, in lower and left of center), and house mouse (*Mus musculus*; smallest tracks, appearing as dots throughout and most abundant) tracks on a tracking card. Tracking cards would be scored as "rat present" for (C), and mongoose, rat, and mouse present for (D).

restricted pesticide category 2 (Forest Pest Control) at the time of the operation. The labeled bait concentration for Diphacinone-50 is 0.0050% (50 ppm), and we verified the diphacinone concentration of our applied bait by sampling (i.e., making $n = 9$ samples of ~30 pellets each) from the entire batch of bait received and then having the U.S. Department of Agriculture (USDA) National Wildlife Research Center's (NWRC) chemistry unit analyze them; this batch was (mean ± SE) 0.00526 ± 0.00006% diphacinone.

Rodent monitoring

We used tracking tunnels to monitor changes in rodent activity in response to the treatments (Shiels and Ramírez de Arellano 2018), as tracking tunnels present an index of the relative abundance of the rodent population. Tracking tunnels consist of inked cards that are baited and placed inside a plastic tunnel. As a rodent investigates a bait inside the tunnel, the ink is transferred onto the foot of the animal, resulting in a footprint left on the card, which can be identified to genus (Figure 4). Tunnels (50 x 10 x 10 cm [length x width x height]; made of plastic) and pre-inked tracking cards (49 x 9 cm [length x width]; made of wax-coated paper; an 18 x 9 cm [length x width] inked area occupies the center of the tracking card; Figure 4) were purchased from Gotcha Traps Ltd (Black Trakka; gotchatraps.co.nz). Twenty-seven tracking tunnels were used at Ohikilolo (treatment site), and 24 tunnels were used at Kapuna (reference site; Figure 1). At Ohikilolo, tunnels were randomly placed, spaced ~50 m apart along the trapping grid transects, and the outer 30 m of the trapping grid was avoided. At Kapuna, tunnels were randomly placed, spaced ~50 m apart along established walking trails (Figure 1). Each tunnel was set by placing peanut butter bait in the center of the tracking card, on top of the inked area (Figure 4), and the tunnel was active during a 24-hour period each 1–2 months from January to December 2016. All tunnels at a site were set on the same day, and the tunnels were left in place in the field for subsequent monitoring events. During the rodenticide application, tracking tunnels

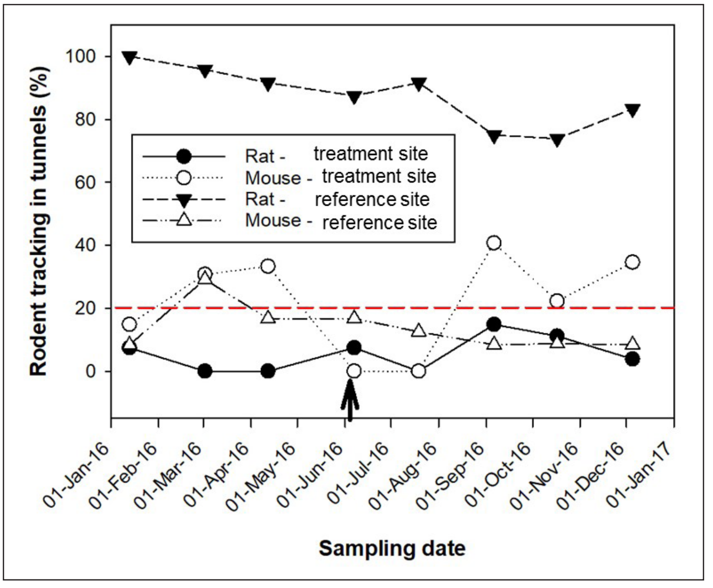

Figure 5. Tracking tunnel results, which indicates rodent activity and population status, for invasive rats (*Rattus* spp.) and house mice (*Mus musculus*) at the treatment site (Ohikilolo; *n* = 27 tunnels) where rat trapping was constant, and the reference site (Kapuna; *n* = 24 tunnels) where no rodent control occurred; both sites are in mesic forest in the Waianae Mountains, Oahu, Hawaii, USA. The arrow represents the date (June 7, 2016) of the first hand-broadcast application of Diphacinone-50 rodenticide bait at the treatment site, which was also when tracking tunnels were activated for a 1-night assessment (recovered on June 8, 2018). A second hand-broadcast occurred at the treatment site 7 days after the first, on June 14, 2016. The horizontal line at 20% presence is the estimated level of suppression needed to protect natural resources from rodent damage.

were set on the day of the first broadcast (June 7, 2016) and collected June 8, 2016, and then 5 weeks post-broadcast (set July 19 and collected July 20) at Ohikilolo. If tracking tunnels at Kapuna were not set on the same day as Ohikilolo, they were set within 2–13 days (average 7.1 days) of those set at Ohikilolo. After 24 hours of deploying tracking tunnel cards, each card was removed, inspected, and tallied for evidence of rat and/or mouse footprints (Figure 4). Although cards varied in the number of individual footprints observed, we only quantified presence or absence of rat and mouse footprints. We determined the ratio or percent of rat and mouse presence for a site and sampling period as the proportion of tunnels where rat or mouse tracks were present relative to the total amount of tunnels set; this provided an index of activity or relative abundance of the site's rat and mouse populations.

Statistical analysis

We used generalized linear models with binomial errors (i.e., logistic regression) to determine if the ratios of rodent presence (tracking) in tunnels were different between the treatment site and reference site during all 8 sampling periods; a total of 2 logistic regressions (1 for rats, 1 for mice) were completed. To determine if the rodenticide bait application was effective at the treatment site, we used chi-square analyses to compare rodent presence prior to treatment (April) to that during treatment (June) and post-treatment (July). We conducted 2 additional chi-square tests (1 for rats, 1 for mice) to determine if there were changes in the rodent populations at the reference site at the time of rodenticide treatment at the treatment site; thus, we compared presence in April, June, and July at the reference site. All statistical analyses were conducted in R version 3.0.3, and significant differences were based on $P < 0.05$.

Results

Rat activity, and therefore the inferred rat population, was lower at the treatment site, averaging 5.6% presence (percentage of tunnels with rat tracks relative to total tunnels set), during the year-long study relative to the reference site (87.4% presence; z = 12.89, SE = 0.37, $P < 0.0001$; Figure 5). Mouse presence averaged 22.1% at the treatment site and was higher than at the reference site (16.1%; z = 2.21, SE = 0.27, $P = 0.03$; Figure 5). When diphacinone rodenticide was applied at the treatment site, it reduced the mouse population for 1.3 months ($\chi^2 = 19.56$, df = 2, $P < 0.0001$), but had no effect on the rat population ($\chi^2 = 3.95$, df = 2, $P = 0.14$; Figure 5).

Tracking tunnels revealed that mouse presence ranged from 15–33% (i.e., percentage of tunnels with mouse tracks relative to total tunnels set) during the prior 6 months to diphacinone bait application (when rat traps were continuously active), and then presence was reduced to 0% within the day after the first bait application (June 7, 2016) and at the subsequent sampling on July 19, 2016. Mouse presence at the treatment site then increased to 40% on September 6, 2016 and persisted above 20% for the remainder of 2016 (Figure 5). Rat presence was <15% during the whole year at the treatment site, averaging about 5% presence during the 6 months prior to diphacinone bait application. Rat presence was 7% within the day after the first bait application (June 7, 2016), 0% on the subsequent sampling on July 19, 2016, and then was 15% by September 6, 2016 (Figure 5). During the period of April to July, around the diphacinone bait application at the treatment site, the reference site did not change in rat (χ^2 = 0.32, df = 2, P = 0.85) or mouse (χ^2 = 0.21, df = 2, P = 0.90) detection rates.

Discussion

Our study documented changes in commensal rat and house mouse populations during a year-long period in Hawaiian forest when rat traps (both snap-traps and A24s) were continuously active and when diphacinone rodenticide bait was applied via a 1-time (2-application) hand-broadcast during rat trapping. Rat trapping alone was effective at maintaining rat population suppression at continuously low levels (i.e., below 20% tracking, or rat presence), which should be beneficial to native and endangered species in this forest (Pender et al. 2013). In contrast, rat trapping did not maintain suppressed mouse populations to the target levels of <20%, with the exception of the first sampling period in 2016. Due to the already low levels of rats at Ohikilolo resulting from constant trapping, there was minimal benefit (and no statistical evidence) of the Diphacinone-50 rodenticide further reducing the rat population. However, Diphacinone-50 was effective at reducing the mouse population from 33% to 0%, but this effect was temporary (~1.3 months). The short reduction period for the mouse population after rodenticide application was likely due to the small-sized area treated, as larger buffers are needed to account for the typically rapid ingress that occurs when doing rodent control rather than whole-island rodent eradication (Duron et al. 2017, Shiels 2017, Shiels et al. 2017).

Our use of a reference site for simultaneous rodent population tracking has given us confidence that rats were suppressed to a sustained level of <20% at our treatment site by use of A24s and rat snap-traps. Although rat activity was not measured >15 years prior to our study when rat suppression at Ohikilolo first began, our assumption that rat tracking would have been similar to that of Kapuna (i.e., ~80%) prior to any rat control was supported by rat tracking tunnel results at nearby (lower elevation) forests prior to any rat suppression (50–90% at Makaha and 40–60% at Lihue) and observations of rat damage prior to and following rat control >15 years ago by OANRP staff (OANRP 2018). With this long-term history of rat suppression at Ohikilolo, we cannot conclude that A24s and snap-traps reduced the rat population from pre-treatment levels; rather, we demonstrated that simultaneous use of these 2 types of traps maintained the rat population at suppressed levels (<20%) that has been previously shown to benefit the endangered species populations that are present in Hawaiian mesic forests (e.g., tree snails: Hadfield et al. 1993; palm trees: Shiels and Drake 2015, OANRP 2013).

There were obvious differences between the 2 trap types used in our study. The classic snap-traps must be reset after each triggering event, which can be logistically challenging at remote sites like Ohikilolo where helicopter access was needed because of the steep terrain, and therefore servicing the traps was limited to a minimum of 4-week intervals. The A24s did not require such frequent trap checks because the gas-powered resetting ability of the A24 allowed for up to 24 triggering events before there was a need to service the traps. This trap feature allowed for several months of active and armed A24s before their gas canisters needed to be changed. The cost difference between rat snap-traps and A24s was substantial (~US$2.50 per snap-trap vs. US$170 for an A24 trap). Additionally, A24s have had mixed results suppressing rats to desired levels in Hawaii and New Zealand (Gillies et al. 2012, Carter et al. 2016, Shiels 2017, Gilbert 2018). While some mesic forest sites on Oahu appear to have invasive rat populations effectively managed (i.e., below 20% rat tracking) using A24s as the sole rat suppression technique or in combination with snap-traps (OANRP

2018), there was at least 1 site (Kahanahaiki) where rat tracking could not be maintained below 20% tracking for the entire year; with an A24 trapping grid spread over 26 ha, rat tracking at Kahanahaiki ranged from 20–40% for half of the year and <20% for the other half of the year (Shiels 2017). It is unknown why rat trapping was not effective year-round at Kahanahaiki, but the high black rat population at Kahanahaiki relative to other mesic forest sites nearby (see Shiels 2010) and the long and skinny shape of Kahanahaiki may play roles in the reduced efficacy of A24 trapping. Additional studies outside of Hawaii have also found that A24s may have variable success in rat population reduction and maintaining the rat populations below target levels (Gillies et al. 2012, Carter et al. 2016, Gilbert 2018).

House mice were not sufficiently suppressed when grids of rat snap-traps and A24s are used. The A24 was designed for rat and stoat control, not mice, and the efficacy of A24s on suppressing house mice has not been previously tested to our knowledge. Rat snap-traps probably were less reliable for mouse control than rat control because mice typically do not produce enough downward force on the treadle of the rat snap-trap to trigger the trap (Shiels et al. 2017). The inability of house mice to consistently trigger a rat snap-trap was therefore in part due to the large difference in average weight of a mouse (~11 g) relative to a Pacific rat (~48 g) or black rat (~111 g) in Oahu forests (Shiels 2010, Shiels et al. 2013). Snap-traps made for mice (Shiels et al. 2017) and repeater live traps for mice (Young et al. 2013) have proven effective and efficient for reducing house mice in natural areas in Hawaii.

A key difference between rodent population control and rodent eradication on islands is that rapid ingress of rodents often occurs when control methods are used, and this is likely the reason that the 1-time hand-broadcast of rodenticide resulted in such a short rodent population reduction. Rodent control at Ohikilolo and other sites was assumed to be constant when using A24 traps, snap-traps, and rodenticide bait stations, as long as these devices were regularly checked and serviced. However, rodents from outside the treatment plot immigrated into the treatment area as rodents were trapped and eliminated. This immigration was rapid when control devices were not baited and active (e.g., the only time since 2009 that rat tracking was >30% at Ohikilolo was in December 2015 when rat control was absent the prior 8 months at this site; OANRP 2018). Because the ingress was constant even when these control devices were in place, resources at the edges of a treatment area received less protection than the core. Therefore, rodent suppression plots need to include appropriate buffers (see Shiels 2010 for daily movement patterns of these rodents) to ensure the management goals and protection of natural resources are to be realized.

To our knowledge, and in addition to a larger mesic forest site (Kahanahaiki) that we treated with hand-broadcast 6 months prior to Ohikilolo (Shiels 2017), there have been just 3 other hand-broadcast applications in Hawaii of a similar bait product as used at Ohikilolo, and these are reported in Dunlevy et al. (2000), Pitt et al. (2013), and Spurr et al. (2013). Both Dunlevy et al. (2000) and Pitt et al. (2013) used the same bait matrix as used at Ohikilolo and Kahanahaiki (i.e., Ramik Green fish-flavored cereal grain bait pellets, Hacco, Wisconsin, USA) but it was inert bait pellets that contained a biomarker instead of the anticoagulant compound diphacinone. Both studies occurred on the east side of Hawaii Island and investigated the optimal bait application rate to maximize exposure to rats (Dunlevy et al. 2000) or mice (Pitt et al. 2013) while minimizing the amount of bait used. The key results that Dunlevy et al. (2000) discovered from trials in wet forest were that all captured Pacific rats had eaten the bait at all application rates (11.25, 22.5, and 33.75 kg/ha), whereas the optimal sowage rate for black rats was determined to be 22.5 kg/ha. Pitt et al. (2013) determined that the optimal sowage rate for house mice in dry grassland-shrubland habitat, with relatively high mouse density, was >14 kg/ha but <22.4 kg/ha. Spurr et al. (2013) conducted a field trial at Hawaii Volcanoes National Park (Hawaii Island) by hand-broadcasting pelleted (6 g each) Ramik Green, which is the same formulation as the 1.1-g pellets of Diphacinone-50, for purposes of registering the product with the U.S. Environmental Protection Agency for hand-broadcast for rat control. The treatments were effective in both forest types, resulting in 100% reduction in the 4-ha plots 1–4 weeks after an application event. Similar to our study at Ohikilolo, Spurr et al. (2013) reported that rodent recolonization into the treatment area occurred, and the rodent abundances recovered within about 2 months after bait application. The major difference from our study relative to these two that occurred on Hawaii Island that targeted rats (i.e., Dunlevy et al. 2000 and Spurr et al. 2013) was that the rat population at our treatment site was already very low (5.6% at Ohikilolo vs. 87.4% at our Kapuna reference site) because of the previous and simultaneous rat trapping at Ohikilolo. Therefore, if rats are already suppressed to these low levels using traps, the efficacy of rodenticide and the need for rodenticide use to control rats are very low.

Diphacinone-50 bait pellets generally last 2–3 weeks when applied by hand-broadcast in a mesic forest like Ohikilolo (Shiels 2017), and there were some visible bait pellets 7 days after the first hand-broadcast at Ohikilolo and no visible bait pellets at the subsequent visit to the site 1.3 months later. At Kahanahaiki, which is a 26-ha mesic forest near Ohikilolo where the same hand-broadcast methods were used to treat the site 6 months prior to Ohikilolo, 50% of the applied bait had disappeared after 1 week, and the remaining had disappeared within 2–3 weeks (Shiels 2017). One week of bait exposure should have been ample time for all rodents in the treatment area to gain a lethal dose of diphacinone poison, and our findings at Ohikilolo reflect this for mice and possibly rats (i.e., 0% rat detection rate 1 month after broadcast). Typically, diphacinone bait should be available to rodents for at least 3–4 nights to allow for the multiple feedings needed to obtain a lethal dose (Witmer et al. 2007, Pitt et al. 2011). In cages, Swift (1998) exposed wild black rats to diphacinone bait (50 ppm) for 7 days and obtained >80% rat mortality, and 6 days for Pacific rats and obtained 90% rat mortality. Thus, for the 2 rat species at Ohikilolo, 7 days of bait availability should have been sufficient to obtain high levels of rat control or suppression at the site. Less is known about the effectiveness of diphacinone bait on house mice in field conditions, but there was similar bait palatability and effectiveness for house mice offered diphacinone baits in the laboratory in Hawaii as found for Pacific rats and black rats offered the same diphacinone bait (Pitt et al. 2011). Additionally, during a no-choice captive feeding trial conducted on Buck Island in the Caribbean, Witmer et al. (2007) determined that 7 of 9 house mice (78%) had succumbed to diphacinone baits within 7 days, and the 2 mice that survived were lethargic at 7 days; the authors expected them to succumb if the trial had lasted a few more days.

Although we observed a complete lack of house mouse activity on the day of diphacinone application, this reduction could not have been from mortality associated with this bait application. Using 1 night to estimate rodent activity has its limitations, and a possibility for the reduced mouse detection on the first night that bait was available (June 7, 2016) may have been due to mice immediately shifting to eating the Diphacinone-50 bait, and therefore they did not go through the tracking tunnels to access the peanut butter bait. By contrast, some rats apparently visited the tracking tunnels even when the newly present diphacinone bait was available. Black rats are competitively dominant over house mice and Pacific rats in these forests (Shiels 2010, Shiels et al. 2013), and therefore the desirable foods and premium microhabitats are typically exploited first by black rats. Because we cannot easily identify black rat tracks from Pacific rat tracks in the tracking tunnels, it is unknown which rat species was utilizing the tracking tunnels on June 7, 2016 or other days sampled.

Management implications

Targeted commensal rodent control rather than island-wide eradication is the current best management practice recommended for protecting resources in ecosystems too large or complex to eliminate all individuals of the target rodent species. In areas where rodenticide use is unwanted or impracticable (e.g., too expensive for long-term rodent control; Ohikilolo diphacinone bait was ~$1,500, and staff plus helicopter time exceeded $3,000), automatic trapping using A24s in combination with snap-trapping can maintain rat populations at desired levels at some sites (e.g., Ohikilolo) but not others (e.g., Kahanahaiki). Hand-broadcast or aerial-broadcast of bait pellets should therefore be considered for some sites where invasive rodents threaten resources. The hand-broadcast of diphacinone bait was effective but short-lived for house mice at Ohikilolo and rats at Kahanahaiki. Repeated baiting during the seasonal peaks in rodent abundance and increasing the size of the buffer area would more likely protect target natural resources from invasive rats and mice.

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