FINAL REPORT

for

Vertebrate Pest Control Research Advisory Committee

STUDY TITLE:

A test of management tools for invasive roof rats in citrus orchards.

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ABSTRACT

Invasive black rats (*Rattus rattus*) are one of the most damaging vertebrate species to agriculture globally. In citrus orchards, rat damage includes fruit consumption and contamination, girdling of branches, and gnawing irrigation equipment. Managing black rats in citrus is challenging given the abundance of food and cover provided by the trees year-round. Anticoagulant rodenticide applications, such as diphacinone-laced baits applied via bait stations, are sometimes used to manage black rats in orchards, but have not been tested in an evergreen crop like citrus. Goodnature A24 self-resetting rat traps are increasingly used to manage black rats for conservation purposes, but have not been tested in agricultural settings. Therefore, we used a replicated treatment-control randomized block design to test the efficacy of: 1) 0.005% diphacinone-treated oats applied via elevated bait stations and 2) A24 traps that were elevated to approximately 1 m height to match the bait station heights. This study was conducted across four citrus orchards in the southern San Joaquin Valley, California, to better identify how to implement these tools to manage invasive black rats in this economically important crop. Although neither trapping nor rodenticide baiting yielded the desired reduction in black rats across all sites, we identified strategies that hold promise for future testing. For rodenticides, reducing the spacing between bait stations may increase efficacy by increasing encounter rates by rats. For trapping, the use of a platform under the A24 traps appeared to increase its effectiveness by allowing easier access to the trap trigger. Furthermore, reducing spacing between traps may also yield better results. Ultimately, a management plan that combines trapping and rodenticide baiting may prove more efficacious than our initial study design and should be investigated further.

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INTRODUCTION

Invasive black rats *(Rattus rattus* L., 1758) cause extensive damage in agricultural systems throughout the world (Pimentel et al. 2005; Wood and Singleton 2015). This damage is especially prevalent in tree fruit and nut crops. Surprisingly, few studies have been undertaken to develop management programs to effectively reduce black rat damage in these orchard systems (but see Campbell et al. 1998; Horskins and Wilson 1999; Baldwin et al. 2014a for examples where management programs were developed or tested). This is particularly relevant for citrus crops, where black rats cause damage in a variety of ways including girdling of branches, stems, and trunks of trees; direct consumption of fruit; damage to irrigation infrastructure; and by posing as a food safety risk through fecal contamination of fruit (Worth 1950; Tobin 1992; Yabe 1998; Dongol et al. 2021). Citrus is an important commodity in California, with the statewide value in excess of US$2.1 billion in 2019–20 (CDFA 2020). Effective management of black rats in citrus crops is an important concern for growers.

Two frequently used tools for managing black rats in tree crops are rodenticides and traps. Of these, rodenticide use is the most commonly used tool for managing black rats in orchards (Horskins and Wilson 1999; Puan et al. 2011; Quinn and Baldwin 2014). Globally, both first- (e.g., warfarin, chlorophacinone, diphacinone) and second-generation (e.g., brodifacoum, bromadiolone, difethialone) anticoagulants are used to manage black rats in agricultural systems (Fall and Fieldler 2015), but in the U.S., only first-generation anticoagulants are allowed for use against field rodents (Baldwin and Salmon 2011). Various rodenticide application strategies have been tested including broadcasting rodenticides on the ground, applying bait within burrows, applying uncovered bait blocks within tree canopies (i.e., no bait station), and by placing within bait stations located on the ground or up in trees (Advani 1986; Campbell et al. 1998; Sugihara 2002; Baldwin et al. 2014a). The use of elevated bait stations containing first-generation anticoagulant rodenticides is particularly appealing for managing black rats in orchards given that the station eliminates access to the bait by those species larger than the opening of the bait station, and elevating the station eliminates risks to ground-dwelling nontarget species. Such stations containing diphacinone have effectively reduced black rat abundance in nut orchards (Baldwin et al. 2014a), but have not been tested in fruit orchards. Furthermore, citrus orchards are relatively unique compared to most other orchard crops in that they are evergreen and have fruit present on the trees throughout most of the year. This abundance in cover and food makes baiting more challenging than in other orchard crops. Testing is needed to determine if such an elevated bait station program can effectively reduce black rat numbers in citrus orchards.

Trapping is also used in orchards to reduce black rat abundance. Historically, snap traps were the primary trap used to manage black rats in tree crops, but snap trapping is labor intensive and costly due to the need for frequent trap resetting and baiting. Additionally, traditional snap traps can result in substantial nontarget captures (Tobin et al. 1993). More recent research in conservation settings has focused on the use of the Goodnature A24 rat and stoat trap (Goodnature Ltd., Wellington, NZ; e.g., Carter et al. 2016; Shiels et al. 2019). These traps are self-resetting, and they have the capability of using a long-lasting lure, which collectively can substantially reduce the labor required to trap a given area. Furthermore, these traps would eliminate all birds and larger mammals (e.g., Virginia opossum [*Didelphis virginiana*] and raccoon [*Procyon lotor*]) that might be captured in snap traps. A24 traps have reduced black rat numbers in some areas, although efficacy has sometimes varied seasonally and temporally (Carter et al. 2016; Shiels et al. 2019; Gronwald and Russell 2022). It is unclear how effective they might be in agricultural settings given the abundance of food in these areas, but their potential is particularly alluring to producers given the limited labor that would be required to use these traps.

Collectively, the use of elevated bait stations containing a first-generation anticoagulant rodenticide and A24 traps could be combined to manage black rats in citrus orchards, but we first need to know how efficacious each are to determine their utility for managing this invasive species. Therefore, our goal for this study was to better define the efficacy of these tools for managing black rats in citrus orchards. Our specific objectives included: 1) determining the effect of A24 trapping and 0.005% diphacinone-treated oat baiting programs on black rats in citrus orchards, and 2) conduct an initial assessment of the impact of varying treatment durations and distances between bait stations on the efficacy of black rat baiting and trapping programs. Results from this investigation will provide the foundation for a larger-scale study intended to develop an integrated pest management (IPM) program for black rats in citrus orchards.

STUDY AREA

We conducted our study in 1 lemon (Site 1) and 3 (Sites 2–4) orange orchards in Kern and Tulare Counties, which are located in the southern San Joaquin Valley, California, USA. Both crops are evergreen and have fruit available at some stage of development year-round. At each site, we established a control plot, a bait station plot, and a trapping plot. Bait station and trapping plots were generally 380 m × 380 m and included a 140-m × 140-m core area where black rat monitoring occurred. The monitoring area was generally surrounded by a 120 m buffer on all sides to reduce the potential of reinvasion of treated areas. However, for Site 4, one side of the buffer extended for only approximately 14 m, as this side of the plot was surrounded by a large road and non-agricultural land not used by black rats (R. Baldwin, University of California, Davis; unpublished data). Control plots consisted of the same 140-m × 140-m core area, but we did not include a buffer zone around these monitoring areas given no efforts to remove rats from the monitoring or outlying areas. Additionally, control plots did not include any sham bait stations or traps. We separated all plots by a minimum of 200 m to maintain independence between all control and treatment plots. All parts of this study occurred from April through October 2021.

MATERIALS AND METHODS

Rodent monitoring

Following procedures outlined by Baldwin and Meinerz (2022), we used a combination of tracking tunnels and remote-triggered cameras to monitor rodent activity within treatment and control plots. For tracking tunnels, we used corrugated plastic tracking tunnels (60 cm × 15 cm × 13 cm, Pest Control Research LP, Christchurch, NZ) that were placed in trees at a height of 0.7–1.6 m following a 5 × 5 grid pattern, with each tracking tunnel separated by approximately 35 m. The tracking tunnels were secured via plastic cable ties to 0.9–1.2 m lengths of 5.1 cm × 10.2-cm wooden boards, with the boards and tracking tunnels placed across stable branches within the trees. We placed a tracking card with a centralized inkpad within each tunnel at the start of the monitoring period to allow us to determine presence of black rats within a tunnel.

We placed a soft bait packet (Liphatech Rat and Mouse Attractant™, Liphatech, Inc., Milwaukee, Wisconsin, USA) that is attractive to black rats at the center of the inkpad to draw the black rat into the tunnel. We staked the bait packet to the tracking tunnel and card via a Grip Rite #12 × 3.18 cm metal square cap roofing nail (Prime Source Building Products, Inc., Irving, Texas, USA) to keep it from falling out of the tunnel (Wales et al. 2021). We operated the tracking tunnels for three consecutive nights to determine presence or absence of black rats at each tunnel, with tracking tunnels operated immediately before and after the treatment periods. We then compared the proportion of tracking tunnels visited before and after treatment periods to determine the percent efficacy for each management tool or control plot.

We also used Bushnell NatureView HD Max cameras (14 megapixel; Bushnell Outdoor Products, Overland Park, Kansas, USA) to track changes in black rat activity pre- and post-treatment. As with the tracking tunnels, we distributed these cameras in a 5 × 5 grid pattern with approximately 35 m between adjacent cameras (Baldwin and Meinerz 2022). The cameras were placed in the tree immediately adjacent to the tree that contained a tracking tunnel, and were placed at a height of 0.7–1.6 m aboveground. The cameras were attached to tree branches and were targeted toward a soft bait packet (Liphatech Rat and Mouse Attractant™) to increase detection opportunities. We set the cameras to take photos when activated by motion at a minimum of a 5-minute interval to reduce the impact of repeat black rat visits on general index values (Baldwin et al. 2014a), and we set the sensitivity level on the cameras to high to minimize the chance of missing a rat. The cameras were operated for three consecutive nights immediately before and after treatment periods. Following previous studies (Baldwin et al. 2014a; Baldwin and Meinerz 2022), we developed a general index value from the photo data, which equated to the mean number of photos per camera night, and we compared this value between the pre- and post-treatment periods to determine efficacy.

Bait application

We applied 0.005% diphacinone-treated rolled oats (California Department of Food and Agriculture [CDFA], Sacramento, California, USA) in treatment areas via the use of tubular bait stations. The bait stations were made of high-density polyethylene plastic tubes (Industrial Plastic Supply, Inc., Anaheim, California, USA) that were 33 cm in length and 10.8 cm in diameter. Steel end caps were placed on both ends of the tubes; the end caps had 4.8-cm openings that allowed access to the bait (see Baldwin et al. [2014a] for an illustration of bait station design). For 2 of 4 sites (Sites 1, 3), the bait stations were placed in a 5 × 5 grid structure, with perimeter stations located 38 m from the plot edge and separated by approximately 76 m from each other. We selected the distance between bait stations given that this was the mean radius of female black rat home ranges in citrus orchards (R. Baldwin, University of California, Davis; unpublished data). For Site 4, the orchard was smaller, but bounded on one side by a road and non-crop area that black rats do not use (R. Baldwin, University of California, Davis; unpublished data). As such, we fit a 5 × 4 grid into this site, but still used 76-m spacing between all bait stations. We were also curious if increasing bait station density might yield greater efficacy given that past studies have used shorter intervals between bait stations (e.g., Baldwin et al. 2014a). As such, for Site 2, we established a 7 × 7 bait station grid structure with perimeter stations 40 m from the plot edge and 50-m spacing between bait stations within the grid (spacing recommended by Quinn and Baldwin [2014]).

All bait stations were secured in the tree canopy via bungee cords at a height of 0.7–1.6 m aboveground. We placed approximately 137 g of 0.005% diphacinone-treated rolled oats within the bait station at the start of each trial, and checked the bait stations approximately weekly to maintain a constant bait supply. If needed, we added additional bait and documented all bait amounts added. At the end of the trial period, we removed and weighed all bait to determine the total amount removed by black rats during the study period. Following Baldwin et al. (2014a), we operated bait stations at 3 of 4 sites (Sites 1–3) for 4 weeks. However, black rats can exhibit a neophobic response to bait stations that can take an extended timeframe to overcome (Wallace and Barnett 1990; Burke et al. 2021). As such, for one site (Site 4), we extended the baiting duration to 6 weeks to determine if this extended timeframe could increase the efficacy of our baiting program.

Trapping

We established 5 × 5 grids for A24 traps at all study sites, with traps separated by 76 m and perimeter traps placed 38 m from the plot edges. The traps were screwed into a wooden plank that was secured to the tree at a height of 0.7–1.6 m off the ground. Traps were generally secured to the tree without a platform provided underneath. However, after a lack of success for three sites, at Site 2, we placed a wooden platform approximately 12 cm below the trap entrance to allow the rat to step up and into the trap more easily (Fig. 1). All traps were equipped with Goodnature Digital Strike Counters to inform us how often a trap was activated, although the counters may not always accurately reflect the number of trap firings (Ogden 2018). As such, for every other trap, we aimed a Bushnell NatureView HD Max camera (12 total per site) at the trap to attempt to document if the counters accurately reflected the number of rats killed. The cameras were set to video to record 10 seconds of video upon activation by animal movement, and they were set to maximum sensitivity to minimize the chance of missing a rat. We set the cameras to take videos at a minimum of a 5-minute interval to reduce the impact of repeat black rat visits. This allowed us to develop a general index value based off these videos (number of videos containing a rat per camera night; Baldwin et al. 2014a), which provided another corroborative method to track black rat activity within the trapping sites during the trapping period.

We used different attractants for the traps to determine if black rats responded differently to any of them. For Sites 1–2, we used the Goodnature Rat and Mouse Chocolate Lure (hereafter, chocolate lure) that was applied via an automatic lure pump (ALP) that periodically drips lure over the course of several months. We used the same chocolate lure for Site 3, although it was applied in the Goodnature Do-It-Yourself Lure Basket (hereafter, lure basket), which is a basket that houses lures above the trigger portion of the trap. For Site 4, we used Jif® creamy peanut butter [The JM Smucker Company, Orrville, OH] in the lure basket. The traps and lures were checked approximately once per week to determine if any adjustments needed to be made to the traps, to document the number of trap firings, and to search for any dead rats that might be present under each trap. The traps were generally operated for 4 weeks, but in keeping with the bait station timeframe at Site 4, we operated the traps for 6 weeks to provide insight into the utility of a longer trapping duration.

a)

b)

Figure 1. For three study sites, we attached Goodnature A24 traps to a wooden plank (a). The trap and plank were then attached to a tree via plastic cable ties. For one study site, we also included a wooden platform underneath the traps to allow better access to the trap for black rats (b).

Analysis

Our study was analyzed as a randomized block design, where the three treatments (trap, bait station, and control) were randomly assigned to plots within each of the four sites (blocks). Our two forms of rat monitoring each used a different type of analysis because the camera index (the number of rat photos divided by the 3-day monitoring period) were continuous data whereas tracking tunnels were discrete (i.e., presence or absence of rat tracks in each tunnel after 3 days). Each monitoring station was considered independent and therefore used in our analysis ($n = 25$ camera stations per plot, and $n = 25$ tracking tunnels per plot), and the effect of time (pre- vs. post-treatment, a repeated measurement for each station) was also accounted for in our analysis. To evaluate treatment effects on the rat population using the camera index, we used a repeated measures ANOVA, and compared the effects of each treatment within site. We were most interested in the treatment × time interaction to compare whether or not treatments reduced the rat population from pre-treatment status. Prior to this analysis, we used a square-root transformation on the camera index data and checked treatment combinations to meet assumptions of homoscedasticity and normality. To evaluate differences in rat incidence (i.e., presence of rat tracks inside tracking tunnels after 3 d of observation) among treatments within each site and over time, we used a binomial generalized linear mixed-effects model that included the interactions of these treatment factors in one model. To account for repeated measurement (pre- and post-treatment), we used the (1|X) notation to specify plot as a random effect, and site was also specified as a random effect. For this analysis, we used command glmer in R package lme4. Rat monitoring analyses were conducted in R version 4.2.0, and significance was based on $P < 0.05$.

Trap, bait station, and control plots were operated in the same timeframe at each site so that results were relatable across treatments at each site. We established a 70% reduction in black rat activity as the threshold to consider trapping and bait station treatments efficacious based on established U.S. EPA guidelines for rodenticide testing (Schneider 1982). To further evaluate the effects of A24 trapping on black rat populations, we plotted the video index values documenting daily black rat visits (mean number of videos recorded per 24-hour period per camera location) and the counter data (i.e., number of times the A24 triggered) for A24s from the start to end of the trapping control program for each of the 4 different citrus orchards. We also conducted linear regression analyses comparing the number of days since trapping was initiated to the mean daily video index scores for each site to better define the impact of trapping efforts on black rat activity within trapping plots. Regression analyses were conducted using SAS (Version 9.4; SAS Institute Inc., Cary, North Carolina, USA).

RESULTS

We observed moderate to high rat visitation rates at indexing plots during the pre-treatment period (tracking tunnels visited by rats: range = 28%–60%; camera index values: range = 0.29–2.03 rat photos per camera night; Table 1). Whereas our statistical analyses produced differing results between camera indexing and tracking tunnels, the one surprising outcome of these analyses was the consistency between methods demonstrating that neither A24 trapping nor diphacinone baiting significantly reduced the black rat population. For camera indices, there was a significant treatment × time interaction ($F_{2,582} = 4.4$, $P = 0.013$), and upon review of Tukey HSD post-hoc analyses, the only significant pairwise comparison was the lower average camera index in A24 trapping plots pre-treatment relative to baiting plots pre-treatment ($P = 0.027$; Table 1). More specifically, and comparing pre- vs. post-sampling for each treatment, there was no effect of A24 trapping ($P = 0.399$) or toxic baiting ($P = 0.348$) on the rat population as measured by motion-triggered cameras. There was a significant site × time interaction ($F_{3,582} = 3.6$, $P = 0.013$) for the camera index data that appears to be driven in part by the changes pre- vs. post-treatment in site 3, which had substantial decreases in rat detections from pre- to post-treatment for bait plots and control plots but an increase in rat detections pre- to post-treatment in A24 trapping plots. These site × time interaction effects were the likely premise for the significant site effect ($P = 0.039$) for camera indexing. Finally, there were no significant main effects of treatment ($P = 0.655$) or time ($P = 0.764$).

Tracking tunnel monitoring revealed a significant interaction between trap treatment and time (z = 3.43, SE = 0.43, $P < 0.001$) where three of the four A24 trapping plots had significantly more detections of rats following the completion of the A24 trapping period than before traps were placed in the treatment plots (Table 1). This significant interaction was likely the premise for the significant main effect of trapping (z = 2.15, SE = 0.40, $P = 0.032$). There were no other significant interactions between treatments and time (z = 1.55, SE = 0.42, $P = 0.122$), nor main effects of treatments (z = 0.95, SE = 0.41, $P = 0.32$) or time (z = 1.78, SE = 0.30, $P = 0.074$).

For bait stations, observed low efficacy may have been due to minimal bait consumption (Site 1: total = 952 g, station $\bar{x} = 38$ g, SE = 4 g; Site 2: total = 617 g, station $\bar{x} = 13$ g, SE = 2 g; Site 3: total = 1,457 g, station $\bar{x} = 58$ g, SE = 9 g; Site 4: total = 1,071 g, station $\bar{x} = 54$ g, SE = 14 g), although we did observe substantial reductions in black rat activity at Sites 2 and 3 (Fig. 2) suggesting that bait may be effective if sufficient amounts are consumed. It also bears noting that bait station interval was reduced at Site 2 to 50-m spacing, suggesting that shorter distances between stations might increase efficacy. Conversely, increasing baiting duration to 6 weeks at Site 4 did not appear to yield any benefits (Fig. 2).

As previously stated, we observed a substantial increase in black rat activity across 3 of 4 trapping sites post-treatment (Fig. 2). The one trapping site where we observed a reduction in black rat activity was the site where we incorporated a platform underneath the trap (Site 2; Fig. 2). Additionally, our video indices for traps indicated either an increase (Site 1: $F_{1,26} = 34.4$, $P < 0.001$, $r^2 = 0.58$) or only a minor decrease (Site 3: $F_{1,26} = 2.2$, $P = 0.147$, $r^2 = 0.08$; Site 4: $F_{1,41} = 9.8$, $P = 0.003$, $r^2 = 0.20$) in black rat activity at the end of our treatment period for 3 of 4 sites, but we observed a substantial decrease in activity for the site that included a platform below the traps (Site 2: $F_{1,26} = 14.1$, $P < 0.001$, $r^2 = 0.36$; Fig. 3). The initial decrease in black rat activity coincided with the period (Days 4–11) that resulted in the greatest number of trap triggers (n = 13; Fig. 3b), suggesting that these triggering's accounted for the reduction in black rats in this orchard. Furthermore, we collected 5 dead black rats in this orchard, which was the only orchard where we documented such mortality. We only documented one black rat mortality via video. As such, we were unable to test the ability of counters to document mortalities, although the videoed mortality was recorded by the trap counter. Collectively, trap counters reported 7, 16, 12, and 2 trap triggers for Sites 1–4, respectively.

Table 1. The proportion of tracking tunnels (Tunnels) visited by black rats and the mean number of photos of black rats recorded per 24-hour period per camera location (Cam index; SE = standard error) for pre-treatment and post-treatment periods for sites that were baited with 0.005% diphacinone-treated rolled oats via elevated bait stations, sites that had Goodnature A24 traps, and control sites (no manipulation) across 4 citrus orchards in the southern San Joaquin Valley, California, during spring through autumn 2021.

				Pre-treatment		Post-treatment	
		Crop	Month sampled	Tunnels	Cam index (SE)	Tunnels	Cam index (SE)
Control	Site 1	Lemon	Apr - May	0.56	0.92 (0.25)	0.64	1.43 (0.37)
	Site 2	Orange	Sep - Oct	0.28	0.36 (0.22)	0.32	0.43 (0.18)
	Site 3	Orange	Jun - Jul	0.32	0.69 (0.40)	0.22	0.15 (0.08)
	Site 4	Orange	Jul - Sep	0.44	1.92 (0.59)	0.48	1.13 (0.40)
A24 trap	Site 1	Lemon	Apr - May	0.28	1.07 (0.41)	0.92	1.67 (0.29)
	Site 2	Orange	Sep - Oct	0.32	0.44 (0.23)	0.16	0.43 (0.22)
	Site 3	Orange	Jun - Jul	0.36	0.29 (0.17)	0.48	0.41 (0.13)
	Site 4	Orange	Jul - Sep	0.36	0.80 (0.24)	0.64	1.04 (0.31)
Bait station	Site 1	Lemon	Apr - May	0.32	0.81 (0.42)	0.24	0.89 (0.30)
	Site 2	Orange	Sep - Oct	0.40	0.63 (0.21)	0.28	0.03 (0.02)
	Site 3	Orange	Jun - Jul	0.52	2.03 (0.49)	0.12	0.40 (0.21)
	Site 4	Orange	Jul - Sep	0.60	1.81 (0.38)	0.72	2.17 (0.41)

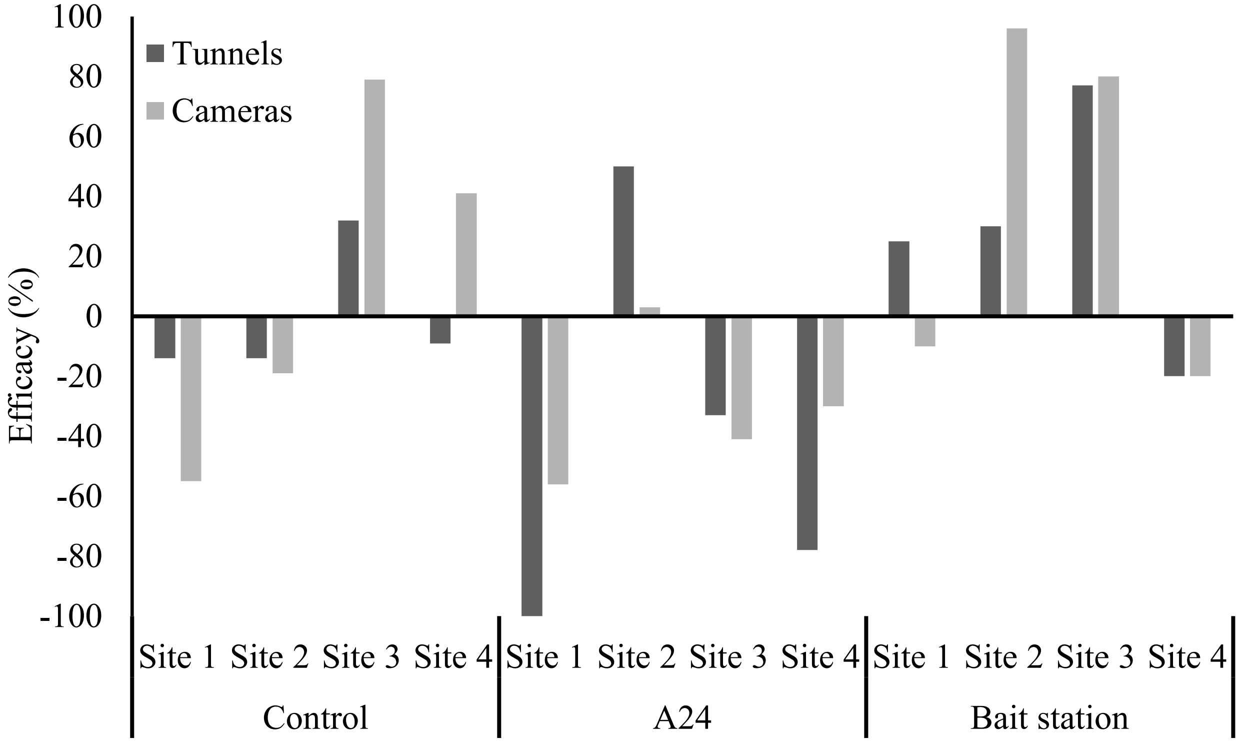

Figure 2. Observed efficacy for Goodnature A24 traps, 0.005% diphacinone rolled oats applied via elevated bait stations, and concomitant control plots (no manipulation) for black rats across four citrus orchards in the southern San Joaquin Valley, California, from spring through autumn 2021. Plot level efficacy was determined via the use of tracking tunnels and remote-triggered cameras using the following equation: efficacy = (pre-treatment index value – post-treatment index value / pre-treatment index value) × 100. Positive efficacy values signify a reduction in black rat activity at a site's treatment plot, while a negative value indicates an increase in activity. Efficacy as determined via tracking tunnels for A24 traps at Site 1 was truncated for graphical purposes (actual value = –229%).

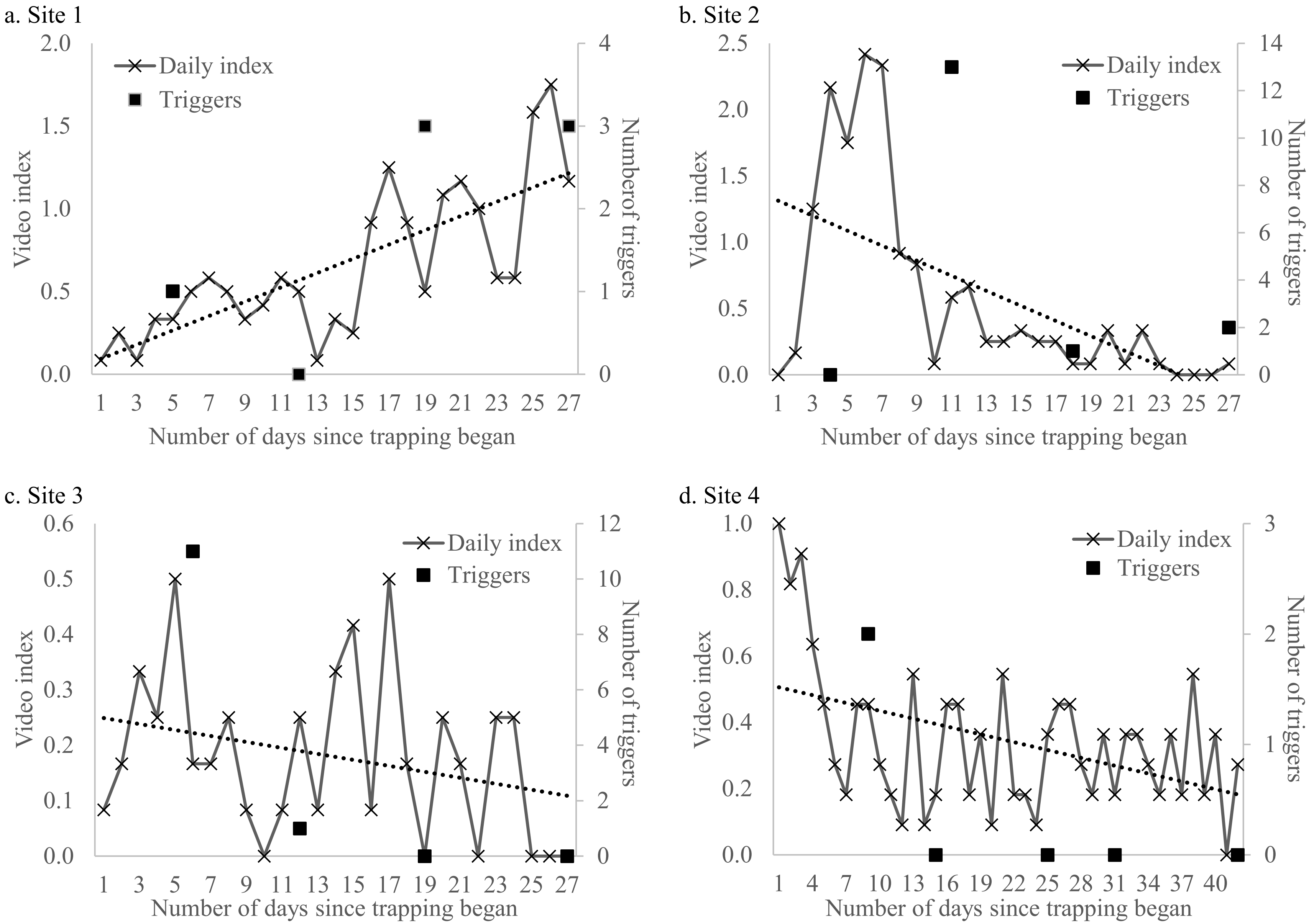
a. Site 1
Daily index
Triggers
Video index
Numberof triggers
Number of days since trapping began
b. Site 2
Daily index
Triggers
Video index
Number of triggers
Number of days since trapping began
c. Site 3
Daily index
Triggers
Video index
Number of triggers
Number of days since trapping began
d. Site 4
Daily index
Triggers
Video index
Number of triggers
Number of days since trapping began

Figure 3. Video index values documenting daily black rat visits (mean number of videos recorded per 24-hour period per camera location) from the start to end of a trapping control program for 4 different citrus orchards in the southern San Joaquin Valley, California, during spring through autumn 2021. Goodnature A24 traps were used during this study, with trapping sessions lasting for 28 days for Sites 1–3 and 42 days for Site 4. We also provided the relationship between the number of days since trapping was initiated and mean daily video index scores for each site, although the regression line for Site 3 was not signficiant ($P = 0.147$). Resultant equations for each site are as follows: Site 1—Video index = 0.050 + (0.043 × days); Site 2—Video index = 1.370 – (0.057 × days); Site 3—Video index = 0.255 – (0.005 × days); Site 4—Video index = 0.514 – (0.008 × days). The number of trap triggers as determined approximately weekly are illustrated to allow a visual assessment of their effect on black rat index values.

DISCUSSION

We established this study to determine how effective diphacinone baiting and trapping with A24 traps were at reducing black rats in citrus orchards, and to determine strategies that might increase the efficacy of each approach. Although both tools have been effective in other settings, we did not find that either approach was consistently effective. For example, the use of the same rodenticide product in elevated bait stations was effective in almond orchards (Baldwin et al. 2014a), and A24 studies have often shown a substantial reduction in black rats after an extended trapping period (Carter et al. 2016; Shiels et al. 2019). Part of the disparity between this project and the other listed examples may be due to the studied environments. Orchard systems contain abundant food resources that may not be present in natural systems where A24 traps have been studied. Conversely, the Baldwin et al. (2014a) study testing diphacinone bait in almond orchards occurred during the nonbearing season when alternative foods and cover were scarce. Citrus trees are evergreen, providing abundant cover and food year-round. Therefore, available food and habitat could be an important factor driving the success of black rat management in citrus orchards. Fine-tuning the implementation of baiting and trapping programs is needed to increase the efficacy of these approaches in citrus orchards.

One promising approach to overcome the lack of efficacy for these tools is to reduce the spacing between bait stations and traps, ostensibly increasing the rate of encounter of these tools by black rats. As previously noted, Baldwin et al. (2014a) observed a 90% reduction in black rat activity using 0.005% diphacinone-treated oats in elevated bait stations in almond orchards, but they used 30-m spacing given their desire to control both black rats and deer mice (*Peromyscus* spp.), which have substantially smaller home-ranges than black rats. Likewise, we observed greater efficacy at the one site where we decreased spacing between bait stations to 50 m, suggesting this practice may hold promise, although additional replicates are needed to fully test this. It bears noting that we selected the 76-m spacing based on movement data for black rats in these orchard systems (R. Baldwin, University of California, Davis; unpublished data), but it could be that more frequent encounters are needed to maximize exposure to black rats especially when considering the limited odor emitted by oats that would reduce the ability to draw rats in from a greater distance when compared to more aromatic baits.

We did not test shorter spacing between A24 traps given the high cost of each trap. For example, the number of traps required to cover a 32-ha orchard with 76-m spacing is 49, but this increases to 121 traps for 50-m spacing. At >US$150 per trap, this would substantially increase the cost of a trapping program. That said, if shorter spacing dramatically increased the efficacy of a trapping program, such spacing might be justified. It is interesting to note that efficacy associated with the video index was greater than what we observed from our primary indexing tools (i.e., tracking tunnels and general index values derived from photos) for 3 of 4 sites (Fig. 3). This disparity could again be a reflection of trap spacing. Not all traps are located close to indexing locations. It could be that traps were effective at removing rats close by, but missed some of the rats that were further way from the traps yet close to indexing locations. This uncertainty needs to be explored further to better identify proper spacing for traps.

Increasing the duration that bait stations remain operational was also considered a possible option for increasing the efficacy of baiting programs. Black rats can exhibit a neophobic response to new items, such as bait stations, in their home ranges (Wallace and Barnett 1990;

Burke et al. 2021). It can take a few days or more for the rats to build up the courage to investigate the stations and ultimately consume the bait. Previous baiting efforts for black rats in almond orchards indicated that 4 weeks was sufficient time to substantially reduce black rat numbers (Baldwin et al. 2014a), so we focused on that duration for the majority of this investigation. However, for one site, we increased the baiting duration to 6 weeks; we did not see an increase in efficacy for this site. In fact, we observed the lowest efficacy at this site. Furthermore, although we did not measure the remaining amount of bait during each station check, we did document when stations were refilled, and almost all refills occurred within the first two weeks of the baiting program. As with bait stations, leaving A24 traps out for a longer timeframe did not lead to increased captures (Fig. 3). As such, we do not believe that increasing the duration of the baiting or trapping program is likely to increase efficacy.

Perhaps the most promising strategy for increasing the efficacy of A24 traps in citrus orchards is to include a platform underneath the traps. Our study design relied on the placement of traps up in trees due to the presence of nontarget species that could access the traps when placed at ground level. For island conservation efforts, A24 traps are generally placed 12 cm off the ground on the trunks of trees, thereby providing a natural platform for black rats to enter into the traps (e.g., Ogden 2018; Gronwald and Russell 2022). The addition of a wooden platform underneath the traps increased trap success at the only site (Site 2) where we included a platform (Fig. 1b), although results must be improved to consider this an efficacious tool (Fig. 2). Furthermore, this was the only site where we noted dead rats at the trap sites, plus general index values derived from video observations of traps clearly showed a reduction in black rat activity following Day 11 of the trapping period, which coincided with the period with the most trap activations (Fig. 3b). We believe the inclusion of a platform should be considered for further testing of A24 traps when elevated aboveground.

Maximizing the attractiveness of the trap's lure should also increase the efficacy of a trapping program. The A24 allows the trapper to use either the lure basket or the ALP. The lure basket allows the trapper to use a variety of lures. We used both the chocolate lure and peanut butter in this study; we did not note an obvious difference between the two. In contrast, Shiels et al. (in press) experimentally determined that house mice (*Mus musculus*) triggered A24s baited with peanut butter 2.3 times faster than A24s baited with Goodnature chocolate lure. One negative consideration when using peanut butter was that it was highly attractive to ants in our study plots, which led to a need to rebait traps far more often than when using the chocolate lure. The ALP has the advantage of constantly dripping out bait over the course of a 4-6 month period, thereby providing substantial labor savings by reducing the need to check traps. Furthermore, Goodnature has recently introduced a nut butter lure (including in ALP) that might be worth trying as well, particularly given that peanut butter has trialed well as a black rat attractant in citrus orchards (Wales et al. 2021). At this point, the use of one of the two ALP lures manufactured by Goodnature appears to be the most practical option for trapping with the A24, but if success continues to elude trappers, the lure basket could be used to explore alternative options.

Likewise, alternative active ingredients could be considered for black rat rodenticide programs. Chlorophacinone and zinc phosphide products have been used against black rats in the past, but neither have consistently proven efficacious (Lefebvre et al. 1985; Baldwin et al. 2014a).

Norbormide is another active ingredient that has been tried at various times over the past several decades, but it has not proven as efficacious as desired given low palatability (Prakkash 1988). Research is currently underway to increase the palatability of norbormide (Shapiro et al. 2018; Witmer 2018). If successful, norbormide could become a useful tool for black rat control in orchards given its high specificity for rat species. That said, even if norbormide is effective in field trials, registration would be many years away, so increasing the effectiveness of currently-available tools is highly desirable in the interim. One method to accomplish this could be to use manufactured bait pellets or blocks rather than treated oats. Their use may improve bait uptake, and there are several extruded pellets and blocks on the market that are approved for use in other settings, including those with diphacinone as the active ingredient. However, the diphacinone-coated oats are currently the only registered rodenticide bait available for California citrus orchards during the bearing season, so testing would be required to prove the efficacy of extruded products in citrus before they could be registered for use.

One potential alternative could be to use snap trapping to manage black rats in orchards. Although the efficacy of snap trapping has not been tested in citrus orchards, Tobin et al. (1993) determined that snap trapping did reduce black rat abundance in macadamia nut orchards. Although snap trapping is time-consuming and relatively expensive to implement, it could have potential for inclusion into an IPM program for managing black rats in citrus orchards as has been shown effective in natural environments (Nelson et al. 2002).

This investigation represents a first step toward understanding how to effectively manage black rats in citrus orchards. That said, there were some limitations with our study design that should be considered when designing future studies. For example, we used both the chocolate lure and peanut butter in this study. This introduced a potentially confounding variable to our assessment, but we felt it was important to determine if the lure or application strategy substantially influenced results. It is also possible that our study plots may not have been large enough to minimize the impact that reinvasion might have had on our population assessments. In a study in natural areas in Hawaii, Nelson et al. (2002) determined that black rats rapidly reinvaded depopulated areas after removal efforts were completed. Similar results have been noted elsewhere (Innes et al. 1999; King et al. 2011). Although we assessed black rat activity immediately following the completion of removal efforts, it is possible that rats moved into our monitoring plots from adjacent areas, subsequently biasing our results. Likewise, it could be that the buffer zone we used was too small to eliminate all black rats that utilized our monitoring plots, again biasing results. Future research efforts could attempt to increase the size of these buffer strips, thereby reducing these potential effects. Furthermore, although we have identified strategies that may increase the efficacy of these approaches, such as reduced spacing between traps and bait stations and the addition of platforms underneath A24 traps, the shorter spacing and platforms were only tested at one site for each approach. As such, additional testing is needed to provide a more robust assessment of these potential management options.

It bears emphasizing that effective rodent management in agricultural systems will require multiple management tools (Campbell et al. 1998; Nelson et al. 2002; Sterner 2008; Baldwin et al. 2014b). Currently, the use of rodenticides and traps are two of the most likely candidates for effectively reducing black rat numbers in citrus orchards. In this study, we did not find that any of these approaches resulted in a significant reduction in black rats across all study sites, but we did identify potential strategies to increase their effectiveness. Future research should focus on increasing the efficacy of these tools and combining them with longer-term monitoring efforts to develop a strategy that is safe and efficacious, while minimizing management costs to producers.

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LITERATURE CITED

Advani R (1986) Field evaluation of single and multiple dose anticoagulant rodenticides in reducing rodent populations and damages in coconut plantations. Proceedings of the Vertebrate Pest Conference 12: 166–172

Baldwin RA, Meinerz R (2022) Developing an effective strategy for indexing roof rat abundance in citrus orchards. Crop Protection 151: 105837.

Baldwin RA, Quinn N, Davis DH, Engeman RM (2014a) Effectiveness of rodenticides for managing invasive roof rats and native deer mice in orchards. Environmental Science and Pollution Research 21: 5795–5802.

Baldwin RA, Salmon TP (2011) The facts about rodenticides. The Wildlife Professional 5: 50–53.

Baldwin RA, Salmon TP, Schmidt RH, Timm RM (2014b) Perceived damage and areas of needed research for wildlife pests of California agriculture. Integrative Zoology 9: 265–279.

Burke CB, Quinn NM, Stapp P (2021) Use of rodenticide bait stations by commensal rodents at the urban-wildland interface: Insights for management to reduce nontarget exposure. Pest Management Science 77: 3126–3134.

Campbell EW III, Koehler AE, Sugihara RT, Tobin ME (1998) The development of an integrated pest management plan for roof rats in Hawaiian macadamia orchards. Proceedings of the Vertebrate Pest Conference 18: 171–175.

Carter A, Barr S, Bond C, Paske G, Peters D, van Dam R (2016) Controlling sympatric pest mammal populations in New Zealand with self-resetting, toxicant-free traps: a promising tool for invasive species management. Biological Invasions 18: 1723–1736.

CDFA (2020) California Agricultural Statistics Review 2019–2020. California Department of Food and Agriculture (CDFA), Sacramento, California, 157 pp.

Dongol EMA, Abdel Samad MA, Ali MK, Baghdadi SAS (2021) Estimation of damage caused by rodents on orange and mandarin orchards at Sohag governorate. Archives of Agriculture Sciences Journal 4: 14–40.

Fall MW, Fiedler LA (2015) Rodent control in practice: tropical field crops. In: Buckle AP, Smith RH (eds), Rodent Pests and their Control, 2nd ed. CAB International, United Kingdom, pp 269–294.

Gronwald M, Russell JC (2022) Behaviour of invasive ship rats, *Rattus rattus*, around Goodnature A24 self-resetting traps. Management of Biological Invasions 13: (in press).

Horskins K, Wilson J (1999) Cost-effectiveness of habitat manipulation as a method of rodent control in Australian macadamia orchards. Crop Protection 18: 379–387.

Innes J, Hay R, Flux I, Bradfield P, Speed H, Jansen P (1999) Successful recovery of North Island kokako *Callaeas cinerea wilsoni* populations, by adaptive management. Biological Conservation 87: 201–214.

King CM, Innes JG, Gleeson D, Fitzgerald N, Winstanley T, O'Brien B, Bridgman L, Cox N (2011) Reinvasion by ship rats (*Rattus rattus*) of forest fragments after eradication. Biological Invasions 13: 2391–2408.

Lefebvre LW, Holler NR, Decker DG (1985) Efficacy of aerial application of a 2% zinc phosphide bait on roof rats in sugarcane. Wildlife Society Bulletin 13: 324–327.

Nelson JT, Woodworth BL, Fancy SG, Lindsey GD, Tweed EJ (2002) Effectiveness of rodent control and monitoring techniques for a montane rainforest. Wildlife Society Bulletin 30: 82–92.

Ogden J (2018) Report on rat trapping and performance of A24 multi-kill traps on Hirakimata over two years. Great Barrier Island Environmental Trust, 28 pp.

Pimentel D, Zuniga R, Morrison D (2005) Update on the environmental and economic costs associated with alien-invasive species in the United States. Ecological Economics 52: 273–288.

Prakash I (1988) Bait shyness and poison aversion. In: Prakash I (ed), Rodent Pest Management. CRC Press, Inc., Boca Raton, Florida, pp 321–329.

Puan CL, Goldizen AW, Zakaria M, Hafidzi MN, Baxter GS (2011) Absence of differential predation on rats by Malaysian barn owls in oil palm plantations. Journal of Raptor Research 45: 71–78.

Quinn N, Baldwin RA (2014) Managing roof rats and deer mice in nut and fruit orchards. University of California, ANR publication 8513, 7 pp.

Schneider B (1982) Pesticide assessment guidelines: subdivision G, product performance. U.S. Environmental Protection Agency, Office of Pesticide and Toxic Substances, Springfield, Virginia, 422 pp.

Shapiro L, Rennison D, Brimble M, MacMorran D, Eason C (2018) Redevelopment of a rat specific rodenticide norbormide. Proceedings of the Vertebrate Pest Conference 28: 47–50.

Shiels AB, Bogardus T, Rohrer J, Kawelo K (2019) Effectiveness of snap and A24-automated traps and broadcast anticoagulant bait in suppressing commensal rodents in Hawaii. Human-Wildlife Interactions 13: 226–237.

Shiels AB, Spock DR, Cochran T, Baeten L (In press) Efficacy testing of Goodnature A24 self-resetting rat traps for wild house mice (*Mus musculus*). Management of Biological Invasions.

Sterner RT (2008) The IPM paradigm: vertebrates, economics and uncertainty. Proceedings of the Vertebrate Pest Conference 23: 194–200.

Sugihara RT (2002) Rodent damage research in Hawaii: changing times and priorities. Proceedings of the Vertebrate Pest Conference 20: 40–45.

Tobin ME (1992) Rodent damage in Hawaiian macadamia orchards. Proceedings of the Vertebrate Pest Conference 15: 272–276.

Tobin ME, Koehler AE, Sugihara RT, Ueunten GR, Yamaguchi AM (1993) Effects of trapping on rat populations and subsequent damage and yields of macadamia nuts. Crop Protection 12: 243–248.

Wales KN, Meinerz R, Baldwin RA (2021) Assessing the attractiveness of three baits for roof rats in California citrus orchards. Agronomy 11: 2417.

Wallace RJ, Barnett SA (1990) Avoidance of new objects by the black rat, *Rattus rattus*, after object presentation and change. The International Journal of Comparative Psychology 3: 253–265.

Witmer, GW (2018) Perspectives on existing and potential new alternatives to anticoagulant rodenticides and the implications for integrated pest management. In: van den Brink NW, Elliott JE, Shore RF, Rattner BA (eds), Anticoagulant Rodenticides and Wildlife. Springer, Cham, Switzerland, pp 357–378.

Wood BJ, Singleton GR (2015) Rodents in agriculture and forestry. In: Buckle AP, Smith RH (eds), Rodent Pests and their Control, 2nd ed. CAB International, United Kingdom, pp 33–80.

Worth CB (1950) Field and laboratory observations on roof rats, *Rattus rattus* (Linnaeus), in Florida. Journal of Mammalogy 31: 293–304.

Yabe T (1998) Bark-stripping of tankan orange, *Citrus tankan*, by the roof rat, *Rattus rattus*, on Amami Oshima Island, southern Japan. Mammal Study 23: 123–127.