FINAL REPORT

for

Vertebrate Pest Control Research Advisory Committee

STUDY TITLE:

Developing and testing an IPM approach for managing roof rats in citrus

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ABSTRACT

Roof rats (*Rattus rattus*) are an invasive rodent that can cause substantial damage in citrus orchards. Roof rats have become a more recognized pest throughout California agriculture, yet little is known about efficacious, cost-effective strategies to manage this invasive pest. Therefore, we developed two Integrated Pest Management (IPM) programs that incorporated both elevated bait stations containing 0.005% diphacinone-treated oats and trapping, and we compared those programs to a bait-station only approach (hereafter, simply referred to as bait station) to determine which strategies were most practical for the management of roof rats in citrus. We initially used a replicated design that utilized a control to test a combination of elevated bait stations followed by a short snap trapping program designed to further reduce roof rat numbers in orchards. We then placed A24 traps to intercept reinvading roof rats to hopefully keep rat numbers at low levels (referred to as Trial 1). Initial bait applications were effective at substantially reducing rat numbers, but populations quickly rebounded with the IPM approach, with similarly low efficacy observed for both IPM and bait station strategies 2- and 5-months post-bait application. Additionally, costs for this IPM approach were almost 5 times as much as a bait station approach.

Our second IPM approach (Trial 2) again used a replicated design that incorporated an initial bait application period with 0.005% diphacinone-treated oats to knock down roof rat populations, followed by the use of trapping tunnels that contained two snap traps to further reduce or maintain rat numbers longer-term. We again observed good initial knockdown with bait applications. However, in contrast to Trial 1, we observed substantial success with trapping tunnels at maintaining, and even increasing, overall efficacy within IPM plots. Conversely, bait station plots exhibited rapid reinvasion 2-months post-bait application, although efficacy did improve for bait station plots 5-months post-bait application. Regardless, IPM plots were always more efficacious than bait station plots. Although bait station applications were less costly than the IPM approach used in Trial 2 for the first year of treatment, the cost disparity was substantially less than that for Trial 1, and no cost difference is predicted between the two treatment approaches for subsequent years. Therefore, if this IPM approach were utilized for several years, the cost of this IPM strategy would be relatively similar to programs that used only bait stations. Ultimately, a management program that incorporates initial bait applications to knock down roof rat populations, followed by a long-term trapping program that uses trapping tunnels, should prove to be an effective strategy for managing this damaging, invasive pest in citrus orchards.

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INTRODUCTION

Rats (*Rattus* spp.) are a common and very damaging invasive pest found throughout much of the world, with one projection of damage caused by rats in the U.S. estimated at $19 billion annually (Pimentel et al. 2005). Although much of the damage they cause occurs in urban/suburban areas, they are also common agricultural pests. In particular, nut and tree fruit crops can incur substantial damage from rats when present. For example, roof rats (*Rattus rattus*) cause an estimated 5–10% loss in developing macadamia nut crops in Hawaii each year (Tobin et al. 1997), while roof rats cause frequent damage to citrus crops (Worth 1950), with anecdotal information suggesting roof rat damage is on the rise in citrus orchards in California. Effective management options for these invasive rodents are needed to minimize losses in these orchard systems.

The best management programs for rodents are considered to be those that rely on an Integrated Pest Management (IPM) given their high efficacy, lower long-term cost, and reduced impact to the environment (Sterner 2008, Baldwin et al. 2014b, Witmer 2018, Taggart et al. 2024). Surprisingly few studies have assessed the utility of IPM approaches for rats in orchard crops, perhaps due to the large amount of information needed to develop such programs (Tripathi 2014). Campbell et al. (1998) introduced methods to implement an IPM program for roof rats in macadamia orchards but never reported the efficacy of this approach. We are not aware of any other explicit attempts to quantify the effectiveness of IPM approaches for roof rats in orchard crops. Such information is needed to support their use in these high-value crops.

Currently, the primary tool used to manage roof rats in orchard systems are first-generation anticoagulant rodenticides (Baldwin 2016), presumably given their ease of use and relative cost-effectiveness (Baldwin et al. 2014b). Baldwin et al. (2014a) tested a 0.005% diphacinone treated oat bait in elevated bait stations for the control of roof rats in almond orchards and found this approach to reduce rat abundance by 90% when stations were spaced 30-m apart. Initial testing in citrus orchards showed that a similar baiting approach that used 76-m spacing was far less effective in citrus orchards (efficacy = 28%; Baldwin et al. 2022). A subsequent trial suggested that shorter spacing of 50 m may be more efficacious (Baldwin et al. 2022), but additional testing is needed to verify. That said, exclusive use of rodenticides can sometimes lead to problems such as bait avoidance and rodenticide resistance. Alternative tools are needed to combine with rodenticide applications to maximize the long-term effectiveness of management programs (Baldwin et al. 2014b).

Several alternative strategies have been proposed for managing roof rats in orchard crops including habitat modification, biocontrol, and trapping. White et al. (1998) showed that removal of preferred habitat along the perimeter of macadamia orchards in Australia was effective at substantially reducing damage caused by roof rats. However, as roof rats began to establish more thoroughly within orchards, this approach was no longer effective (Whitehouse et al. 2012). In California citrus orchards, roof rats are also established throughout the orchards (Baldwin et al. 2024), suggesting that habitat removal on orchard perimeters is not likely to be effective. Alternatively, biocontrol of various *Rattus* species through the implementation of barn owl (*Tyto alba*) boxes has been explored as a possibility in oil palm plantations in southeast Asia. Barn owls provided some relief from rat pressure in these plantations (Duckett 1991, Zainal Abidin et al. 2021, Primananda et al. 2024). However, citrus is an evergreen crop that provides thick cover year-round which would likely impede the barn owl's ability to effectively hunt in these orchards (Bunn et al. 1982). For these reasons, we did not view habitat modification or biocontrol as likely solutions to roof rat damage in citrus orchards.

As such, we selected trapping as the primary tool to supplement rodenticide applications for roof rats in orchards. Snap trapping has historically been the primary approach used for roof rats, but they require checking traps frequently to remove captured individuals and to resupply bait. Still, snap trapping can effectively reduce and maintain rat populations at low levels (Shiels et al. 2019), and they could be a viable tool to help combat roof rat damage in citrus. Additionally, the recent introduction of the Goodnature® A24 trap (Goodnature Ltd., Wellington, NZ; hereafter A24 traps) into the U.S. has the potential to increase the utility of trapping as a management tool in that the traps allow for the capture of up to 24 rats without the need to check or reset over a 4–6-month period. These traps have substantially reduced rat abundance in some island conservation situations (Carter et al. 2016, Gronwald and Russell 2022), but they have had only limited testing in orchards (but see Baldwin et al. 2022). If proven efficacious, the use of A24 traps could result in substantial savings in labor costs, making trapping a more viable tool for managing roof rats in orchards.

Although IPM approaches are generally considered more effective than using only rodenticides, many growers still exclusively use rodenticides for rodent control given the high efficacy and perceived cost of IPM programs (Baldwin et al. 2014b). To increase the implementation of IPM programs for rodent control, growers need to be satisfied that these programs are not only efficacious but also cost effective. A combination of bait application and trapping, combined with periodic monitoring for roof rat activity to inform when additional management actions are needed, has the potential to increase the long-term efficacy and cost-effectiveness of roof rat management programs, but to date, remains unstudied. Therefore, we established a study to compare both the efficacy and cost-effectiveness of an IPM approach to a rodenticide-only management program to manage roof rats in citrus orchards. We incorporated information previously derived from roof rat monitoring (Wales et al. 2021, Baldwin and Meinerz 2022), movement (Baldwin et al. 2024), and management investigations (Baldwin et al. 2022) to construct our IPM program. If successful, this IPM approach should provide citrus growers with a management approach that will limit roof rat damage and food safety concerns in a cost-effective, practical manner.

MATERIALS AND METHODS

Study area and site dimensions

We conducted all trials at 4 different naval orange orchards in Tulare and Kern Counties in the southern San Joaquin Valley, California, from spring 2022 through Autumn 2023. Each site consisted of a 2 ha (140 m × 140 m) interior core where we conducted all indexing for the trials. We included an external buffer around the interior cores to reduce the likelihood that roof rats would reinvade the indexing core after initial removal efforts (mean radius of home range of roof rats = 87 m; Baldwin et al. 2024), ultimately resulting in plots 16 ha in size (400 × 400 m). At each site, we included a bait station-only plot (hereafter, bait station), an IPM plot, and a control plot. No treatments were applied in the control plots during the duration of both Trials 1 and 2, although indexing occurred in the control plots at the same intervals as those that were conducted for the bait station and IPM plots. Trial 1 was initiated in May 2022 at Site 1, with subsequent sites initiating in six-week staggered intervals. For Trial 2, we started Site 1 during December 2022. We used five-week staggered intervals to initiate Sites 2–4, although Site 2 did not start until February 2023 given inclement weather.

Trial 1

Bait station

Similar to Baldwin et al. (2022), we used elevated bait stations that contained 0.005% diphacinone-treated rolled oats (manufactured by California Department of Food and Agriculture [CDFA], Sacramento, California, USA) to initially remove roof rats from bait station plots (see Baldwin et al. 2014a for design details of the bait station). The bait stations were secured via bungee cords approximately 1.5 m up in the trees following an 8 × 8 grid structure with bait stations separated by 50 m (Fig. 1). We initially filled each bait station with approximately 128 g of bait, and we checked them at approximately 1-week intervals for 4 weeks. Additional bait was added and recorded as needed during bait checks. However, we operated one of the four sites for approximately 6 weeks given substantial rodent activity prior to bait application (details in Results section), combined with continual removal of bait indicating additional rat activity. For this site, after completing post-treatment indexing protocols, we noted little reduction in roof rat activity, likely given initial saturation of the orchard by roof rats. As such, we continued to bait at this site for a total of 4 months until bait consumption appeared to stabilize at a low level. This duration would likely have been somewhat less but extensive rainfall during this period saturated bait rendering it inedible for portions of the baiting period. This problem was exacerbated by our inability to access the field site to replace bait given flooded and extreme muddy conditions.

IPM

We initiated baiting in IPM trials at all four plots concurrent with baiting in the bait station plots, with baiting strategies and duration consistent across the two treatment types. Upon completion of post-treatment indexing using tracking tunnels (details in indexing section), we initiated a separate monitoring strategy across the entire treatment site (monitoring plus buffer zone) that involved the placement of a single soft bait (Liphatech Rat & Mouse Attractant™; Liphatech, Inc., Milwaukee, Wisconsin, USA) attached to a tree branch at the same sites used for bait application (Fig. 1). We then checked each soft bait for chewing three days later. If a soft bait was chewed, we placed two snap trap tunnels (each tunnel contained two snap traps; Tomcat® Tunnel™ Trapping System; Motomco, Madison, Wisconsin, USA) separated by approximately 35 meters with the soft bait location serving as the approximate center of that distance. The snap traps were baited with Goodnature® Chocolate Rat & Mouse Lure. We also placed two snap trap tunnels in the same manner around any tracking tunnel locations where we detected roof rat activity following the completion of our baiting program. The purpose of the snap trapping was to further reduce roof rat activity before implementing our maintenance program (i.e., A24 traps). We operated the snap traps for two weeks, with trap check and rebaiting occurring approximately one week after the initiation of the trapping period.

Following the completion of our two-week snap trapping period, we deployed A24 traps in a 6 × 6 grid with traps spaced approximately 75 m apart (Fig. 2). This distance was 12 m less than the radius of an average roof rat home range in California citrus orchards (Baldwin et al. 2024), with this design expected to intercept reinvading roof rats. The A24 traps contained

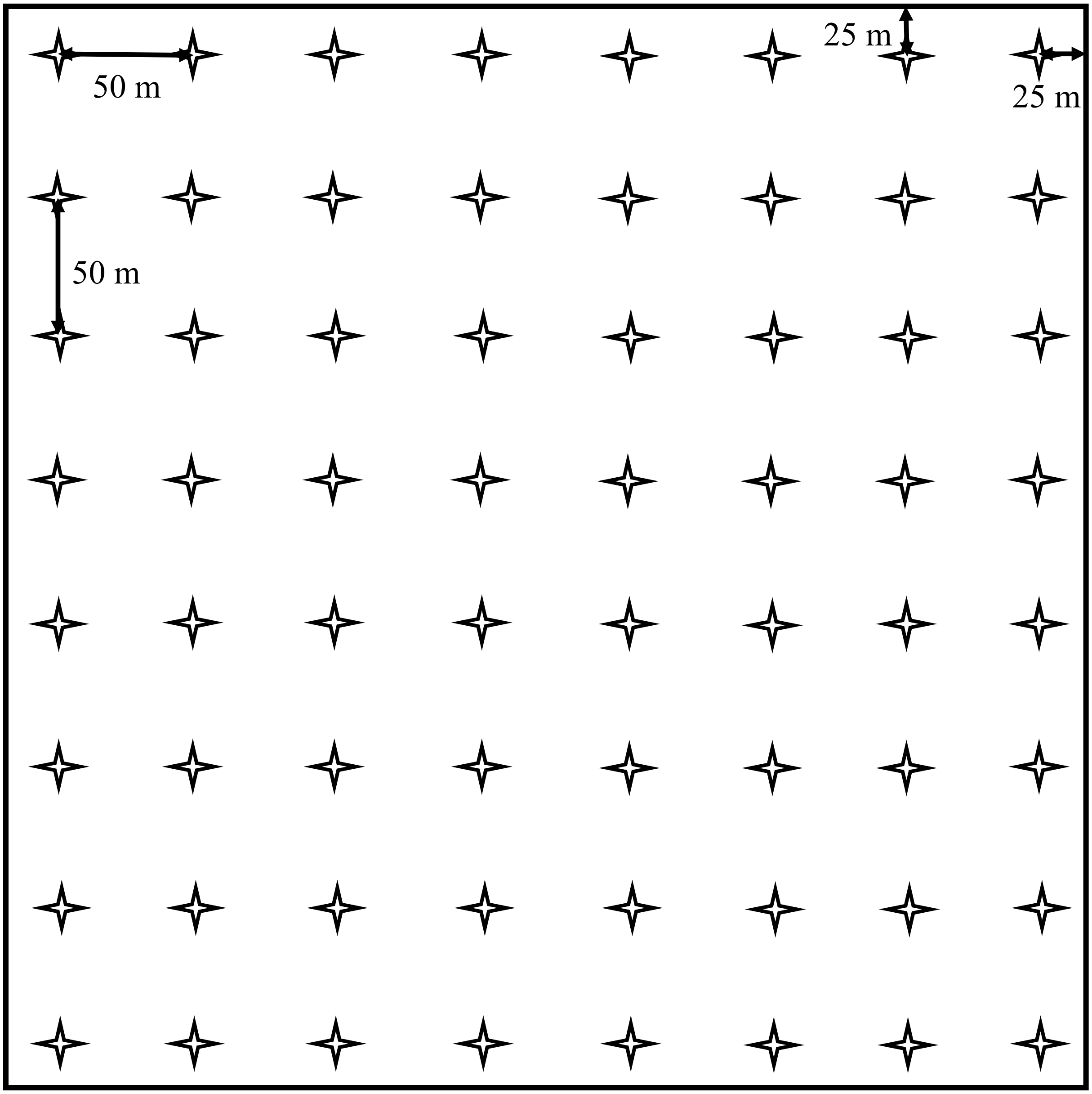

Figure 1. Example of plot layout (400 m × 400 m) for both bait station and soft bait monitoring locations (represented by stars) in citrus orchards in the southern San Joaquin Valley, CA. The arrows illustrate distances between bait station/soft bait locations, as well as distances to the plot edges.

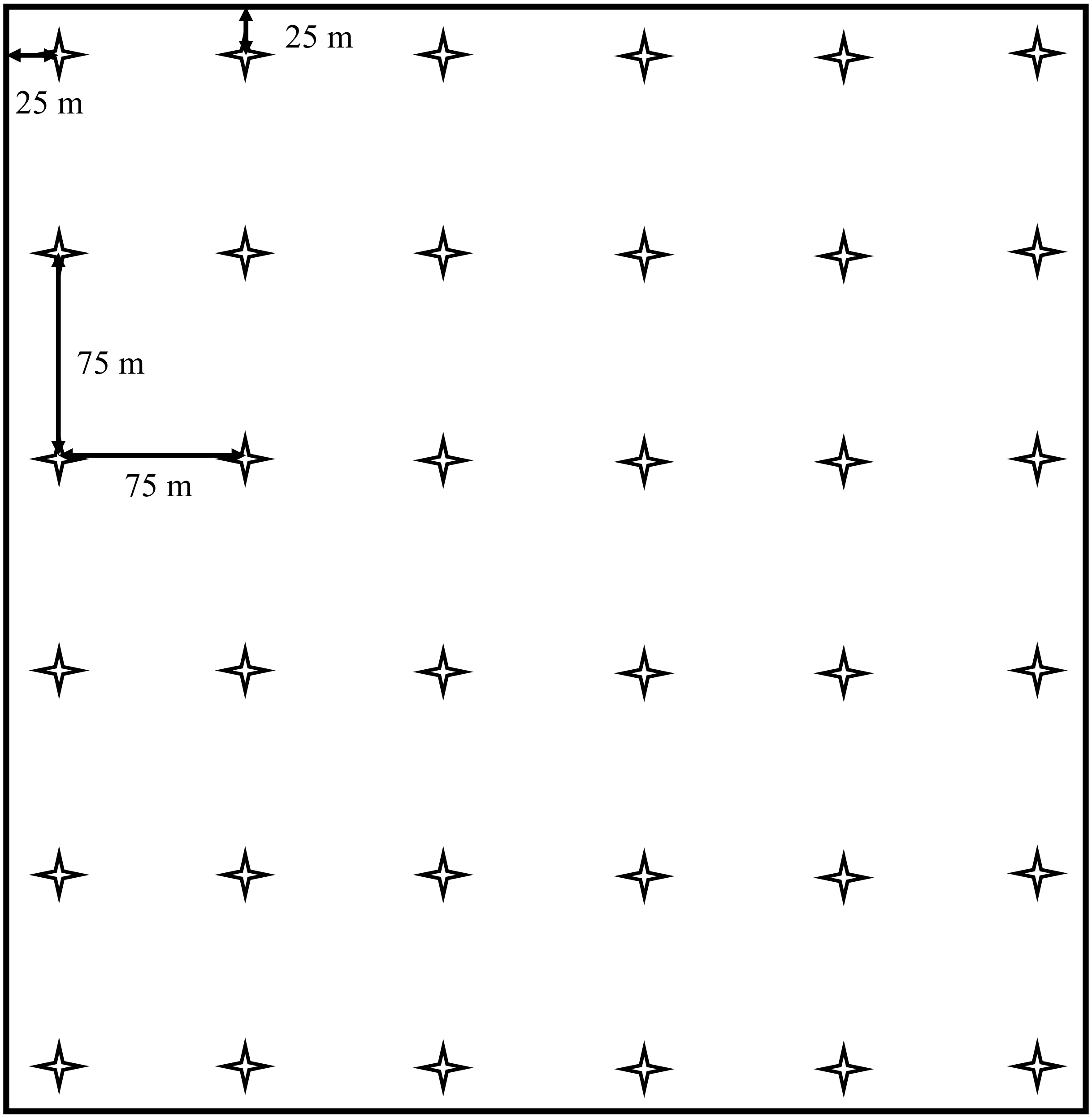

Figure 2. Example of plot layout (400 m × 400 m) for both Goodnature® A24 and trapping tunnel locations (represented by stars) in citrus orchards in the southern San Joaquin Valley, CA. The arrows illustrate distances between trap locations, as well as distances to plot edges.

Goodnature® Chocolate Rat & Mouse Lure Automatic Lure Pumps (ALP) which allowed fresh bait to be automatically dispensed throughout the duration of their use. We placed the A24 traps up in the tree canopies (generally 0.9–1.8 m aboveground) to eliminate access to ground-dwelling nontarget species. Following the recommendation by Baldwin et al. (2022), we placed a wooden platform underneath the trap to potentially allow easier entry into the triggering area of the trap. The traps were operated for approximately 5 months for three of the sites, but for the fourth site that received a longer bait application period, we were able to conduct A24 trapping for approximately 2 months. The A24 traps were checked opportunistically (usually around once a month) throughout the trapping period. This process involved checking the ALP to ensure it was still providing bait and replace as needed, and to test fire the trap to ensure they were working properly.

Trial 2

Bait station

We followed the same approach as with Trial 1. Our goal for baiting duration was again 1 month, and we used the same 0.005% diphacinone-treated rolled oats deployed in elevated bait stations as in Trial 1. However, for Site 2, very heavy and consistent rain for several weeks led to moldy bait and inaccessible field conditions for changing bait when necessary. As such, the baiting period for this site was extended to two months. For Site 4, we again noted very high roof rat abundance from tracking tunnel visitation leading to an extended baiting period of 3.5 months. Bait consumption stabilized at a low level at that point, leading to the cessation of baiting at that site.

IPM

We again applied bait in the same manner and for the same duration as described for the bait station plots. We then initiated a snap trapping program upon completion of baiting. For this approach, we placed the Tomcat® Tunnel™ Trapping System following a 6 × 6 grid structure with trapping tunnels located 75 m apart (Fig. 2). This is the same distance interval as used with the A24 traps. Traps were baited with Goodnature® Chocolate Rat & Mouse Lure and were operated for approximately 5 months for Sites 1–3. Because of the extended baiting period for Site 4, we were able to operate trapping tunnels for approximately 2 months at this site. Trapping tunnels were checked every 2–4 weeks depending on previous rat activity combined with landowner field operations (e.g., pesticide applications that eliminated access to the field site for an extended period). Captured rats were documented, traps reset, and bait reapplied as needed.

Indexing

We followed the general guidelines provided by Baldwin and Meinerz (2022) in using tracking tunnels (Black Trakka; Gotcha Traps, Warkworth, NZ) to assess changes in roof rat activity across the duration of this study. Each treatment or control plot contained an inner monitoring plot that was 0.4 ha in size. Within each monitoring plot, we placed a 5 × 5 grid of tracking tunnels, with each tunnel separated by 35 meters (Fig. 3). Tracking tunnels were secured to 1.2 m lengths of 5.1 × 10.2 cm boards up in the tree canopy (generally 0.9–1.8 m aboveground). We used Liphatech Rat and Mouse Attractant™ soft baits fixed to the tracking tunnels to attract the rats to the tracking pad, which was located in the middle of the tracking card. Tracking tunnels were operated for 4 nights. At the conclusion of each 4-night monitoring

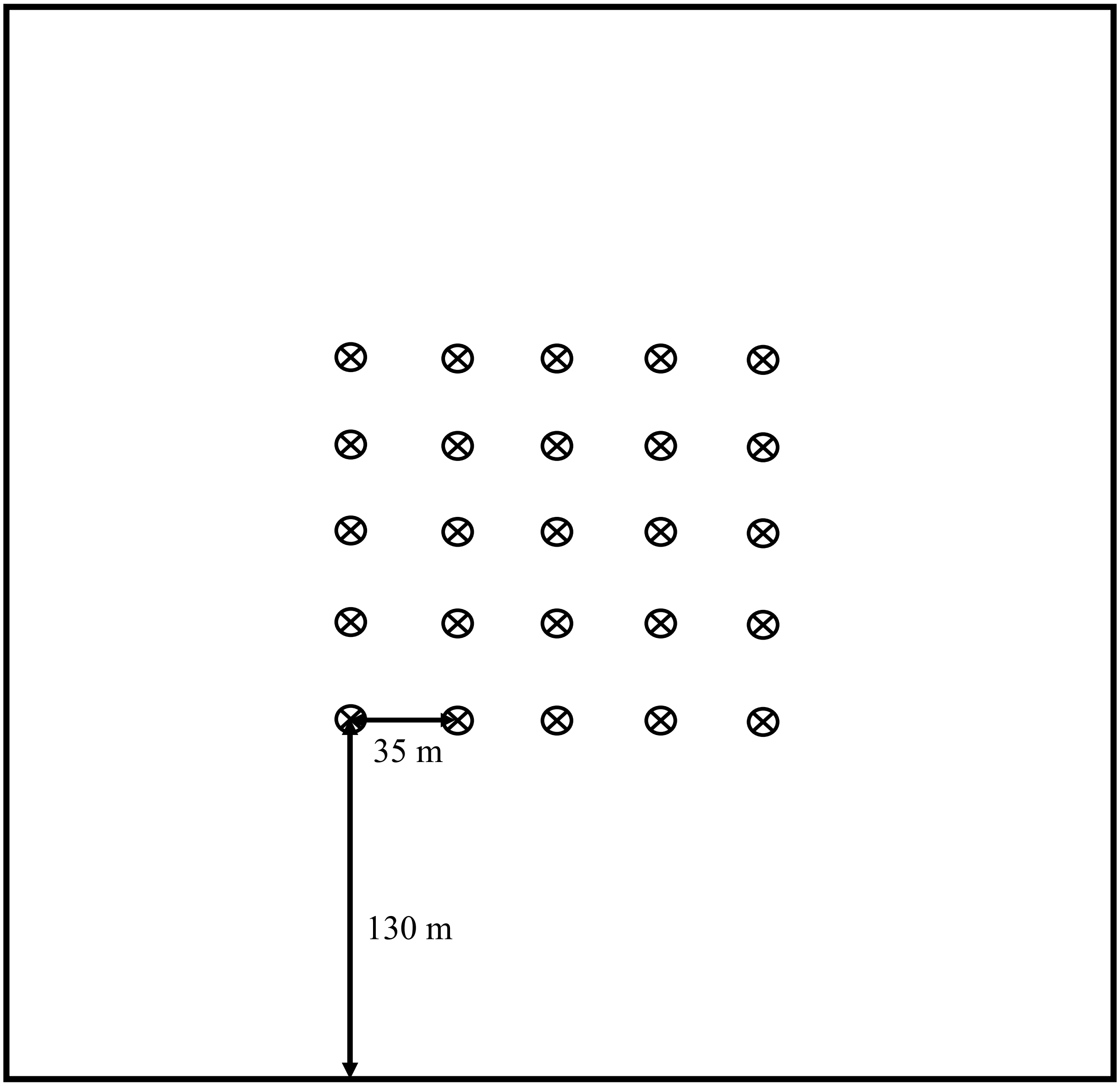

Figure 3. Example of plot layout (400 m × 400 m) for tracking tunnel locations (represented by circles with x's) in citrus orchards in the southern San Joaquin Valley, CA. The arrows illustrate distances between tracking tunnel locations, as well as distances from tracking tunnels to the plot edge.

period, we recorded the presence or absence of roof rat tracks on the cards. This process was identical for all indexing periods of this study.

Tracking tunnels were operated to assess the effectiveness of baiting and trapping efforts. For this, we operated tracking tunnels before the implementation of the baiting program in bait station, IPM, and control plots, and we again repeated their operation following the completion of the baiting program. We determined efficacy through the following equation:

(1 – [number of active tunnels after treatment/number of active tunnels before treatment]) × 100%

We were also interested in assessing potential reinvasion following the completion of the initial baiting period. As such, we conducted additional assessments approximately two months following the completion of the baiting program and again at the end of the trial period. This generally occurred 5 months following the completion of the baiting program, although for Site 4, we were only able to conduct assessments for 2 months post-bait application for both Trials 1 and 2.

Analysis

We used the Cochran-Mantel-Haenszel test to determine differences in efficacy between the treatment types (bait station, IPM, and control) across the different monitoring periods while accounting for potential differences across our different study sites (Cochran 1954, Mantel and Haenszel 1959). Following Lai et al. (2011) and Wales et al. (2021), we tested for homogeneity across sites using PROC CATMOD, which allowed us to fit a log-linear model to test for three-way interactions across sites, treatment types, and monitoring period using a likelihood ratio test (Lai et al. 2011). If we observed homogeneity across sites, but we observed a significant difference in efficacy associated with the different treatment types, we combined data for each treatment type across the four sites. We then used Fisher's exact test to determine which treatment types differed within each monitoring period. This process was conducted for both Trial 1 and 2. We conducted analyses using SAS version 9.4 (SAS Institute Inc., Cary, NC, USA).

Cost assessment

Operational timing

To calculate costs, we first assessed the amount of time required to conduct each operation of the study. To accomplish this, we used a subset of locations per site, and we recorded the amount of time it took to complete each task from start to finish (e.g., initiation of placement of bait station through the completion of bait station installation). This was repeated at each site, with the average number of seconds required per placement calculated across all study locations (see Table 1 for sample sizes and mean time estimates). This average time was then multiplied by the number of placements for each operation per site to calculate the total amount of time required per site. These assessments were conducted for site set up, maintenance when required (e.g., trap and bait checks), and material removal upon completion of each task.

All study sites were assumed to be 400 m × 400 m to provide standardization across management programs and study sites. For time-commitment calculations, we assumed a 6 × 6 grid for

Table 1. The mean completion times (in seconds) for various portions of our management programs as recorded for installation, maintenance, and removal efforts for a roof rat study conducted in citrus orchards in the southern San Joaquin Valley, CA.

	Installation			Maintenance			Removal		
	Mean (s)	SE	*n*	Mean (s)	SE	*n*	Mean (s)	SE	*n*
Tracking tunnels	105	2	104				68	3	104
Bait station	204	3	160	65	3	160	153	3	160
Soft bait indexing	44	1	52				21	1	52
Snap trapping	92	7	28	55	10	46	84	9	28
A24 trapping	418	7	52	29	0.3	52	70	2	39

indexing sites with each grid point separated by 70 m. This differed from the monitoring approach for assessing efficacy in which we used a 5 × 5 grid with grid points separated by 35 m. We used the wider, more extensive monitoring approach to represent how a pest control operator would likely monitor an entire orchard (i.e., they would be interested in rat activity throughout the orchard rather than solely within the orchard interior), and the wider spacing has been shown to be equally effective at monitoring changes in roof rat activity over time (Baldwin and Meinerz 2022). All other spacings were consistent with what was reported for the assessment of efficacy of each management approach.

We assumed that all pest control operators would use an All-Terrain Vehicle (ATV) to transport materials and conduct management activities throughout the study. To account for this timing, we assumed that all ATVs would be operated at a speed of 12 kph. The number of trips up and down rows of the orchards varied depending on the operation of the study, so that portion was factored into the labor cost. For Trial 1, this equated to the following: tracking tunnels = 6 trips, bait stations = 8 trips, soft bait indexing = 8 trips, snap traps = 6 trips, A24 traps = 6 trips. For Trial 2, we used the following: tracking tunnels = 6 trips, bait stations = 8 trips, snap traps = 6 trips. This time requirement was added to the time values derived for installation, maintenance, and removal efforts for each management task to develop an average value (see Table 2 for a breakdown for each management task).

Calculating costs

We initially determined labor costs for the 6-month study periods for bait station plots and the IPM plots for Trials 1 and 2. For bait station plots, we assumed that pest control operators would operate the tracking tunnels before and after the completion of the baiting program, but they would not operate them at any other time during that 6-month period. For bait application, we assumed an initial bait application, followed by 2 bait checks, and then one final check to remove the bait stations. For our cost comparisons, we assumed that bait application occurred over a 1-month period. No other actions were assumed to occur during this 6-month period. This was consistent between both Trial periods 1 and 2.

For IPM plots during Trial 1, we assumed pest control operators would operate tracking tunnels before and after the completion of the baiting program, and again 3 months after the initiation of the baiting program to track potential changes in roof rat activity over time. We followed the same approach to calculate labor costs for bait application as described for the bait station plots. Soft bait indexing was conducted following a singular application and removal process. For trapping tunnels, we assumed that 16 tunnels would be placed across 8 sites. We estimated 8 locations with rat activity to represent a situation where roof rats were largely removed from the orchards via bait application but were not completely eradicated. For time calculations, we included trap tunnel placements, a single check one week following trap placement, and trap removal. Likewise, we included placement for A24 traps, a single check 2.5–3 months after the placement of the traps to ensure functionality, and a final check to remove traps.

Time assessments for tracking tunnels and bait application were the same for IPM plots during Trial 2. For trapping tunnels, we included placement times for the tunnels, seven trap checks (roughly 3-week intervals), and trap removal. All time estimates were summed for each

Table 2. Mean estimates of time (in minutes) and associated standard errors required to install, maintain, and remove various management and monitoring tools per study plot for roof rats in citrus orchards in the southern San Joaquin Valley, CA.

	Installation		Maintenance		Removal	
	Mean	SE	Mean	SE	Mean	SE
Tracking tunnels	78	0.2			57	0.3
Bait station	238	0.5	89	0.4	183	0.4
Soft bait indexing	67	0.2			42	0.1
Trap tunnel[a]	40	0.5	30	0.6	38	0.6
Trap tunnel[b]	71	0.7	49	0.9	64	0.9
A24 trapping	266	0.7	33	0.1	57	0.2

[a] Represents snap trapping effort as part of Trial 1. Estimates include 8 trap locations with 2 trap tunnels at each site. Further details are provided in text.

[b] Represents snap trapping effort as part of Trial 2, which included operating a 6 × 6 grid of trapping tunnels (i.e., 36 trap locations) with tunnels separated by approximately 75 m.

treatment category and multiplied by \$17.00/hr as the going rate for field labor at the time of this study (B. Carmen, Sun Pacific, pers. comm.).

We were also interested in assessing costs over a 2-year period to determine how they would compare between bait station plots and IPM plots conducted during Trial 2. In this assessment, for bait station plots, we assumed indexing with tracking tunnels would occur every 6 months over the course of the two-year study period. We assumed 4 bait applications, each separated by 6 months. The protocol for time assessments was the same as that reported previously. No other activities occurred during this proposed management action.

For IPM plots, we assumed quarterly indexing via tracking tunnels to detect changes in roof rat activity over time. We assumed an initial bait application, followed by a second bait application approximately 6 months later. We assumed no additional bait applications for the remainder of the two-year sampling period. The protocol for time assessments was the same as has already been reported. Following this program, we then planned to operate trapping tunnels for 5 months following the completion of the initial baiting program. We included trapping tunnel placement and trap checks approximately once every 3 weeks. We did not include trap removal, as we deemed it unnecessary given our intent to again use these trapping tunnels following the completion of the second baiting session. All other aspects of these cost calculations included installation and removal times for each iteration. Upon completion of the final bait application, we again initiated trapping tunnels. We assumed operation of the trapping tunnels for the remainder of the study, with 3-week trap checks included in our estimates. We again assumed a labor rate of \$17.00/hour.

A variety of supplies were required to operate the various management actions tested in this study (see Table 3). We provided the market prices for these supplies at the time of data analysis for this project (March 2024). We did not include shipping or tax costs in these estimates, as these will vary depending on a number of factors. Ultimately, supply costs were added to labor costs to better reflect the total costs for each management strategy. See Tables 3–4 for a breakdown of each cost for the different portions of the investigation.

RESULTS

Trial 1

We observed a difference in efficacy among the treatment types for the initial post-bait application period ($\chi^2_2 = 29.6$; $P < 0.001$), but not for the periods 2-months ($\chi^2_2 = 5.6$; $P = 0.062$) or 5-months post-bait application ($\chi^2_2 = 2.1$; $P = 0.346$). Results were homogenous across our study sites ($\chi^2_6 \leq 12.3$; $P \geq 0.057$). Not surprisingly, bait station and IPM plots were equally effective at reducing roof rat abundance immediately following the completion of the baiting program given that bait application programs were the same in these plots (Fig. 4). Although we did not observe a statistical difference between treatment types for the 2- and 5-month post-bait application periods, IPM plots exhibited the greatest mean efficacy (Fig. 4).

Trial 2

Bait applications were again largely successful, although efficacy was a bit lower in the bait station plot (Fig. 5). We observed a difference in efficacy among the treatment types for all post-bait application periods (post-bait: $\chi^2_2 = 9.8$; $P = 0.007$; 2-months post-bait: $\chi^2_2 = 13.7$; $P =$

Table 3. Labor and supply costs for bait station plots, as well as IPM plots for both trials 1 and 2. To calculate costs, we multiplied the number of units (No. units) by the cost per unit for each item. Costs are calculated across a 16-ha area.

	Expense	Cost/unit ($)	Bait station		IPM—Trial 1		IPM—Trial 2	
			No. units	Total ($)	No. units	Total ($)	No. units	Total ($)
Labor[a]	Tracking tunnel monitoring	17.00	4.50	76.57	6.76	114.85	6.76	114.85
	Bait station	17.00	10.00	169.98	10.00	169.98	10.00	169.98
	Soft bait indexing	17.00			1.81	30.72		
	Trapping tunnels	17.00			1.81	30.84	7.93	134.88
	A24 trapping	17.00			5.95	101.08		
Supplies	Tracking tunnel	7.82	36	281.52	36	281.52	36	281.52
	Tracking card and ink	1.06	72	76.32	108	114.48	108	114.48
	Soft bait	0.17	72	11.88	172	28.38	108	17.82
	1.2 m length of 5.1 × 10.2 cm board	1.44	36	51.84	52	74.88	72	103.68
	28-cm cable tie	0.09	72	6.41	312	27.77	144	12.82
	Bait station	10.66	64	682.24	64	682.24	64	682.24
	Diphacinone grain (kg^{-1})	3.77	11.92	44.94	11.92	44.94	11.92	44.94
	Bungee cord	2.50	64	160.00	64	160.00	64	160.00
	Trapping tunnels	23.99			16	383.84	36	863.64
	Prefeed paste	11.99			0.25	3.00	2.67	32.01
	0.6 m length of 5.1 × 10.2 cm board	0.72			36	25.92		
	A24 trap kit	151.99			36	5471.64		
Tot cost				1561.70		7746.08		2597.98

[a] Units for labor cost are provided on a per hour basis.

Table 4. Labor and supply costs for proposed bait station and IPM strategies over two years. To calculate costs, we multiplied the number of units (No. units) by the cost per unit for each item. Costs are calculated across a 16-ha area.

			Year 1				Year 2			
			Bait station		IPM		Bait station		IPM	
	Expense	Cost/unit ($)	No. units	Total ($)	No. units	Total ($)	No. units	Total ($)	No. units	Total ($)
Labor[a]	Monitoring	17.00	4.50	76.57	9.01	153.14	4.50	76.57	9.01	153.14
	Bait station	17.00	20.00	339.97	20.00	339.97	20.00	339.97		
	Trapping tunnels	17.00			13.35	226.98			13.79	234.41
Supplies	Tracking tunnel	7.82	36	281.52	36	281.52				
	Tracking card	1.06	72	76.32	144	152.64	72	76.32	144	152.64
	Soft bait	0.17	72	11.88	144	23.76	72	11.88	144	23.76
	1.2 m of 5.1 × 10.2 cm board	1.44	36	51.84	72	103.68				
	28-cm cable tie	0.09	72	6.41	144	12.82				
	Bait station	10.66	64	682.24	64	682.24				
	Diphacinone grain (kg^{-1})	3.77	23.84	89.88	23.84	89.88	23.84	89.88		
	Bungee cord	2.50	64	160.00	64	160.00				
	Trapping tunnels	23.99			36	863.64				
	Goodnature prefeed paste	11.99			5.34	64.03			6.41	76.86
Tot cost				1776.63		3154.30		594.62		640.81

[a] Units for labor cost are provided on a per hour basis.

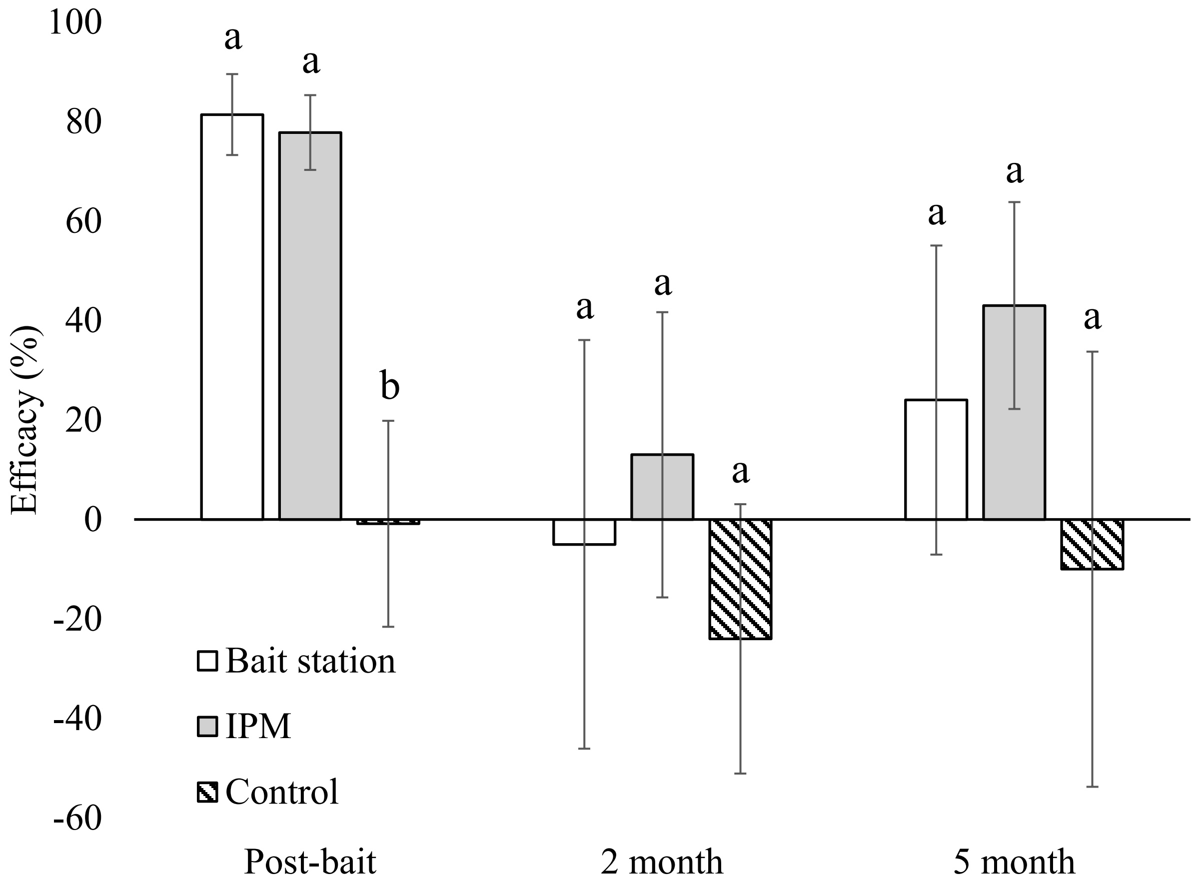

Figure 4. The mean percent efficacy (percent change in roof rat visitation across respective monitoring periods with positive efficacy representative of a reduction rat activity) and associated standard errors of bait station, IPM, and untreated plots (Control) for roof rat control within 4 citrus orchards in the southern San Joaquin Valley, California, from spring 2022 through spring 2023 (Trial 1). We applied 0.005% diphacinone-treated oats in elevated bait stations for bait station and IPM plots, with efficacy after this baiting period represented as "Post-bait". For IPM plots, we followed up bait application with trapping via snap traps and Goodnature® A24 traps. We conducted additional indices of roof rat activity 2-months and 5-months post-bait application to detect differences over the duration of the 6-month trial. Significant differences across treatment types within a specified time period are denoted by different letters.

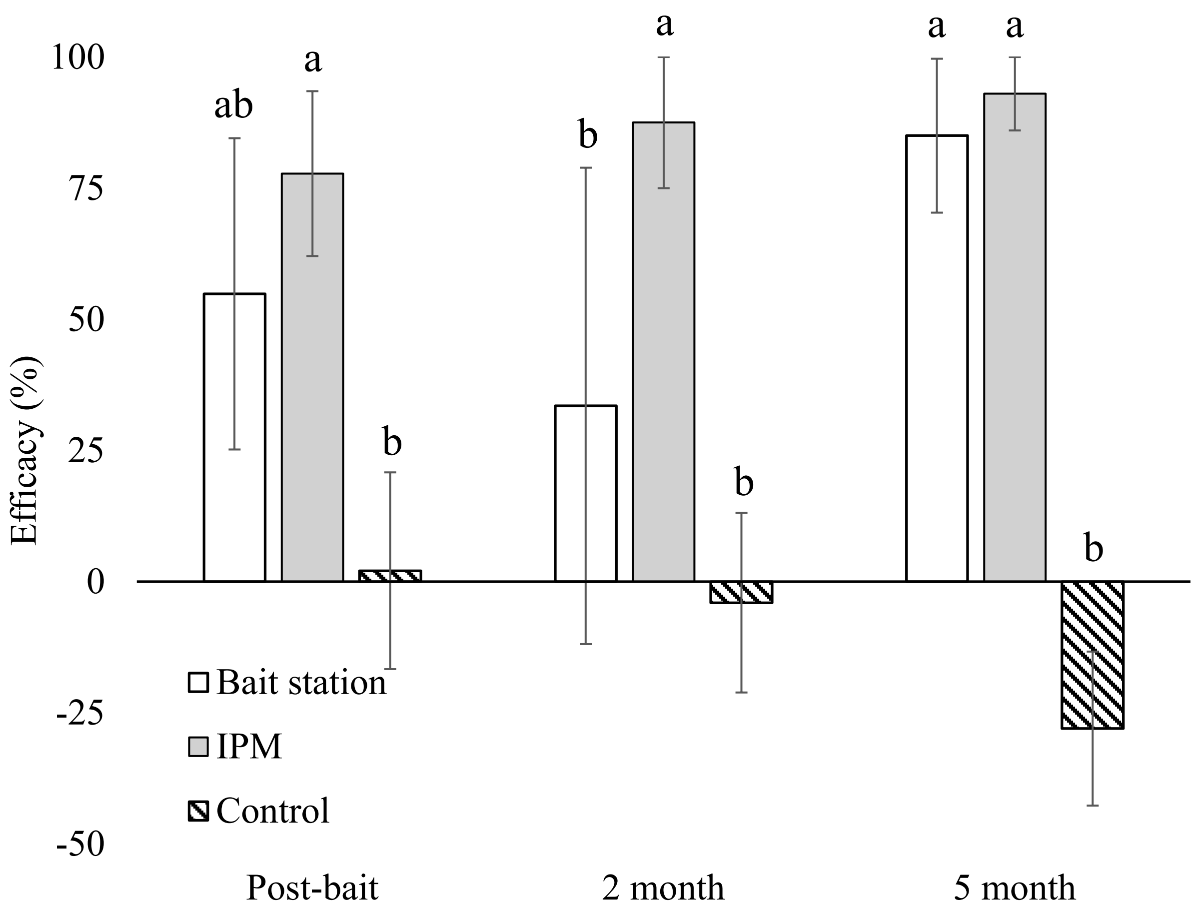

Figure 5. The mean percent efficacy (percent change in roof rat visitation across respective monitoring periods with positive efficacy representative of a reduction rat activity) and associated standard errors of bait station, IPM, and untreated plots (Control) for roof rat control within 4 citrus orchards in the southern San Joaquin Valley, California, from autumn 2022 through autumn 2023 (Trial 2). We applied 0.005% diphacinone-treated oats in elevated bait stations for bait station and IPM plots, with efficacy after this baiting period represented as "Post-bait". For IPM plots, we followed up bait application with snap trapping for the remainder of the trial period. We conducted additional indices of roof rat activity 2-months and 5-months post-bait application to detect differences over the duration of the 6-month trial. Significant differences across treatment types within a specified time period are denoted by different letters.

0.001; 5-months post-bait: $\chi^2_2 = 30.0$; $P < 0.001$). Results were homogenous across our study sites ($\chi^2_6 \leq 12.2$; $P \geq 0.057$). Although we observed a rapid repopulation of rats within the first two months in bait station plots, the IPM plots were successful at keeping populations from rebounding post-bait application. In fact, trapping further reduced roof rat numbers in the IPM plots after both 2- and 5-months post-bait application (Fig. 5). Within bait station plots, we observed a dramatic reduction in rat activity (i.e., elevated efficacy) 5-months post-treatment. Although we observed a difference between roof rat activity in IPM and bait station plots 2-months post-bait application, we did not observe a significant difference at the end of the trial. Collectively, during the entire trapping period, we removed 97 roof rats with snap traps, further indicating their value in intercepting reinvading rats. We observed an increase in roof rat activity in control plots over the duration of the trial (Fig. 5), indicating that efficacy results may be conservative.

Cost assessment

Supply costs were the driving expense behind all management actions for roof rats regardless of the tactic used (Fig. 6). Supply costs were exorbitantly high for the IPM program used in Trial 1 (a 6-month study), while bait station plots exhibited the lowest total costs. When relating costs across a two-year management program, we again see that bait station plots were less expensive and that supply costs were the primary expense for both management actions (Fig. 7). However, we noted little difference in costs between bait station and IPM programs during the second year of the management plan, suggesting that long-term costs would likely be similar between the two management plans.

DISCUSSION

Similar to a study in almond orchards (Baldwin et al. 2014a), the use of elevated bait stations containing 0.005% diphacinone-treated oats was effective as an initial approach to knock down roof rat populations in citrus (Figs. 4–5), with mean (73%; SE = 8%) and median (87%) values across both treatment periods above the 70% threshold that U.S. EPA uses to consider a rodenticide effective (Schneider 1982). We were unsure how effective this approach would be in citrus given that early pilot work showed low efficacy across 3 of 4 study sites (Baldwin et al. 2022). However, in Baldwin et al. (2022), 76-m spacing was used between bait stations in the three sites where efficacy was lower, while shorter 50-m spacing was used at a fourth site where they observed a 77% reduction in roof rat activity after the bait treatment period. Although roof rats move extensive distances (mean daily displacement: males = 201 m, SE = 3; females = 148 m, SE = 11) within citrus orchards (Baldwin et al. 2024), shorter spacing between bait stations (i.e., ≤50 m) appears to be important to maximize exposure to roof rats, particularly given the need to consume diphacinone multiple times over the course of several days to ensure lethality (Elias and Johns 1981, Donlan et al. 2003).

Although bait stations were effective at reducing roof rat abundance immediately post-treatment, we observed rapid reinvasion as soon as two-months post-treatment (Figs. 4–5). Such reinvasion is common with rats and other rodent species following depopulation events (Shiels et al. 2019), and it stresses the need for management actions to be put in place to intercept reinvaders. That said, larger-scale removal efforts would slow down the potential for reinvasion. For this study, we were limited by various logistics (e.g., cost, protocol restrictions, staff), so we could not bait all the adjacent orchards. A concerted baiting program throughout the entire growing region

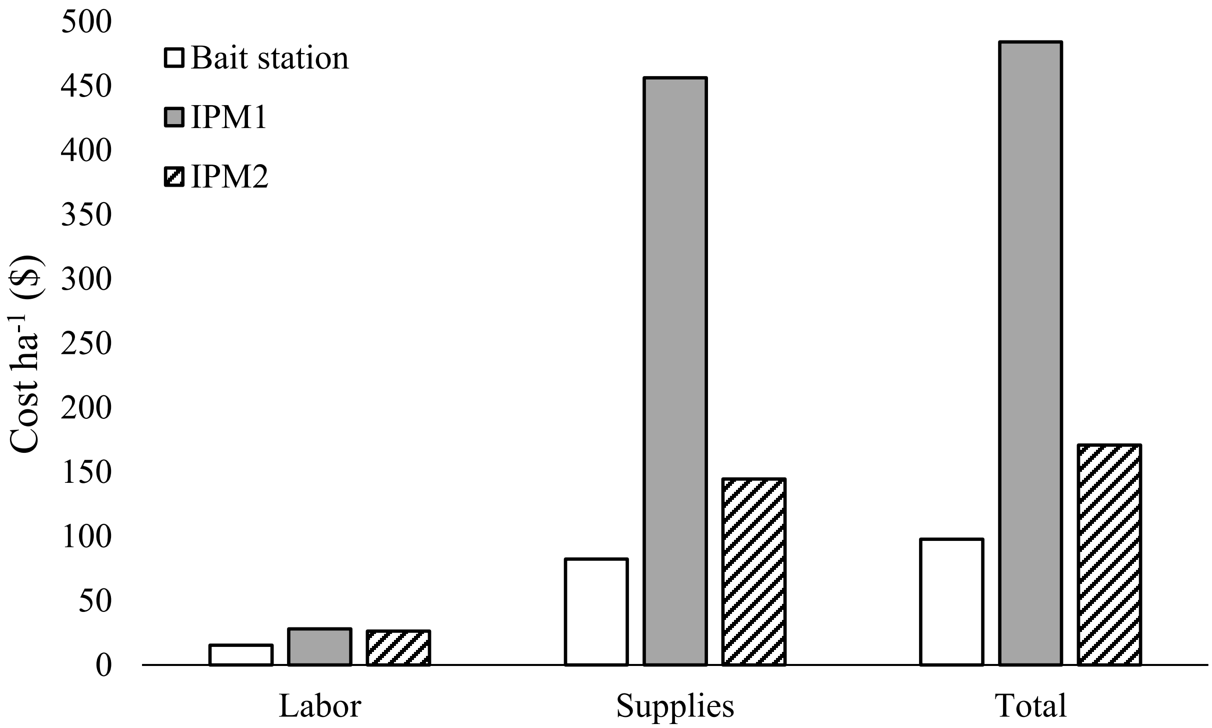

Figure 6. Labor, supplies, and total costs for three different strategies for managing roof rats in citrus orchards over 6 months in the southern San Joaquin Valley, California.

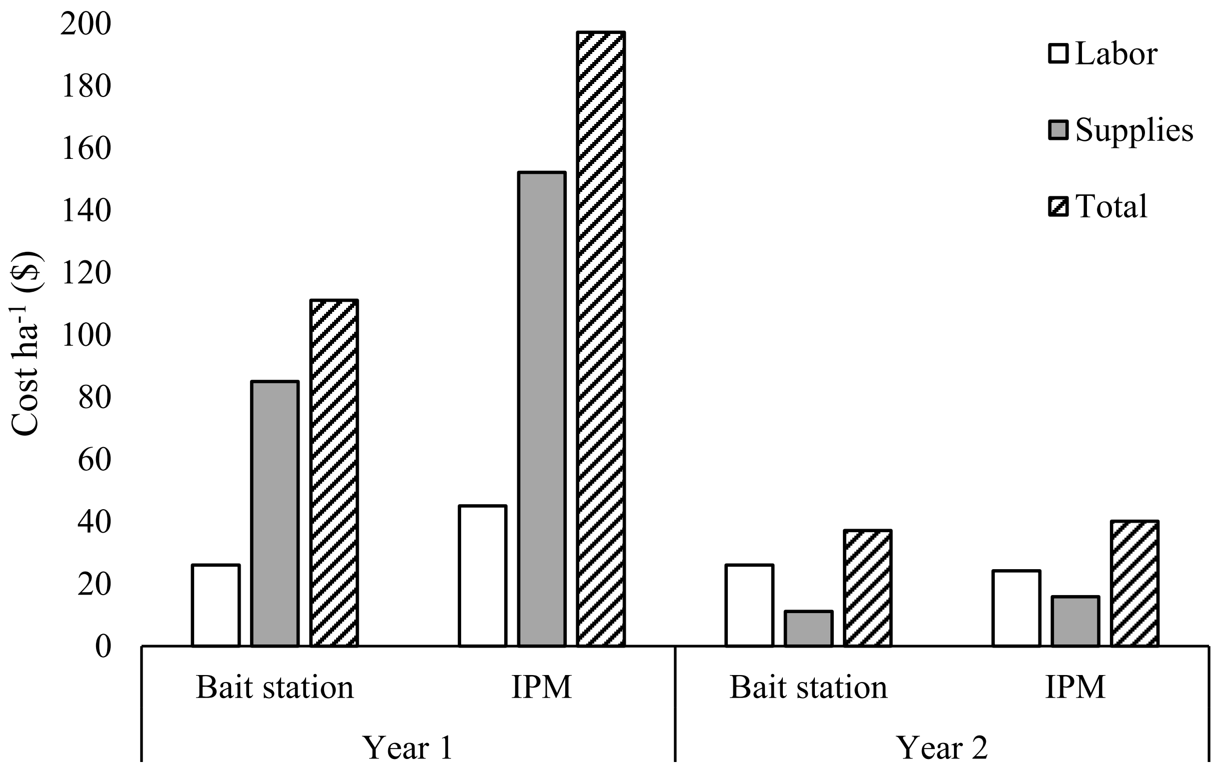

Figure 7. Labor, supplies, and total costs for bait station and IPM management strategies for managing roof rats in citrus orchards over two years in the southern San Joaquin Valley, California.

would greatly reduce reinvasion and increase the longevity of such management programs. As such, a coordinated effort to maximize the area where roof rat removal efforts occur would increase the utility of any management program and should be strongly considered.

As previously noted, we observed rapid reinvasion within two months following the completion of our baiting program. However, roof rat numbers again declined 5-months post-treatment in the bait station plots (represented by increased efficacy; Figs. 4-5). Reasons for this are unclear given that no additional bait applications occurred during this timeframe, but this reduction could be due to an equilibration of rat populations throughout the entire study site as rats began to reestablish individual territories (Shiels et al. 2019). Regardless, we observed a medium-term reduction in roof rats within orchards following bait application, although we still stress that longer-term management programs via additional bait applications or a trapping program will be needed to either further reduce or maintain roof rat numbers at low levels.

Unfortunately, our initial IPM approach that relied heavily on the use of Goodnature A24 traps was not significantly better than the use of only bait stations. The A24 trap has been effective in reducing roof rat populations in a few island conservation situations (e.g., Carter et al. 2016, Gronwald and Russell 2022), but not in all island settings where it has been tested (reviewed in Shiels et al. 2022). Given the limited labor required to check A24 traps compared to snap traps, we had hoped they would make a good addition to an IPM program. Pilot work with A24 traps indicated relatively poor success across 3 of 4 sites in citrus orchards (Baldwin et al. 2022). However, we observed better results at one site where we provided a platform underneath the trap; we wanted to test this approach further. After further testing, the use of the A24 traps appears to be ineffective in citrus orchards, at least in the manner that we used them. Reducing the distance between A24 traps from 76 m to 30–50 m like practiced in most island settings (Shiels et al. 2022) might help improve efficacy, yet this would increase the already expensive total costs (mostly due to added traps/supplies) at least 2-fold.

One potential strategy to increase their utility could be to place the A24s at ground level. This is how they are often used in island conservation settings (e.g., 10-15 cm above ground; Carter et al. 2016, Gronwald and Russell 2022, Shiels et al. 2022), as roof rats regularly use both the ground and tree canopies (Dowding and Murphy 1994). This ground level placement of the A24 may allow the rat to more easily push up into the trap to trigger it. We opted to elevate the traps in our study given that we have a number of potential nontarget species at ground level that might be caught or interfere with these traps. Caution would need to be used if attempting to trap rats at the ground level where nontarget rodents or other small vertebrate species are present given that A24 traps have killed some of these species (see Table 2 in Shiels et al. 2022). Nonetheless, traps or bait stations placed both concurrently on the ground and in the tree canopy could yield better results than either by themselves and could be investigated further (Harper et al. 2015). Alternatively, a better attractant or a lowered trigger mechanism could be deployed to increase capture success. In a previous study, we placed remote-triggered cameras on these traps and frequently observed rats crawling on, and part-way up, the A24 trap but not reaching into the trap to the point that it was activated (Baldwin et al. 2022).

Although A24 traps were ineffective at reducing roof rat reinvasion in our study, we did have success with an IPM program that utilized trapping tunnels, as illustrated both by the large number of rats that we removed (n = 97), as well as by the increasing efficacy values observed throughout the duration of the study (from 78% to 93%; Fig. 5). This IPM approach resulted in efficacy values more than two times greater than for bait station plots two-months post-bait application, highlighting the value of including an efficacious mechanism to account for reinvasion into depopulated sites. Snap trapping has been effective at reducing and maintaining low-density populations in island conservation settings, but it has often been considered too time consuming and costly to implement over a larger scale. In contrast to island conservation settings, growers can quickly and easily access trap sites through the use of an ATV, which greatly reduces the labor cost associated with this approach. In fact, even if the efficacy of the A24 trap could be greatly increased to a level on par with the trapping tunnels, it would be difficult to justify this approach given the fact that such IPM programs incorporating A24s cost 3 times as much as an IPM program that uses trapping tunnels (Fig. 6). Therefore, as long as labor is available to operate the traps every few weeks, the use of trapping tunnels appears to be the more viable partner to a bait application program.

As previously noted, we observed an increase in efficacy five-months post-bait application in the bait station plots (Fig. 5). Equilibration of adjacent populations may account for some of this, as the reinvasion often seen after depopulation events (e.g., Innes et al. 1995, Shiels et al. 2019) can eventually lessen, again leading to more stable space use and population dynamics by local residents. This ultimately may lead to lower roof rat activity within baited areas once exploratory movements of rats from adjacent nontreated areas are reduced and the social hierarchies of remaining rats are re-established within these depopulation zones (Hansen et al. 2020). Regardless of the cause, we always observed greater efficacy, even if not always significant, when incorporating trapping into our management programs (Figs. 4–5). This greater efficacy is an important consideration, as it was less costly to operate bait stations than an IPM program that includes trapping tunnels as a mechanism to slow reinvasion. It's important to remember that IPM programs generally provide longer-term efficacy given that we can more effectively target all individuals in a population by using multiple strategies (Sterner 2008, Baldwin et al. 2014b). Repeated exposure to first-generation anticoagulant rodenticides can also lead to resistance in wild populations (Berny 2018), and the use of trapping to maintain low-density rat populations reduces potential food web and nontarget exposure risks associated with bait application (Carter et al. 2016, Witmer 2018). These factors collectively stress the need to use multiple management tools to maximize their effectiveness and minimize environmental risk. Therefore, the advantages of incorporating trapping tunnels into a roof rat management program in citrus likely outweigh the added costs. The greater cost of incorporating trapping tunnels is further mitigated when operating the IPM program over two years given that most of the cost associated with roof rat management is due to supply costs (Fig. 7). Assuming traps remain operational for several years, the added cost of operating an IPM program will likely be minimal and justified.

Management costs for bait stations plus trapping tunnels averaged \$170.80 ha^{-1} for the first year and \$40.05 ha^{-1} for a second year. Assuming a price of \$12.00 for a box of fancy lemons (115 lemons per box) or a box of navel oranges (72 per box), then around 14 boxes of fruit would have to be saved per hectare per year to justify management costs for the first year; much less fruit would need to be saved to justify expenditures for subsequent years. It is important to note that roof rats often girdle branches of trees, which could permanently reduce fruit production for a tree, further increasing the value of rat management. This cost comparison also does not account for potential damage to irrigation infrastructure, which would further increase the value of roof rat control, and it does not consider potential food safety concerns associated with rodent presence in orchards, for which there is little tolerance (Jay-Russell 2013). We currently lack information on estimated losses attributed to roof rats in California citrus, but given the costs associated with rat management, control efforts seem economically feasible, at least in some situations.

In this study, we focused on bait stations and trapping as the two primary management tools for reducing roof rat abundance in citrus orchards given the rapid knockdown capability of these approaches. However, one of the stated goals of IPM programs is to reduce the usage of pesticides to limit their effect on native ecosystems (Witmer 2018). Increasing pressure is being exerted by regulatory and legislative bodies to minimize the use of rodenticides in production agricultural systems to reduce environmental concerns, which has led to the exploration of alternative management strategies. One approach likely to be considered in the future is fertility control (e.g., Shuster et al. 2023). Although fertility control may not be an ideal strategy to quickly remove rats from orchards given the generational time requirement for these products to work, they might potentially serve as a viable option to slow reinvasion (Ray and Pyzyna 2022). Additional work is warranted on this approach to determine the efficacy and cost effectiveness of including fertility control into roof rat IPM programs in orchard systems, particularly if the use of rodenticides is further reduced in production agriculture. In the interim, an IPM management program that uses a diphacinone bait application to substantially reduce burgeoning roof rat populations, followed by snap trapping and periodic monitoring for rat activity should yield efficacious and cost-effective management of roof rats while substantially reducing nontarget exposure to rodenticides when compared to a rodenticide-only management plan.

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