Research Article

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Testing an integrated approach for managing roof rats in citrus orchards

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Abstract

Background: Roof rats (*Rattus rattus*) are a substantial pest throughout citrus crops, yet little is known about efficacious, cost-effective strategies to manage this rodent. Therefore, we developed two integrated pest management (IPM) programs that incorporated elevated bait stations containing diphacinone-treated oats and trapping, and we compared those programs to a bait-station only approach to determine which strategies were most practical for the management of roof rats in citrus orchards.

Results: Bait applications substantially reduced rat activity within orchards. However, our initial IPM approach that used a combination of baiting, snap trapping and Goodnature® A24 traps were not successful at keeping rats from rapidly repopulating. A second IPM strategy that relied on baiting and more extensive snap trapping was effective at reducing rat activity up to, and likely beyond, a 6-month treatment period. Although baiting by itself was less expensive than IPM plots, the difference in cost between baiting and the IPM approach that used only baiting and snap trapping should be minimal during long-term management programs.

Conclusion: The high efficacy of a management program that incorporates an initial bait application, followed by a long-term snap-trapping program, should yield effective management of roof rats in citrus orchards.

Supporting information may be found in the online version of this article.

Keywords: bait station; citrus; diphacinone; integrated pest management; lethal trapping; *Rattus rattus*

1 INTRODUCTION

Rats (*Rattus* spp.) are a common and damaging invasive pest found throughout much of the world, with one projection of damage caused by rats in the United States estimated at US$19 billion annually.[1] In particular, nut and tree fruit crops can incur substantial damage from roof rats (*Rattus rattus*) when present.[2–4] The best management programs for rodents are considered to be those that rely on integrated pest management (IPM) given their high efficacy, lower long-term cost and reduced impact to the environment.[5–8] Surprisingly few studies have assessed the utility of IPM approaches for rats in orchard crops (but see Campbell *et al.*[9] for rare example), perhaps owing to the large amount of information needed to develop such programs.[10] Such information is needed to support their use in these high-value crops.

Currently, a common tool used to manage roof rats in orchard systems are first-generation anticoagulant rodenticides,[11] presumably given their ease of use and relative cost-effectiveness.[5] Baldwin *et al.*[12] 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%[13]). A subsequent trial suggested that shorter spacing of 50 m may be more efficacious,[13] but additional testing is needed to verify this. That said, exclusive use of rodenticides can sometimes lead to problems such as bait avoidance and rodenticide resistance.[14] Alternative tools are needed to combine with rodenticide applications to maximize the long-term effectiveness of management programs.[5]

Several alternative strategies have been proposed for managing roof rats in orchard crops including habitat modification, biocontrol and trapping. White *et al.*[15] showed that removal of preferred habitat along the perimeter of macadamia orchards (*Macadamia integrifolia*) in Australia was effective at substantially reducing nut damage caused by roof rats. However, as roof rats established throughout the orchards and were less reliant on the surrounding

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habitat, this approach was no longer effective.[16] In California citrus orchards, roof rats also are established throughout the orchards,[17] 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.[18–20] However, citrus is an evergreen crop that provides thick cover year-round that would likely impede the barn owl's ability to effectively hunt in these orchards.[21] For these reasons, we did not view habitat modification or biocontrol as likely solutions to roof rat damage in citrus orchards. Instead, we selected trapping as the primary tool to supplement rodenticide applications.

Historically, snap trapping has been a frequent approach to managing roof rats, but snap traps require frequent checking to remove captured individuals and to resupply bait. Still, snap trapping can effectively reduce and maintain rat populations at low levels.[22] 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, as each A24 trap allows 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,[23,24] but they have had only limited testing in orchards (but see Baldwin *et al*.[13]). 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. 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.[5] 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,[25,26] movement[17] and management investigations[13] 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.

2 MATERIALS AND METHODS

2.1 Study area and site dimensions

We conducted all trials in four navel orange orchards (*Citrus sinensis*) in Tulare and Kern Counties in the southern San Joaquin Valley, California, from spring 2022 to Autumn 2023. Each treatment plot 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 in these orchards = 87 m[17]), 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 an untreated control plot. The plots for each site were generally adjacent to one another, although for one site, the control plot was ≈3 km from the treatment plots. However, at this site, there was contiguous citrus production between the treatment and control plots suggesting that rat populations should be representative across all plots within each study site. Trial 1 was initiated in May 2022 at Site 1, with subsequent sites initiated at 6-week staggered intervals. Given a lack of efficacy observed for IPM plots in Trial 1, we conducted a second trial using a different IPM strategy (details provided in subsequent sections). For Trial 2, we started Site 1 during December 2022. We used 5-week staggered intervals to initiate Sites 2–4, although Site 2 did not start until February 2023 given inclement weather.

2.2 Trial 1

2.2.1 Bait station

Similar to Baldwin *et al*.,[13] we used elevated bait stations that contained 0.005% diphacinone-treated rolled oats (manufactured by California Department of Food and Agriculture [CDFA], Sacramento, CA, USA) to initially remove roof rats from bait station plots (see Baldwin *et al*.[12] for design details of the bait station). The bait stations were secured via bungee cords ≈1.5 m up in the trees following an 8 × 8 grid structure with bait stations separated by 50 m (Fig. S1). We initially filled each bait station with ≈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 ≈4 months given substantial rat activity before baiting (details in Results section). We ceased baiting at this site when bait consumption stabilized at low levels.

2.2.2 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, WI, USA) attached to a tree branch at the same sites used for bait application (Fig. S1 in Supporting information). We then checked each soft bait for chewing 3 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, WI, USA) separated by ≈35 m 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 2 weeks, with trap check and rebaiting occurring ≈1 week after the initiation of the trapping period.

Following the completion of our 2-week snap-trapping period, we deployed A24 traps in a 6 × 6 grid with traps spaced ≈75 m apart (Fig. S2). This distance was 12 m less than the radius of an average roof rat home range in California citrus orchards,[17] with this design expected to intercept reinvading roof rats. The A24 traps contained Goodnature® Chocolate Rat & Mouse Lure

Automatic Lure Pumps which allowed fresh bait to be automatically dispensed throughout the duration of their use. We placed the A24 traps 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.*,[13] we placed a wooden platform underneath the A24 trap to potentially allow easier entry into the triggering area of the trap. The traps were operated for ≈5 months for three of the sites, but for a 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 per month; process involved checking bait and test-firing the trap) throughout the trapping period.

2.3 Trial 2

2.3.1 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 bait and bait-station design as in Trial 1. However, for Site 2, the baiting period was extended to 2 months because heavy and consistent rainfall for several weeks led to moldy bait and prevented field staff from changing bait when necessary. 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.

2.3.2 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. S2). 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 ≈5 months for Sites 1–3. Because of the extended baiting period for Site 4, we were able to operate trapping tunnels for ≈2 months at this site. Trapping tunnels were checked every 2–4 weeks depending on previous rat activity and pesticide applications that temporarily halted access to the field site. Captured rats were documented, traps reset, and bait reapplied as needed.

2.4 Indexing

We followed the general guidelines provided by Baldwin and Meinerz[26] in using tracking tunnels (Black Trakka; Gotcha Traps, Warkworth, New Zealand) 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 m (Fig. S3). 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. Tracking tunnels were operated for 4 nights; at the conclusion of each 4-night monitoring 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 all plots, and we again repeated their operation following the completion of the baiting program. We determined efficacy using the following equation:

$$(1-[\text{number of active tunnels after treatment}/\text{number of active tunnels before treatment}])\times 100\%.$$

We also were interested in assessing potential repopulation following the completion of the initial baiting period. As such, we conducted additional assessments ≈2 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. All assessments of efficacy were made by comparing indexing values for a respective time-period to the initial pre-treatment period. All aspects of this project were approved by the University of California, Davis' Institutional Animal Care and Use Committee (IACUC, protocol no. 22736), and USDA/National Wildlife Research Center's IACUC (protocol QA-3320).

2.5 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.[27,28] Following Lai *et al.*[29] and Wales *et al.*,[25] 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.[29] If we observed homogeneity across sites, yet 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 v9.4 (SAS Institute Inc., Cary, NC, USA).

2.6 Cost assessment

2.6.1 Operational timing

In order 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 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

Table 1. Mean completion times 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

orchard, and the wider spacing has been shown to be equally effective at monitoring changes in roof rat activity over time.[26] 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 (Table S1 presents a breakdown for each management task).

2.6.2 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 two 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 that pest control operators would operate tracking tunnels before and after the completion of the baiting program, and again 2 months after the completion 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 eight sites. We estimated eight 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 1 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 (≈3-week intervals) and trap removal. All time estimates were summed for each treatment category and multiplied by US $17.00/h as the going rate for field labor at the time of this study (B. Carmen, Sun Pacific, pers. comm.).

We also were 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 that indexing with tracking tunnels would occur every 6 months over the course of the 2-year study period. We assumed four 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. We assumed an initial bait application, followed by a second bait application ≈6 months later. We assumed no additional bait applications for the remainder of the 2-year sampling period. The protocol for time assessments was the same as has already been reported. Following the baiting program, we planned to operate trapping tunnels for 5 months. 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 assumed a labor rate of US$17.00/h.

A variety of supplies were required to operate the various management actions tested in this study (see Table 2). 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 2 and 3 for a breakdown of each cost for the different portions of the investigation.

3 RESULTS

3.1 Trial 1

We observed a difference in efficacy among the treatment types for the initial post-bait application period ($\chi^2_2 = 29.6$; $P < 0.001$),

Table 2. Labor and supply costs for bait station plots, as well as integrated pest management (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

			Bait station		IPM—Trial 1		IPM—Trial 2	
	Expense	Cost/unit (US$)	No. units	Total (US$)	No. units	Total (US$)	No. units	Total (US$)
Labor[a]	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	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 set-up	151.99			36	5471.64		

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

Table 3. Labor and supply costs for proposed bait station and integrated pest management (IPM) strategies over 2 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 (US$)	No. units	Total (US$)	No. units	Total (US$)	No. units	Total (US$)	No. units	Total (US$)
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

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

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. 1). Although we did not observe a statistical difference between treatment types for the 2- and 5-month post-

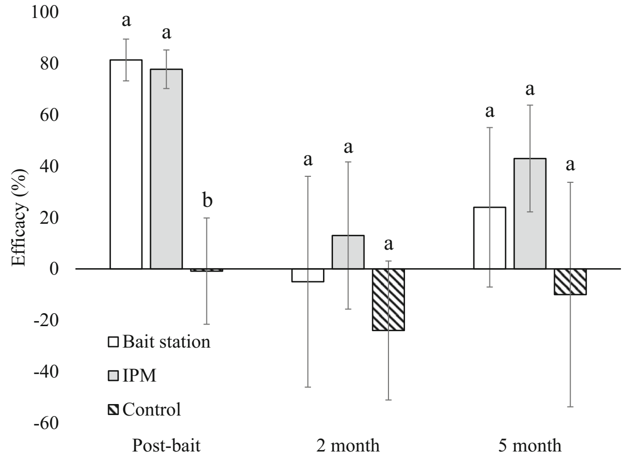

Figure 1. The mean percent efficacy (percent change in roof rat visitation across respective monitoring periods with positive efficacy representative of a reduction in rat activity) and associated standard errors of bait station, integrated pest management (IPM) and untreated plots (Control) for roof rat control within four citrus orchards in the southern San Joaquin Valley, California, from spring 2022 to 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 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.

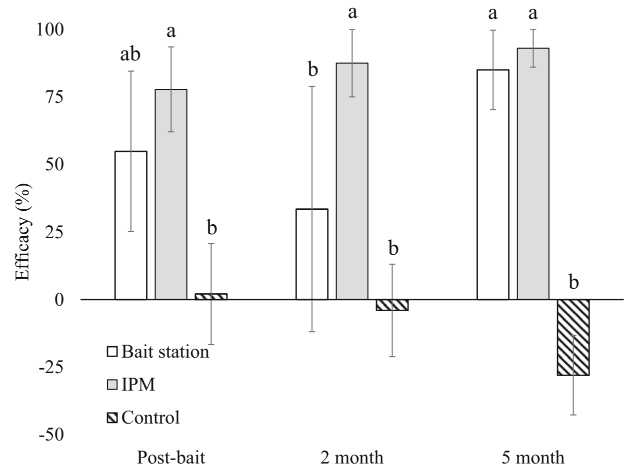

Figure 2. The mean percent efficacy and associated standard errors of bait station, integrated pest management (IPM) and untreated plots (Control) for roof rat control within four citrus orchards in the southern San Joaquin Valley, California, from autumn 2022 to autumn 2023 (Trial 2). We applied 0.005% 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.

bait application periods, IPM plots exhibited the greatest mean efficacy (Fig. 1).

3.2 Trial 2

Bait applications were again largely successful, although efficacy was a bit lower in the bait station plot (Fig. 2). 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: $\chi^2_2 = 13.7$; $P = 0.001$; 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 2 months in bait station plots, the IPM plots were successful at keeping populations from rebounding. In fact, trapping further reduced roof rat numbers in the IPM plots both 2- and 5-months post-bait application (Fig. 2), with a total of 97 roof rats removed via snap trapping. 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. We observed an increase in roof rat activity in control plots over the duration of the trial (Fig. 2), indicating that efficacy results may be conservative.

3.3 Cost assessment

Supply costs were the driving expense behind all management actions for roof rats regardless of the tactic used (Fig. 3). Supply costs were much higher for the IPM program used in Trial 1 (a 6-month study), whereas bait station plots exhibited the lowest total costs. When relating costs across a 2-year management program, we again found that bait station plots were less expensive and that supply costs were the primary expense for both management actions (Fig. 4). 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.

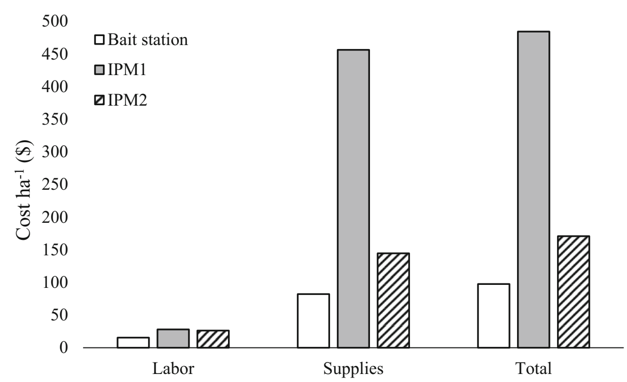

Figure 3. Labor, supplies and total costs for three different strategies for managing roof rats in citrus orchards over 6 months in the southern San Joaquin Valley, California.

4 DISCUSSION

Similar to a study in almond orchards,[12] 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 1 and 2), 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.[30] We were unsure how effective this approach would be in citrus given that early pilot work showed low efficacy across three of four study sites.[13] However, in Baldwin *et al.*,[13] 76-m spacing was used between bait stations in the three sites where efficacy

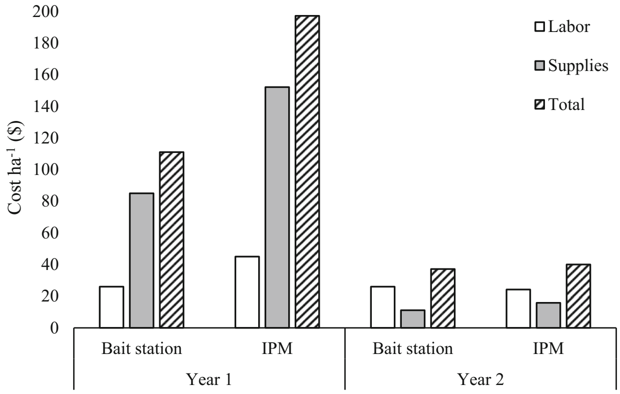

Figure 4. Labor, supplies, and total costs for bait station and integrated pest management (IPM) strategies that incorporated bait stations and snap traps (i.e. Trial 2) for managing roof rats in citrus orchards over 2 years in the southern San Joaquin Valley, California. Supply costs were substantially lower for Year 2 given that most supplies purchased during Year 1 could again be used for subsequent years.

was lower, while shorter 50-m spacing was used at a fourth site where they observed a 77% reduction in roof rat activity. Although roof rats move extensive distances within citrus orchards (mean daily displacement: males = 201 m, SE = 3; females = 148 m, SE = 11),[17] 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.[31,32] In fact, reducing spacing to 30 m may further increase efficacy, as shown in almond orchards (by 90%; Baldwin *et al.*[12]). Longer duration bait application periods also may increase overall efficacy, as shown in our study site with the greatest roof rat abundance. However, these actions come at an additional cost which would need to be considered by the grower when determining ideal spacing for their orchard.

Although bait stations were effective at reducing roof rat abundance, we observed rapid reinvasion as soon as 2-months post-treatment (Figs 1 and 2). Such reinvasion is common with rats and other rodent species following depopulation events,[22] and it stresses the need for management actions 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 of the adjacent orchards. A concerted baiting program throughout the entire growing region 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 should be strongly considered.

As previously noted, we observed rapid reinvasion within 2 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 1 and 2). 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 re-establish individual territories.[22] 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,[23,24] but not in all island settings where it has been tested (reviewed in Shiels *et al.*[33]). 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 three of four sites in citrus orchards.[13] However, better results were observed at one site where a platform was provided underneath the trap; we wanted to test this approach further. After further testing, the use of the A24 traps was 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 as practiced in most island settings might help improve efficacy,[33] yet this would increase the already expensive total costs at least two-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 aboveground),[23,24,33] as roof rats regularly use both the ground and tree canopies.[34] 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 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 given that A24 traps have killed some nontarget species (see Table 2 in Shiels *et al.*[33]). 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.[35] Alternatively, a better attractant or a lowered trigger mechanism could be deployed to increase capture success. In a previous study, Baldwin *et al.*[13] placed remote-triggered cameras on A24 traps and frequently observed rats crawling on, and partway up, the trap but not reaching into the trap to the point that it was activated.

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 removed ($n = 97$), as well as by the increasing efficacy values throughout the study (from 78% to 93%; Fig. 2). This IPM approach resulted in efficacy values more than two-fold greater than for bait station plots 2-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 with 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 high cost of the A24s (Fig. 3). 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 noted previously, we observed an increase in efficacy 5-months post-bait application in the bait station plots (Fig. 2). Equilibration of adjacent populations may account for some of this, as the reinvasion often seen after depopulation events can eventually lessen, leading to more stable space use and

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population dynamics by local residents.[22,36] 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.[37] Regardless of the cause, we always observed greater efficacy, even if not always significant, when incorporating trapping into our management programs (Figs 1 and 2). 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' is 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.[5,6] Repeated exposure to first-generation anticoagulant rodenticides also can lead to resistance in wild populations,[14] and the use of trapping to maintain low-density rat populations reduces potential food-web and nontarget exposure risks associated with bait application.[7,23] These factors collectively stress the need to use multiple management tools. 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 2 years given that most of the cost associated with roof rat management is the supply costs (Fig. 4). Assuming that 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 US\$170.80 ha^{-1} for the first year and US\$40.05 ha^{-1} for a second year. Assuming a price of US\$12.00 for 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.[38] We currently lack information on estimated losses attributed to roof rats in 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 use of pesticides to limit their effect on native ecosystems.[7] One approach likely to be considered in the future is fertility control.[39] Although fertility control may not be an ideal strategy to quickly depopulate rats given the generational time requirement for these products to work, they might provide a viable option to slow reinvasion.[40] It bears noting that we included diphacinone application as an initial knockdown approach in this study given an assumption that roof rat numbers were at thresholds that justified their use over less-proven methods. However, the high efficacy of snap trapping in this study suggests that this approach could warrant further investigation as a primary tool for roof rat depopulation in orchards, although costs of this management program would likely be high given the need to regularly check traps. Most importantly, research is needed to establish thresholds of roof rat damage in citrus to inform when management actions are likely to be economically viable. 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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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

SUPPORTING INFORMATION

Supporting information may be found in the online version of this article.

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