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# Developing an effective strategy for indexing roof rat abundance in citrus orchards

Roger A. Baldwin*, Ryan Meinerz

*Department of Wildlife, Fish, & Conservation Biology, University of California, Davis, CA, 95616, United States*

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ABSTRACT

Effective rodent monitoring tools are needed to allow agricultural producers and pest control specialists to determine when rodent control strategies are needed, as well as to allow researchers to assess the efficacy of various management options. General indexing tools that utilize continuous response metrics, as well as traditional presence-absence indexing strategies, are commonly used for such monitoring programs, but their ability to track rodent abundance should be verified in different ecological systems. Therefore, we tested the ability of tracking tunnels (binary response only) and remote-triggered cameras (both binary and continuous response) to effectively track roof rat (*Rattus rattus*) abundance in three lemon (*Citrus limon*) and two orange (*Citrus sinensis*) orchards in the southern San Joaquin Valley, California. We placed remote-triggered cameras and tracking tunnels both on the ground and within trees to assess activity, and subsequently live-trapped roof rats in these same plots to determine an estimate of population size and minimum number known values. We used multiple linear regression to compare these values to allow us to determine the effectiveness of these monitoring tools at tracking roof rat abundance depending on the monitoring tool used, the vertical zone where traps were placed (i.e., within trees or on the ground), and the crop that was monitored. We determined that both tracking tunnels and remote-triggered cameras (both binary and continuous response metrics) were correlated to roof rat abundance irrespective of their location on the ground or in the trees. We also noted a difference in the relationship between index values and roof rat abundance for lemon and orange orchards, indicating the importance of considering orchard type when interpreting models. Regardless, tracking tunnels and remote-triggered cameras both effectively reflected roof rat abundance irrespective of orchard type, and as such, they both should prove useful for future monitoring projects in citrus orchards.

## 1. Introduction

Many rodent species cause extensive damage in agricultural systems throughout the world (see Wood and Singleton 2015 for review), thereby requiring efficacious management tools to mitigate this damage. To manage these damaging rodents, we need effective strategies to monitor the status of rodent populations to know when management tools are required to reduce numbers. Researchers also need monitoring tools to assess the efficacy of management strategies. The general indexing paradigm has often been used to effectively monitor changes in rodent abundance (e.g., tracking surfaces—Whisson et al., 2005; remote-triggered cameras—Engeman et al., 2006, Baldwin et al., 2014; chewing blocks—Whisson et al., 2005, Engeman et al., 2016). This approach uses observations of activity on consecutive days at multiple stations spread throughout the study area (Engeman 2005). General indexing approaches are sensitive to changes in population size, and when constructed properly, provides a precise measure of change in abundance over time. Furthermore, general indexing procedures should rely on few analytical assumptions, and they should be practical for use (e.g., inexpensive to apply, minimal user bias, and robust to environmental variability; Engeman 2005).

General indexing tools utilize continuous measures of activity rather than binary responses (i.e., presence-absence). Binary observations are considered less descriptive and sensitive to changes in abundance, and more likely to lead to erroneous inferences (Engeman et al., 1989). However, binary responses are still commonly used as a relative index of rodent activity given that they are easy to implement (e.g., Brown et al., 1996; Thomas et al., 1999; Shiels et al., 2019), and they have proven effective at tracking changes in rodent abundance in many situations (e.g., Engeman et al., 1993; Quy et al., 1993; Brown et al., 1996). Ease of

* Corresponding author.
*E-mail address:* rabaldwin@ucdavis.edu (R.A. Baldwin).

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use is a particularly important consideration when developing monitoring strategies for producers and pest control specialists, as they generally have little time to devote to extensive monitoring of rodent pests. Therefore, consideration of monitoring tools that rely on a binary response is worthy of consideration.

One rodent species of substantial concern in agricultural systems is the roof rat (*Rattus rattus*). In particular, roof rats cause extensive damage in citrus crops, often girdling limbs and trunks of trees, consuming fruit, and chewing on irrigation lines (Worth 1950; Yabe 1998; Baldwin 2016). Previous research in almond (*Prunus dulcis*) orchards determined that a general index approach using remote-triggered cameras was effective at monitoring roof rat abundance (Baldwin et al., 2014). This approach involved the calculation of the mean daily number of roof rat photos at sampling stations. Remote-triggered cameras could also be used to provide simple presence-absence data for each sampling station, thereby providing an easier assessment tool. We considered both approaches as potentially promising strategies for monitoring roof rat abundance.

Tracking tunnels are another tool that is regularly used to monitor changes in roof rat abundance (Innes et al., 1995; Brown et al., 1996; Lindsey et al., 1999; Shiels et al., 2019). Tracking tunnels house a tracking card with an inkpad and attractant located in the middle of the card. Rodents leave ink footprints on the card after investigating the attractant, thereby indicating presence at a specific station. These tracking tunnels are generally used as a binary response tool (but see Whisson et al., [2005] for an example of how tracking plates could be used as a continuous response variable) for monitoring roof rat populations. They are popular given the ease with which they are operated and because they are relatively quick and inexpensive to operate (Brown et al., 1996). Simple assessments of rodent activity are of particular importance to producers given limited time, resources, and expertise for monitoring rodents, yet monitoring for pests is a central tenant of Integrated Pest Management (Sterner 2008). A simple, cost-effective tool, such as tracking tunnels, could fill this need if proven effective.

Interestingly, roof rats appear to use arboreal habitats differently depending on the dominant cover type. For example, roof rats located in natural areas regularly use ground habitats (Dowding and Murphy 1994; Lindsey et al., 1999; Whisson et al., 2007), whereas in orchard systems, roof rats spend extensive time on tree branches and canopies (Tobin et al., 1996; Baldwin et al., 2014). The effectiveness of both tracking tunnels and remote-triggered cameras as indexing tools could vary depending on where they are located (i.e., in trees or on the ground). Likewise, different orchard crops could influence roof rat activity as well given differences in vegetative structure and food resources within the orchard. For example, Lisbon lemons (*Citrus limon*) often have more compact branches and more abundant thorns than navel oranges (*Citrus sinensis*), thereby potentially influencing how roof rats use each of these habitat types. Furthermore, roof rat damage to lemons and oranges differs, with substantial girdling occurring in lemons, but rarely observed in oranges. Conversely, damage to fruit is more common in oranges than in lemons (R. Baldwin, pers. obs.). This is of importance given that indexing tools should be calibrated for ecological systems when possible, as the relationship between the index and rodent abundance may vary across different systems (Engeman and Whisson 2006). As such, the crop type and the vertical structure associated with indexing stations (i.e., on tree branches vs. on the ground) should be considered. Therefore, we established a study to address these important questions. Specifically, our objectives were to: 1.) determine how visitation rates (binary response metric) to tracking tunnels and remote-triggered cameras correlate to population estimates and minimum number known values of roof rats in sample plots, 2.) determine how a general index derived from remote-triggered cameras (continuous response metric) correlates to population estimates and minimum number known values of roof rats in sample plots, 3.) determine if the vertical location of monitoring tools (i.e., in trees or on the ground) influences the effectiveness of our indexing strategies, and 4.) determine if roof rat response to indexing strategies varies across crop types. This will all be assessed across two different grid sizes (5 × 5 and 3 × 3) to determine if a smaller subset of sampling locations can be used to save material and labor costs when indexing roof rat abundance.

## 2. Materials and methods

### 2.1. Study area

We selected three orchards that were comprised of Lisbon lemons and two orchards that were comprised of navel oranges for this study. The total size of the orchards ranged from 10 to 40 ha. Two of the lemon orchards and one of the orange orchards were located in southwestern Kern County, California, while one lemon and one orange orchard were located in southwestern Tulare County, California. We sampled the first orchard in late winter 2020. However, Covid-19 concerns halted the study following the completion of that site. We continued our study in autumn 2020 and completed data collection in early 2021.

### 2.2. Indexing stations

At each site, we set up a 210 × 210 m indexing plot, within which we established a 5 × 5 grid of remote-triggered camera and tracking tunnel stations (Fig. 1). The outer tracking tunnel and remote-triggered camera stations were located approximately 35 m from the edge of the indexing plot, and were located approximately 35 m from other station points within the grid. At each station on the grid, we located the two closest trees in a given row (approximately 3–4 m apart depending on the site). For one of the paired trees, we placed a tracking tunnel up in the tree and a remote-triggered camera on the ground. For the other paired tree, we placed the remote-triggered camera up in the tree and the tracking tunnel on the ground. We determined this order randomly. This process was repeated throughout the entire indexing plot so that we had a total

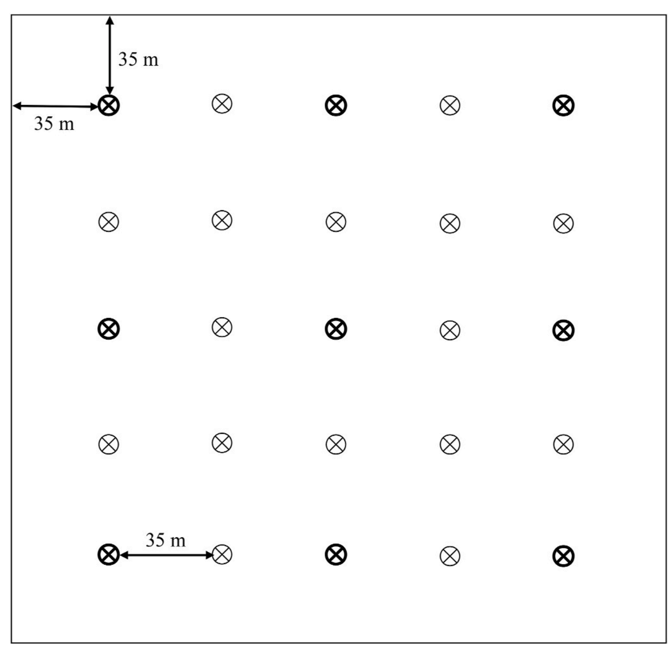


**Fig. 1.** Roof rat indexing stations (circled x) located within citrus orchards in the southern San Joaquin Valley, California, during autumn and winter 2020–2021. Stations were located a minimum of 35 m from the edge of the index plot, and were separated by 35 m from the next closest station. Each station consisted of two adjacent trees in the same tree row. One tree housed a remote-triggered camera with a tracking tunnel located at the base of the tree. The other tree housed a tracking tunnel with a remote-triggered camera located at the base of the tree. We also used a 3 × 3 subset of these indexing stations for analysis as well. The distribution of these stations is shown in bold.

of 25 tracking tunnels and 25 remote-triggered cameras in trees, and 25 tracking tunnels and 25 remote-triggered cameras on the ground at each indexing plot.

### 2.3. Monitoring procedures

For tracking tunnels set in trees, we first placed 0.9–1.2 m lengths of 5.1 × 10.2-cm wooden boards across branches to serve as a base for the tracking tunnels. The boards were established anywhere from 0.7 to 1.6 m above ground. We placed the tracking tunnels (60 × 15 × 13 cm, Pest Control Research LP, Christchurch, New Zealand) on the boards and secured them via plastic cable ties. We applied ink to the center of tracking cards and placed them into the tunnels. We then placed a soft bait packet (Liphatech Rat and Mouse Attractant™, Liphatech, Inc., Milwaukee, Wisconsin, USA) into the center of the inkpad of each tracking tunnel. This process was repeated for ground sets, except tunnels were staked on the ground to keep wind or animals from knocking them over. We considered the number of tracking tunnels visited by roof rats as a simple index of roof rat abundance.

We also monitored roof rat activity using Bushnell NatureView HD Max cameras (Bushnell Outdoor Products, Overland Park, Kansas, USA) that were set to the high-sensitivity setting to minimize the likelihood of missing a visit by any animal. Each camera was set with a 5-min delay after triggering to minimize the effect of repeat visits on general index values (Baldwin et al., 2014). For tree-sets, we secured the cameras to branches in the trees at heights ranging from 0.7 to 1.6 m above ground. The cameras were targeted on a soft bait packet (Liphatech Rat and Mouse Attractant™) that was attached to a branch in the same tree. For ground sets, we attached the cameras to wooden stakes in the ground that were targeted on a soft bait packet that was staked to the ground with a wire flag. The remote-triggered cameras and tracking tunnels were operated at the same time, and were checked daily for three days to determine if bait needed replenishing. At the end of the three-day period, tracking cards were removed to determine presence or absence of roof rats at each tunnel. For remote-triggered cameras, we downloaded images to a laptop computer for review. We considered the number of remote-triggered cameras visited by roof rats as a simple index of roof rat abundance. We also developed general index values following protocols established by Baldwin et al. (2014). In short, we documented the total number of roof rat photos for a given camera location and divided this value by the number of nights the camera was operational to determine the nightly average number of roof rat photos for a given camera.

### 2.4. Live trapping

Immediately following the completion of indexing trials, we removed all remote-triggered cameras and tracking tunnels. At each monitoring station, we placed a wire cage trap (13 × 13 × 46 cm, Tomahawk Live Trap, Hazelhurst, Wisconsin, USA) on the ground at the base of one of the paired trees ($n = 25$ per site), and we attached another wire cage trap on the same wooden boards that we secured tracking tunnels to up in the other paired tree ($n = 25$ per site). We randomly selected which of the paired trees received the elevated trap and which tree had a trap placed on the ground. Traps were baited with Liphatech Rat and Mouse Attractant™ and were checked in the early morning for roof rat captures. All new captures were released into a pillowcase where we ear tagged them with uniquely numbered tags to allow for individual identification. All rats were then released at their point of capture. Whenever we recaptured a tagged rat, we made note of the capture and immediately released them. This process was repeated for a minimum of 4 days. If we captured >1 new roof rat after day 4, we continued live trapping until we captured ≤1 new capture. Collectively, we trapped for 4 days on 3 sites and 5 days for 2 sites. At the end of trapping efforts, we summed all unique roof rat captures for each indexing plot to determine a minimum number known at each site for comparison to derived index values (Whisson et al., 2005; Baldwin et al., 2014; Engeman et al., 2016). We also estimated population size for each plot using the Schumacher-Eschmeyer method given that we had repeated sampling from a closed population (Krebs 1999). All aspects of this project were approved by the University of California, Davis' Institutional Animal Care and Use Committee (protocol no. 21521).

### 2.5. Data analysis

We used multiple linear regression to compare index values (the number of tracking tunnels visited, the number of remote-triggered cameras visited, the mean number of photos taken per night for each remote-triggered camera) to roof rat population estimates and the minimum number known values for each site (Zar 1999). We included orchard type (lemon and orange) as a dummy variable to account for potential differences in roof rat response between these two crop types. We also included vertical location of each monitoring tool (tree and ground) as a dummy variable to determine if the location of these monitoring tools was an important consideration. In addition to testing for the entire 5 × 5 grid, we used the same regression approach to assess a potential relationship between indices and roof rat numbers for a 3 × 3 subset of these same indexing stations to determine if fewer stations could accurately reflect roof rat population size (see Fig. 1 for illustration of this subset). For all models, we tested for normality of residuals using the Shapiro-Wilks test (Shapiro and Wilk 1965), and we checked for homogeneity of variance using the White test (White 1980). Analysis of the residuals indicated homoscedasticity for all models. The residuals for most models were normally distributed. However, residuals for the mean number of photos taken per night for the 3 × 3 grid analyses did deviate from normality, so we cube root transformed the index values to alleviate this concern. All analyses were conducted using SAS (Version 9.4; SAS Institute Inc., Cary, North Carolina, USA).

## 3. Results

Visits to tracking tunnels were generally high and consistent between ground and tree locations (Table 1). Conversely, no obvious pattern was visible between camera index values and the number of visits to camera stations for ground and tree locations, nor for lemon and orange orchards (Table 1). The number of unique roof rats trapped was always greater in trees (range = 7–23) than on the ground (range = 1–12) for a sampled orchard, and the number of unique individuals trapped in lemons (range = 20–34) was always greater than that observed in oranges (range = 11–13; Table 1). Our estimates of population size (range = 11–34) were generally similar to minimum number known estimates (range = 9–33), although they differed by 31% for one orange orchard (Table 1). All photos at camera stations occurred at night, indicating exclusive nocturnal visitation to indexing stations.

Initial models for both 5 × 5 and 3 × 3 grids indicated that the location of the tracking tunnels and remote-triggered cameras (i.e., on the ground or in the trees) had little relationship to roof rat abundance ($t \leq 1.0$, $p \geq 0.356$), so this variable was removed from subsequent models. The number of tracking tunnel and remote-triggered camera locations visited by roof rats, as well as the general index valued derived from camera visitation, accurately reflected population estimates and minimum number known values for our study orchards for both 5 × 5 and 3 × 3 grids, although relationships were generally stronger for the 5 × 5 grid structure (Table 2). The type of citrus orchard had a substantial effect on all models, with index values greater in lemons than in oranges (Table 2).

## 4. Discussion

Effective strategies for monitoring changes in rodent abundance are needed to mitigate damage and food safety concerns in agricultural systems. As with many other studies (e.g., Brown et al., 1996; Engeman

**Table 1**
Number of tracking tunnels visited by roof rats (T visit), roof rat index values derived from remote-triggered cameras (C index), number of cameras visited by roof rats (C visit), and the number of unique individuals live trapped (Caps) at locations on the ground and in the trees within lemon (Lem) and orange (Or) orchards in the southern San Joaquin Valley during autumn and winter 2020–2021. Tracking tunnels and remote-triggered cameras were established following a 5 × 5 grid pattern with tree and ground tracking tunnels and cameras paired together in adjacent trees. We calculated population size (Pop size) and 95% confidence intervals (Pop CI) for each site using the Schumacher-Eschmeyer estimator. We also separated out a 3 × 3 subset of indexing locations for separate analysis, but used the number of unique individuals captured and estimates of population size for the entire grid for comparisons to determine how the reduced indexing effort reflected roof rat numbers over the entire sampling area.

| | | Ground | | | | Tree | | | | Total | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Grid | Site | T visit | C index | C visit | Caps | T visit | C index | C visit | Caps | Caps | Pop size | Pop CI |
| 5 | Lem 1 | 20 | 4.43 | 16 | 10 | 22 | 2.63 | 18 | 23 | 33 | 34 | 32–36 |
| | Lem 2 | 12 | 0.19 | 5 | 7 | 11 | 0.48 | 6 | 12 | 19 | 20 | 17–25 |
| | Lem 3 | 17 | 1.08 | 10 | 12 | 16 | 1.95 | 10 | 17 | 28 | 34 | 26–49 |
| | Or 1 | 16 | 1.33 | 12 | 1 | 15 | 0.97 | 7 | 7 | 9 | 13 | 8–38 |
| | Or 2 | 15 | 0.81 | 13 | 2 | 19 | 0.83 | 10 | 8 | 10 | 11 | 7–24 |
| 3 | Lem 1 | 7 | 4.63 | 6 | | 7 | 2.07 | 5 | | | | |
| | Lem 2 | 2 | 0.15 | 2 | | 3 | 0.04 | 1 | | | | |
| | Lem 3 | 8 | 2.19 | 8 | | 8 | 2.74 | 4 | | | | |
| | Or 1 | 3 | 1.04 | 3 | | 4 | 0.00 | 0 | | | | |
| | Or 2 | 5 | 1.59 | 4 | | 6 | 1.48 | 5 | | | | |

**Table 2**
Results of multiple linear regression models comparing visitation data at tracking tunnels and remote-triggered cameras to population estimates derived via the Schumacher-Eschmeyer estimator (S-E) and the minimum number known (MNK) of roof rats as determined through live trapping in citrus orchards in Kern and Tulare Counties, CA, during autumn and winter 2020–2021. Statistics are provided for the overall model, as well as for individual variables (Visits = visitation data, Citrus = lemon versus orange orchard; β reflects lemons = 1, oranges = 0 for dummy value).

| | | | Model | | | Visits | | | | Citrus | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Tool[a,b] | Pop est | Grid[c] | $F_{2,7}$ | $p$ | $r^2$ | $t_1$ | $p$ | β | SE | $t_1$ | $p$ | β | SE |
| T_tunnels | S-E | 5 × 5 | 32.1 | <0.001 | 0.90 | 3.5 | 0.010 | 1.27 | 0.37 | 7.2 | <0.001 | 17.23 | 2.40 |
| | | 3 × 3 | 49.6 | <0.001 | 0.93 | 4.7 | 0.002 | 2.24 | 0.48 | 6.9 | <0.001 | 14.34 | 2.07 |
| | MNK | 5 × 5 | 115.3 | <0.001 | 0.97 | 6.8 | <0.001 | 1.30 | 0.19 | 13.5 | <0.001 | 17.06 | 1.26 |
| | | 3 × 3 | 44.7 | <0.001 | 0.93 | 3.8 | 0.007 | 1.85 | 0.49 | 7.0 | <0.001 | 14.70 | 2.09 |
| C_index | S-E | 5 × 5 | 23.2 | <0.001 | 0.87 | 2.7 | 0.030 | 3.28 | 1.21 | 5.0 | 0.002 | 14.69 | 2.94 |
| | | 3 × 3[d] | 20.9 | 0.001 | 0.86 | 2.5 | 0.043 | 7.30 | 2.95 | 5.2 | 0.001 | 15.48 | 3.00 |
| | MNK | 5 × 5 | 55.1 | <0.001 | 0.94 | 4.4 | 0.003 | 3.42 | 0.78 | 7.6 | <0.001 | 14.41 | 1.91 |
| | | 3 × 3[d] | 32.5 | <0.001 | 0.90 | 3.0 | 0.020 | 7.00 | 2.33 | 6.5 | <0.001 | 15.39 | 2.37 |
| C_visits | S-E | 5 × 5 | 22.8 | <0.001 | 0.87 | 2.7 | 0.032 | 0.92 | 0.35 | 6.1 | <0.001 | 17.03 | 2.80 |
| | | 3 × 3 | 19.3 | 0.001 | 0.85 | 2.3 | 0.056 | 1.55 | 0.68 | 4.9 | 0.002 | 15.27 | 3.14 |
| | MNK | 5 × 5 | 74.5 | <0.001 | 0.96 | 5.3 | 0.001 | 1.01 | 0.19 | 10.8 | <0.001 | 16.83 | 1.56 |
| | | 3 × 3 | 25.1 | <0.001 | 0.88 | 2.4 | 0.048 | 1.39 | 0.58 | 5.7 | <0.001 | 15.32 | 2.69 |

[a] Monitoring tools included the use of tracking tunnels (T_tunnels) to assess presence or absence at a site, a general index developed from remote-triggered cameras (C_index), and the use of remote-triggered cameras to assess the presence or absence at a site (C_visits).
[b] Tracking tunnels, remote-triggered cameras, and live traps were either located on the ground or in the trees. See Methods for additional details.
[c] Indexing stations followed a 5 × 5 grid structure. We also tested a subset of these indexing stations following a 3 × 3 grid structure.
[d] These general index values were cube root transformed so that residuals approximated a normal distribution.

2005; Baldwin et al., 2014), we found that indexing tools were effective at monitoring roof rat numbers in citrus crops, with strong relationships observed between index values and both population estimates and minimum number known counts. General indices have often been correlated to minimum number known estimates to verify their ability to reflect rodent numbers (e.g., Whisson et al., 2005; Baldwin et al., 2014; Engeman et al., 2016). That said, population estimates may provide a more robust assessment given their ability to account for individuals that were potentially present but not identified. The fact that both approaches resulted in similar estimates of roof rat numbers, as well as similar relationships to index values, corroborates the effectiveness of our indexing tools. Indices derived from tracking tunnels and remote-triggered cameras provide a robust assessment of roof rat numbers and should be a useful tool for managing roof rats in citrus orchards.

Monitoring for changes in roof rat numbers can be time-consuming, labor intensive, and costly. Using a practical number of monitoring stations is an important consideration if citrus producers are to adopt monitoring protocols as part of an integrated pest management program. We determined that a 3 × 3 grid structure of monitoring stations separated by 70 m effectively reflected roof rat numbers over the study area. This requirement of only 9 monitoring stations instead of 25 should result in a substantial cost- and time-savings for citrus producers and pest control specialists. That said, for all models except for tracking tunnel indices compared to population estimates, using a 5 × 5 grid structure resulted in stronger models than when using 3 × 3 grids (Table 2). Therefore, for research studies where maximum sensitivity is required, using a 5 × 5 grid structure may provide a more robust assessment.

Interestingly, we did not find the vertical location of these indexing tools (i.e., on the ground or in the trees) to be an important factor. Roof rats have been documented to use vertical structure differently depending on the ecological system where they are found. In natural ecosystems, roof rats frequently use ground habitats, presumably given the abundant cover often provided by ground vegetation as well as an abundance of ground-level foods (Dowding and Murphy 1994; Lindsey et al., 1999; Whisson et al., 2007). Conversely, in orchard crops, roof rats heavily use tree branches and canopies where cover and food is more readily available (Tobin et al., 1996; Baldwin et al., 2014). The reason for the lack of effect that this variable had in citrus orchards is unclear but may be due to the fact that citrus trees are evergreen, and as such, maintain abundant cover year-round. This leaf cover often extends down to ground level potentially allowing for safe foraging by roof rats on the surface. Regardless, roof rat monitoring in citrus orchards appears to be equally effective both on the ground and in the trees. This is a particularly important consideration for citrus producers and pest control specialists, as the placement of tracking tunnels and cameras at the ground level requires less work. That said, we did observe consistently higher capture rates up in trees than on the ground. Therefore, if trapping is to be conducted either as a monitoring tool or as a management tool, the placement of traps within trees may be warranted.

Tracking tunnels are commonly used to track changes in roof rat numbers in a variety of settings (Innes et al., 1995; Brown et al., 1996; Lindsey et al., 1999; Shiels et al., 2019), in part because they are quick and easy to deploy. They also require limited training to operate given that simple presence or absence of rats is generally the metric recorded (Brown et al., 1996). As such, tracking tunnels could be a valuable tool for citrus producers and associated pest control specialists for tracking changes in roof rat numbers over time.

Conversely, our use of remote-triggered cameras provided two measures of roof rat abundance: simple presence or absence at a camera station (i.e., binary response), or a mean estimate of the nightly number of visits to a camera station (i.e., continuous response). We found that remote-triggered cameras provided accurate assessments of roof rat numbers with both binary and continuous monitoring responses. Many other projects have shown that general index values derived using a continuous response metric have outperformed binary response methods (e.g., Whisson et al., 2005; Baldwin et al., 2014; Engeman et al., 2016), presumably because of the ability to account for multiple individuals at a monitoring station when using a continuous response approach (Engeman 2005). The use of a continuous response metric could afford the opportunity to better detect changes in population size when roof rats are at saturation levels (i.e., when most monitoring stations result in detections). That said, this might not be as important in agricultural systems given that roof rat control efforts are likely to be deployed regardless of whether roof rats are at or near saturation levels, and control efforts will likely continue until those numbers are reduced below some pre-established threshold regardless of what the initial population size was in the orchard. As such, the use of remote-triggered cameras as a binary response tool may be more practical for citrus producers and pest control specialists than using it as a continuous response tool given that general index values require substantial review time for tabulating roof rat activity in each photo. Even if used as a binary response tool, remote-triggered cameras would be more time-consuming and costly to use than tracking tunnels given their initial costs combined with the time required to program the cameras, secure and target them at an attractant, and review and document photos. For these reasons, tracking tunnels may be more practical for citrus producers to use to track roof rat numbers. It bears noting that a few researchers have attempted to develop strategies for using tracking surfaces as a continuous variable as well (Whisson et al., 2005; Raheli-nirina et al., 2021). We did not attempt to do this in this study given the increased time required for such monitoring, combined with the fact that this approach is not widely used. However, future assessment of a continuous response metric for tracking tunnels in orchard crops may prove useful and could be considered.

Although the utility of remote-triggered cameras for monitoring roof rats for citrus producers and pest control specialists may be somewhat limited, they do provide more detailed information on rodent activity. For example, the use of remote-triggered cameras allowed us to verify that roof rats were almost exclusively nocturnal within our study orchards. Previous research in California almond orchards also noted exclusive nocturnal activity by roof rats (R.A. Baldwin, University of California, Davis, unpublished data). As such, cameras could be set to record photos only during the night to reduce time spent reviewing photos. Likewise, this information indicates that bait stations and traps could be operated exclusively at night should access to these devices by non-target diurnal species be a concern.

It is worth emphasizing that both tracking tunnels and remote-triggered cameras were effective monitoring tools in citrus orchards. This is of importance given that corroborating tools are required by the United States Environmental Protection Agency when testing the efficacy of a management tool (Schneider 1982). The simultaneous use of both tracking tunnels and remote-triggered cameras should allow researchers to effectively test the efficacy of a variety of management tools. However, it is interesting to note that we consistently observed greater visitation rates to tracking tunnels than we did to remote-triggered camera stations. It could be that the tracking tunnel itself served as an attractant, presumably as shelter or as a novel item to investigate (Witmer et al., 2020).

We also noted a difference in the relationship between roof rat abundance and visits to tracking tunnels and remote-triggered cameras for lemon and orange orchards (Table 2). Although roof rats were captured more frequently in lemon orchards, they were detected in tracking tunnels and cameras relatively equally between lemon and orange orchards. We are not sure why we observed such a disparity. It may be related to a differential use of habitats between orange and lemon orchards, but this is currently unknown. A telemetry study that assesses habitat use and movement patterns in both orange and lemon orchards may help to explain this disparity. Regardless, the differences observed between orange and lemon orchards reinforces the need to test how accurately indices reflect rodent abundance within differing habitat types (Engeman and Whisson 2006). That said, tracking tunnels and remote-triggered cameras both effectively reflected roof rat abundance regardless of orchard type, and as such, they both should prove useful for future monitoring projects in citrus orchards so long as these differences in response are accounted for.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.


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