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WILDLIFE RESEARCH

Identifying black rat (*Rattus rattus*) movement patterns aids the development of management programs in citrus orchards

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ABSTRACT

Context. The black rat (*Rattus rattus*) is an invasive species found throughout much of the globe, including in many agricultural areas, where they cause significant damage to many crops including citrus. Understanding how black rats move in these orchards would substantially aid the development of management programs to combat this pest species. **Aim.** Our goal was to determine the home-range size and mean maximum distance moved over a 24-h period, as well as to determine the activity period for black rats in orchards. **Methods.** We used innovative cellular tracking technology to provide a more complete assessment of home-range size and maximum daily movements than previously reported in other investigations. We also used remote-triggered cameras to assess activity periods for black rats to better inform management actions. **Key results.** We observed large home ranges for black rats in citrus orchards ($\bar{x} = 2.36$ ha). Although mean home-range size did not differ between males and females, we did identify an effect of sex on the mean maximum daily distance moved by black rats (males: $\bar{x} = 201$ m; females: $\bar{x} = 148$ m). Black rats were most active during the early evening, with all observations made during night-time. **Conclusions.** Black rats moved relatively large distances within orchards, with activity occurring exclusively at night. **Implications.** This information on black rat activity patterns will greatly assist in the development of management programs by informing ideal spacing between traps and bait stations to minimise cost, while still yielding efficacious results. A reliance on trapping or baiting during night-time would ensure access by black rats, while eliminating access to diurnal non-target species, although such actions would be labour-intensive and may be cost-prohibitive.

Keywords: agriculture, cell tracking technology, daily movement, diel activity pattern, home range, invasive pest, roof rat, ship rat.

Introduction

Black rats (*Rattus rattus*) are an invasive species throughout much of the world (Pimentel *et al.* 2005; Wood and Singleton 2015). They are particularly problematic in fruit and nut orchards where they cause mortality of trees, a reduction in crop production, damage to irrigation infrastructure, and they pose a food safety risk (Worth 1950; Tobin 1992; White *et al.* 1998; Yabe 1998; Dongol *et al.* 2021). Effective management of black rats in orchard systems requires a good understanding of how they move about the landscape. For example, knowing home-range size and daily maximum distances moved has direct implications on spacing of traps and bait stations (Whisson *et al.* 2004). Several studies have defined black rat home-range sizes in forested habitats. In Californian riparian forested habitats, Whisson *et al.* (2007) noted substantially different home-range sizes between males ($\bar{x} = 1.04$ ha) and females ($\bar{x} = 0.39$ ha). Conversely, home-range sizes of black rat in kauri (*Agathis australis*) forest in New Zealand did not differ between males and females, with an average home-range size of 0.85 ha (Dowding and Murphy 1994). Surprisingly, little research has been conducted to identify black rat movement patterns in orchard crops. In the only published paper of home-range sizes in orchards that we are aware of, Tobin *et al.* (1996) observed a mean home-range size of 0.2 ha in macadamia nut orchards. This did not vary between males and females. These home-range sizes were also substantially smaller than

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those observed in forested habitats, indicating the potential variability in movement patterns across land-cover types.

One of the hurdles when assessing movement patterns in rodents is their size. These rodents are often not large enough to support GPS or satellite collars that will consistently record location data, thereby limiting inference to a relatively small number of locations collected via VHF collars throughout the sampling period. One potential solution for circumventing this problem is to use cellular tracking technology that allows the collection of data points multiple times per minute, thereby allowing for a much greater understanding of how target animals move throughout the landscape. This technology is rapidly advancing, potentially allowing for more accurate estimates of daily movement patterns in small vertebrates, given more abundant location data. As such, the use of cellular tracking technology is worth investigating to better define home-range size and daily movement patterns of black rat in orchard systems.

Diel activity patterns can also inform management by helping target actions during a timeframe that will maximise efficacy while minimising costs or non-target effects. Black rats are generally considered nocturnal although they are sometimes seen during the daytime (Denys *et al.* 2017). However, this has not been quantified in most orchard systems. Visitation to remote-triggered cameras would provide a useful approach to quantify activity periods for black rats in such settings. Clearly, there is a paucity of data available on movement patterns of black rats in orchards. As such, we established the following objectives to provide some guidance on this important ecological attribute: (1) to determine home-range size of black rats in orchards and to determine whether this varies by sex, (2) to determine mean maximum distance moved over a 24-h period in orchards and to determine whether this varies by sex, and (3) to determine activity periods of black rat in orchards. Collectively, this information should greatly assist in the development of management plans designed to substantially reduce impacts of these invasive rodents in orchard systems.

Materials and methods

Study area

We selected two study sites in the southern San Joaquin Valley, California, during summer through autumn 2020. Site 1 was located exclusively within a navel orange orchard in Kern County (35.033708, −119.225225). Site 2 was located in Tulare County (35.810040, −119.075003), and was centred in Lisbon lemons and navel oranges, but also overlapped Ruby Red grapefruit and mandarin orchards as well.

Capture and collaring

We placed 25–50 wire-cage traps (13 cm × 13 cm × 46 cm, Tomahawk Live Trap, Hazelhurst, Wisconsin, USA) throughout the 0.4-ha core of monitoring plots at both study sites during early summer 2020 to capture black rats for collaring. We baited traps with Liphatech Rat and Mouse Attractant™ (Liphatech, Inc., Milwaukee, Wisconsin, USA). Traps were operated up to three nights per site with the goal of capturing approximately 15 rats per site. The traps were checked during early morning. On capture, we sexed and weighed all rats. We then fitted PowerTag collars (<4.5 g; Cellular Tracking Technologies [CTT], Rio Grande, New Jersey, USA) around the necks of individuals >100 g and released the collared rats at the capture site.

Location data

To collect location data, we used the Internet of Wildlife System of CTT that serves as a complete radio-telemetry system. Following this approach, we placed CTT nodes in a 5 × 5 systematic manner across a 16-ha study area at each study site. These nodes allowed us to collect location data from collared black rats when they passed within sensor range of the node. Given the potential variability in vegetative structure throughout an orchard, as well as the novelty of this approach, it was not clear what maximum or mean distances the nodes were able to detect transmitters aboveground. However, aboveground locations, including in tree canopies, could readily be detected at ranges of >50 m, leading to our placement of nodes that were separated by approximately 100 m. Nodes were placed approximately 2.4 m above ground to allow clear transmission to the CTT SensorStation, as well as for easy detection of black rats in tree canopies. Although detections of black rats underground may have been possible if located close to a node, we do not believe that such detections were reliable, and as such, we do not interpret any movement data on the basis of belowground locations. The SensorStation was located in the centre of each study site; it was connected to an omni antenna placed approximately 8 m above ground. This allowed us to collect signals from each node located throughout each study site. Location data were collected every few seconds when a transmitter was within sensor range of a node, and location data from each node was transmitted to SensorStations every few minutes for storage. We downloaded data from SensorStations every 1–2 weeks for analysis. To reduce data used in analyses, we combined location data into 5-min intervals. SensorStations remained operational for 15–16 weeks per site.

To test the spatial resolution of the CTT system, we randomly placed a transmitter at nine locations at both Sites 1 and 2, and we recorded the coordinates for each location via a hand-held GPS unit. The transmitter was left in place at each location for a minimum of 22 min to allow the SensorStation to collect multiple readings per location. We then determined the linear distance between GPS and SensorStation locations and averaged those values to assess spatial resolution for each site.

Movement analysis

Home ranges were estimated for each individual using kernel-density estimation with the reference bandwidth and a 95% isopleth. We calculated daily displacement distance as the farthest distance between any two points during a 24-h period for a single individual. We summarised the daily displacement distance for each individual by taking the mean value of all estimates.

To test the influence of site, sex, and their interaction on home-range size and daily displacement, we fit five linear models for each response variable with the following sets of covariates: (1) sex only; (2) site only; (3) site and sex; (4) site, sex, and their interaction; and (5) a null model. We compared these models using Akaike's information criterion corrected for small sample sizes (AIC_c; Burnham and Anderson 2002), and we selected the best-supported model as the one with the fewest number of covariates within 2 ΔAIC_c of the smallest AIC_c value.

Activity period

Following Baldwin and Meinerz (2022), we established a 5 × 5 remote-triggered camera grid (approximately 35-m spacing between cameras) spread across a 0.4-ha square at the centre of each monitoring plot to determine when black rats were active in our study orchards. We placed one Bushnell NatureView HD Max camera (Bushnell Outdoor Products, Overland Park, Kansas, USA) up in the tree at each grid point (generally 0.9–1.8 m aboveground). Cameras were set to high sensitivity to maximise the likelihood of detecting a black rat at each site, and cameras were set with a 5-min minimum delay between activations to reduce the impact of repeat visits on our assessment. We operated cameras across three consecutive days, by using Liphatech Rat and Mouse Attractant™ sachets as an attractant to draw the black rat in front of the cameras. We determined the proportion of visits to camera sites on an hourly basis and plotted these visits to graphically represent periods of black rat activity. Cameras were operated at Site 1 from 28 to 31 October 2020, whereas cameras at Site 2 were operated from 2 to 5 December 2020. All aspects of this project were approved by the University of California, Davis, Institutional Animal Care and Use Committee (Protocol no. 21521).

Results

We collared 16 (11 male, 5 female) and 13 (7 male, 6 female) black rats at Sites 1 and 2 respectively, with a mean weight of 183 g (s.e. = 9; Supplementary Table S1). Although we recorded data across a large number of days for most black rats (Site 1 $\bar{x} = 69$ days, s.e. = 11; Site 2 $\bar{x} = 59$ days, s.e. = 13), we removed one male and one female black rat from Site 1 and one female from Site 2 given a lack of location data (<5 days) for these individuals. We collected spatial-resolution data for nine locations each at Sites 1 and 2, with accuracy being similar between both locations (Site 1 $\bar{x} = 17$ m, s.e. = 2.0; Site 2 $\bar{x} = 14$ m, s.e. = 0.6).

We did not observe a significant impact of sex or site on home-range size (Table 1), with home-range size averaging 2.36 ha (s.e. = 0.19). In contrast, we did observe an impact of sex on the mean daily displacement distance moved by black rats (Table 2), with males (201 ± 3 m s.e.) travelling further than females (148 ± 11 m s.e.); mean daily displacement distance did not vary by site (Bakersfield: 190 ± 5 m s.e.; Tulare: 174 ± 6 m s.e.).

We observed 182 photos of black rats during the study period. Activity varied some across sites, with a strong peak noted at Site 1 between 19:00 hours and 21:00 hours (Fig. 1). Activity then dropped around the middle of the night and reached a smaller secondary peak toward early morning. The same general trend was observed at Site 2, although activity

Table 1. Relationship of five candidate models comparing the effect of site, sex, and their interaction on black rat home-range size in citrus orchards.

Model	Coefficient			P-value			AIC_c	ΔAIC_c
	Site[A]	Sex[B]	Site:Sex	Site	Sex	Site:Sex		
Site + Sex	−	+		0.258	0.148		555.03	
Sex		+			0.110		555.60	0.57
Null							555.86	0.83
Site	−			0.191			556.54	1.51
Site × Sex	+	+	−	0.759	0.064	0.225	558.26	3.23

Models were compared using Akaike's information criterion corrected for small sample size (AIC_c), with differences denoted by the change in AIC_c (ΔAIC_c).
[A]Coefficient sign is reflective of Site 2 (i.e. + means larger home range size at Site 2).
[B]Coefficient sign is reflective of males (i.e. + means larger home range size for males).

Table 2. Relationship of five candidate models comparing the effect of site, sex, and their interaction on black rat daily maximum distance travelled in citrus orchards.

Model	Coefficient			P-value			AIC_c	ΔAIC_c
	Site[A]	Sex[B]	Site:Sex	Site	Sex	Site:Sex		
Sex		+			0.010		277.98	
Site + Sex	−	+		0.620	0.014		280.51	2.53
Null							282.75	4.77
Site × Sex	+	+	−	0.992	0.048	0.711	283.44	5.46
Site	−			0.442			284.67	6.69

Models were compared using Akaike's information criterion corrected for small sample size (AIC_c), with differences denoted by the change in AIC_c (ΔAIC_c).
[A]Coefficient sign is reflective of Site 2 (i.e. + means larger daily displacement at Site 2).
[B]Coefficient sign is reflective of males (i.e. + means larger daily displacement for males).

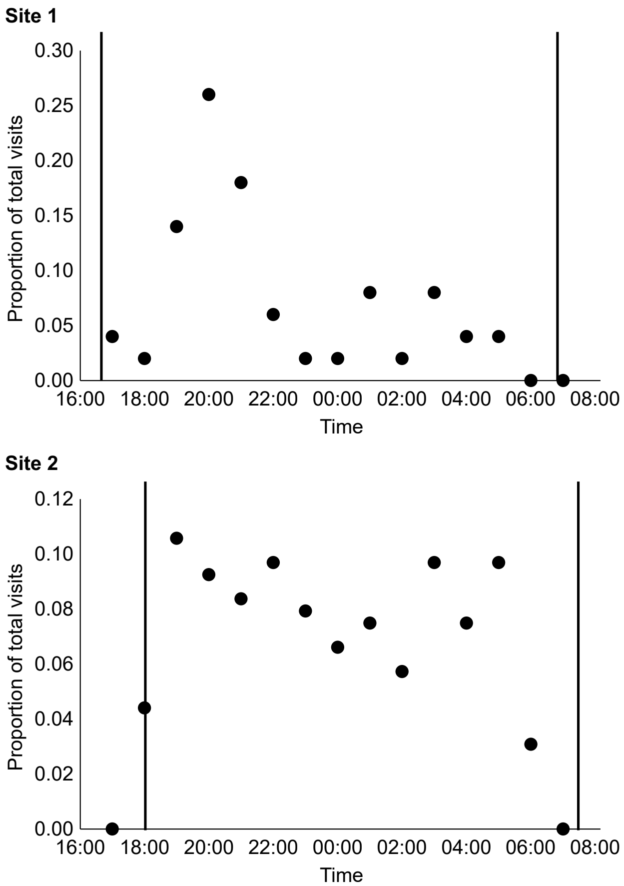

Fig. 1. The proportion of total black rat visits per hour to remote-triggered camera sites across two citrus orchards in the southern San Joaquin Valley, California, during autumn 2020. Site 1 was sampled from 28 to 31 October 2020 and Site 2 was sampled from 2 to 5 December 2020. The times corresponding to sunrise and sunset are illustrated by black vertical lines.

was more consistent throughout the night at this location. The most notable trend was that black rats were observed only during the night (Fig. 1).

Discussion

Black rat home-range sizes ($\bar{x} = 2.36$ ha) were on the larger end of the spectrum previously reported for this species in forested habitats (e.g. 0.85 ha, Dowding and Murphy 1994; 0.3–1.1 ha, Hooker and Innes 1995; 0.39–1.04 ha, Whisson *et al.* 2007), and they were substantially larger than home ranges observed in macadamia orchards (0.2 ha, Tobin *et al.* 1996). Likewise, black rats in our study system moved substantial distances on a daily basis (148–201 m), with mean daily movements of approximately the width of the mean home-range size (173 m). These larger daily movement patterns could be representative of a number of factors. For example, previous investigations have relied on relatively few locations collected at set times via VHF telemetry, whereas our study collected location data continuously throughout the entire study period. The larger observed home-range size in this study may simply reflect a more accurate assessment of movement patterns, given the more extensive data set. Alternatively, larger movement patterns could reflect resource availability within citrus orchards. For example, Tobin *et al.* (1996) suggested that small home-range sizes in macadamia nut orchards were likely to be a reflection of the black rat's ability to find all its dietary requirements in a small area, given the resource-rich nature of this nut crop. Exact diets of black rats in our study system are unknown, but we regularly observed feeding on discarded fruit (generally on the ground), the cambium layer of trees, and snails. Although discarded fruit and tree cambium were found throughout the orchards, snails had a patchy distribution (R. Baldwin, pers. obs.), and as such, black rats may have required substantial movement to utilise this important protein resource. It also bears noting that black rat movement was likely to be facilitated in citrus orchards by the close spacing of trees (approximately 7-m spacing) combined with the linear nature of orchard rows that would allow the rats to move from tree to tree underneath or within the sheltered evergreen canopy. This linear orientation may have expedited movement throughout larger areas by providing protection from predators.

Interestingly, although we did not observe a difference in home-range size between male and female black rats, we did note a difference in daily movement patterns, with males moving further distances than females. Black rats have been observed to reproduce year-round in macadamia nut orchards (Tobin *et al.* 1994), were suggested as year-long breeders in California riparian forests (Whisson *et al.* 2007) and fruit orchards in Florida (Kern 2012), and were observed in breeding condition throughout the year in citrus orchards (R. Baldwin, pers. obs.), presumably owing to the availability of abundant food resources in these areas (Bronson and Perrigo 1987). As such, increased daily displacement distances by male black rats may reflect their efforts to seek out females for reproduction. That said, they did not occupy significantly larger home ranges, indicating that the spacing of traps or bait stations would not need to be adjusted to effectively manage both sexes assuming that such tools would be left within the orchard for an extended period of time.

It bears noting that a potential limitation of our monitoring approach could occur if collared individuals roamed extensively outside of the established monitoring area (i.e. too far for the perimeter nodes to pick up location data). To mitigate this potential impact, we focused all capture and collaring efforts on the interior core of each study site. This approach appeared to be effective as all portions of the black rats' home ranges were found within our study area (see Supplementary Fig. S1 for illustration). Nonetheless, it is possible that some portion of the rat home ranges may have occurred outside of the monitored area, and as such, the home ranges should be considered as minimum estimates. Likewise, we noted an error associated with black rat locations (14–17 m). This error was due in large part to the thick vegetative cover provided by the trees. Studies requiring greater spatial resolution (e.g. fine-scale habitat assessments) would benefit from reduced spacing between nodes to allow for greater signal strength and greater numbers of nodes detecting locations, which in turn would result in greater accuracy of locations. However, we feel the spatial resolution observed in this study provided a good initial test of the applicability of this monitoring approach for small mammals, and given the constant collection of location data from transmittered rats over the course of many weeks, provided the best approximation of movement data for black rats in orchard crops.

As expected, black rats were active almost exclusively at night. As witnessed in other locations (e.g. Tobin *et al.* 1996; Whisson *et al.* 2007), activity was greatest towards the early to middle portion of the night and was lowest right after dusk and again before daybreak. Given their strong adherence to nocturnal activity, control efforts could be focused exclusively at night. Such actions would likely entail closing traps or bait stations during daylight hours, which would be time-consuming and expensive, and perhaps not needed in many settings. However, this approach would eliminate threats to diurnal non-target species of concern, thereby eliminating this conservation threat to susceptible species. Given the current and anticipated regulatory environment, such mitigation measures could be implemented to allow continued use of some management tools when and where needed, although these closures may make these management tools too time-consuming and cost-prohibitive to be practical.

As previously noted, invasive black rats pose substantial problems for agricultural producers around the globe (Pimentel *et al.* 2005; Wood and Singleton 2015). Our study has provided much needed information on movement patterns of black rats in orchard systems in one of the most important food-producing regions in the world (CDFA 2022). This movement data should be extremely valuable in guiding management programs designed to reduce or eliminate black rats in these orchards (Whisson *et al.* 2004). For example, systematically placing traps or bait stations at distances that equate to the radius of the mean home-range size of black rats (i.e. 87 m) should ensure visitation to at least one of these management tools by most individuals in these orchard systems, while also minimising the required number of these control mechanisms to reduce treatment costs. However, maximising efficacy may require that every black rat has access to more than one of these management tools. In this study, the minimum home-range size observed had an estimated radius of 48 m. This spacing is similar to the 50-m spacing used or recommended for some other black rat studies (Whisson *et al.* 2004; Quinn and Baldwin 2014). Additional testing will be needed to identify ideal spacing, but data from this study provide an informed starting point for such trials.

It should be noted that data collection for this study occurred during summer and autumn months. Although our general observations of black rat activity in these orchards over the course of several years suggest continual use by black rats of these areas, we do not definitively know how they use the orchards during other seasons. Future research could address movement patterns during winter and spring to better inform management decisions. In lieu of these data, we suggest using proposed spacing and activity periods at all times of the year to maximise efficacy and efficiency of trapping and baiting programs, with testing of such management tools being warranted to determine their utility for controlling this injurious, invasive rodent.

Supplementary material

Supplementary material is available online.

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Data availability. The data collected during this study are available from the corresponding author, RAB, upon reasonable request.

Conflicts of interest. The authors declare that they have no conflicts of interest.

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