FINAL REPORT

for

Vertebrate Pest Control Research Advisory Committee

STUDY TITLE:

Assessing the efficacy of carbon monoxide producing machines at controlling burrowing rodents.

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June 2016

EXECUTIVE SUMMARY

Burrow fumigants are a management tool used to mitigate rodent damage. Until recently, only gas cartridges and aluminum phosphide were registered for use in California for managing burrowing rodents. However, as of 2012, pressurized exhaust machines were legalized for use, although their efficacy and cost effectiveness were unknown. Therefore, we established a study to assess the efficacy and cost effectiveness of two pressurized exhaust machines (Pressurized Exhaust Rodent Controller [PERC] and Cheetah rodent control machines) for managing California ground squirrels (*Otospermophilus* spp.) and pocket gophers (*Thomomys* spp.) across various localities in California from 2012–2015. Furthermore, we compared these results to previously tested burrow fumigants to determine the utility and applicability of these machines. Specific details for our sampling methodology and findings include:

1. We tested the efficacy of the Cheetah rodent control machine for California ground squirrels across three treatment plots in Fresno County, CA during March 2012. Soil was considered sufficiently moist for effective application. Efficacy was tested using both ground squirrel and open burrow counts.
2. We tested the efficacy of the PERC machine for California ground squirrels across two treatment plots in Alameda County during May 2014. Soil conditions during this study were hot and dry, which were not considered ideal conditions for a fumigation application. Efficacy was tested using both ground squirrel and open burrow counts.
3. We tested the efficacy of the PERC machine for California ground squirrels across two treatment plots in San Joaquin County during March 2015. Soil conditions during this study were considered sufficiently moist for effective application. Efficacy was tested using both ground squirrel and open burrow counts.
4. Application costs for California ground squirrels were determined on a per burrow basis for the PERC machine and compared to estimated costs for aluminum phosphide and gas cartridges. These costs were amortized over 1,250 days to account for the substantial start-up cost associated with the PERC machine.
5. We tested the efficacy of the PERC machine for pocket gophers across two fields in Siskiyou County during March 2014. Soil was considered sufficiently moist for effective application. Efficacy was tested using the open-hole method.
6. Application costs were determined for pocket gophers when using the PERC machine. These costs were compared to estimates derived from a similar study in Modoc County to determine how they may vary across localities.
7. The PERC machine was highly effective in moist soil conditions for California ground squirrels (efficacy = 100%). It was less effective in dry soil conditions (efficacy = 66%), but would likely outperform other fumigants in similarly dry conditions.
8. The Cheetah rodent control machine was ineffective against California ground squirrels (efficacy = –15%).
9. The PERC machine was moderately effective at controlling pocket gophers (efficacy = 68%), and performed better in this investigation than in previous studies, perhaps due to applications in less porous, heavy mineral soils.
10. Initial application costs for California ground squirrels were high for the PERC machine given the large start-up investment in the machine ($5,425–$15,275), but if used extensively over time, costs could drop below that of other burrow fumigants.

11. Increases in efficacy or reductions in application times for the PERC machine dramatically increase the cost effectiveness of this device given the greater number of treatments that can be applied simultaneously.

Based on this study, aluminum phosphide appears to be the most effective burrow fumigant for pocket gophers, but the PERC machine was as efficacious as aluminum phosphide for California ground squirrels. Furthermore, the PERC machine is likely more effective than other burrow fumigants for ground squirrel management in dry soil conditions, which should increase its utility in year-round programs. It bears noting that the use of pressurized exhaust machines is less restrictive than aluminum phosphide, and can be at least as cost effective in some situations if used extensively over time. As such, we may see increased usage of these machines by land managers in the future.

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INTRODUCTION

Burrow fumigants are one of the more effective tools available for managing burrowing rodents (Salmon et al. 1982, Hygnstrom and VerCauteren 2000, Baker 2004, Baldwin and Holtz 2010, Baldwin et al. 2014). Burrow fumigants are gases that are introduced into burrow systems with the intent of lethal control of the target species. Although they can be more time-consuming to implement, and thus more costly than some alternative management strategies (Salmon and Schmidt 1984; Marsh 1992, 1994), this increased cost is often offset by a number of benefits including: 1) direct targeting of rodents within the burrow system, 2) no reliance on bait acceptance that sometimes hinders rodenticide and trapping efforts, 3) no secondary toxicity concerns for scavengers and predators, 4) they seldom require handling of animals after treatment, which reduces the risk of disease and parasite transmittance to humans, and 5) they can be highly efficacious. Because of these benefits, burrow fumigants are often included as part of an integrated pest management (IPM) program for burrowing rodents (Marovich et al. 2002, Baldwin et al. 2016).

Historically, a number of burrow fumigation options were available including methyl bromide, carbon bisulfide, chloropicrin, nitrocellulose film bombs, and acrolein (Miller 1954, O'Connell and Clark 1992, Marsh 1994, Matschke et al. 1998, Hygnstrom and VerCauteren 2000), although none of these products are currently registered for use in this capacity in the U.S. Until recently, only 2 burrow fumigants were still registered: gas cartridges and aluminum phosphide. Gas cartridges are pyrotechnic devices that have been around since at least the 1940's (Savarie et al. 1980). When gas cartridges are lit, they create carbon monoxide which asphyxiates the animal within the burrow system. Aluminum phosphide is available in pellet or tablet formulations, which when introduced into moist environments, releases phosphine gas that is toxic to vertebrates and invertebrates alike (Salmon et al. 1982, Baker 1992). Both fumigants have positive and negative attributes. Gas cartridges are less effective, particularly for pocket gophers (Geomyidae), but its use is far less restrictive. Aluminum phosphide tends to be more efficacious and cost effective, but also is far more restrictive on where it can be legally used (Salmon et al. 1982, Baldwin 2012). As such, there is an opportunity for the development of another burrow fumigant that could circumvent some of these shortcomings.

Historically, the use of pressurized exhaust for burrowing rodent management was illegal in California. However, in 2011 California Assembly Bill 634 was passed that legalized the use of pressurized exhaust for managing burrowing rodent pests. At least two commercial machines have been available for use since that time: the Pressurized Exhaust Rodent Controller (PERC; H & M Gopher Control, Tulelake, CA) and the Cheetah rodent control machine (Cheetah Industries, Paso Robles, CA). The PERC machine consists of a small gasoline-powered engine that creates exhaust that is pumped through coils to cool the emissions and stores the exhaust in a large tank. The pressurized exhaust contains 25,000 ppm of carbon monoxide (HMGC 2016) which is injected into a burrow system via a hose and probe. The PERC machine comes in various sizes ranging from 2–6 probes per unit, thereby allowing for the treatment of multiple burrow systems at once.

The Cheetah rodent control machine is essentially a modified leaf blower that is comprised of a two-cycle engine that produces over 25,000 ppm of carbon monoxide (CRCM 2016). A single exhaust tube extends from the engine to allow application of exhaust into a burrow system. This device only allows for one application at a time, but it was cheaper (PERC range = $5,425–$15,275, Cheetah rodent control machine = $1,280; prices as of June 2016) and more portable than the PERC machine.

Since the passing of California Assembly Bill 634, the use of pressurized exhaust machines has increased throughout the state and in other parts of western North America, but relatively little data exists on their efficacy or cost effectiveness. Initial limited testing of the PERC machine suggested relatively good efficacy ($\bar{x}$ efficacy = 76%) for Belding's ground squirrel (*Urocitellus beldingi*), but only marginal efficacy ($\bar{x}$ efficacy = 56%) for pocket gophers (*Thomomys* spp.; Orloff 2012). Further testing for pocket gophers in northern California corroborated previous estimates ($\bar{x}$ efficacy = 56%, Baldwin et al. 2016), but no data had yet been collected for California ground squirrels (*Otospermophilus* spp.), which is often the wildlife species deemed most damaging to California agriculture (Baldwin et al. 2014). Furthermore, although results for pocket gophers were consistent between Orloff (2012) and Baldwin et al. (2016), it should be noted that both studies were conducted in the same geographic area, and subsequently, the same soil types. This is of potential relevance given that burrow fumigants are substantially influenced by soil morphology and soil moisture (Miller 1957, Salmon et al. 1982, Moline and Demarais 1987, Proulx et al. 2011); the more porous the soil, the less effective it is at holding the fumigant within the burrow at a concentration sufficient to euthanize the target species. That being said, pressurized exhaust machines inject carbon monoxide into burrow systems rapidly and in high concentrations. This may overcome some fumigant loss through cracks and pores in dry or more porous soils and may make these devices more appropriate to use in these less ideal substrates. As such, further testing of pressurized exhaust machines in different soil types and moisture levels would provide a more robust assessment of the utility of these machines for managing burrowing rodents.

Even if proven effective, the cost of pressurized exhaust machines, and associated labor to treat individual burrow systems with these machines, may prove uneconomical for use in many situations. A better understanding of these costs and how they relate to other burrow fumigants would provide land managers with much needed information to determine what role, if any, pressurized exhaust machines might play in an IPM program. Given all of these knowledge gaps regarding the utility of pressurized exhaust machines for managing burrowing rodents, we established field trials to address the following objectives: 1) determine the efficacy of pressurized exhaust machines for managing California ground squirrels (both PERC and Cheetah rodent control machines) and pocket gophers (PERC machine only) in differing soil types and soil moisture levels, 2) determine the amortized cost of operating pressurized exhaust machines (PERC machine only), and 3) compare efficacy and cost of operation of pressurized exhaust machines (PERC machine only) to alternative burrow fumigation strategies currently available.

STUDY AREAS

We tested the Cheetah rodent control machine during March 2012 in oak savannah rangeland in the low foothills of the Sierra Nevada mountain range 32 km east of Fresno, CA. Soils ranged from Fallbrook sandy loam to Fallbrook very rocky sandy loam. Soils were deemed sufficiently moist for effective use of a fumigant given the ability to form a ball of soil collected at burrow depth when squeezed in the palm of the hand. Recent ground squirrel control at the study site had been limited to occasional shooting by the rancher although no shooting occurred on our study sites during the duration of this study.

We initially tested PERC treatments for California ground squirrel management in a pasture setting just outside of Livermore, CA during May 2014. The soil was Positas gravelly loam and was classified very dry given a hard, dusty surface, with occasional cracks in the soil apparent throughout the study site. This lack of moisture was verified down to burrow depth given that soil would not form a ball when squeezed together in the palm of a hand. We also tested the efficacy of the PERC machine for California ground squirrels in moist soil conditions in an almond (*Prunus dulcis*) orchard approximately 8 km north of Escalon, CA during March 2015. Soil type was Madera sandy loam, and was verified as moist given that the soil at burrow depth would readily form a ball in the hand when squeezed. No ground squirrel management efforts were conducted prior to or during these investigations.

For pocket gophers (*Thomomys bottae*), we established treatment areas in two separate alfalfa (*Meticago sativa*) fields approximately 24 km southeast of Yreka, CA in March 2014 to test the PERC machine. Soil type was defined as Louie loam, which is a fine, loamy mineral soil that was conducive to burrow fumigation. Soil conditions were deemed relatively moist given the ability to ball up soil collected at burrow depth in the palm of the hand. No additional pocket gopher management activities occurred for several months prior to or during the treatment period.

METHODS

California ground squirrels

Efficacy of Cheetah rodent control machine.—We divided the study site into five plots consisting of a 1-ha core area surrounded by a 50-m buffer zone (totaling 3 ha). The buffer zone allowed us to minimize the impact of immigration and emigration into and out of the study plots following treatment. Of the five plots, three served as treatment plots, while the remaining two served as control plots. Following Salmon et al. (1982), we counted the number of ground squirrels observed through binoculars in each core area on five separate occasions at 5-min intervals; locations for these counts occurred at a fixed location outside the treatment plots where ground squirrels could not detect our presence. Ground squirrel counts occurred between 07:00 and 12:00 for three consecutive days to coincide with periods of relatively high activity for ground squirrels. We also counted ground squirrels from 14:45 to 17:30 for one day during this 3-day period in case activity was greater during late afternoon. This yielded 20 counts per core area. All individual ground squirrels within core areas were counted during each survey period; no ground squirrels observed outside the core area were included in these counts. All counts were conducted by the same individual to eliminate the potential for surveyor bias. The maximum count for each sampling period was used to serve as a minimum number known estimate of ground squirrels present in each core area.

Following the completion of the ground squirrel counts, we went through the entire core and buffer areas of each treatment site and plugged all burrow systems with soil. We came back two days later to count the number of burrows reopened within the core area. This provided a corroborative estimate of ground squirrel activity pre-treatment. Also, we were able to reduce the number of burrow systems we treated by plugging all burrow systems prior to treatment efforts (i.e., we subsequently only treated those burrows that were reopened by ground squirrels).

Following the conclusion of reopened ground squirrel burrow counts, we initiated Cheetah rodent control machine applications. We treated all active burrows by first inserting the exhaust hose of the Cheetah 0.3 m into the active burrows. We then plugged the opening around the hose with loose soil thereby sealing the burrow. Exhaust was pumped into the burrow system for three min. Upon removal of the exhaust hose, we sealed the opening with additional sod or soil. While pumping exhaust into a burrow system, we observed other burrow openings in the immediate vicinity for air movement to determine if they were connected to the burrow system that was being treated. If so, those openings were sealed as well. If not, those burrow systems were subsequently treated. All treatment plots were treated within one day.

Approximately 2.5 days post-treatment, we counted the number of reopened burrows within the core area of each treatment plot. The exact time-frame varied somewhat given that some burrow openings were treated in the morning, while others were not treated until late in the day. As such, we waited a little more than two days post-treatment to count the number of reopened burrows to ensure a minimum of 48 hrs since the conclusion of treatment activities.

The day following the completion of post-treatment burrow counts, we conducted ground squirrel counts using the same protocol followed during the pre-treatment period. We determined efficacy for both reopened burrow and ground squirrel counts using the following equation:

$$\text{Efficacy (\%)} = ([\text{pre-treatment} - \text{post-treatment}] / \text{pre-treatment}) \times 100$$

where pre-treatment and post-treatment equal the number of reopened burrows or number of observed ground squirrels before and after treatment.

Efficacy of PERC machine in dry soil conditions.—We established three study plots (two treatment and one control) that were 1.55 ha in area, with a core area of 0.4 ha. We used the different size treatment area than that used for the Cheetah rodent control machine trials given a more clustered distribution of ground squirrels in the PERC trials. We followed the same general protocol for ground squirrel counts except that instead of counting ground squirrels only once during the afternoon, we counted across all three afternoons (i.e., 30 total counts). We initiated post-treatment counts two days following the completion of treatment activities.

We conducted reopened burrow counts for the pre-treatment period in the same manner as described for the Cheetah rodent control machine. For the post-treatment period, we filled all reopened burrows within the treatment census plots the day following the completion of the post-treatment squirrel counts. Reopened burrows were counted two days later. Treatment efforts started the day after the completion of our pre-treatment burrow counts. All application protocols followed those outlined for the Cheetah rodent control machine except that the number of days required to complete the treatment period extended across four days. For treatment, we used the PERC 412 machine which allowed for exhaust applications in up to four burrow openings at once.

Efficacy of PERC machine in moist soil conditions.—At this location, we established study sites with a core area of 0.4 ha. Because of time and resource constraints, no buffer zone was included. Therefore, it was possible that some ground squirrels could move into the vacated treatment area even if treatments were successful. However, this would only bias efficacy estimates low, so derived efficacy values should be considered conservative. Furthermore, there were relatively few ground squirrels outside the treatment area, further reducing this potential risk. Due to limitations in ground squirrel population size at this study site, we were not able to include a control site.

For monitoring purposes, we again conducted ground squirrel and reopened burrow counts. The protocols for these approaches followed that defined previously for the PERC machine in dry soil conditions. Applications of the PERC machine also followed that defined for dry soil conditions as well, except that instead of injecting exhaust for three min, we injected exhaust for approximately six min per burrow system. The longer injection time was driven by the increased size of burrow systems at the almond orchard sites. We felt additional injection time was needed to completely fill these burrow systems and adjusted our applications accordingly.

Financial cost.—We recorded the number of burrow openings that we plugged in the treatment plots for both PERC trials, as well as the time required to plug these burrow openings, before any treatments were applied. This plugging activity was conducted to reduce the number of vacated burrow systems that we might otherwise treat. We also recorded the amount of time required to treat each treatment area when using the PERC machine, as well as the number of burrow openings that were treated. We excluded all personnel break times from these assessments. Because we considered the reopened burrows as occupied, we divided the total time spent plugging burrow systems, plus the time spent on PERC applications, by the number of reopened burrow entrances to determine a mean application time for each occupied burrow entrance. We then divided the time required to treat each burrow system by 480 min to represent the number of burrow systems that could be treated during an 8-hr work day. Application times were analyzed separately for the two PERC studies given differences in efficacy and PERC machine application times.

Because burrow fumigation with aluminum phosphide and gas cartridges are also commonly used to manage ground squirrels, for comparative purposes we determined relative time commitments for these treatment approaches using the same data collected for the PERC machine application sites. In a previous study (Salmon et al. 1982), treatment times averaged 1.5 and 2.2 min per burrow opening for aluminum phosphide and gas cartridges, respectively. In addition to treatment time, we also needed to account for search time to find new burrow openings between treatments. For purposes of treatment-time calculation, we estimated 30 sec of search time between treated burrow openings for all study sites. This estimated search time was determined post-hoc, but was based on our experience of required search time between burrow systems for tested study sites. We then multiplied the combined treatment plus search times by the number of burrow systems treated to estimate treatment times for each treatment plot for these two fumigation approaches. We followed the same calculations identified for the

PERC applications to determine the number of burrow systems that could be treated in an 8-hr period for both aluminum phosphide and gas cartridges. Given the uncertainty surrounding estimated search time, combined with the fact that we used treatment times calculated from a different study area, we used resultant comparisons only to describe general trends in financial cost comparisons between the different fumigation approaches.

To compare the financial cost per treatment for the different burrow fumigation options, we first calculated fixed costs. For PERC machine applications, we amortized the cost of the machine ($8,425) and daily fuel use (15.1 liters of gasoline used daily × $0.92/liter = $14.00) across 1,250 days. We felt that 1,250 days of use (5 days/week × 25 weeks/year × 10 years) was representative of high-end use by a professional pest control operator over a 10-yr period. For aluminum phosphide and gas cartridges, we assumed the use of four tablets ($0.09 per tablet) and one gas cartridge ($2.16) per burrow opening. For these burrow fumigants, fixed costs did not change over time given no need for specialized equipment for application. Lastly, we divided the daily fixed costs by the average number of burrow openings treated on a per-day basis to determine the average cost of treatment per burrow opening for each day of use.

For labor costs, we assumed a payment rate of $12.00 per hr. This resulted in a daily labor rate of $96.00. These daily labor rates were also divided by the number of burrow openings treated during an 8-hr work day to determine the labor cost associated with each application. Lastly, we graphed the combined fixed plus labor costs over a 1,250 day period to compare and contrast their estimated costs over time. It bears noting that with aluminum phosphide applications, filing of paperwork and posting of signs around treatment areas were required before treatments could begin. This time commitment was not accounted for in cost estimations given that these costs are variable from site-to-site. That being said, this time commitment was fairly minimal (generally < 30 min per field), so it should not impact cost estimates to a great extent.

Pocket gophers

Efficacy of PERC machine.—We used the open-hole method to monitor the efficacy of PERC applications (Engeman et al. 1993, 1999) in paired treatment and control plots (each approximately 4 ha in size) in each field. For this approach, we established twenty 9.2 × 9.2-m monitoring plots that were focused on areas with fresh pocket gopher mounding activity. Each monitoring plot was at least 18.3 m from adjacent monitoring plots to maintain independence. Also, no monitoring plots were placed within 9.2 m of the border of the treatment plots to reduce the likelihood that individuals would reinvade treatment plots from outlying areas post-treatment. Within each monitoring plot, we opened two holes into pocket gopher burrow systems. Pocket gophers do not tolerate openings into their burrow systems; they plug holes with soil when encountered thereby rendering this approach very sensitive to pocket gopher presence (Engeman et al. 1993, 1999). We checked breached burrows two days after opening holes to determine if they were plugged by pocket gophers. If either of the holes were plugged, we considered the plot occupied. This approach allowed us to determine efficacy by comparing the number of plots occupied before and after treatment.

For application, we used the PERC 412 machine to inject exhaust into pocket gopher burrow systems for approximately three min. We attempted to treat all active burrow systems at least once within each of the two treatment plots. Once injections were complete, we levelled all mounds associated with that burrow system so that we could rapidly identify new activity for subsequent treatments. One to two days post-treatment, we initiated another assessment of pocket gopher activity using the open-hole method. This second assessment allowed us to determine efficacy for the first treatment period. We then conducted a second round of PERC treatments three days after completion of the second open-hole assessment given that 20–30% of individuals are missed each treatment session due to variable mounding activity (Richens 1965, Baldwin et al. 2016). The final assessment of pocket gopher activity was initiated the day following completion of the second PERC treatment. This quick turn-around time for assessing post-treatment activity almost completely eliminated the possibility of reinvasion by pocket gophers from adjacent burrow systems. No activities occurred in the control plots other than the use of the open-hole method for monitoring pocket gopher occupancy.

Financial cost.—We recorded the total number of burrow systems treated, as well as the total time required to treat the treatment plots for both fields and both treatment periods. We excluded all personnel break times from these tabulations. We determined the mean time per application by dividing the total time for PERC machine applications by the number of burrow systems treated. To allow for comparisons across study sites, we tabulated the number of burrow systems treated over an 8-hr work day by dividing 480 min by the mean time per application. We then multiplied this value by the mean efficacy of PERC machine applications during this study to estimate the number of pocket gophers removed per day. Because we had variance both from the number of daily PERC machine applications and efficacy estimates, we used bootstrapping with 1,000 iterations to develop 95% confidence intervals around the mean (Efron and Tibshirani 1993).

We used the same methodology to determine the daily fixed and labor costs over a 1,250 day period as was defined for ground squirrels previously. We then divided this daily cost by the number of pocket gophers removed on a daily basis to determine a mean cost estimate per pocket gopher. These cost estimates were graphically compared to estimates derived from a previous study (Baldwin et al. 2016) to show how removal costs may vary across regions. All methodologies were consistent across both studies.

Statistical analysis

Generally for a rodenticide to be considered efficacious, they need to obtain a field efficacy value of 70% or more, although lower efficacy levels are sometimes considered useful as well (Schneider 1982). This general efficacy level should serve as a good baseline for burrow fumigants as well. Therefore, for all efficacy analyses, if mean values were >70%, we used a one-factor *t*-test to determine if efficacy was significantly ≥70% (Zar 1999). If mean efficacy was <70%, we did not test for a difference. All aspects of this project were approved by the University of California, Davis' Institutional Animal Care and Use Committee (protocol no's. 16864, 16915, 18626).

RESULTS

California ground squirrels

Efficacy.—For the Cheetah rodent control machine, we observed a greater number of California ground squirrels in both treatment ($\bar{x}$ efficacy = –15%, SE = 8) and control ($\bar{x}$ efficacy = –17%, SE = 1) sites post-treatment (Table 1). We observed an even more extreme response with reopened burrow counts at treatment sites ($\bar{x}$ efficacy = –113%, SE = 79; Table 1), indicating no utility for this device when managing California ground squirrels.

For PERC applications in dry soil conditions, the number of observed California ground squirrels and unplugged burrow openings declined by an average of 66% (SE = 11) and 74% (SE = 26), respectively (Table 1). Efficacy derived from burrow counts was not significantly >70% (t_1 = 0.2, P = 0.901), due to substantial variability between sites. We did not observe any difference in California ground squirrel counts within the control plot (n = 14 before and after treatment period) indicating that the observed reduction in ground squirrels was due to the applied treatment. For PERC applications in moist soil conditions, we observed a 100% (SE = 0) and 98% (SE = 2) reduction in California ground squirrel counts and unplugged burrow openings, respectively (Table 1). These reductions were significantly greater than 70% ($t_1 \geq 16.4$, $P \leq$ 0.038).

Financial cost.—Initial cost of using the PERC machine per treated burrow system was quite high when compared to the other burrow fumigant approaches (Fig. 1). However, the cost of PERC machine applications on a per-burrow system basis quickly dropped below that of gas cartridges given the substantial cost of repeatedly purchasing these cartridges over time. The only situation in which the cost of any of the alternative burrow fumigants fell below the cost of aluminum phosphide was after approximately 830 days when using the PERC machine with approximate 3-min application times (Fig. 1).

Pocket gophers

Efficacy.—Efficacy associated with the initial PERC treatment ranged from 40–55% across the two treatment plots (Table 2). Efficacy values increased to a mean of 68% (SE = 2.5) after a second treatment (Table 2). Although mean values never attained the desired 70% threshold, the resultant values were close to this threshold and indicate that this approach likely has some utility for pocket gopher management. Control plots exhibited little variability in occupancy across treatment periods (Table 2), thereby indicating that the observed reductions in pocket gopher activity in treatment plots was due to the PERC applications.

Financial cost.—Initial costs per pocket gopher removed were quite high with the PERC machine given the substantial cost of the machine (Fig. 2). However, costs rapidly diminished if used repeatedly, primarily due to the large number of burrow systems that were treated daily ($\bar{x}$ = 276, SE = 55), and the subsequent large number of pocket gophers that were removed daily ($\bar{x}$ = 117, 95% CI = 74–162). Although a rigorous comparison across study sites is not warranted given differences in soil type and pocket gopher density, the observed per-pocket gopher costs

Table 1. The number of California ground squirrels and associated reopened burrow systems before (Pre) and after (Post) treatment as well as the efficacy associated with each monitoring approach for treatment (Trt) and control sites at various locations in California. Treatments included Pressurized Exhaust Rodent Controller (PERC) applications at sites with dry and moist soil conditions, as well as the Cheetah rodent control machine applications at sites with moist soil conditions.

		Ground squirrel counts			Burrow counts		
Treatment	Site	Pre	Post	Eff (%)	Pre	Post	Eff (%)
PERC dry	Control	14	14	0			
	Trt 1	24	11	54	27	14	48
	Trt 2	13	3	77	19	0	100
	Trt mean			66			74
PERC moist	Trt 1	6	0	100	45	0	100
	Trt 2	5	0	100	58	2	97
	Trt mean			100			98
Cheetah	Control 1	19	22	-16			
	Control 2	11	13	-18			
	Trt 1	18	21	-17	56	88	-57
	Trt 2	14	18	-29	49	55	-12
	Trt 3	17	17	0	35	129	-269
	Trt mean			-15			-113

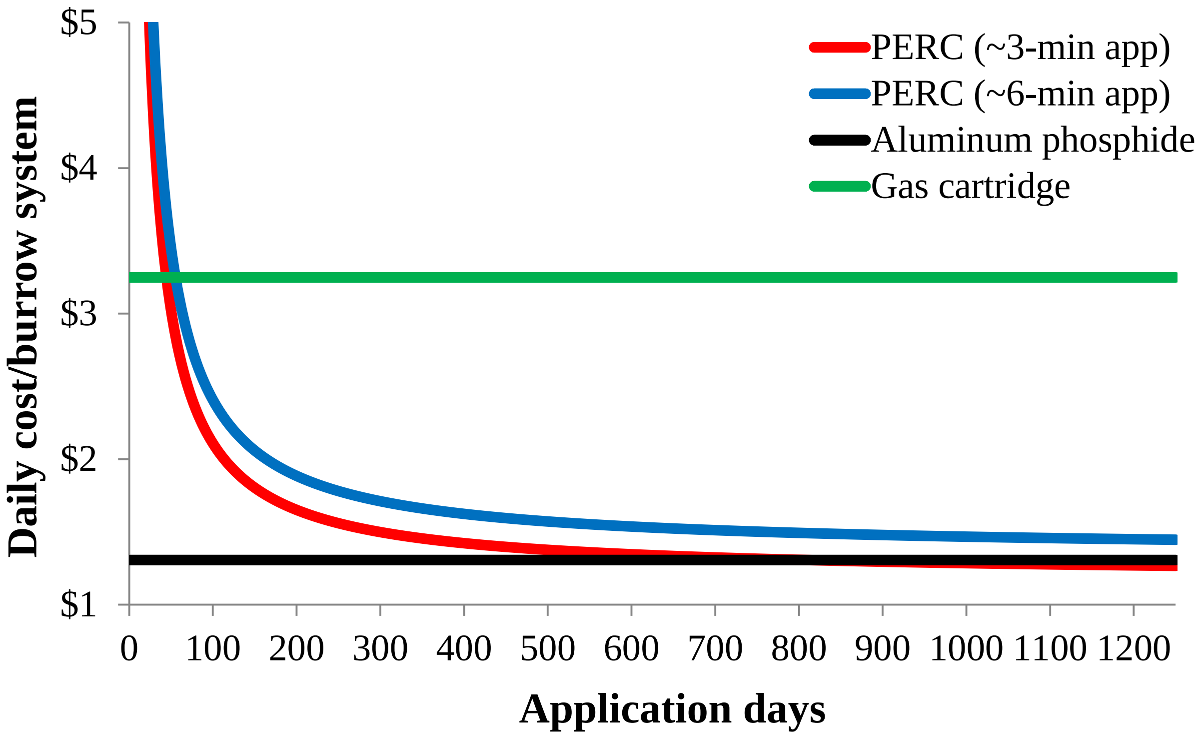

Fig. 1. Comparative amortized daily labor plus fixed costs on a per-burrow system basis for 4 different management strategies for California ground squirrels. The vertical axis has been truncated at $5 per burrow system per day to better illustrate amortized costs after several days of application. For reference, initial fixed plus labor costs on a per-burrow system basis on Day 1 for 3- and 6-min Pressurized Exhaust Rodent Controller (PERC) applications (app) were $93 and $106, respectively.

Table 2. The number of open-hole monitoring plots occupied by pocket gophers before (Pre) and after (Post) treatment for first and second treatment periods, as well as resultant efficacy (Eff) when using the Pressurized Exhaust Rodent Controller across 2 treatment and paired control sites in 2 alfalfa fields in California during March 2014.

		First treatment		Second treatment	
Site	Pre	Post	Eff (%)	Post	Eff (%)
Control 1	20	19	5	20	0
Control 2	20	20	0	20	0
Treatment 1	20	9	55	6	70
Treatment 2	20	12	40	7	65
Treatment mean			48		68

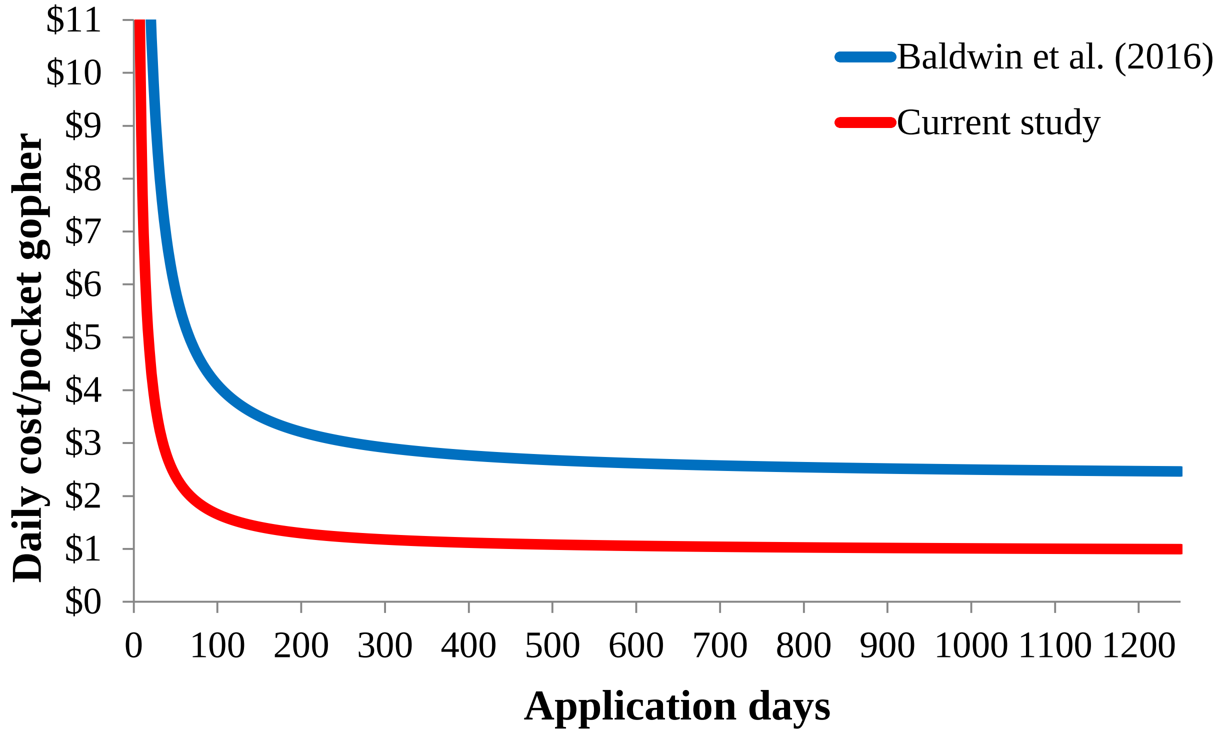

Fig. 2. Comparative amortized Pressurized Exhaust Rodent Controller daily labor plus fixed costs on a per-pocket gopher basis between the current study and a Baldwin et al. (2017). The vertical axis has been truncated at $11 per pocket gopher per day to better illustrate amortized costs after several days of application. For reference, initial fixed plus labor costs on a per pocket gopher basis on Day 1 for the current study and Baldwin et al. (2017) were $73 and $180, respectively.

from this study were generally lower than those observed from a similar study in northern California given greater efficacy and quicker application rates (Fig. 2).

DISCUSSION

Management of rodent pests is essential in many agricultural areas, with most successful management programs relying on IPM approaches that incorporate multiple tools to maximize efficacy while minimizing environmental impact (Baldwin et al. 2014). However, the number of tools available to mitigate rodent impacts are shrinking, usually due to regulatory or legislative changes (Eason et al. 2010), but occasionally due to supply limitations as well (e.g., limited importation of strychnine into the U.S., Baldwin et al. 2017). As such, the development and registration of pressurized exhaust machines provides a much needed tool for burrowing rodent IPM programs. The PERC machine in particular appears to hold promise, especially for ground squirrel management. In moist soil conditions, aluminum phosphide has generally been considered the most effective burrow fumigant for ground squirrels (Table 3). Gas cartridges have also been effective, though more so for Belding's ground squirrels than California ground squirrels (Table 3). Tests of the PERC machine for ground squirrels have indicated similar removal rates of ground squirrels when compared to other burrow fumigants (Table 3), although soil moisture is likely a principal factor influencing the efficacy of these machines. It is well understood that dry soil conditions are far less conducive to effective use of burrow fumigants given increased porosity in the soil (Salmon et al. 1982). Although not directly tested, we observed substantially greater efficacy at sites with higher soil moisture than at dry sites (100% vs. 66%, respectively) further indicating the importance of treating when soil moisture is high. That being said, even in dry soil conditions, PERC machine applications yielded substantially greater efficacy when compared to aluminum phosphide applications for Richardson's ground squirrels (*Urocitellus richardsonii*; 47% vs. 81% efficacy for dry and moist soil conditions, respectively) in dry soil conditions (Proulx et al. 2011). This is not surprising given the very slow evolution of phosphine gas from aluminum phosphide tablets in dry soil conditions (Salmon et al. 1982, Baker 1992) and suggests that repeated applications via the PERC machine may have some utility year-round for ground squirrel application. This could be particularly useful in situations where other management options are either ineffective or unavailable. For example, in almond orchards, California ground squirrels cause extensive damage when nuts are on the trees (Salmon et al. 1982, Baldwin et al. 2014). At this point, rodenticides and trapping are relatively ineffective, as ground squirrels will not consume alternative food sources given the abundance of almonds on the trees (Marovich et al. 2002). Traditional burrow fumigants also do not work during this period given dry soil conditions. In such a setting, repeated applications via the PERC machine may provide sufficient relief to save the nut crop even if efficacy is lower than when used in more ideal soil conditions.

It bears noting that although we did observe greater efficacy from PERC applications at sites with greater soil moisture, we also experienced longer injection times at these sites given the presence of larger burrow systems. Longer injection times could have resulted in greater concentrations of carbon monoxide within burrow systems. At this point, ideal injection durations are unknown and worthy of further investigation.

Table 3. Resultant efficacy from aluminum phosphide, gas cartridge, and the Pressurized Exhaust Rodent Control (PERC) machine applications from several studies for three burrowing rodents found throughout much of the western U.S. All tests were conducted in relatively moist soil conditions unless otherwise noted.

Species	Fumigant	Efficacy (%)	Study
Belding's ground squirrel	Aluminum phosphide	94	Baldwin and Quinn 2012
	Gas cartridge	100	Baldwin and Quinn 2012
	PERC	76	Orloff 2012
California ground squirrel	Aluminum phosphide	100	Salmon et al. 1982
	Aluminum phosphide	99	Baldwin and Holtz 2010
	Gas cartridge	50	Salmon et al. 1982
	Gas cartridge	74	Baldwin and Holtz 2010
	PERC	66[a]	This study
	PERC	100	This study
Pocket gopher	Aluminum phosphide	90	Baker 2004
	Aluminum phosphide	81	Baldwin et al. 2016
	Gas cartridge	17	Matschke et al. 1995
	PERC	56	Orloff 2012
	PERC	56	Baldwin et al. 2016
	PERC	68	This study

[a] Study conducted in dry soil conditions.

Somewhat surprisingly, the Cheetah rodent control machine was completely ineffective at reducing California ground squirrel populations. It is possible that soil characteristics at the tested sites may have been less conducive to effective burrow fumigation, but even if so, we would have expected some reduction, even if relatively minimal, from applications. This was not the case. At this point, the Cheetah rodent control machine does not appear to be an effective tool for managing ground squirrel populations.

Although PERC machine applications are effective at reducing ground squirrel populations, they may not be the most cost effective burrow fumigant available. Aluminum phosphide is generally the least expensive option (Fig. 1). Even gas cartridges are initially less expensive given the large start-up cost of purchasing the PERC machine. However, with substantial use, the cost associated with using the PERC machine becomes more cost effective than using gas cartridges, and may eventually become less expensive than the use of aluminum phosphide depending on the injection duration and associated efficacy. In this study, 3-min injections occurred in dry soil conditions, while 6-min injections occurred in moist soil. If 3-min injections in moist soil could be equally effective as 6-min injections, then the cost effectiveness of the PERC machine for ground squirrels would substantially improve, making it a much more viable option for many land managers in these soil conditions. Furthermore, it is important to remember that data reported from different burrow fumigants were not collected from head-to-head comparisons. Such comparisons may show slightly different results. Additionally, the use of a 2-hose or 6-hose PERC unit would change this dynamic as well. Regardless, when efficacy is high and injection times can be reduced, the PERC machine becomes a more viable burrow fumigation option.

Based on our findings, the PERC machine does not appear to be as effective for pocket gophers as it is for ground squirrels (Table 3), nor is the PERC machine as efficacious as aluminum phosphide. We are uncertain as to why, although there are several likely factors worth considering. First, pocket gopher tunnel systems are longer and narrower than ground squirrel burrow systems, and they have more branches to their tunnel systems (Witmer et al. 2012). As such, it may be more difficult for the exhaust to completely fill the pocket gopher tunnel system, thereby rendering it less effective. Phosphine gas is heavy compared to the air in a tunnel system (Salmon et al. 1982) and may be better able to fill the entire burrow system more completely than carbon monoxide. Alternatively, pocket gophers may be more sensitive to carbon monoxide than ground squirrels. Gas cartridges produce high concentrations of carbon monoxide and are not typically reported effective for pocket gophers (Matschke et al. 1995, Nolte et al. 2000). Pocket gophers apparently detect the gas and smoke and quickly build a wall in their tunnel system that blocks the gas from reaching them. A similar situation may occur in some pocket gopher tunnel systems when using the PERC machine. Pocket gophers do not seem to have an adverse reaction to aluminum phosphide. In fact, pocket gophers may be attracted to aluminum phosphide, as tablets have been identified in nesting chambers following application (R. O. Baker, California State Polytechnic University, Pomona, personal communication). It is also possible that our injection times were insufficient to maximize efficacy. For our studies, approximately 3-min injection times were recommended by the manufacturer. However, duration of injection deserves additional scrutiny to determine the optimal time for injection so as to maximize efficacy while minimizing application time and treatment costs.

As with ground squirrels, soil moisture and soil morphology likely influence efficacy for pocket gophers. All pocket gopher tests in this study and in Baldwin et al. (2016) were conducted at the same time of year, and soil moisture was deemed sufficient for effective burrow fumigation in all areas. However, soil types did differ between sites tested in Baldwin et al. (2016) and this study, with soil type having a higher organic matter content and greater porosity in the Baldwin et al. (2016) investigation. Lower porosity of soils is highly beneficial for burrow fumigation, and may have contributed to the higher efficacy reported in our current investigation (Table 3). Furthermore, soils with substantial organic matter are softer than mineral soils, which increases the difficulty in accurately detecting tunnel systems. Baldwin (2014) quantified the importance of accurate detection of active pocket gopher tunnel systems for effective management programs. If we were less accurate in detecting active tunnel systems in softer soils, then resultant efficacy would be lower as well. In fact, efficacy from aluminum phosphide treatments that occurred at the same locations reported in Baldwin et al. (2016; Table 3) were somewhat lower than what has been reported elsewhere (e.g., Baker 2004), providing further evidence of the potential negative impact that heavy organic, porous soils can have on burrow fumigation. A more comprehensive examination of the impact of soil morphology and soil moisture on the efficacy of pressurized exhaust machines would assist in determining when and where they are likely to be most effective. Nonetheless, at this point, aluminum phosphide appears to be a more efficacious burrow fumigant than the PERC machine for pocket gopher management (Table 3).

The PERC machine also does not initially appear to be as cost effective as some other strategies for pocket gopher control (Baldwin et al. 2016). However, the PERC machine was substantially cheaper to use on a per-pocket gopher basis in this study than when compared to results from Baldwin et al. (2016), principally due to the increased efficacy observed in this study. This increased efficacy would fairly quickly drop treatment costs below that observed for alternative management tools (e.g., approximately 33 days for aluminum phosphide) if compared directly to results from Baldwin et al. (2016). Such a direct comparison, however, is not appropriate given differing field conditions between the two study areas, but it does highlight the fact that even slight increases in efficacy can greatly increase the cost effectiveness of the PERC machine, and in situations where resultant efficacy is high, the PERC machine is likely an economically viable tool if used for a long enough period of time to overcome the initial purchase price.

Lastly, it should be pointed out that the PERC machine has inherent advantages over aluminum phosphide. For example, the PERC machine appears to be more effective than aluminum phosphide in dry soil conditions, and as such, is a more practical tool for year-round applications. The PERC machine can be used to treat an area more rapidly given the ability to treat multiple burrow systems at once. Therefore, if large areas must be treated rapidly, this approach may be superior to other fumigation options. Aluminum phosphide is also far more restrictive on when and where it can be used when compared to the PERC machine, and aluminum phosphide treatment areas must have signs posted at application sites that provide application details that are not required when using the PERC machine. Therefore, even if efficacy is lower, the PERC machine may be a preferred management tool in some settings (e.g., school grounds, parks, athletic fields; Baldwin 2012) as other potential options may not be practical or allowed. Ultimately, the best tool to use for managing burrowing rodents will vary depending on a number of factors, but at a minimum, the PERC machine appears to be an effective tool to include in the IPM toolbox for reducing burrowing rodent damage in a number of situations.

ACKNOWLEDGMENTS

We would like to thank numerous growers and ranchers for access to their land while testing the pressurized exhaust machines. We also thank E. Duarte, M. Mendoza, and F. Rinder for assistance in identifying field sites, and E. Duarte and staff, A. Hurlburt and staff, H. Jantz, R. Murphy, D. Kratville, D. Shaw, and N. Stevens for providing valuable field assistance and support. This project was funded in part by the University of California's (UC) Division of Agriculture and Natural Resources, the UC Cooperative Extension–Siskiyou County office, the UC Statewide IPM Program, and the Vertebrate Pest Control Research Advisory Committee of the California Department of Food and Agriculture.

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