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Burrow fumigation versus trapping for pocket gopher (*Thomomys* spp.) management: a comparison of efficacy and cost effectiveness

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Abstract

Context. Pocket gophers (Geomyidae) cause extensive damage to many crops throughout western North America. A variety of methods are available to manage these populations, but data are often lacking on their efficacy and especially their cost effectiveness. Additionally, little peer-reviewed data are available that compare multiple methods simultaneously.

Aims. We tested aluminum phosphide and pressurised exhaust using the Pressurised Exhaust Rodent Controller (PERC) as burrow fumigants, and compared them to trapping to determine which approach was most efficacious and cost effective.

Methods. We assessed the efficacy of aluminum phosphide, the PERC machine, and trapping through the use of the open-hole monitoring method after single and multiple treatments over multiple years. We determined material and labour costs for each treatment type and amortised this cost over 1250 days of application to determine which treatment type was most cost effective.

Key results. Aluminum phosphide had the shortest time for application, but we were able to make far more applications per day using the PERC machine, given our ability to treat multiple burrow systems at once with this machine. Trapping and aluminum phosphide were more efficacious than was the PERC machine. When costs were amortised over time, trapping was the most cost-effective approach even with longer application times, given high efficacy. Multiple treatment applications were needed to maximise the efficacy of management programs.

Conclusions. For small-scale management efforts, aluminum phosphide was a cost-effective and efficacious option. For a greater number of treatments, trapping was the most successful and cost effective. However, a modest increase in efficacy could make the PERC machine a preferred tool as well. We also stress that regardless of the management approach, multiple treatment applications will generally be needed to manage pocket gopher populations.

Implications. The present study provides growers with information needed to determine efficient and cost-effective methods for managing pocket gophers. This information can be used to craft an integrated pest-management approach to manage damaging pocket gopher populations.

Additional keywords: aluminum phosphide, carbon monoxide, pressurised exhaust, trap.

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Introduction

Pocket gophers (Geomyidae) are one of the most damaging vertebrate pests to alfalfa and other crops throughout the western USA, as well as other portions of North America (Howard and Childs 1959; Luce *et al*. 1981; Entz *et al*. 1995; Messmer and Schroeder 1996; Whisson and Villa-C 1996; Proulx 2002; Baldwin *et al*. 2014*b*). A variety of methods exists to help manage pocket gopher populations (e.g. flood irrigation, habitat modification, trapping, rodenticide baiting, burrow fumigation; Marsh 1992; Baldwin *et al*. 2014*b*), but the efficacy of many of these approaches is either not well studied or has not been compared simultaneously to determine which provides the greatest reduction in pocket gopher numbers in a given area. Studies that involve direct comparisons between management tools are needed to determine which approaches are most effective or appropriate, given that local conditions (e.g. soil type, soil moisture, season) can influence the efficacy of different management strategies.

One management tool that is frequently used to reduce pocket gopher populations is burrow fumigation. Historically, burrow fumigants (e.g. methyl bromide, chloropicrin, gas cartridges) were deemed ineffective or impractical (Miller 1954; Marsh 1992; Matschke *et al*. 1995), but more recent research indicated that aluminum phosphide was a highly efficacious option (Marsh 1992; Baker 2004). Aluminum phosphide comes in a pellet or tablet form. The pellets or tablets are inserted into pocket gopher burrow systems where they slowly evolve phosphine gas as a result of a reaction with moisture in the burrow system. Phosphine is highly toxic to vertebrates and invertebrates alike, with mortality generally occurring within 24 h after insertion of tablets or pellets into the burrow systems. Given its high efficacy and relatively low material cost, aluminum phosphide is the preferred method for pocket gopher management by many pest-control professionals in California (Baker 2004; Baldwin 2012).

Pressurised exhaust containing a high concentration of carbon monoxide is an alternative burrow fumigant that has shown some potential promise. Several different pressurised exhaust systems are currently available for use, including the Pressurised Exhaust Rodent Controller (PERC; H & M Gopher Control, Tulelake, CA, USA), Cheetah rodent-control machine (Cheetah Industries, Paso Robles, CA, USA), and GopherX (El Cajon, CA, USA). These devices allow the user to inject lethal concentrations of carbon monoxide into mammal burrow systems. The PERC machine has been around the longest. It utilises a small gasoline engine to produce exhaust that is stored in an air compressor where it is pressurised, thereby allowing forced injection into burrow systems through a combination of hoses and probes (Orloff 2012). Preliminary trials indicated moderate success for pocket gophers (mean efficacy = 56%) and Belding's ground squirrels (*Urocitellus beldingi*, mean efficacy = 76%; Orloff 2012), but more in-depth investigation is needed to better describe its utility. One of the potential benefits of the PERC machine is that it allows the user to treat multiple burrow systems at once (up to 6, depending on the size of the unit purchased), thereby potentially allowing for quicker treatment of infested areas. A greater understanding of how efficacy and rate of application relates to the large start-up cost of these machines (range = US$5425–15 275 as of November 2015, depending on the unit purchased) would be of real benefit to individuals tasked with managing pocket gophers.

Trapping is another tool frequently used for managing pocket gophers. Trapping has many benefits including high efficacy (Smeltz 1992; Proulx 1997), very low risk to non-target species (Witmer *et al*. 1999), minimal learning curve on how to implement (Baldwin 2014) and knowledge of the number of individuals removed from the treatment area (i.e. a direct measure of treatment success). However, trapping is usually considered too time consuming and expensive for use over large acreage (Marsh 1992; Engeman and Witmer 2000; Baldwin *et al*. 2014*b*), although direct comparisons of the cost of a trapping program to alternative management options are generally lacking or grossly outdated and incomplete (e.g. Smeltz 1992). As such, we established a study to determine the efficacy and cost effectiveness of several understudied pocket gopher management tools. Our specific objectives were to (1) determine the efficacy of aluminum phosphide, the PERC machine, and trapping at reducing pocket gopher populations, (2) determine the number of pocket gophers removed over an 8-h time frame using each method and (3) determine the amortised cost of each of these management methods on a daily and per pocket gopher basis, to determine which approach was most practical and cost effective. Our findings should provide growers and pest-control professionals with much needed information on the efficacy and long-term viability of these management tools.

Materials and methods

Study area

We established study sites in nine alfalfa fields along the California–Oregon border north and east of Tulelake, CA (41.95°N–121.48°E). We selected fields that exhibited moderate to heavy pocket gopher infestations on the basis of general abundance of mounding activity to maximise our ability to detect differences before and after treatment. Soils consistently comprised sandy and silty loam throughout all fields. Both Botta's and northern pocket gophers (*Thomomys bottae* and *T. talpoides* respectively) were found in our study sites.

Treatment applications

We conducted treatments at three fields per year from 2012 to 2014. Treatments were conducted during early spring 2012 (30 March – 11 April; Fields 1–3) and 2013 (19 March – 8 April; Fields 4–6), and autumn 2014 (12 October – 16 November; Fields 7–9). The plants were just resuming growth in spring or were entering dormancy in the fall, thereby eliminating the impact of new plant growth on our ability to detect pocket gopher mounds. Following a randomised complete block design, for 2012 and 2013, we divided fields into four similar-sized plots, and we randomly assigned one of four treatment types (aluminum phosphide, PERC, trapping or control (no treatment applied)) to each plot. In 2014, we established only one treatment plot at each field site where only trapping was conducted. Treatment plots were 6.1–6.9 ha in area, depending on the size of the field and the density of pocket gophers in a given plot.

For all treatment types, we visually scanned the fields for fresh pocket gopher mounds or feeder holes to identify areas where individuals were likely to be located. We then used a probing device to locate the tunnel system. For aluminum phosphide applications, we placed 2–4 tablets (Fumitoxin®, D & D Holdings, Inc., Weyers Cave, VA, USA) into the tunnel system, depending on the moisture of the soil at the time. We then used the heel of our boot to close the probe-hole opening, being careful not to cover the tablets with loose soil. When possible, we applied tablets twice per burrow system to maximise the likelihood that applications would occur in a part of the burrow system still used by the pocket gopher. However, we were able to apply tablets only once for many burrow systems because of the difficulty in finding additional tunnels within the same burrow system.

We injected exhaust into burrow systems using the PERC 412 unit, which allowed treatments of up to four burrow systems at a time; exhaust was pumped into the tunnel for approximately 3 min. We covered the probe hole after application was complete by using the heel of our boot to reduce the loss of exhaust from the opening.

Trapping treatments involved placing Gophinator (Trapline Products, Menlo Park, CA, USA) traps into both main and lateral tunnels of pocket gopher burrow systems; we set as many traps per trap set as there were branches of the tunnel system (typically one or two but occasionally three or more). Gophinator traps were selected for the study, given their effective track record (Baldwin *et al*. 2013, 2015). Traps were staked down to reduce the likelihood of scavengers removing carcasses. We used open trap sets to accelerate the process of trap setting and checking (Baldwin *et al*. 2013); no attractants were used given their limited effectiveness (Baldwin *et al*. 2014*a*). Traps were set one day and checked the next, as most pocket gopher captures occur within 24 h of setting traps. Once the trap site was checked, the traps were pulled and reset at another location until the entire plot was trapped.

We recorded the gender of captured pocket gophers at all but one field site, following Baldwin and Meinerz (2015). We used the Wilcoxon signed-rank test (Zar 1999) to determine whether gender ratio differed across study sites, so as to better describe the study population. Occasionally, scavengers consumed too much of captured pocket gophers to allow identification of gender. We made note of any traps that were sprung or plugged with loose dirt; along with captures, these sites were considered visited by pocket gophers. We also recorded whether there was no discernable activity at the trap site. To further describe the effectiveness of trapping, we calculated capture efficiency (the number of captures divided by the number of trap sets receiving a visit) and visitation rate (the number of trap sets visited divided by the number of trap sets that were placed) for each trapping plot.

Data collected during 2012 served as a pilot effort to initially test the efficacy of aluminum phosphide fumigation, PERC applications and trapping on reducing the size of pocket gopher populations. As such, only one application was applied that year. Two applications of each treatment type were applied in 2013 to allow us to target additional individuals in the field that we did not target in the first session, as 20–30% of pocket gophers are often missed at a single time given variable mounding activity (Richens 1965). To further test the efficacy of trapping to potentially eradicate high-density pocket gopher populations from fields, we trapped fields three times in 2014. We exclusively used trapping in 2014 because it was the most efficacious of the management strategies. All treatment applications except for one were initiated within 0–4 days following the completion of the previous monitoring activity for that same treatment plot. For Field 9, 10 days passed between the end of the pretreatment monitoring period and the beginning of the initial trapping period, given the length of time required to initially trap Fields 7 and 8.

Monitoring activity

Pocket gophers maintain a closed burrow system, so that when the burrow system is breached, the occupant closes the opening with soil very soon after the breach occurs. Also, during most of the year, a burrow system is occupied by only one pocket gopher, thereby allowing an observer to open a hole into a burrow system to assess occupancy status of that burrow system. Therefore, we used the open-hole method to assess the impact of management strategies on pocket gopher populations (Engeman *et al*. 1993, 1999). In 2012 and 2013, we established twenty 9.2-m $\times$ 9.2-m monitoring units within each treatment and control plot. We placed monitoring units in areas where abundant pocket gopher activity was found, so as to maximise initial occupancy values of treatment plots, although monitoring units were always located a minimum of 18.3 m from each other to maintain independence. In 2014, we placed 49 similarly sized monitoring units throughout each trapping plot to more thoroughly survey the treatment area. Each monitoring unit was separated by 18.3 m from the next-closest monitoring unit to maintain independence. Following a well established protocol (Engeman *et al*. 1993, 1999), we opened two holes into pocket gopher burrow systems within each monitoring unit across all seasons. We checked these units 2 days later to determine whether they were plugged by pocket gophers; if plugged, the unit was considered occupied. Occupancy was again assessed $\leq$8 days post-treatment. We calculated efficacy by dividing the number of units that had no pocket gopher activity post-treatment by the number of units that had pocket gopher activity pretreatment. For toxicants to be considered effective, a 70% field efficacy threshold is typically required by the USA Environmental Protection Agency to be considered effective, although management practices may still be considered useful even if efficacy falls below this level (Schneider 1982). We used this 70% threshold level to provide an approximation of effectiveness of the management tools we tested in the present study. All aspects of the study were approved by the Institutional Animal Care and Use Committee of the University of California, Davis (Protocol numbers 16 915, 18 347).

We used a two-factor ANOVA to test for differences in efficacy across treatment types and between trapping sessions for data collected from 2012 and 2013 (Zar 1999). If the model was significant, we used Fisher's least significant difference (l.s.d.) *post hoc* test to determine which treatment types or sessions were different (Zar 1999). We excluded 2014 from this analysis because we had only trapping data for that year. Therefore, we used a Student's *t*-test to test for any potential differences in trapping efficacy between the second and third trapping sessions (Zar 1999).

Application time

For the 2013 study, we recorded all start and stop times for individuals involved in trapping, aluminum phosphide applications and PERC treatments. We recorded only times when these individuals were active (i.e. we did not count meal or water breaks). This provided an estimate for the total number of minutes required to treat each field per treatment type for both initial and secondary applications. For trapping, we also recorded the amount of time required to check traps the following day, because this is part of the time commitment when using trapping as a management tool.

These time recordings provided an estimate of treatment time that included search time (i.e. the time required to find a tunnel system to treat). Search time is a parameter that will vary from site to site, but should not vary across treatment types. As such, we also recorded the length of time required to complete a treatment application without including search time in this value. This included the time from when a tunnel was found until the application was complete. We tested for differences in application times across the three treatment types using a one-factor ANOVA. If the model was significant, we used Fisher's l.s.d. *post hoc* test to determine which treatment types were different (Zar 1999).

Burrow systems treated

We recorded the number of burrow systems that were treated during the 2013 study period. With pocket gophers, it is not possible to know which tunnels are connected (Miller 1957), so we estimated individual burrow systems on the basis of linear arrangement of mounds and proximity of mounds to one another. For trapping, we placed traps only once per an estimated burrow system. For aluminum phosphide, we attempted to apply tablets twice per a burrow system, although we were not always able to do so. For PERC applications, we generally treated each burrow system only once; however, if burrow systems seemed large, we treated it twice. We kept track of the number of total applications and the number of individual burrow systems treated for both aluminum phosphide and PERC applications for later cost calculations. To determine the mean number of applications per burrow system, we divided the total number of applications by the estimated number of burrow systems for each treatment type in each field.

To provide context into how these different treatment types might compare in a field setting, as well as to relativise across treatment types, we represented application times and treatment costs across an 8-h workday. For this, we first calculated the mean time it took to treat a burrow system for each treatment type for each field (time spent treating a field divided by the number of burrow systems treated). We then divided 480 min (equivalent of 8 h) by the mean application time per field for each treatment type to estimate the number of burrow systems that could be treated in an 8-h day. We tested for differences in the number of burrow systems treated per day across the three treatment types by using a one-factor ANOVA. If the model was significant, we used Fisher's l.s.d. *post hoc* test to determine which treatment types were different (Zar 1999).

We then multiplied the number of burrow systems treated on a daily basis by the mean efficacy of the respective treatment type to determine the estimated number of pocket gophers removed on a daily basis. Mean efficacy was determined for each round by dividing the number of plugged monitoring units post-treatment by the number of monitoring units plugged before treatment. Because we had variance parameters for both the number of burrow systems treated and mean efficacy, we used bootstrapping to develop 95% confidence intervals (CI) around the mean to account for both sources of variance (Efron and Tibshirani 1993). Last, we determined whether the number of pocket gophers removed differed across treatments through the use of a randomisation test (bootstrapping; Efron and Tibshirani 1993). We ran 1000 bootstrap iterations of the mean difference in the number of pocket gophers removed across the treatment types; the proportion of values in the ranked frequency distribution that fell below 0 indicated the probability of a difference in the number of pocket gophers removed across the treatment types.

Financial costs

We used a combination of fixed costs and labour costs to estimate total cost for each treatment type. For aluminum phosphide, we first multiplied the mean number of applications per day by three tablets (2–4 tablets allowed per application). We then multiplied the number of tablets by the cost per tablet (US\$0.09; canister of 500 tablets = US\$45), to provide a total material cost per day.

For PERC applications, we estimated costs on the basis of the use of the PERC 412, which cost US\$8425. The PERC machine requires gasoline to operate. We estimated the use of 15.1 L over an 8-h period. At a cost of US\$0.92 L^{-1}, we estimated the daily expenditure on fuel at US\$14.00. An all-terrain vehicle (ATV) is needed to haul the PERC machine around. However, an ATV is used by many growers and pest-control professionals regardless of the application technique, so we did not include this cost in our estimate.

For trapping, we assumed a cost of US\$5.40 per Gophinator trap, with an initial purchase requirement of 107 traps (71.3 trap sets multiplied by an estimated 1.5 traps per burrow system). However, with trapping, we lose traps occasionally to scavengers seeking pocket gopher carcasses in traps. To account for this, we assumed that we would have to replace one trap per day for the duration of the cost-estimation period.

The impact of fixed costs can diminish over time because the costs of these materials are spread out over the life of their use. As such, we amortised costs over 1250 days to illustrate how these costs change over time. This time frame was chosen on the basis of our estimated lifespan of the PERC machine. We assumed the PERC machine would operate for 10 000 h, which would be equivalent to a use pattern of 40 h per week for 25 weeks across 10 years. Many growers and pest-control professionals may never use the machine this extensively; however, this provides a reference for those individuals who do.

For daily labour, we assumed a pay rate of US\$12 per hour across an 8-h day for all treatment types. These labour costs were added to the amortised fixed costs on a daily basis. We graphed these costs over a 1250-day period to illustrate how these costs will change with increased usage. Last, we were interested in showing how these costs would translate to pocket gopher removal efforts. To accomplish this, we divided the material costs plus labour costs amortised over time by the number of pocket gophers removed per day, to provide a cost per individual pocket gopher removed per day; these results were graphed across time for comparative purposes.

Results

Efficacy trials

Both the treatment type ($F_{3,34} = 57.0$, $P < 0.001$) and the number of times a field was treated ($F_{1,34} = 26.0$, $P < 0.001$) affected the overall efficacy. Because we did not observe an interaction between these model parameters ($F_{3,34} = 1.4$, $P = 0.260$), we present comparisons across treatment types and the number of treatment sessions separately (Fig. 1), so as to better illustrate their impact on pocket gopher management.

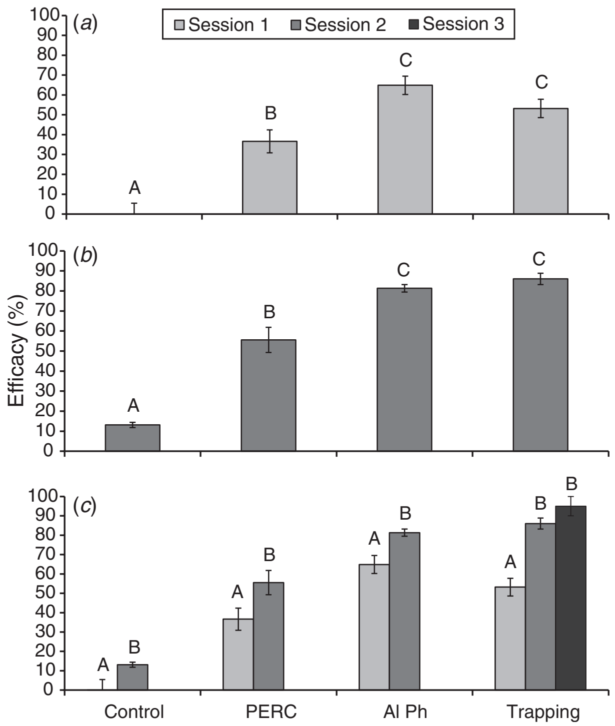

Fig. 1. The percentage efficacy of three treatment types (Pressurised Exhaust Rodent Controller (PERC), aluminum phosphide (Al Ph) and trapping) and a control for pocket gopher management across nine alfalfa fields in northern California. Differences across all treatment types are provided for both (*a*) the first and (*b*) second treatment sessions, as well as (*c*) differences among first, second and third treatment sessions within each treatment type. Significant ($P<0.10$) differences are denoted by different letters.

Aluminum phosphide ($\bar{x}=65\%$, s.e. = 5) and trapping ($\bar{x}=53\%$, s.e. = 5) were more effective than PERC applications ($\bar{x}=37\%$, s.e. = 6; Fig. 1) during the initial treatment period. However, all three treatment types were below the preferred 70% efficacy threshold after the initial application (Fig. 1). Efficacy from PERC machine applications increased following the second application session ($\bar{x}=56\%$, s.e. = 6; Fig. 1), although efficacy never did attain the preferred 70% threshold. In contrast, aluminum phosphide ($\bar{x}=81\%$, s.e. = 2) and trapping ($\bar{x}=86\%$, s.e. = 3) treatments were significantly more effective than was the PERC machine, with both treatment types achieving efficacy values substantially >70% after the second treatment (Fig. 1). Although a third trapping session removed almost all pocket gophers from the tested fields, the increase in efficacy between the second ($\bar{x}=86\%$, s.e. = 3) and third ($\bar{x}=95\%$, s.e. = 5) trapping sessions was not significant ($t_2=2.4$, $P=0.131$; Fig. 1). The total reduction in activity in the control plot was quite low after both the first ($\bar{x}=-1\%$, s.e. = 6) and second ($\bar{x}=13\%$, s.e. = 1; Fig. 1) application periods, indicating that our observed results were a result of treatment effects.

Of 1281 pocket gopher captures, ~56% were male (Table 1), although this did not represent a significantly larger proportion of male pocket gophers in the study populations ($S=11$, $P=0.148$). We observed consistently high capture efficiencies ($\bar{x}=80\%$, s.e. = 1.6; Table 1), providing further evidence that trapping can be a highly efficacious approach to removing pocket gophers from unwanted areas. Visitation rates ($\bar{x}=61\%$, s.e.= 4.3; Table 1) were more variable because of differences in frequency of pocket gopher mounding and pocket gopher spacing within the study fields.

Table 1. The number of male (M cap), female (F cap), unknown gender (U cap) and total captures (T cap) of pocket gophers, the number of visited trap sets (N vis), the number of trap sets established (N set), capture efficiency (T Cap divided by N vis; Cap %), and the trap visitation rate (N vis divided by N set; Vis %) combined for all trapping sessions across nine alfalfa fields in northern California

Number of trapping sessions for Fields 1–3, Fields 4–6 and Fields 7–9 was 1, 2, and 3 respectively. Composite (Comp) data are provided for comparative purposes

Location	M cap	F cap	U cap	T cap	N vis	N set	Cap %	Vis %
Field 1	32	19	3	54	66	101	82	65
Field 2	23	11	2	36	45	78	80	58
Field 3[A]				14	20	33	70	61
Field 4	60	40	3	103	125	260	82	48
Field 5	38	29	2	69	87	197	79	44
Field 6	44	37	3	84	102	227	82	45
Field 7	196	223	9	428	499	689	86	72
Field 8	242	147	10	399	529	698	75	76
Field 9	57	32	5	94	112	144	84	78
Comp	692	538	37	1281	1585	2427	80	61

[A]Gender was not identified for this study location.

Application time

We observed a significant ($F_{2,9}=71.5$, $P<0.001$) difference in application time between the three treatment types, with aluminum phosphide by far the quickest to apply ($\bar{x}=23$ s, s.e. = 1; $P<0.001$). We observed little difference ($P=0.169$) between trapping ($\bar{x}=181$ s, s.e. = 9) and PERC ($\bar{x}=204$ s, s.e. = 11) application times. An average of 1.6 (s.e. = 0.1) and 1.1 (s.e. = 0.04) treatments were applied per burrow system for aluminum phosphide and PERC applications respectively; only one application was made per burrow system for trapping.

The number of burrow systems treated per 8-h day varied depending on the treatment type ($F_{2,6}=38.6$, $P<0.001$), with a substantially greater number of burrow systems treated using the PERC machine ($\bar{x}=156$, s.e. = 10; $P<0.001$), given that multiple burrow systems could be treated at once when using this device. We did not observe an appreciable difference in the number of burrow systems treated daily between aluminum phosphide ($\bar{x}=81$, s.e. = 7) and trapping ($\bar{x}=71$, s.e. = 5; $P=0.395$), presumably, given large search times to find additional tunnels of the same burrow system to treat with aluminum phosphide tablets. Although we were able to complete many more PERC applications in a day, we did not notice an appreciably greater number of removals during an 8-h day for any of the treatment methods ($P\geq0.526$; PERC: $\bar{x}=47$, 95% CI = 29–67; aluminum phosphide: $\bar{x}=42$, 95% CI = 30–54; trapping: $\bar{x}=47$, 95% CI = 31–54), given lower efficacy associated with PERC applications.

Financial costs

Fixed costs plus labour costs were quite high for the PERC machine (US\$8535) and trapping (US\$674) when compared with aluminum phosphide (US\$131) after an initial day of treatment. These costs rapidly diminished (Fig. 2). By Day 20, treatment costs for trapping were below those for aluminum phosphide (US\$ 131 per day), and by Day 401, daily application costs for the PERC machine fell below those for aluminum phosphide as well (Fig. 2). When related to the number of pocket gophers removed per day, aluminum phosphide provided the lowest cost per individual removed if $\leq$12 total days of treatment were required (US\$3.14 per pocket gopher; Fig. 3). After 12 days, trapping became a less expensive approach (US\$3.12 per pocket gopher). At ~218 days of treatments, the PERC machine became a cheaper option (US\$3.13 per pocket gopher) than aluminum phosphide, although trapping was always a less expensive alternative than the PERC machine (Fig. 3).

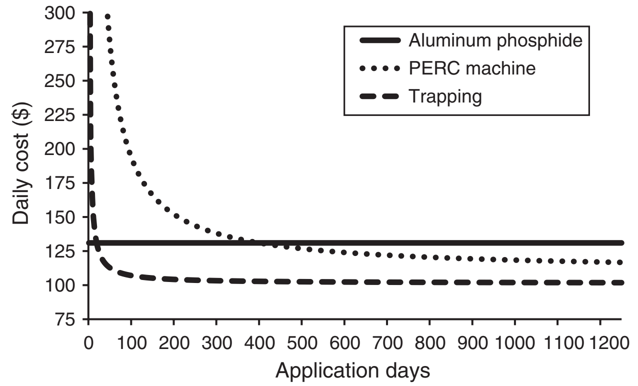

Fig. 2. The amortised daily (8-h day) fixed cost plus labour cost for three pocket gopher management tools in alfalfa fields during winter in northern California. The vertical axis has been truncated at US\$300 per day to better illustrate amortised daily costs after several days of application. For reference, initial fixed costs plus labour costs on Day 1 for the PERC machine and trapping were US\$8535 and US\$674 respectively.

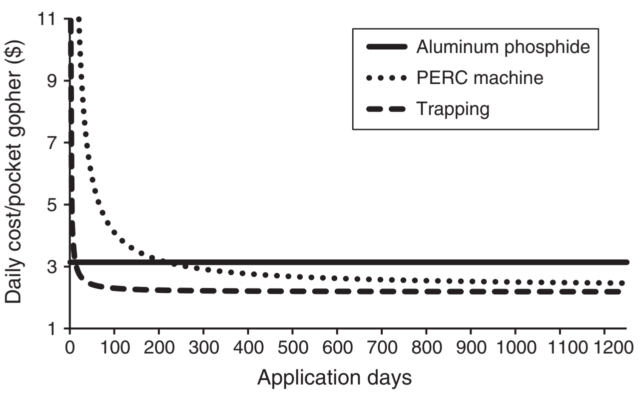

Fig. 3. The amortised daily (8-h day) fixed cost plus labour cost per pocket gopher removed for three management tools in alfalfa fields during winter in northern California. The vertical axis has been truncated at US\$11 per pocket gopher per day to better illustrate amortised costs after several days of application. For reference, initial fixed plus labour costs on a per pocket gopher basis on Day 1 for the Pressurised Exhaust Rodent Controller (PERC) machine and trapping were US\$180 and US\$14 respectively.

Discussion

Few recent peer-reviewed comparative studies have assessed the efficacy of various management strategies for pocket gophers (but see Frey and Wilks 2012 for exception), which highlights the need for such studies. Of the management tools we addressed, trapping exhibited the greatest mean efficacy and has been the most thoroughly studied. Both Proulx (1997, 2002) and Smeltz (1992) have noted the high efficacy associated with trapping, and Proulx (1997, 2002) indicated that trapping could be a cost-effective approach for pocket gopher management, given this high efficacy. Still, many growers and pest-control professionals have shied away from using trapping as a primary tool for pocket gopher management, given the perceived time constraint and subsequent cost associated with trapping (Marsh 1992; Engeman and Witmer 2000; Baldwin *et al*. 2014*b*). We have shown that this concern may not be warranted in all situations, because trapping yielded the lowest management cost on a per-gopher basis, while removing an equivalent number of pocket gophers when compared with the other approaches during an 8-h work day. Furthermore, we have demonstrated that high densities of pocket gophers can be completely removed from a field after three treatment periods when using trapping. Such complete removal efforts are strongly advocated and often critical for crops such as alfalfa where minimal pocket gopher population densities can cause substantial damage to crop yields, farm equipment and irrigation infrastructure (Baldwin 2011; Baldwin *et al*. 2014*b*).

Burrow fumigation with aluminum phosphide has been less thoroughly investigated than trapping, although available literature suggests 74–100% efficacy with pocket gophers (Moline and Demarais 1987; Baker 2004). Our findings are in line with these studies, indicating that aluminum phosphide burrow fumigation is a viable option for pocket gopher management. Interestingly, application times when excluding search time were far shorter for aluminum phosphide than for PERC applications or trapping, yet the number of burrow systems treated per day was not different than that for trapping and was far less than that observed for the PERC machine. This was due to the increased search time associated with multiple applications of aluminum phosphide per burrow system. If search times could be diminished, the number of applications and, subsequently, the number of pocket gophers removed per day, would increase.

One of the benefits of aluminum phosphide is the lack of expensive equipment to purchase. Therefore, if relatively few applications are required to manage pocket gophers, it can be the most cost-effective option, particularly for newly established fields with low population densities. However, on the basis of our criteria, if more than 12 8-h days of application were expected, even over many years, then trapping would become a more economically beneficial option. Even PERC applications were cheaper on a per pocket gopher basis if a great enough effort (~218 total days) was expended on pocket gopher management. It also bears mentioning that the use of aluminum phosphide, as with most burrow fumigants, requires high soil moisture for the method to be effective. Additionally, some applicators of aluminum phosphide have noted nausea and other signs of discomfort following applications (Proulx *et al*. 2011), although other studies have noted no such symptoms or concerns (Baker and Krieger 2002). Certainly, aluminum phosphide has a role for pocket gopher management, but other options may be more economically sound if extensive efforts are required, and other tools (e.g. trapping) may be less restrictive when and where they can be effectively used.

The present investigation has provided the most thorough review of efficacy of pressurised exhaust devices to date. Only Orloff (2012) had previously investigated the PERC machine; he found similar results ($\bar{x} = 56\%$). On the basis of efficacy alone, the PERC machine is somewhat effective, although certainly less so than other options. Repeated applications may increase the overall efficacy of this approach, although there is some concern that not all individuals in a population will be susceptible to this management tool (e.g. some individuals may learn or inherently know to plug burrow systems close to the point of gas injection, thereby negating treatment efforts). This does not seem to be as substantive of a concern with trapping, where total elimination of pocket gophers in high-density areas was possible at two of three sites after three treatment periods. Further investigation may be needed to better address this issue.

On a positive note, the PERC machine allowed for by far the greatest number of applications per day, given the ability to treat multiple burrow systems at once. Therefore, if large areas of treatment are required, this would be the quickest method to cover those areas. This benefit could be increased by moving to a larger machine that would allow treatments of up to six burrow systems at once, although two operators would be needed to allow for that number of treatments.

It bears emphasising that all efficacy and cost estimates provided here were formulated from a unique set of criteria based on our study area, study period and study design. Changes in these attributes could result in different outcomes. For example, sandy loam soils are ideal for trapping, because identification of tunnel systems and tunnel excavation are simple and relatively short in duration, given the presence of a friable soil. In heavy, dry, clay soils or gravely soils, trapping would be far more time consuming and would not be likely to be the most cost-effective option in those areas. Alternatively, sandy loam soils are more porous than are clay soils, so burrow fumigation is likely to be less effective in these soil types (unless fairly moist) than in a heavier, moist clay soil. As such, PERC applications in heavier soils may yield greater efficacy. This is of particular importance because even modest gains in PERC efficacy could yield a significantly greater number of pocket gopher mortalities, given the substantially greater number of daily applications possible with this approach.

Furthermore, our cost analysis was based on cost estimates that will vary over time and across locations. For example, substantial differences in fuel price could alter the feasibility of the PERC machine. In contrast, we did not account for repair costs for the PERC machine, because we do not have any data on the likelihood or cost of such repairs, yet it is likely that such repairs will be needed; this will add to the overall cost of this approach and should be considered. In short, our estimates should be taken as an example of what a grower or pest-control professional might experience when using these management tools, particularly when used in similar situations as experienced in our investigation. Additionally, our methods can serve as a template for consideration of the different factors that can influence efficacy and cost effectiveness, so that pest-control managers can consider them when deciding on the appropriate management strategy. Ultimately, a web-based tool that incorporates all of these varying factors would be of great benefit to all individuals interested in managing pocket gophers over large areas.

It should be pointed out that initial applications of all treatment types were insufficient to reduce pocket gopher activity to the preferred level of 70%. However, this was likely due to variable mounding activity within pocket gopher populations. Many factors including soil moisture and season can influence the frequency with which pocket gophers create mounds (Miller 1948; Proulx *et al*. 1995; Romañach *et al*. 2005). Some individuals may go 1–2 weeks without creating a mound (Richens 1965). In fact, Richens (1965) noted that 20–30% of pocket gophers were missed during treatment activities because of variable mounding patterns. If we assumed that only 75% of the pocket gopher population was targeted by our treatment applications, then resultant efficacy values for both aluminum phosphide ($\bar{x} = 86\%$) and trapping ($\bar{x} = 71\%$) after the first treatment period would have been above this 70% threshold; PERC applications ($\bar{x} = 49\%$) would have still been well below 70%. However, this selection of 75% is somewhat arbitrary given that the percentage of the population targeted would be difficult to determine and would vary across sites. As such, it appears to be most practical to assess efficacy following two treatment periods, preferably within 2 weeks of each other, so as to maximise the likelihood that all or almost all individuals within a field will create a mound, and thus will be targeted sometime during the treatment period. This multiple-application approach indicated a substantial reduction in pocket gophers from trapping and aluminum phosphide treatments in the present study, and has proven effective at determining efficacy in other management studies as well (Baldwin *et al*. In press).

Although the present study has focussed on management of pocket gophers, many pest species utilise burrow systems for part of their life cycle, and, as such, they may be susceptible to burrow-fumigation strategies. For example, aluminum phosphide has proven effective against California ground squirrels (*Otospermophilus* spp.), Belding's ground squirrels and black-tailed prairie dogs (*Cynomys ludovicianus*) (Salmon *et al*. 1982; Hygnstrom and VerCauteren 2000; Baldwin and Holtz 2010; Baldwin and Quinn 2012), whereas carbon monoxide-producing cartridges are used to manage California ground squirrels, Belding's ground squirrels, Richardson's ground squirrels (*Urocitellus richardsonii*), black-tailed prairie dogs, woodchucks (*Marmota monax*), Indian crested porcupines (*Hystrix indica*) and various canid species (Savarie *et al*. 1980; Salmon *et al*. 1982; Matschke and Fagerstone 1984; Dolbeer *et al*. 1991; Hygnstrom and VerCauteren 2000; Baldwin and Holtz 2010; Khan *et al*. 2011; Baldwin and Quinn 2012). Carbon monoxide-producing machines (i.e. PERC) would be likely to have great utility for similar species and may merit further investigation, particularly given the frequent increase in restrictions or complete loss of many management tools for vertebrate pest species (Eason *et al*. 2010). It bears reiterating that an increase in efficacy would greatly increase the cost effectiveness of the PERC machine. If the PERC machine proves to be highly effective for other burrowing mammal species, it could be a cost-effective management tool for those species.

It is important to point out that the most effective management programs will utilise an integrated pest-management approach that incorporates multiple techniques (Engeman and Witmer 2000; Baldwin 2011). This includes methods not explicitly tested in this investigation (e.g. rodenticides, habitat modification, flood irrigation, deep soil tillage and potentially natural predation). Although we have identified strategies that can successfully reduce and even eliminate pocket gophers from fields, reliance on a single approach may ultimately result in a behavioural or physiological adaptation to that strategy, thereby rendering it ineffective (e.g. strychnine resistance; Lee *et al*. 1990, 1992; Marsh 1992). Therefore, the use of a combination of these strategies is likely to provide the best long-term solution to pocket gopher damage.

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References

Baker, R. O. (2004). Field efficacy of Fumitoxin® (55% aluminum phosphide) tablets for controlling valley pocket gopher. In 'Proceedings of the 21st Vertebrate Pest Conference'. (Eds R. M. Timm and W. P. Gorenzel.) pp. 253–257. (University of California: Davis, CA.)

Baker, R. O., and Krieger, R. (2002). Phosphine exposure to applicators and bystanders from rodent burrow treatment with aluminum phosphide. In 'Proceedings of the 20th Vertebrate Pest Conference'. (Eds R. M. Timm and R. H. Schmidt.) pp. 26–31. (University of California: Davis, CA.)

Baldwin, R. A. (2011). Developing an IPM program for controlling pocket gophers and voles in alfalfa. In 'Proceedings, 2011 Western Alfalfa and Forage Conference'. (Eds D. Putnam, M. Ottman and E. Creech.) pp. 99–107. (University of California: Davis, CA.)

Baldwin, R. A. (2012). The importance of aluminum phosphide for burrowing pest control in California. In 'Proceedings of the 25th Vertebrate Pest Conference'. (Ed. R. M. Timm.) pp. 151–159. (University of California: Davis, CA.)

Baldwin, R. A. (2014). Determining and demonstrating the importance of training and experience for managing pocket gophers. *Wildlife Society Bulletin* **38**, 628–633. doi:10.1002/wsb.439

Baldwin, R. A., and Holtz, B. A. (2010). Fumigation of California ground squirrels revisited: are fumigants an effective method for controlling ground squirrels? In 'Proceedings of the 24th Vertebrate Pest Conference'. (Eds R. M. Timm and K. A. Fagerstone.) pp. 129–132. (University of California: Davis, CA.)

Baldwin, R. A., and Meinerz, R. (2015). Using external characteristics for rapid identification of gender in pocket gophers. *Western North American Naturalist* **75**, 251–258. doi:10.3398/064.075.0302

Baldwin, R. A., and Quinn, N. (2012). The applicability of burrow fumigants for controlling Belding's ground squirrels in alfalfa. In 'Proceedings of the 25th Vertebrate Pest Conference'. (Ed. R. M. Timm.) pp. 160–163. (University of California: Davis, CA.)

Baldwin, R. A., Marcum, D. B., Orloff, S. B., Vasquez, S. J., Wilen, C. A., and Engeman, R. M. (2013). The influence of trap type and cover status on capture rates of pocket gophers in California. *Crop Protection* **46**, 7–12. doi:10.1016/j.cropro.2012.12.018

Baldwin, R. A., Meinerz, R., and Orloff, S. B. (2014*a*). The impact of attractants on pocket gopher trapping. *Current Zoology* **60**, 472–478. doi:10.1093/czoolo/60.4.472

Baldwin, R. A., Salmon, T. P., Schmidt, R. H., and Timm, R. M. (2014*b*). Perceived damage and areas of needed research for wildlife pests of California agriculture. *Integrative Zoology* **9**, 265–279. doi:10.1111/1749-4877.12067

Baldwin, R. A., Chapman, A., Kofron, C. P., Meinerz, R., Orloff, S. B., and Quinn, N. (2015). Refinement of a trapping method increases utility for pocket gopher management. *Crop Protection* **77**, 176–180. doi:10.1016/j.cropro.2015.08.003

Baldwin, R. A., Meinerz, R., and Witmer, G. (In press). Novel and current rodenticides for pocket gopher *Thomomys* spp. management in vineyards: what works? *Pest Management Science.* doi:10.1002/ps.4307

Dolbeer, R. A., Bernhardt, G. E., Seamans, T. W., and Woronecki, P. P. (1991). Efficacy of two gas cartridge formulations in killing woodchucks in burrows. *Wildlife Society Bulletin* **19**, 200–204.

Eason, C. T., Fagerstone, K. A., Eisemann, J. D., Humphrys, S., O'Hare, J. R., and Lapidge, S. J. (2010). A review of existing and potential New World and Australasian vertebrate pesticides with a rationale for linking use patterns to registration requirements. *International Journal of Pest Management* **56**, 109–125. doi:10.1080/09670870903243463

Efron, B., and Tibshirani, R. J. (1993). 'An Introduction to the Bootstrap.' (Chapman and Hall: New York.)

Engeman, R. M., and Witmer, G. W. (2000). Integrated management tactics for predicting and alleviating pocket gopher (*Thomomys* spp.) damage to conifer reforestation plantings. *Integrated Pest Management Reviews* **5**, 41–55. doi:10.1023/A:1009649614385

Engeman, R. M., Campbell, D. L., and Evans, J. (1993). A comparison of 2 activity measures for northern pocket gophers. *Wildlife Society Bulletin* **21**, 70–73.

Engeman, R. M., Nolte, D. L., and Bulkin, S. P. (1999). Optimization of the open-hole method for assessing pocket gopher, *Thomomys* spp., activity. *Canadian Field Naturalist* **113**, 241–244.

Entz, M. H., Bullied, W. J., and Katepa-Mupondwa, F. (1995). Rotational benefits of forage crops in Canadian prairie cropping systems. *Journal of Production Agriculture* **8**, 521–529. doi:10.2134/jpa1995.0521

Frey, S. N., and Wilks, R. (2012). A case study involving pocket gopher damage abatement in alfalfa. *Journal of Extension* **50**, Article 5RIB9. Available at http://www.joe.org/joe/2012october/rb9.php?pdf=1 [Verified 16 September 2015]

Howard, W. E., and Childs, H. E. Jr (1959). Ecology of pocket gophers with emphasis on *Thomomys bottae mewa. Hilgardia* **29**, 277–358. doi:10.3733/hilg.v29n07p277

Hygnstrom, S. E., and VerCauteren, K. C. (2000). Cost-effectiveness of five burrow fumigants for managing black-tailed prairie dogs. *International Biodeterioration & Biodegradation* **45**, 159–168. doi:10.1016/S0964-8305(00)00037-8

Khan, A. A., Mian, A., and Hussain, R. (2011). A delivery system for carbon monoxide fumigation of Indian crested porcupine, *Hystrix indica*, den using two-ingredient cartridge. *Pakistan Journal of Zoology* **43**, 727–732.

Lee, L. L., Howard, W. E., and Marsh, R. E. (1990). Acquired strychnine tolerance by pocket gophers. In 'Proceedings of the 14th Vertebrate Pest Conference'. (Eds L. R. Davis and R. E. Marsh.) pp. 87–90. (University of California: Davis, CA.)

Lee, L. L., Howard, W. E., and Marsh, R. E. (1992). Laboratory studies of more durable baits for controlling pocket gophers. In 'Proceedings of the 15th Vertebrate Pest Conference'. (Eds J. E. Borrecco and R. E. Marsh.) pp. 303–307. (University of California: Davis, CA.)

Luce, D. G., Case, R. M., and Stubbendieck, J. L. (1981). Damage to alfalfa fields by plains pocket gophers. *The Journal of Wildlife Management* **45**, 258–260. doi:10.2307/3807898

Marsh, R. E. (1992). Reflections on current (1992) pocket gopher control in California. In 'Proceedings of the 15th Vertebrate Pest Conference'. (Eds J. E. Borrecco and R. E. Marsh.) pp. 289–295. (University of California: Davis, CA.)

Matschke, G. H., and Fagerstone, F. A. (1984). Efficacy of a two-ingredient fumigant on Richardson's ground squirrels. In 'Proceedings of the 11th Vertebrate Pest Conference'. (Eds D. O. Clark.) pp. 17–19. (University of California: Davis, CA.)

Matschke, G. H., Ramey, C. A., McCann, G. R., and Engeman, R. M. (1995). Evaluation of a 2-active ingredient gas cartridge for controlling northern pocket gophers. *International Biodeterioration & Biodegradation* **36**, 151–160. doi:10.1016/0964-8305(95)00085-2

Messmer, T. A., and Schroeder, S. (1996). Perceptions of Utah alfalfa growers about wildlife damage to their hay crops: implications for managing wildlife on private land. *The Great Basin Naturalist* **56**, 254–260.

Miller, M. A. (1948). Seasonal trends in burrowing of pocket gophers (*Thomomys*). *Journal of Mammalogy* **29**, 38–44. doi:10.2307/1375279

Miller, M. A. (1954). Poison gas tests on gophers. *California Agriculture* **8**, 10.

Miller, M. A. (1957). Burrows of the Sacramento Valley pocket gopher in flood-irrigated alfalfa fields. *Hilgardia* **26**, 431–452. doi:10.3733/hilg.v26n08p431

Moline, P. R., and Demarais, S. (1987). Efficacy of aluminum phosphide for black-tailed prairie dog and yellow-faced pocket gopher control. In 'Proceedings of the 8th Great Plains Wildlife Damage Control Workshop'. (Eds D. W. Uresk, G. L. Schenbeck and R. Cefkin.) pp. 64–66. (United States Department of Agriculture, Forest Service: Fort Collins, CO.)

Orloff, S. B. (2012). Evaluation of a pressurized exhaust device to control pocket gophers and Belding's ground squirrels in alfalfa. In 'Proceedings of the 25th Vertebrate Pest Conference'. (Ed. R. M. Timm.) pp. 329–332. (University of California: Davis, CA.)

Proulx, G. (1997). A northern pocket gopher (*Thomomys talpoides*) border control strategy: promising approach. *Crop Protection* **16**, 279–284. doi:10.1016/S0261-2194(96)00089-0

Proulx, G. (2002). Effectiveness of trapping to control northern pocket gophers in agricultural lands in Canada. In 'Proceedings of the 20th Vertebrate Pest Conference'. (Eds R. M. Timm and R. H. Schmidt.) pp. 26–31. (University of California: Davis, CA.)

Proulx, G., Badry, M. J., Cole, P. J., Drescher, R. K., Kolenosky, A. J., and Pawlina, I. M. (1995). Summer above-ground movements of northern pocket gophers, *Thomomys talpoides*, in an alfalfa field. *Canadian Field Naturalist* **109**, 256–258.

Proulx, G., MacKenzie, N., MacKenzie, K., and Walsh, K. (2011). Efficacy of aluminum phosphide tablets to control Richardson's ground squirrel (*Spermophilus richardsonii*) populations in southern Saskatchewan, Canada. *Crop Protection* **30**, 1039–1042. doi:10.1016/j.cropro.2011.04.003

Richens, V. B. (1965). An evaluation of control on the Wasatch pocket gopher. *The Journal of Wildlife Management* **29**, 413–425. doi:10.2307/3798038

Romañach, S. S., Reichman, O. J., and Seabloom, E. W. (2005). Seasonal influences on burrowing activity of a subterranean rodent, *Thomomys bottae*. *Journal of Zoology* **266**, 319–325. doi:10.1017/S0952836905006941

Salmon, T. P., Gorenzel, W. P., and Bentley, W. J. (1982). Aluminum phosphide (Phostoxin) as a burrow fumigant for ground squirrel control. In 'Proceedings of the 10th Vertebrate Pest Conference'. (Ed. R. E. Marsh.) pp. 143–146. (University of California: Davis, CA.)

Savarie, P. J., Tigner, J. R., Elias, D. J., and Hayes, D. J. (1980). Development of a simple two-ingredient pyrotechnic fumigant. In 'Proceedings of the 9th Vertebrate Pest Conference'. (Ed. J. P. Clark.) pp. 215–221. (University of California: Davis, CA.)

Schneider, B. (1982). 'Pesticide Assessment Guidelines: Subdivision G, Product Performance.' (US Environmental Protection Agency, Office of Pesticide and Toxic Substances: Springfield, VA.)

Smeltz, M. D. (1992). Summary of a USDA Forest Service pocket gopher trapping contract. In 'Proceedings of the 15th Vertebrate Pest Conference'. (Eds J. E. Borrecco and R. E. Marsh.) pp. 296–298. (University of California: Davis, CA.)

Whisson, D., and Villa-C, B. (1996). The pocket gopher as a pest in Mexico. In 'Proceedings of the 17th Vertebrate Pest Conference'. (Eds R. M. Timm and A. C. Crabb.) pp. 151–153. (University of California: Davis, CA.)

Witmer, G. W., Marsh, R. E., and Matschke, G. H. (1999). Trapping considerations for the fossorial pocket gopher. In 'Mammal Trapping'. (Ed. G. Proulx.) pp. 131–139. (Alpha Wildlife and Research Management: Sherwood Park, Alberta, Canada.)

Zar, J. H. (1999). 'Biostatistical Analysis.' (Prentice-Hall: Upper Saddle River, NJ.)