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RESEARCH ARTICLE

An assessment of vegetation management practices and burrow fumigation with aluminum phosphide as tools for managing voles within perennial crop fields in California, USA

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Abstract
Voles (Cricetidae) cause extensive damage to a variety of crops throughout much of the Northern Hemisphere. The removal of vegetation from crop fields at the end of the growing season, combined with a subsequent burrow fumigant application of aluminum phosphide, has the potential to substantially curtail vole activity but has not been thoroughly examined. We set up a study to test the impact of these management tools in perennial globe artichoke (*Cynara cardunculus* var. *scolymus*) fields in Monterey County, CA, during 2010 and 2011, to determine their potential utility as part of an integrated pest management (IPM) program for managing California voles (*Microtus californicus*). We used both chewing indices and mortality estimates derived via radiotelemetry to assess the efficacy of aboveground vegetation removal and aluminum phosphide applications on vole abundance. We determined the impact of plowing artichoke fields on vole activity as well. Both removal of vegetation and applications of aluminum phosphide substantially reduced vole presence within treated fields. Plowing also reduced vole abundance to the point of little residual activity following treatment. These management practices appear to be effective at eliminating voles from crop fields. Combining these tools with management practices designed to slow down reinvasion by neighboring vole populations (e.g., barriers, repellents, traps) has the potential to substantially reduce farmer reliance on rodenticides for vole management, although rodenticides will still be needed to curtail populations that reestablish within crop fields. Such an IPM approach should substantially benefit both farmers and agro-ecosystems.

Keywords Aluminum phosphide · Burrow fumigation · California vole · *Microtus californicus* · Plowing · Vegetation management

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Introduction

Voles (Cricetidae) cause extensive damage to a variety of field crops throughout much of the northern hemisphere (Baldwin et al. 2014; Jacob and Tkadlec 2010; Witmer et al. 2009). Depopulation of fields through the use of rodenticides can be an effective short-term tool for managing these rodents (Baldwin et al. 2016b; Clark 1984; Jokić et al. 2010; Salmon and Lawrence 2006b), but an integrated pest management (IPM) approach that focuses on multiple tools generally provides better long-term success (Baldwin et al. 2014; Witmer et al. 2009). Vegetation management is one such tool. The removal of vegetative cover afforded by crops is believed to force voles to move to adjacent crops or natural areas (Edge et al. 1995; Jacob and Hempel 2003; Rodríguez-Pastor et al. 2016; Witmer et al. 2007), although this supposition has not been tested for many vole species (e.g., California voles [*Microtus californicus*]). If effective, exclusionary practices

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(e.g., fencing, chemical repellents) could be used to keep voles from moving back into fields once the crops renew growth (Schlötelburg et al. In press; Witmer et al. 2000), thereby reducing treatment costs associated with removal efforts. However, if voles remain in moderate to large numbers within fields even after vegetative removal, exclusion approaches will be an ineffective, costly practice.

Combining vegetative management with a targeted removal tool, such as a burrow fumigant, could further reduce vole numbers in fields. Aluminum phosphide is a burrow fumigant that can be used for vole control in the USA (Baldwin 2012). Aluminum phosphide comes in tablet or pellet forms. The tablets or pellets are placed into the burrow system of the vole where it reacts with moisture in the soil and air to create phosphine gas. This gas is highly toxic to all animals and has been shown to be a highly effective management tool for pocket gophers (Geomyidae) and ground squirrels (Sciuridae; Baker 2004; Baldwin and Holtz 2010; Baldwin and Quinn 2012; Baldwin et al. 2016a; Salmon et al. 1982); impacts to nontarget species are believed to be minimal when aluminum phosphide is appropriately applied within active vole burrow systems. The efficacy of aluminum phosphide for voles has yet to be tested but has often been considered less practical for these species given that their shallow burrow systems may be incapable of holding phosphine at a high enough rate to cause mortality (Witmer et al. 2009). Comprehensive testing of the combined utility of vegetation removal and burrow fumigation via aluminum phosphide would greatly assist us in our understanding of their utility as part of an IPM program for controlling voles in field crops.

Perennial globe artichoke (*Cynara cardunculus* var. *scolymus*) fields along the central coast of California provided an excellent opportunity to test these management practices. California voles cause extensive damage to artichoke plants through consumption of root systems and stalks of plants (Clark 1984). Historical management practices have relied heavily on chlorophacinone-treated artichoke bracts, but continual use has resulted in resistance build-up in some vole populations in these fields (Horak et al. 2015; Salmon and Lawrence 2006a). This has led to a renewed interest in developing an IPM program for voles in these crop fields. Artichoke producers in the central coast region of California have historically mowed and cut back all aboveground vegetation at the end of the production season in mid-spring to stimulate new growth. This cut-back was also believed to help reduce vole populations in the fields, while also removing vegetation to allow for an unobscured assessment of vole burrow openings for aluminum phosphide application. Local farmers believed that these practices reduced vole numbers within artichoke fields, but no data were available to support this assertion. Furthermore, although these were perennial artichoke fields, they occasionally needed to be taken out of production through plowing activities to allow for crop rotation and replanting. Plowing was an effective tool for reducing common vole (*Microtus arvalis*) activity in central Germany (Jacob 2003), but has yet to be tested against California voles. Therefore, we established a study to test the efficacy of these management activities for reducing vole numbers in artichoke fields. Our specific objectives included the following: (1) determine the impact of vegetation removal on vole activity, (2) determine the utility of aluminum phosphide as a burrow fumigant for vole management, (3) determine the collective utility of vegetation removal and aluminum phosphide for vole management, and (4) determine the effectiveness of plowing at reducing vole numbers. These tools will be discussed relative to alternative management strategies to suggest an IPM program for voles in perennial field crops.

Materials and methods

Study area

All study sites were located in perennial globe artichoke fields within 10 km of the town of Castroville in Monterey County, CA. Artichokes were grown in rows on berms with broad ditches (approx. 3 m across and 0.5 m deep) located between the rows, with study fields ranging from 5 to 14 ha in size ($\bar{x}$ = 7.5 ha). Study fields were selected randomly from a set of potential fields that contained abundant vole activity. Temperatures during spring are generally cool, averaging around 20 °C and 9 °C for highs and lows during May, respectively. Rainfall is relatively sparse during May ($\bar{x}$ = 1.1 cm), but foggy conditions are common during mornings. All components of this study occurred from 29 April to 29 May 2010, and 10 May to 14 June 2011.

Vole management activities

Following the end of the artichoke production season (late April to early May), all vegetation was mowed and then cut back via a v-knife at ground level to the point that no aboveground vegetation remained. Shortly following vegetation removal (range = 0–11 days; $\bar{x}$ = 4.6 days), all burrow openings were treated with aluminum phosphide tablets (55% active ingredient) by placing the tablets into the burrow system, closing the burrow opening with a small wad of paper, and covering the paper and burrow opening with loose soil. Occasionally, fields were taken out of production by plowing the entire field to a depth of approximately 0.5 m. It bears noting that these were functional production fields, so assessments at untreated sites were not possible. Therefore, all treatments applied in this project were applied throughout each study field.

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Chewing index

Chewing indices have proven effective at monitoring changes in population size for a variety of rodent species including California voles (e.g., Engeman and Whisson 2006; Whisson et al. 2005). In particular, Engeman et al. (2016) determined that chewing on wax monitoring blocks well-tracked California vole numbers ($r = 0.90$) in artichoke fields within our study area. Therefore, we used wax blocks (NoTox™, Liphatech, Inc., Milwaukee, WI) to monitor changes in vole activity across all treatment sites during this study. To determine the proportion of the wax block removed, we first determined the initial mean mass of the wax blocks by weighing 20 blocks at the beginning of the study ($\bar{x}$ weight = 20.7 g, SE = 0.05 g). We then established an indexing protocol that entailed placing wax blocks in a grid pattern; we followed Engeman et al. (2016) by using a 6 × 6 grid pattern with blocks placed at 5-m intervals underneath artichoke plants. Grids were established in areas with abundant vole sign (i.e., burrow openings and chewing damage to plants) to allow for enough vole activity to potentially detect changes via treatment application. The perimeter of all grids was at least 30 m from the nearest field edge to minimize potential edge effects. The blocks were collected 2 days after initial placement, sealed in individually marked plastic bags, and later weighed in the lab to determine mass removed by rodents. This process was repeated before (pretreatment) and after (posttreatment) various management activities to determine the associated efficacy (percent reduction in amount of block chewed) of each approach. This process was repeated for each of the 36 wax blocks located within each monitoring grid. Pretreatment assessments were completed 1 to 9 days ($\bar{x}$ = 3 days) before the initiation of all management actions, while posttreatment assessments were initiated within 1 to 6 days ($\bar{x}$ = 3 days) of the completion of all management activities.

Radiotracking

We used mortality rates of radiotransmittered voles as a corroborative assessment of efficacy for vegetation removal and aluminum phosphide application. Voles were captured during May 2011 in four artichoke fields (different than those used for our chewing index assessment; number per field = 1, 6, 8, and 15) to allow us to fit collars for radiotracking and mortality assessment. We selected three of these fields randomly from a set of fields that contained abundant vole activity. A final vole was opportunistically captured and collared in a fourth field. Voles were obtained through a hand-capture approach outlined in Baldwin et al. (2015). This approach involved digging up voles from active burrow systems, which allowed for rapid capture of our target of 30 voles. Upon capture, we sedated voles via an isoflurane nose cone following the procedures provided in Parker et al. (2008). We fitted immobilized voles with a cable tie attached to the transmitter (PIP3 Ag376, mass = 1.4 g; Biotrack Ltd., Wareham, UK). The vole was then released in a storage container for 15–30 min to ensure that the vole was fit to be released. Voles were released at their respective capture site once we determined they were in good health.

For mortality assessment, we generally tracked voles daily following release, although inclement weather or other factors occasionally precluded us from recording a location on 3 out of 37 days. On days of vegetation removal and aluminum phosphide application, we tracked voles following treatment application to better determine the immediate impact of the respective treatment. We recorded each vole location through the use of a GPS unit. Temperature sensors were included in our radiotransmitters to allow us to determine mortality events; a substantial drop in temperature representative of mortality transmitted a different signal. However, we did not find the temperature sensors to always be effective at identifying mortalities. Therefore, if we noted that a vole had not moved for 3–4 days, we attempted to dig up the collar to determine mortality. Dead voles located above ground were documented and the collar removed. If a transmittered vole went missing, we documented the date that this event occurred to determine if one of our management activities was the likely cause. All procedures were conducted in accordance with the ethical standards of the University of California, Davis (Study Protocol 15732).

Data analysis

The number of fields sampled varied across years and management activity. In 2010, we were not able to separate out aluminum phosphide treatments from combined vegetation removal plus aluminum phosphide treatments ($n = 7$ sites) given an insufficient amount of time to conduct monitoring trials before farmers applied aluminum phosphide. Furthermore, some fields were not treated with aluminum phosphide ($n = 9$); these sites were only included in vegetation removal analyses. In 2011, all sites ($n = 5$; two of which were the same fields sampled during 2010, although monitoring plots were not the same) received both vegetation removal and aluminum phosphide treatments, and we were able to separate out vegetation removal impacts from aluminum phosphide impacts given sufficient time intervals (5–11 days, $\bar{x}$ = 9) to run chewing indices between the respective management activities. We also sampled three sites during 2010 to determine the impact of plowing on vole numbers. We analyzed chewing index values annually for each management activity using a mixed effect model (repeated measures) with site as a random "subject" term nested in treatment (Zar 1999), and with the before and after treatment wax block weights representing the repeated observations on each site.

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We determined mortality rates of radiotransmittered voles for the vegetation removal, aluminum phosphide, and post-treatment application periods by dividing the number of voles that died during a specific monitoring period by the number of uncensored voles in that same monitoring period. Mortality was broadly defined as the elimination of a vole from a given study field. This operational definition was required given that most voles were not recovered following treatment (only 6 of 20 carcasses were recovered). We believe this was largely due to destruction of the collars and scavenging or predation of collared voles following vegetation removal activities rather than the result of emigration given that only one vole was ever documented outside of the study fields following management activities. We checked for vole locations ≥ 500 m from the study sites starting the day of each management activity, so rapid emigration appears unlikely. Regardless, our ultimate goal was the removal of voles from the artichoke fields and not necessarily actual mortality of voles, so our operational definition was the measurement of interest.

Results

The removal of vegetation reduced vole activity as determined from chewing blocks by 89% (from 21.0 to 2.3% of block removed) and 71% (from 10.7 to 3.1% of block removed) during 2010 ($F_{1,8} = 5.7$, $P = 0.044$) and 2011 ($F_{1,4} = 29.1$, $P = 0.006$), respectively (Fig. 1). We observed a further reduction in vole activity in 2011 (from 3.1 to 1.3% of block removed; $\bar{x}$ = 59%) following the application of aluminum phosphide ($F_{1,4} = 7.8$, $P = 0.049$). Collectively, vegetation removal and aluminum phosphide application yielded an 88% reduction (from 10.7 to 1.3% of block removed) in vole activity during 2011 ($F_{1,4} = 28.4$, $P = 0.006$; Fig. 1). Although not as substantial as 2011, we also observed a reduction (from 9.1 to 6.3% of block removed; $\bar{x}$ = 31%) in vole activity following the combination of vegetation removal and aluminum phosphide application in 2010 ($F_{1,6} = 6.1$, $P = 0.048$). We observed almost the complete removal (from 3.3 to 0.3% of block removed; $\bar{x}$ = 92%) of voles from artichoke fields following plowing ($F_{1,2} = 11.2$, $P = 0.079$; Fig. 1).

Of the 30 initially radiotransmittered voles, six went missing within 3 days of release, and two more went missing 10 days and 6 days before any treatment applications (they went missing 10 and 16 days after initial release, respectively). Additionally, two voles died before the start of any management action (one 10 days after release, and the other ≥ 10 days after release). Therefore, these 10 voles were removed from further analysis. Mortality was high following both vegetation removal and aluminum phosphide applications, with cause-specific mortality rates of 80% (16 out of 20) and 100% (4 out of 4), respectively. The average time from the application of a management action (i.e., vegetation removal and aluminum phosphide application) and time to death or when a signal went missing was 0.7 days, and was 2 days or less for all voles indicating that mortality was likely due to treatment application rather than some other effect. Furthermore, no radiotransmittered voles remained in the artichoke fields at the end of the study, suggesting complete or almost complete removal of voles following vegetation removal and aluminum phosphide applications.

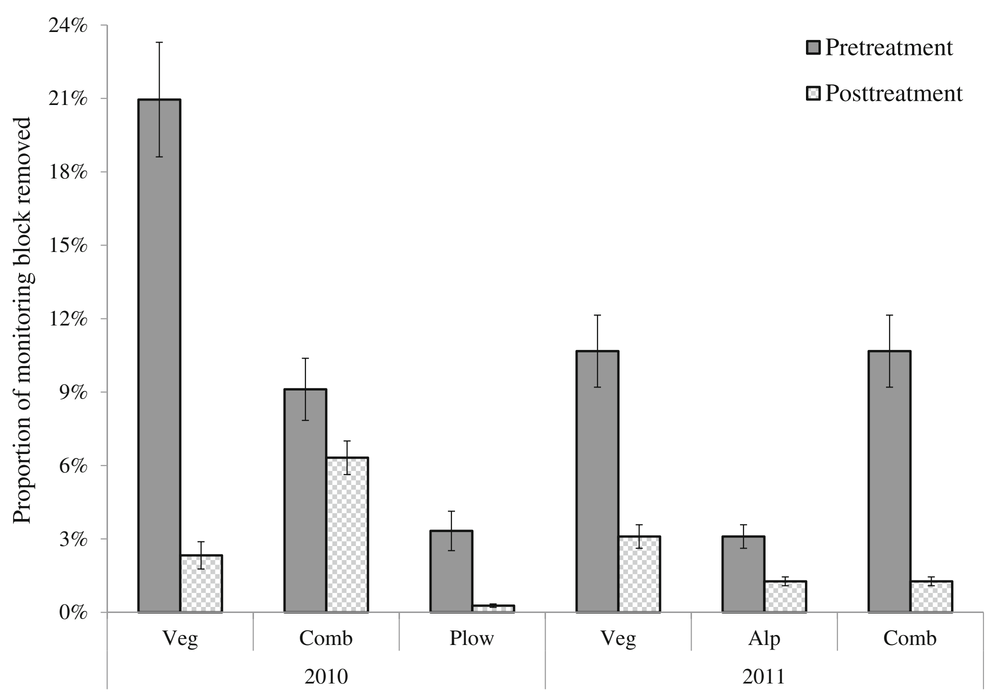

Fig. 1 Mean proportions and associated standard errors of monitoring blocks that were removed by California voles in artichoke fields in Monterey County, CA, during spring 2010 and 2011. Vole activity was monitored before (pretreatment) and after (posttreatment) various management strategies including vegetation removal (Veg), burrow fumigation with aluminum phosphide (Alp), a combination of vegetation management and aluminum phosphide (Comb), and plowing of entire fields (Plow)

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Discussion

Aboveground vegetation removal proved highly effective at reducing vole numbers within artichoke fields during both 2010 and 2011. Although we cannot be certain if voles emigrated from fields or were killed during the mowing and v-knife process, the rapid disappearance of radiotransmittered voles shortly after the initiation of these vegetation removal activities suggests that the voles were killed and transmitters destroyed. Vole losses via direct mortality would likely be desired so that voles did not move into adjacent crops where they could potentially cause additional damage (Witmer et al. 2007).

Although initial vole numbers were already low, plowing further reduced vole activity, as plowing not only leads to complete vegetation removal but also to burrow destruction. Plowing has previously proven effective at suppressing common vole numbers in certain cropping systems (Jacob 2003), but this is the first record of its effectiveness against California voles. Although highly effective at reducing vole activity, plowing is obviously not a tool that farmers will be able to employ as a regular part of a management program in a perennial crop such as globe artichokes. However, it should be a useful tool for eliminating voles from fields before periodic replantings occur.

Burrow fumigation for vole control has generally been considered ineffective given the shallow nature of vole burrow systems and the substantial labor cost associated with these applications (Witmer et al. 2009). That said, it has not been extensively tested in the past. We observed varying efficacy from aluminum phosphide applications between chewing indices and telemetry, with telemetry results indicating 100% efficacy with a limited sample size ($n = 4$). Results from chewing indices indicated a significant reduction in vole activity as well, although reductions in chewing were less extreme (Fig. 1). The variable efficacy we observed may simply have been an artifact of small sample sizes for radiotransmittered voles given that most voles were eliminated before the burrow fumigation phase. Alternatively, it could be due to the application process required to treat a field with aluminum phosphide. For aluminum phosphide application, each burrow system must be individually treated by hand. Fields often contain hundreds to thousands of vole burrow systems. It would be easy to miss some of these burrow systems during the application process. The failure to treat a subset of burrow systems may be more likely to show up in broad-scale chewing indices than it would be for a limited number of radiotransmittered voles.

It is interesting to note that the combination of vegetation removal and aluminum phosphide applications resulted in lower efficacy than vegetation removal by itself in 2010. This is likely an artifact of site-to-site variability as the combination of both these tools was highly effective in 2011 (based on results from both chewing indices and mortality data), and vegetation removal alone resulted in substantial reductions in vole activity in 2010. Even so, the reduction in vole activity was significant (Fig. 1). Ultimately, the combination of these two management strategies is likely to increase the efficacy of vole management programs. What is less clear is if aluminum phosphide applications are a cost-effective addition to vole management programs. Vegetation removal alone does a good job of reducing vole numbers, and aluminum phosphide applications are costly given the substantial labor required to individually treat burrow systems. This warrants further investigation, but at this time, artichoke farmers believe the extra effort is warranted given the added efficacy associated with these applications combined with the extreme damage that voles can cause to artichoke fields (JF Castaneda, Ocean Mist Farms, Castroville, CA; personal communication).

Conclusions

The combination of vegetation removal and aluminum phosphide application provided an effective strategy for eliminating voles during the nonproduction portion of the growing season. However, without additional management tools, voles will simply move back into crop fields once vegetation begins to regrow. Exclusionary fencing, trapping, and repellent applications show some promise for inclusion with vegetation removal and fumigation approaches. For example, Witmer et al. (2000) indicated that a tall exclusionary barrier combined with coyote urine as a repellent could substantially reduce vole movements into excluded areas, recent laboratory research by Schlötelburg et al. (in press) has identified potential repellents for keeping voles out of designated areas, while a combination of barriers and traps have shown substantial promise for reducing rodent damage in various cropping systems (e.g., Fuelling et al. 2010; Singleton et al. 2005). Utilizing these tools after a field has been depopulated of voles should substantially slow movement of voles back into crop fields, ultimately reducing the need for rodenticides within crop fields during the growing season. That said, these approaches will not completely exclude voles from crop fields. Because voles reproduce very rapidly, rodenticides will still be needed to control vole populations when they build up to damaging numbers (Witmer et al. 2009). However, an IPM approach that includes vegetation removal, aluminum phosphide application, and exclusionary fencing has greatly reduced the amount of rodenticide applied by artichoke farmers at our study sites (RA Baldwin, University of California, Davis; unpublished data), while resulting in reduced damage caused by voles (JF Castaneda, Ocean Mist Farms, Castroville, CA; personal communication). A similar approach could be considered for other rodent species and cropping systems.

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Compliance with ethical standards

All procedures were conducted in accordance with the ethical standards of the University of California, Davis (Study Protocol 15732).

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