ELSEVIER
International Biodeterioration & Biodegradation 45 (2000) 159–168
INTERNATIONAL BIODETERIORATION & BIODEGRADATION
www.elsevier.com/locate/ibiod

Cost-effectiveness of five burrow fumigants for managing black-tailed prairie dogs

Scott E. Hygnstrom[a,*], Kurt C. VerCauteren[b]

[a]School of Natural Resource Sciences, University of Nebraska, Lincoln, NE 68583-0819, USA
[b]National Wildlife Research Center, United States Department of Agriculture, Fort Collins, CO 80521-2154, USA

Abstract

We evaluated the cost-effectiveness of two solid form burrow fumigants (aluminum phosphide and gas cartridges) and three pressurized gas–liquid burrow fumigants (methyl bromide, chloropicrin, and a methyl bromide–chloropicrin mixture) for managing black-tailed prairie dogs (*Cynomys ludovicianus*). Fifty-two variable-sized plots, including 25 treatment and 25 control burrows, were established within 13 prairie dog colonies in central Nebraska during spring 1989. Each group of 25 treatment burrows was fumigated with one of the five fumigants according to label directions or manufacturer recommendations. All five fumigants reduced burrow activity 95–98%, as measured by a plugged burrow technique. No significant differences in efficacy ($P = 0.453$) were detected among the five treatments. Total costs for materials and labor for the aluminum phosphide and gas cartridges, excluding application equipment, were twice ($75.00 to $96.88 ha^{-1}) the cost of the pressurized gas–liquid fumigants ($37.67 to $41.76 ha^{-1}). Costs for the application equipment were considerably higher for the pressurized materials. Each treatment required labor for burrow plugging, which accounted for 50–75% of the total cost. None of the products tested met all requirements of a proposed selection criteria for fumigants.

Keywords: Aluminum phosphide; Animal damage control; Chloropicrin; *Cynomys* spp; Economics; Fumigants; Gas cartridges; Methyl bromide; Prairie dog

1. Introduction

The black-tailed prairie dog (*Cynomys ludovicianus*) is a native species of the Great Plains region of North America. Prairie dogs live in colonies and are recognized for their ability to modify habitat by clipping vegetation and constructing burrows. They create a unique patchwork of prairie habitat that benefits a variety of wildlife (Foster and Hygnstrom, 1990). Unfortunately, prairie dogs may become a threat to livestock production and other agricultural interests in certain situations (Merriam, 1902; South Dakota Department of Agriculture, 1981; Hygnstrom and Virchow, 1994). Prairie dogs feed on many of the same species of grasses and forbs as livestock (Koford, 1958; Fagerstone et al., 1981; Uresk, 1984) and they may remove up to 80% of the available forage through their feeding and burrowing activities (Hansen and Gold, 1977; O'Meilia et al., 1982). Their selective feeding changes the species composition of rangelands they colonize over time (Koford, 1958; Bonham and Lerwick, 1976; Hansen and Gold, 1977; Coppock et al., 1983; Uresk, 1984; Archer et al., 1987). Prairie dogs also pose a threat to human health because they serve as a host of the bacterial agent of plague (*Yersinia pestis*) (Barnes, 1982, 1990). As a result, prairie dog colonies have been reduced or eliminated through a variety of means to enhance economic returns from crop and livestock production and to reduce the threat of plague epidemics.

* Corresponding author. Tel.: +1-402-472-6822.
E-mail address: shygnstrom@unl.edu (S.E. Hygnstrom).

0964-8305/00/$ - see front matter
PII: S0964-8305(00)00037-8

Prairie dog management has been reevaluated in recent years, particularly as it relates to the role of prairie dogs in the prairie ecosystem (Uresk, 1987; Whicker and Detling, 1988; Miller et al., 1994; Johnson et al., 1995; Stapp, 1998). Prairie dog colonies are used by up to 163 species of wildlife (Clark et al., 1982; Agnew et al., 1986; Reading et al., 1989; Sharps and Uresk, 1990) and are critical habitat for the endangered black-footed ferret (*Mustella nigripes*) (Mulhern and Powell, 1993). The area of land currently occupied by prairie dogs may represent less than 10% of their historical range (Anderson et al., 1986). The decline of prairie dog populations has been caused primarily by the conversion of native prairie to farmland and large-scale poisoning campaigns (US Fish and Wildlife Service, 1999). In addition, outbreaks of plague in prairie dog colonies and unrestricted prairie dog shooting may have contributed to the decline. Miller et al. (1994) criticized federally-sponsored eradication programs and called for the protection of prairie dogs under the Endangered Species Act (ESA). The US Fish and Wildlife Service is currently conducting a comprehensive review of the status of the black-tailed prairie dog to determine whether the species should be proposed for listing as a threatened or endangered species. In addition, development of a range-wide conservation strategy for black-tailed prairie dogs has been initiated by affected state and federal agencies and Native American Tribes.

Although environmental and conservation concerns are necessary and appropriate, private and public land managers feel they are justified in controlling the areal distribution and density of prairie dogs for economic, public health, and political reasons. A committee of the National Academy of Sciences (1970) concluded, 'the numerous eradication campaigns against prairie dogs and other small mammals were formerly justified because of safety for human health and conflicts with livestock for forage.' Currently, only three pesticides (zinc phosphide, aluminum phosphide, and gas cartridges) are federally registered by the US Environmental Protection Agency (EPA) for use in managing prairie dogs. Zinc phosphide, formulated as a grain bait or pellet (2% active ingredient [ai]), has been the most widely used toxicant for prairie dog control in recent history (Hygnstrom and Virchow, 1994), but concerns have been raised over bait avoidance, weather-dependent effects, general efficacy, environmental hazards, and labor requirements for application. Aluminum phosphide and gas cartridges are solid form fumigants registered for treating the tunnel systems of prairie dogs and other burrowing rodents. Magnesium phosphide (a solid form grain fumigant) and acrolein (a pressurized gas aquatic herbicide) are also registered by Special Local Needs provisions in some western States for the control of ground squirrels (*Spermophilus* spp.), prairie dogs, and other burrowing rodents (Timm, 1994). Concerns have been raised regarding the cost-effectiveness and ease of use of solid form fumigants (Hygnstrom and Virchow, 1994; Marsh, 1994), and the efficacy of these fumigants has been highly variable (Table 1).

Current limitations on pesticides for managing prairie dogs underscore the need for additional research on candidate compounds and alternative methods. We compared the cost-effectiveness of two solid form fumigants (aluminum phosphide [AP] and gas cartridges [GC]) and three pressurized gas–liquid fumigants (methyl bromide [MB], chloropicrin [CP], and a methyl bromide–chloropicrin mixture [MBCP]) for managing black-tailed prairie dogs. Our null hypothesis was that the mean reduction in burrow activity would be similar across the five treatments.

2. Materials and methods

2.1. Materials tested

The two solid form burrow fumigants tested were Phostoxin® (55% AP ai; 3 g tablets; Degesch America, Weyers Cave, Virginia, USA; EPA Reg. No. 40285-1), and Six-ingredient Gas Cartridges (ai include sodium nitrate [43.36%], charcoal [17.37%], mineral oil [14.09%], sawdust [3.52%], red phosphorus [3.25%], and sulfur [0.84%]; 9 cm long × 5 cm in diameter; US Department of Agriculture — Animal and Plant Health Inspection Service — Wildlife Services, Pocatello, Idaho, USA; EPA Reg. No. 56228-2). The three pressurized gas–liquid fumigants included Meth-O-Gas® (>99.5% MB ai; Great Lakes Chemical Corp. [GLCC], West Lafayette, Indiana, USA; EPA Reg. No. 5785-41), Chloropic® (>96.5% CP ai; GLCC; EPA Reg. No. 5785-17), and Brom-O-Gas® (98% MB ai and 2% CP [warning agent]; GLCC; EPA Reg. No. 5785-42). Reference to products is for identification only — it does not imply endorsement nor does exclusion of other products imply criticism.

Aluminum phosphide tablets function by releasing phosphine gas (H_3P) when they come in contact with moisture in the soil or atmosphere (Timm, 1994). The rate of hydrolysis of the tablets is directly proportional to the levels of soil temperature and moisture. Complete liberation of H_3P will occur within 2 days at 18–21°C and 90% relative humidity (Degesch America, 1986). The colorless gas has a specific gravity of 1.2 and it moves easily through burrows and associated porous soils. Death in rodents results from H_3P-induced asphyxia at minimum levels of 200 ppm (Timm, 1994), 10 mg m^{-3} for 6 h, or 300 mg m^{-3} for 1 h (Royal Society of Chemistry, 1990).

Pyrotechnic GC consist of a capped paper tube that contains six ai (reduced to two in 1994). When ignited by a fuse, the two primary ingredients (sodium nitrate and carbon) produce carbon monoxide (CO), sodium carbonate (Na_2CO_3), and nitrogen (N_2) (Ramey and Schafer, 1996). The gases and smoke flood the burrow and displace oxygen (O_2). The inhaled CO binds with hemoglobin in the red blood cells and inhibits O_2 transport in the circulatory system. Exposure of rodents to 1000 ppm of CO will result in unconsciousness in 1 h and death within 4 h (Timm, 1994).

Methyl bromide and CP are currently registered for the control of rodents in enclosed areas such as ship holds, storage bins, and warehouses (Food and Agriculture Organization of the United Nations, 1986; Jacobs, 1994), but neither is registered for use on prairie dogs. Methyl bromide (CBr_4) is used primarily as an insecticide in soil and storage facilities. The colorless, nonflammable gas has a specific gravity of 1.732 at 0°C. Acute exposure results in pulmonary edema, respiratory failure, cardiac arrest, and depression of the central nervous system. The 6-h inhalation LC_{100} for Norway rats is 17.8 mg m^{-3} (Royal Society of Chemistry, 1990). Chloropicrin (CCl_3NO_2) is a colorless, nonflammable, highly volatile liquid with a specific gravity of 1.636 at 20°C. The lachrymatory action of CP has led to its primary use as tear gas for warfare and crowd control. Chloropicrin is detectable at 0.2 mg m^{-3}. It is toxic to rodents at 32 ppm (Tigner and Bowles, 1964) or 3.4 mg m^{-3} for 30–60 min (Royal Society of Chemistry, 1990). The MBCP exhibits the combined chemical characteristics and toxic effects of MB and CP (Great Lakes Chemical Corporation, 1988).

2.2. Study area

We conducted the study on 13 black-tailed prairie dog colonies in central Nebraska during March–April, 1989. The colonies had been established more than five years and varied in size from 2 to 20 ha. Soils were characterized as deep, well-drained silty soils formed in loess on uplands, or in alluvium and loess on terraces and foot slopes (US Department of Agriculture —

Table 1
Efficacy of selected burrow fumigants for reducing rodent activity and density

Fumigant	Efficacy (%)	Method	Species	Reference
Acrolein	90	Burrow count	*Spermophilus beecheyi*	O'Connel and Clark (1992)
	90	Burrow count	*Spermophilus beecheyi beecheyi*	Clark (1994)
	90	Burrow count	*Spermophilus belingi oregonus*	Clark (1994)
	59	Burrow count	*Thomomys talpoides*	Matschke et al. (1998)
Aluminum phosphide	100	Excavation	*Spermophilus beecheyi*	Salmon and Bentley (1982)
	96	Burrow count	*Thomomys bottae*	Moline and Demarias (1987)
	95	Burrow count	*Cynomys ludovicianus*	Moline and Demarias (1987)
	80–90	Burrow count	*Rattus norvegicus*	Krishnamurthy and Singh (1967)
	69–82	Burrow count	*Oryctolagus cuniculus*	Oliver and Blackshaw (1979)
	64	Burrow count	*Oryctolagus cuniculus*	Ross (1986)
	36	Burrow count	*Nesokia indica*	Greaves et al. (1977)
Chloropicrin	69–82	Burrow count	*Oryctolagus cuniculus*	Oliver and Blackshaw (1979)
	48	Burrow count	*Thomomys bottae*	Miller (1954)
	50	Burrow count	*Oryctolagus cuniculus*	Gleeson and Maguire (1957)
Gas cartridge (2-ai[a])	100	Excavation	*Cricetelus barabensis*	Zhi and Chang (1986)
	100	Excavation	*Cricetelus triton*	Zhi and Chang (1986)
	100	Excavation	*Mus musculus*	Zhi and Chang (1986)
	100	Excavation	*Apodemus agrarius*	Zhi and Chang (1986)
	100	Excavation	*Rattus flavipectus*	Zhi and Chang (1986)
	100	Excavation	*Bandicota indica*	Zhi and Chang (1986)
	100	Excavation	*Rattus losea*	Zhi and Chang (1986)
	100	Excavation	*Marmota hymalayana*	Zhi and Chang (1986)
	84	Excavation	*Spermophilus richardsonii*	Matschke and Fagerstone (1984)
	77	Burrow count	*Rattus norvegicus*	Savarie et al. (1980)
	76	Burrow count	*Nesokia indica*	Khan et al. (1991)
Gas cartridge (6-ai)	80	Burrow count	*Marmota monax*	Dolbeer et al. (1991)
	22	Burrow count	*Thomomys talpoides*	Rost (1978)
	8	Burrow count	*Thomomys talpoides*	Sullins and Sullivan (1993)
Magnesium phosphide	86	Burrow count	*Nesokia indica*	Khan et al. (1991)
Methyl bromide	51–58	Burrow count	*Thomomys bottae*	Miller (1954)

[a] Active ingredient.

Soil Conservation Service, 1978, 1981). Annual precipitation in the region averaged 49 cm, with 25% occurring between November and March (Lewis, 1989). Soil moisture was relatively high due to the recent snowmelt and subsequent infiltration of water into the soil. The dominant vegetation was blue grama (*Bouteloua gracilis*), associated with buffalograss (*Buchloe dactyloides*), little bluestem (*Schizachyrium scoparium*), big bluestem (*Andropogon gerardii paucipilus*), prairie sandreed (*Calamovilfa longifolia*) and needleandthread (*Stipa comata*). Nearly all of the vegetation was dead or dormant due to the post-winter conditions. No livestock were present on the prairie dog colonies during the study. Before applying fumigants, the authors and three field assistants searched each colony four times for evidence of selected nontarget wildlife, using a survey protocol authorized by the Nebraska Game and Parks Commission. No evidence of black-footed ferrets, swift fox (*Vulpes velox*), or burrowing owls (*Speotyto cunicularia*) was observed.

2.3. Study design

Fifty-two variable-sized plots (~0.4 ha) were randomly located in the prairie dog colonies, each consisting of 50 active prairie dog burrows. The densities of burrows within the plots were similar (100–120 burrows ha^{-1}). We identified active burrows by sign of recent prairie dog excavation and feces, and lack of vegetation, spider webs, and debris in and around the burrows. We treated 25 of the burrows in each plot with one of the five randomly selected burrow fumigants. The remaining 25 burrows in each plot were untreated and served as controls. Materials were applied by experienced two- to four-person crews as efficiently as possible to allow for realistic cost analyses. Time periods associated with field preparation, application, and completion, were recorded.

We applied AP according to label directions, by inserting a polyvinyl-chloride (PVC) pipe (1.3 m long × 5 cm in diameter) into a burrow, rolling three tablets through the pipe and into the burrow, and removing the pipe. To minimize loss of the fumigant, we inserted a crumpled newspaper and packed soil into the burrow opening to form a tight seal. The GC were applied according to label directions, by inserting a screwdriver into one end and stirring the contents, inserting a 14-cm fuse into the same end, lighting the fuse, holding the cartridge until the contents ignited, and tossing the cartridge into the burrow, fuse end first. We packed soil into each burrow entrance and occasionally into adjacent burrows to minimize the loss of fumigant from the burrow.

The MB, CP and MBCP were contained in 66-kg pressurized cylinders mounted on the back of an all-terrain vehicle (ATV). A regulator; 15-m long, 1.25-cm diameter polyethylene hose; and 1-m brass wand with a hand-operated positive shut-off valve allowed application of the pressurized gases into the burrows. We inserted the wand into a burrow, and shoveled soil around it to help keep the gases in the burrow. The release valve was opened for 2 s to inject approximately 10 cm^3 of product into the burrow (Food and Agriculture Organization of the United Nations, 1986). We removed the wand and packed soil into the burrow entrance to minimize loss of fumigant from the burrow.

We used a modified plugged burrow technique (Tietjen and Matschke, 1982) to determine prairie dog activity in the treatment and control burrows. Shortly after fumigating the 25 treatment burrows in each plot, we plugged the entrances of the 25 untreated control burrows using the same procedure as the treatment burrows. All treatment and control burrows were marked with engineering flags to facilitate identification. We examined the treatment and control burrows in each study plot for activity 24 h later. Burrow activity was determined by the number of burrows opened by prairie dog excavation. Counts of reopened control burrows were used to adjust for possible bias in the plugged burrow counts of treatment burrows due to non-treatment mortality, animal activity, and observer error in identifying active burrows. The percent reduction in burrow activity attributed to each treatment was determined by the following:

1. No. of pre-treatment burrows active = ([No. of control burrows open/25] × No. of treatment burrows plugged) + No. of treatment burrows open then,
2. percent reduction in active burrows = (No. of treatment burrows plugged/No. of pre-treatment burrows active) × 100 (max = 100%).

We entered the data into an Excel spreadsheet (Microsoft, Remond, Washington, USA) and used a one-factor analysis of variance to determine if percent reduction in burrow activity differed among the five fumigant treatments (Snedecor and Cochran, 1980). The data were independent and variances among treatment groups ($F_{max[8,\,9]} = 2.33$) and control groups ($F_{max[8,\,10]} = 1.81$) were homogeneous.

We used a computer program developed by Cox and Hygnstrom (1991) to model the net cost-benefit of prairie dog control with applications of zinc phosphide (Zn_3P_2) baits followed by applications of AP. The program was designed to help ranchers, land managers, and resource agency personnel make informed decisions regarding prairie dog management. This project was approved by the University of Nebraska Institutional Animal Care and Use Committee (IACUC No. 88-11-004).

3. Results and discussion

3.1. Observed efficacy and costs

All five burrow fumigants were very effective in reducing burrow activity, with means ranging from 95 to 98% (Table 2). We failed to reject our null hypothesis as no significant differences ($P = 0.453$) in efficacy were evident among the five treatments. Variances were small and the number of opened treatment burrows per study plot ranged from 0 to 3 and opened control burrows ranged from 20 to 25. This level of efficacy is considerably higher than the 70% minimum standard established by the EPA (US Environmental Protection Agency, 1982). Tietjen and Matschke (1982) reported that the US Bureau of Indian Affairs used an unpublished minimum standard of 80% for the reduction of prairie dog activity on reservation lands.

Several fumigants have been proven to be effective at reducing the activity of burrowing rodents, particularly ground squirrels, prairie dogs, and woodchucks (*Marmota monax*) (Table 1). We feel our efficacy results were high, largely because the conditions for our field study were very conducive to fumigant activity. All of the plots were located in areas with relatively heavy, low porosity soils and we conducted the study about one month after snowmelt, so soil moisture was high. Low soil porosity (Matschke and Fagerstone, 1984; Ramey and Schafer, 1996) and high soil moisture (McClean, 1981; Ramey and Schafer, 1996) have been identified as important factors affecting the diffusion and efficacy of fumigants in burrow systems. Other factors affecting fumigant efficacy include: body weight (Matschke and Fagerstone, 1984); burrow configuration, burrow plugging behavior, and species tolerance to low levels of O_2 (Ramey and Schafer, 1996); species susceptibility to toxicants, concentration and properties of the fumigant, and duration of exposure (Gleeson and Maguire, 1957); and timing of application (Marsh, 1994).

Table 2
Percent reduction of black-tailed prairie dog burrow activity by five burrow fumigants, in variable-sized plots (*n* includes 25 treated and 25 untreated burrows), as measured by a plugged burrow technique in central Nebraska, 1989

Fumigant	*n*	Burrows opened				%
		Treatment		Control		
		x	Range	*x*	Range	
Aluminum phosphide	10	0.7	0–2	23.5	20–25	98
Gas cartridges	10	1.4	0–3	23.7	21–25	96
Methyl bromide	12	0.9	0–3	23.5	20–25	97
Chloropicrin	9	1.5	0–3	23.4	20–25	95
Methyl bromide-chloropicrin	11	1.0	0–3	23.9	21–25	97

The efficacy of AP in our study was similar to that reported by Moline and Demarias in 1982. Four unpublished reports also indicate 80–95% efficacy with AP on prairie dogs (Boggess, Kansas State University, 1979; US Fish and Wildlife Service, 1983a, 1983b; Bodenchuck and White, New Mexico Department of Agriculture, 1984). Aluminum phosphide has been relatively effective at reducing the activity of a variety of rodents, with the exception of the European rabbit (*Oryctolagus cuniculus*) and *Nesokia indica* (Table 1). Diminished efficacy may be related to low rates of H_3P liberation under cool or dry conditions (Degesch America, 1986). In addition, Oliver and Blackshaw (1979) experienced low dispersal rates of H_3P through burrow systems, but reported high levels of efficacy.

We found no differences in performance of the GC compared to the other four fumigants tested (Table 2). Efficacy of the GC on other species of burrowing rodents has been highly variable (Table 2). Gas cartridges are registered by EPA as a "General Use Product" and therefore are much more easily obtained than all other fumigants, which are registered as "Restricted Use Products." Annual sales of GC increased from 700,000 before 1975 to 2,000,000 after 1981, largely due to increased EPA restrictions on pesticide use and registration (Matschke and Fagerstone, 1984). Nearly one million GC were sold in 1991 (Packham, 1992). The six-ingredient GC, which we studied, was replaced in 1994 by the two-ingredient GC, primarily to simplify reregistration procedures. Ramey and Schafer (1996) provided an excellent review of the development of the pyrotechnic GC.

All three pressurized gas–liquid formulations in this study had relatively high levels of efficacy (Table 2). Methyl bromide has been used for fumigating soil, grain, food warehouses, processing plants, ship holds, cargo containers, and quarantined areas for years. The use of MB as a burrow fumigant has not been widely studied. Miller (1954) reported that MB was 51–58% effective in controlling valley pocket gophers (*Thomomys bottae*). Timm (1994) reported that Berry experienced success using 10 cm^3 of MB in burrows to kill ground squirrels in California. We found MB to be 97% effective in controlling prairie dogs. One concern with the use of MB is that it is essentially odorless and colorless, which increases the risk of human exposure, especially in enclosed areas. Hazards associated with outdoor applications are minimal if conducted by trained individuals and care is taken to avoid direct contact (Howard and Marsh, 1974). In 1992, the international treaty known as the Montreal Protocol identified MB as a chemical that contributes to the depletion of the Earth's ozone layer. The EPA has implemented a phase-out plan that will result in a ban on production and importation of MB in the US by 2005 (www.epa.gov/docs/ozone/mbr). About 43% of the worldwide consumption of MB occurs in the US (Anonymous, 1993). Several developing countries have agreed to stop using MB by 2015.

Chloropicrin is being promoted as an alternative to MB (www.msue.msu.edu/msue/imp/modcl) because it is an effective soil fumigant and it exhibits synergistic effects when mixed with other toxic gases. It is considered to be much safer than MB because its irritating effect to mucous membranes makes it easy to detect and humans could not withstand concentrations that would be lethal. Chloropicrin reduced prairie dog activity by 95% in our study. Efficacy on European rabbits and valley pocket gophers (*Thomomys bottae*) was considerably lower (Table 1). We were unable to find any studies in which CP was used on prairie dogs. Tigner and Bowles (1964) tested the efficacy of CP as a repellent for house mice (*Mus musculus*) in granaries, but reported that it might be more useful as a toxicant. Gleeson and Maguire (1957) noted that CP may not be a humane tool considering the irritation that must be endured by an animal exposed to concentrations of CP over a long period of time. The MBCP mixture is marketed by GLCC as Brom-O-Gas®, a commonly used soil fumigant for nematode control. It was initially considered as an alternative burrow fumigant because of the high efficacy of MB and the added safety of the CP as a warning agent. The MBCP was highly effective (97%) at reducing prairie dog activity. We were unable to locate any other studies in which MBCP was used as a burrow fumigant.

Retail costs for the five burrow fumigants in 1990 were as follows: AP — \$50.00 flask^{-1} (500 tablets), GC — \$32.00 carton^{-1} (100 cartridges), MB — \$0.91 kg^{-1}, CP — \$1.36 kg^{-1}, and MBCP — \$0.91 kg^{-1}. Material costs (\$ ha^{-1}) for the application of AP and GC were three to four times the cost of the three pressurized materials (Table 3). Our costs for AP and GC were similar to costs associate with applying acrolein as a burrow fumigant (O'Connel and Clark, 1992). Zhi and Chang (1986), reported that GC were cheaper to use than other fumigants. Gas cartridges are easier to obtain and have fewer restrictions than other prairie dog toxicants. Material costs are provided for comparative purposes and are subject to change by volume, season, year, and geographic region.

Table 3
Application costs (\$ ha^{-1} at 1990 prices) of five burrow fumigants for managing black-tailed prairie dogs (does not include application equipment) in central Nebraska, 1989

Fumigant	Materials	Labor	Total
Aluminum phosphide	37.50	37.50	75.00
Gas cartridges	40.63	56.25	96.88
Methyl bromide	9.54	28.13	37.67
Chloropicrin	13.63	28.13	41.76
Methyl bromide-chloropicrin	9.54	28.13	37.67

The application of fumigants, in general, has been recognized as time consuming and expensive (Hygnstrom and Virchow, 1994; Marsh, 1994). The time required to apply AP (7.5 h ha^{-1}) and GC (11.25 h ha^{-1}) was considerably more than the three pressurized gas–liquid fumigants (5.6 h ha^{-1}). Use of the ATV and mobile application system for the pressurized materials reduced application times considerably. ATVs would not be practical for the application of AP or GC. Each treatment required labor for burrow plugging, which accounted for 50–75% of the total cost for all fumigant applications. At \$5.00 h^{-1}, the labor costs to apply the five fumigants ranged from \$28.13 to \$56.25 ha^{-1} (Table 3). Salmon and Bentley (1982) reported that GC required 30% more time to apply than AP and did not achieve very effective control of California ground squirrels (*Spermophilus beecheyi*). The time required to apply fumigants varies relative to burrow density and topography.

The total cost of application of AP and GC was nearly twice the cost of either of the three pressurized gas–liquid fumigants (Table 3). Costs for application equipment were not included in the analysis because they are fixed and independent of the area of application. The equipment needed to apply AP (gloves, PVC pipe, newspaper, and shovel ~\$30) and GC (lighter, screwdriver, and shovel ~\$25) is readily available and costs considerably less than the equipment needed to apply pressurized gases (goggles, shovel, pressure regulator, 10-m hose, wand, ATV, trailer, and maintenance ~\$2500 to \$5000). To maintain cost-effectiveness with the pressurized materials, application equipment would have to be rented or purchased and used over a large area and depreciated over time.

Although costs from this study were closely monitored, the short duration of the project precluded examination of prairie dog recolonization rates. Subsequently, costs associated with repeat applications and long-term benefit-cost ratios were not reported. Prairie dogs have repopulated colonies to initial levels in as few as three years after poisoning (Schenbeck, 1982; Cincotta et al., 1987). Other research has indicated that a >95% reduction of prairie dogs is needed to preclude recolonization of an area within three to five years (Knowles, 1986). Perimeter and partial treatment led to recolonization in one to two years. Collins et al. (1984) reported that prairie dog control with Zn_3P_2 baits (a less expensive product ~\$18.75 ha^{-1} (Hygnstrom et al., 1998)) was not economically feasible on shortgrass prairie because the annual costs of controlling prairie dogs is greater than the annual value of forage gained. Uresk (1985) reported that prairie dog towns in South Dakota treated with Zn_3P_2

yielded no increase in forage production after four years.

3.2. Modeled cost/benefit

We used a computer program developed by Cox and Hygnstrom (1991) to model the net cost-benefit of a recommended procedure for prairie dog control using fall applications of Zn_3P_2 followed by spring applications of AP (Hygnstrom and Virchow, 1994). Comparisons of application frequency (no application; year 1 only; year 1, 4, and 7; and year 1 and 2) were made on hypothetical 64-ha shortgrass (SG) and mixed-grass (MG) pastures occupied by prairie dogs over a ten-year period (Table 4). The model estimates population growth and areal expansion of individual prairie dog colonies in the northern Great Plains with adjustments for age of the colony, range conditions, and other environmental factors. Costs include the economic value of forage lost due to prairie dogs on existing areas, costs of Zn_3P_2 and AP applications, and reduced stocking rates (in Animal Unit Months [AUMs]). Benefits include the value of AUMs gained on areas with reduced prairie dog densities or AUMs saved from the expansion of prairie dog colonies. Cost-benefit is equal to the total benefits minus the total costs. Uncontrolled population growth over ten years resulted in the expected areal expansion of the colony from 64 to 79 ha in SG and 64 to 68 ha in MG pastures. Clearly, the most costly strategies were to allow uncontrolled growth of the colonies (−$9,225 SG, −$8,910 MG, Table 4). Just one application of Zn_3P_2 in the fall and AP the following spring resulted in positive benefit/cost ratios in both SG and MG. The most cost-effective strategy in both SG and MG was to apply both Zn_3P_2 and AP during the first and second years. This approach in SG would lead to the elimination of all prairie dogs in the colony in two years with a net economic benefit of +$5,546. Eradication of a colony on MG would also be achieved in two years with a net economic benefit of +$5,084.

Control of prairie dogs with fumigants is not always cost-effective, but economic benefits from the model were maximized when fumigants were used in conjunction with previous fall applications of Zn_3P_2 bait, and when whole colonies were treated, no neighboring colonies were present, physical barriers inhibit immigration, and mid- and tallgrass species were present. Caution must be exercised when using economic models because of the risk of spurious results relative to potential inaccuracies in parameter values, multiplicative error, and violated assumptions (Maynard Smith, 1974). The model presented by Cox and Hygnstrom (1991) provides variables with default values that are supported in the scientific literature. Values can also be modified to reflect local conditions and data. At the very least, economic output can be used for relative comparisons of management strategies.

Fischer and Timm (1987) also recommended the application of Zn_3P_2 bait in the fall for managing prairie dogs, followed by the application of burrow fumigants in the spring. The Zn_3P_2 application should reduce burrow densities by about 75%. Bait shyness and EPA label restrictions limit the use of Zn_3P_2 to one application each year (Hygnstrom and Virchow, 1994). In addition, prairie dog populations are usually lowest before the spring birth pulse and soil moisture is relatively high. Since fumigant applications cost two to five times more than Zn_3P_2 applications, it is economical to apply fumigants to the relatively few active burrows that remain after a fall baiting program.

3.3. Nontarget effects

We observed no impacts to nontarget animals during this study. When used according to the label,

Table 4
Net cost/benefit ($ and Animal Unit Months [AUMs]) of prairie dog control using zinc phosphide (Zn_3P_2) baits and aluminum phosphide (AP) on 64-ha shortgrass and mixed-grass pastures occupied by prairie dogs over a ten-year period, as predicted by a model by Cox and Hygnstrom (1991)[a]

Application strategy	Shortgrass		Mixed-grass	
	Cost/benefit	AUMs lost	Cost/benefit	AUMs lost
No treatment	−9225	789	−8910	740
Zn_3P_2 and AP during year 1	+1380	574	+2163	460
Zn_3P_2 and AP during years 1, 4, 7	+2317	469	+1804	444
Zn_3P_2 and AP during years 1 and 2	+5546	285	+5084	256

[a] Model parameters and their default values include: prairie dog density in shortgrass prairie (SG) = 25 ha^{-1}, prairie dog density in mixed-grass prairie (MG) = 15 ha^{-1}, colony age = 20 years, maximum population finite rate of increase = 1.99, maximum area finite rate of increase = 1.87, forage lost to prairie dogs in SG = 90% reduction in cattle stocking rate, forage lost to prairie dogs in MG = 70% reduction in cattle stocking rate, forage consumed by one prairie dog = 9.9 kg $year^{-1}$, plant clippage by one prairie dog = 3.6 kg $year^{-1}$, cattle-prairie dog dietary overlap = 85%, forage consumed by one AUM = 405 kg, cost of hourly labor = 5.00 h^{-1}, cost of pasture lease = $18.75 ha^{-1}, cost of Zn_3P_2 application = $18.75 ha^{-1}, cost of AP application = $75.00 ha^{-1}, Zn_3P_2 efficacy = 75%, AP efficacy = 98%.

burrow fumigants are considered safe to humans and the environment because they are applied underground (Savarie et al., 1980). Littrell (1990) found no documentation of adverse effects associated with the use of burrow fumigants in California and ranked AP and GC among the least hazardous vertebrate pesticides. Current labels clearly present methods for reducing risks to nontarget animals (Fagerstone and Schafer, 1998). Fumigants should only be applied to active burrows. Burrows that show evidence of nontarget animals should be avoided. Surveys should be conducted for black-footed ferrets before applying burrow fumigants (Hygnstrom and Virchow, 1994). Apply fumigants in early spring before burrowing owls migrate back to prairie dog colonies.

4. Conclusions

The burrow fumigants we tested were highly variable in their formulation, cost, mode of action, and ease of use, but they all reduced black-tailed prairie dog activity ≥95%. Selection criteria for burrow fumigants were proposed by Savarie and Connolly (1984), which included (1) humaneness to the species in concern, (2) safety to humans and the environment, (3) availability at low cost, and (4) likelihood of registration with EPA or the US Food and Drug Administration. An additional criteria (a preference for a solid fumigant that is easy to handle, transport, apply, and store) was suggested by Fiedler et al. (1990). Some of the materials we tested excelled in certain areas, but none satisfied all of the selection criteria. Currently, AP and GC are registered by EPA, but they are relatively expensive and time-consuming to use. Candidate fumigants such as MB and CP are much less expensive and easier to use, but questions remain about the continued availability, environmental safety, and humaneness of these products. We encourage continued research on pressurized gas–liquid fumigants and alternative methods of prairie dog management.

Acknowledgements

We thank Claude Cole, Sonny Dimmit, Elmer Graham, Robert Lind, Edward MacMullin, Pete Matthews, Louise Miller, Russell Peterson, Gary Phillips, and Gary Stoelting for providing access to their property and allowing us to apply fumigants in their prairie dog colonies. Degesch, Incorporated, Great Lakes Chemical Company and the Pocatello Supply Depot, US Department of Agriculture — Animal and Plant Health Inspection Service — Wildlife Services provided materials for the study. Jim Sargent provided access to materials and technical expertise. Nancy Foster-McDonald assisted with various aspects of the field work. Jerry Evert, Rite-Way Fumigation provided application equipment and assisted with fumigant application. James Luchsinger, James Sargent, Dallas Virchow, and Gary Witmer reviewed various drafts of the manuscript. This project was funded by the University of Nebraska Integrated Pest Management — Vertebrates Program through a grant from the US Department of Agriculture — Cooperative State Research, Extension and Education Service.

References

Agnew, W., Uresk, D.W., Hansen, R.M., 1986. Flora and fauna associated with prairie dog colonies and adjacent ungrazed mixed-grass prairie in western South Dakota. J. Range. Manage. 39, 135–139.

Anderson, E., Forrest, S., Clark, T.W., Richardson, L., 1986. Paleobiology, biogeography, and systematics of the black-footed ferret *Mustella nigripes* (Audubon and Bachman), 1851. Great Basin Naturalist Memoirs 8, 11–62.

Anonymous, 1993. EPA plans phase out of methyl bromide. Grain Probe 6, 2. Gustafson, Dallas, Texas.

Archer, S., Garrett, M.G., Detling, J.K., 1987. Rates of vegetation change associated with prairie dog (*Cynomys ludovicianus*) grazing in North American mixed grass prairie. Vegetatio 22, 159–166.

Barnes, A.M., 1982. Surveillance and control of bubonic plague in the United States. Symposium of the Zoological Society of London 50, 237–270.

Barnes, A.M., 1990. Plague in the US: present and future. Proc. Vertebrate Pest Conf. 14, 43–46.

Bonham, C.D., Lerwick, A., 1976. Vegetation changes induced by prairie dogs on shortgrass range. J. Range Manage. 29, 221–225.

Cincotta, R.P., Uresk, D.W., Hansen, R.M., 1987. Demography of black-tailed prairie dog populations reoccupying sites treated with rodenticide. Great Basin Nat. 47, 339–343.

Clark, J.P., 1994. Acrolein as a ground squirrel burrow fumigant. Proc. Vertebrate Pest Conf. 16, 78–79.

Clark, T.W., Campbell, T.M., Socha, D.G., Casey, D.E., 1982. Prairie dog colony attributes and associated vertebrate species. Great Basin Nat. 42, 572–582.

Collins, A.R., Workman, J.P., Uresk, D.W., 1984. An economic analysis of black-tailed prairie dog (*Cynomys ludovicianus*) control. J. Range Manage. 37, 358–361.

Coppock, D.L., Detling, J.K., Ellis, J.E., Dyer, M.I., 1983. Plant–herbivore interactions in a North American mixed grass prairie. Oecologia 56, 1–9.

Cox, M.K., Hygnstrom, S.E., 1991. Prairie dog control: a computer model for prairie dog management on rangelands. Proc. Great Plains Wildl. Damage Control Workshop 10, 68–69.

Degesch America, 1986. Applicators manual for Degesch Phostoxin pellets and tablets. Degesch America, Weyers Cave, VA, 17 pp.

Dolbeer, R.A., Bernhardt, G.E., Seamans, T.W., Woronecki, P.P., 1991. Efficacy of two gas cartridge formulations in killing woodchucks in burrows. Wildl. Soc. Bull 19, 200–204.

Fagerstone, K.A., Tietjen, H.B., Williams, O., 1981. Seasonal variation in the diets of black-tailed prairie dogs. J. Mammal 62, 820–824.

Fagerstone, K.A., Schafer, E.W., 1998. Status of APHIS vertebrate pesticides and drugs. Proc. Vertebrate Pest Conf. 18, 319–324.

Fiedler, L.A., Ahmed, M.S., Ya, Z., 1990. Efficacy of burrow fumi-

gation in reducing rodent activity in Philippine rice fields. Proc. Internat. Conf. Plant Protection Tropics 3, 115–122.
Fischer, D.D., Timm, R.M., 1987. Laboratory trial of chlorophacinone as a prairie dog toxicant. Great Plains Wildl. Damage Control Workshop 8, 67–69.
Food and Agriculture Organization of the United Nations, 1986. Manual of fumigation for insect control. FAO Plant Production and Protection Paper No. 54, United Nations, New York.
Foster, N.S., Hygnstrom, S.E., 1990. Prairie dogs and their ecosystem. University of Nebraska, Department of Forestry, Fisheries and Wildlife. Lincoln, 8 pp.
Gleeson, J.P., Maguire, F.S., 1957. A toxicity study of rabbit fumigants. CSIRO Wildl. Res. 2, 71–77.
Great Lakes Chemical Corporation, 1988. Material safety data sheet. Great Lakes Chemical Corporation, West LaFayette, IN, 6 pp.
Greaves, J.H., Choudhry, M.A., Khan, A.A., 1977. Pilot rodent control studies in rice fields in Sind using five rodenticides. Agro-ecosystems 3, 119–130.
Hansen, R.M., Gold, I.K., 1977. Blacktail prairie dogs, desert cottontails and cattle trophic relations on shortgrass range. J. Range Manage. 30, 210–213.
Howard, W.E., Marsh, R.E., 1974. Rodent control manual. Pest Control 42 (8), D–U.
Hygnstrom, S.E., McDonald, P.A., Virchow, D.R., 1998. Efficacy of three formulations of zinc phosphide for managing black-tailed prairie dogs. Internat. Biodeter. Biodegrad. 42, 147–152.
Hygnstrom, S.E., Virchow, D.R., 1994. Prairie dogs. In: Hygnstrom, S.E., Timm, R.M., Larson, G.E. (Eds.), Prevention and Control of Wildlife Damage. University of Nebraska Cooperative Extension, Lincoln, pp. B85–96.
Jacobs, W.W., 1994. Pesticides federally registered for control of terrestrial vertebrate pests. In: Hygnstrom, S.E., Timm, R.M., Larson, G.E. (Eds.), Prevention and Control of Wildlife Damage. University of Nebraska Cooperative Extension, Lincoln, pp. G1–22.
Johnson, R.J., Case, R.M., Beck, M.M., 1995. Biodeterioration of the biosphere: where does wildlife damage management stand? Internat. Biodeter. Biodegrad. 36, 7–23.
Khan, A.A., Ahmad, M., Hussain, I., 1991. Evaluation of four fumigants against the short-tailed mole rat, *Nesokia indica* Gray and Hardwicke, 1932. Tropical Pest Management 37, 96–99.
Knowles, C.J., 1986. Population recovery of black-tailed prairie dogs following control with zinc phosphide. J. Range Manage. 39, 249–251.
Koford, C.B., 1958. Prairie dogs, whitefaces and blue grama. Wildl. Mono. 3, 1–78.
Krishnamurthy, K., Singh, P., 1967. Studies on rodents and their control. Part II: Control of field rats with aluminum phosphide. Bull. Grain Tech. 5, 173–175.
Lewis, D.T., 1989. Soils. In: Bleed, A., Flowerday, C. (Eds.), An Atlas of the Sandhills. Conservation Survey Division, University of Nebraska, Lincoln, pp. 57–66.
Littrell, E.E., 1990. Effects of field vertebrate pest control on nontarget wildlife (with emphasis on bird and rodent control). Proc. Vertebrate Pest Conf. 14, 59–61.
Marsh, R.E., 1994. Current (1994) ground squirrel control practices in California. Proc. Vertebrate Pest Conf. 16, 61–65.
Matschke, G.A., Fagerstone, K.A., 1984. Efficacy of a two-ingredient fumigant on Richardson's ground squirrels. Proc. Vertebrate Pest Conf. 11, 17–19.
Matschke, G.A., McCann, G.R., Doane, R.A., 1998. Evaluation of acrolein as a fumigant for controlling northern pocket gophers. Proc. Vertebrate. Pest Conf. 18, 223–227.
Maynard Smith, J., 1974. Models in Ecology. Cambridge University Press, New York, p. 146.
McClean, G.S., 1981. Factors influencing the composition of respiratory gases in mammal burrows. Comp. Biochem. Physiol. 69, 373–380.
Merriam, C.H., 1902. The prairie dog of the Great Plains. In: Yearbook of the USDA. US Government Printing Office, Washington, DC, pp. 257–273.
Miller, B.K., Ceballos, G., Reading, R.P., 1994. The prairie dog and biotic diversity. Conserv. Biol. 8, 677–681.
Miller, M.A., 1954. Poison gas tests on gophers. California Agric. 8, 7–14.
Moline, P., Demarias, S., 1987. Efficacy of aluminum phosphide for black-tailed prairie dog and yellow-face pocket gopher control. In: Great Plains Wildl. Damage Control Workshop, vol. 8, pp. 64–66.
Mulhern, D.W., Powell, K.L., 1993. The prairie dog ecosystem and endangered species. In: Proc. Great Plains Wildl. Damage Control Workshop 11, pp. 187–195.
National Academy of Sciences, 1970. Vertebrate Pests: Problems and Control. National Academy of Sciences, Washington, DC, 153 pp.
O'Connel, R.A., Clark, J.P., 1992. A study of acrolein as an experimental ground squirrel burrow fumigant. Proc. Vertebrate Pest Conf. 15, 326–329.
Oliver, A.J., Blackshaw, D.D., 1979. The dispersal of fumigant gases in warrens of the European rabbit (*Oryctolagus cunicularius*). Australian Wildl. Res. 6, 39–55.
O'Meilia, M.E., Knopf, F.L., Lewis, J.C., 1982. Some consequences of competition between prairie dogs and beef cattle. J. Range Manage. 35, 580–585.
Packham, C.J., 1992. The Pocatello supply depot: brief history, current functions, supplies available, and annual output. Proc. Vertebrate Pest Conf. 15, 22–24.
Ramey, C.A., Schafer Jr, E.W., 1996. The evolution of the APHIS two-gas cartridge. Proc. Vertebrate Pest Conf. 17, 219–224.
Reading, R.P., Bessinger, S.R., Gensten, J.J., Clark, T.W., 1989. Attributes of black-tailed prairie dog colonies in Northcentral Montana with management recommendations for conservation of biodiversity. In: Clark, T.W., Hinckley, D., Rich, T. (Eds.), The Prairie Dog Ecosystem: Managing for Biodiversity, Wildl. Technical Bull. No. 2. Montana Bureau of Land Management, Billings, pp. 13–27.
Ross, J., 1986. Comparison of fumigant gases used for rabbit control in Great Britain. Proc. Vertebrate Pest Conf. 12, 153–157.
Rost, G.R. 1978. Effectiveness of gas cartridges for pocket gopher control. US Fish and Wildlife Service Report. Boise, ID, 6 pp.
Royal Society of Chemistry, 1990. The Agrochemicals Handbook, 2nd ed. Thomas Graham House, Cambridge, England.
Salmon, T.P., Bentley, W.J., 1982. Aluminum phosphide (Phostoxin) as a burrow fumigant for ground squirrel control. Proc. Vertebrate Pest Conf. 10, 143–146.
Savarie, P.J., Connolly, G.E., 1984. Criteria for the selection and development of predacides. In: Kaukinen, D.E. (Ed.), Am. Soc. Testing Materials, Philadelphia, Pennsylvania, pp. 278–284.
Savarie, P.J., Tigner, J.R., Elias, D.J., Hayes, D.J., 1980. Development of a simple 2-ingredient pyrotechnic fumigant. Proc. Vertebrate Pest Conf. 9, 215–221.
Schenbeck, G.L., 1982. Management of the black-tailed prairie dog on the National Grasslands. Great Plains Wildl. Damage Control Workshop 5, 207–217.
Sharps, J.C., Uresk, D.W., 1990. Ecological review of black-tailed prairie dogs and associated species in western South Dakota. Great Basin Nat. 50, 339–345.
Snedecor, G.W., Cochran, W.G., 1980. Statistical Methods. Iowa State University Press, Ames, p. 507.
South Dakota Department of Agriculture, 1981. Vertebrate Rodent Economic Loss, South Dakota 1980, US Department of Agriculture, Statistical Reporting Service, Sioux Falls, 4 pp.

Stapp, P., 1998. A reevaluation of the role of prairie dogs in Great Plains grasslands. Conserv. Biol. 12, 1253–1259.

Sullins, M., Sullivan, D. 1993. Observations of a gas exploding device for controlling pocket gophers. Technical Report 93-01. Montana Department of Agriculture, Helena, 5 pp.

Tietjen, H.P., Matschke, G.H., 1982. Aerial prebaiting for management of prairie dogs with zinc phosphide. J. Wildl. Manage. 46, 1108–1112.

Tigner, J.R., Bowles, W.A., 1964. Chloropicrin tested as an area repellent for house mice. Wildl. Soc. Bull. 28, 748–751.

Timm, R.M., 1994. Description of active ingredients. In: Hygnstrom, S.E., Timm, R.M., Larson, G.E. (Eds.), Prevention and Control of Wildlife Damage. University of Nebraska Cooperative Extension, Lincoln, pp. G23–61.

Uresk, D.W., 1984. Black-tailed prairie dog food habits and forage relationships in western South Dakota. J. Range Manage. 37, 325–329.

Uresk, D.W., 1985. Effects of controlling black-tailed prairie dogs on plant production. J. Range Manage. 38, 466–468.

Uresk, D.W., 1987. Relation of black-tailed prairie dogs and control programs to vegetation, livestock, and wildlife. In: Caperinera, J.L. (Ed.), Integrated Pest Management on Rangeland: A Shortgrass Prairie Perspective. Westview Press, Boulder, CO, pp. 312–322.

US Department of Agriculture — Soil Conservation Service, 1978. General Soil Map of the Grand Island, Nebraska. Conservation and Survey Division, University of Nebraska, Lincoln.

US Department of Agriculture — Soil Conservation Service, 1981. General Soil Map of the Broken Bow Area, Nebraska. Conservation and Survey Division, University of Nebraska, Lincoln.

US Environmental Protection Agency, 1982. Pesticide assessment guidelines, subdivision G: product performance (96-13: Rodent Fumigants). EPA-540/9-82-026. Office of Pesticide Programs, Washington, DC, pp. 316–318.

US Fish and Wildlife Service, 1999. US Fish and Wildlife Service to Conduct Comprehensive Review of black-Tailed Prairie Dog Status. US Fish and Wildlife Service, Lakewood, CO News release and associated fact sheet.

Whicker, A.D., Detling, J.K., 1988. Ecological consequences of prairie dog disturbances. BioScience 38, 778–785.

Zhi, D., Chang, Z.W., 1986. Efficacy of a carbon monoxide gas cartridge against field rodents. Proc. Vertebrate Pest Conf. 12, 163–165.