Ecological Effects of Deltamethrin Insecticide in Prairie Dog Colonies of Western South Dakota

by

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A thesis submitted to the Graduate Faculty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Master of Science

Auburn, Alabama
May 7, 2016

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Abstract

In North America, plague is a relatively novel disease, causing many species to be highly to moderately susceptible to infection. The plague bacterium, *Yersinia pestis,* is spread between mammals by fleas (Siphonaptera), and, during an outbreak, causes entire prairie dog (*Cynomys* spp.) colonies to die off. These outbreaks are of particular conservation concern as they have slowed the recovery of the endangered black-footed ferret (*Mustela nigripes*) which feeds almost entirely on prairie dogs. In many areas where black-footed ferrets have been reintroduced, prairie dog colonies are treated with deltamethrin, a pytheroid insecticide that reduces flea populations and therefore reduces the spread of plague. Although this treatment has been successful at increasing survival of ferrets and prairie dogs while preventing outbreaks of the disease, little is known about the secondary effects of this treatment. I aimed to determine the effects of deltamethrin of non-target flea and arthropod populations to assess impacts to small mammals present on prairie dog colonies. Fleas, insects, and small mammals were assessed on prairie dog colonies at Wind Cave National Park, SD and Custer State Park, SD across six pairs of treated and untreated grids. In both 2013 and 2014, four small mammal trapping sessions occurred resulting in the capture of 146 and 280 deer mice (*Peromuscus maniculatus*) and the collection of 167 and 67 fleas respectively. Mouse fecal samples were collected from captured mice to analyze the consumption of arthropods and pit fall traps were placed throughout grids and opened for 3 sessions annually to assess the abundance of arthropods on the grids. Deltamethrin was shown to reduce the likelihood of flea infestation in mice on grids treated with deltamethrin in 2013 but not 2014 when overall infestation was low. Due to the large amounts of insects collected, specimens are still being identified to family. Three major beetle families, Scarabaeidae, Tenebrionidae and Carabidae, were pulled from 2014 samples and tallied. Scarabaeidae beetles were found in reduced numbers on treated grids, before the second annual treatment but returned to similar number after treatment.

Fecal sample analysis revealed that deer mice on treated and untreated grids did not vary in their consumption of arthropods in either year. Analysis of mouse survival and population in frequentist and Bayesian frameworks revealed minimal to no change in mouse populations between treated and untreated areas as a small decline was noted in one session from one analysis. Overall, deltamethrin has a positive impact by reducing the fleas present on small mammals with minimal and non-lasting negative effects on arthropod populations. These effects did not impact mouse populations present on treated areas, supporting the use of deltamethrin. However, deltamethrin should be used with caution as minor declines observed in arthropod and mouse populations could be magnified with repeated uses. To maximize the benefits deltamethrin should be applied in years of high flea populations while forgoing treatment in low population years to reduce any negative impacts.

Acknowledgements

I would like thank my adviser, Bob Gitzen, for his unending cheerfulness and optimism throughout the duration of the project. I would additionally like to thank Todd Steury, Charles Ray, and Josh Millspaugh for their assistance as committee members. I am additionally grateful to Charles Ray and his team at the ALFA lab for their assistance in identifying almost countless arthropods.

A special thanks to the National Park Service, particularly Dan Licht, for the funding and creation of this project. I cannot forget those Dan Roddy and Barb Muenchau at Wind Cave National Park for allowing me to use their park, knowledge, and expertise to complete this project. Additional thank to those at Custer State Park that allowed me utilize their prairie dog colony. Thank you to the Rocky Mountain Research Station for the use of their traps. This project would have been impossible to complete without the aid of my technicians and those at Wind Cave that sacrificed their weekends to assist us. Additionally I would like to thank those at the National Park Service Wildlife and Health Division and the Wildlife Health Lab in Madison, Wisconsin for their assistance in identifying and testing collected fleas.

Finally, I have to thank my family who listened to me rant about parasites, poo, and mice for the past 24 years. I additionally thank them for spending their past 3 vacations in South Dakota and for spending those days digging holes in the prairie.

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CHAPTER 1

Deltamethrin Impacts on Flea Populations of Non-target Deer Mice (*Peromyscus maniculatus*) in Prairie Dog Colonies

INTRODUCTION

Since its introduction into North America in the early 1900's, the plague bacterium, *Yersinia pestis*, has spread throughout much of the western part of the continent (Centers of Disease Control 1994). Also known as the black plague, this bacterium is well known as the cause of human pandemics in Europe and Asia. It is spread between mammals by flea bites (Simond 1898). In North America, plague is a relatively novel disease, causing many species to be highly to moderately susceptible to infection (Thomas et al 1988). This is of particular concern for already declining populations that are further impacted by this disease, particularly prairie dog (*Cynomys) species*, which can suffer near 100% mortality during an outbreak (Biggins and Kosoy 2001, Cully et al. 1997, and Pauli et al. 2006). Before plague entered prairie dog systems, many colonies were being poisoned, shot, or trapped, reducing the range of prairie dogs by over 99% (Luce 2002, Proctor et al. 2006). The removal of this keystone mammal contributed to declines in many species that occupy the unique habitat of prairie dog colonies, including the endangered black-footed ferret (*Mustela nigripes*), burrowing owl (*Athene cunicularia*), and American badger (*Taxidea taxus)* (Dinsmore et al. 2001, Kotliar et al. 1999, and Miller et al. 2000, Stapp 1998). The addition of plague has made the already vulnerable colonies more fragile, by reducing the connectivity of colonies and survival of prairie dogs within colonies (Antolin et al. 2002, and Biggins et al. 2010).

In prairie dog systems, plague exists in both enzootic and epizootic states. When a colony is in an enzootic state, plague is not rapidly spread but still reduces survival of susceptible animals (Biggins et.al 2010). However, during an epizootic outbreak, the infection is widely spread between hosts, causing large die offs or local extirpations of infected populations of susceptible species (Cully et al. 1997). Although it is still unclear what maintains enzootic states and triggers epizootic events, these dynamics are likely driven by weather and climate variables (Stapp et al. 2004, Collinge et al. 2005). Fleas in shallow burrows are sensitive in hot dry years and if not protected by the microclimate of the burrow can easily desiccate, leading to reduced populations (Krasnov 2008, Salkeld and Stapp 2008). However after wet mild years, flea populations increase. The additional precipitation benefits the fleas

directly, by reducing desiccation of fleas, and indirectly, by increasing the growth of vegetation. This boost in available food leads to population growth in prairie dogs and other rodents, thereby increasing food sources for the fleas (Collinge et al. 2005).

Flea species that are present on prairie dogs and other mammalian hosts vary in their ability to transmit the plague bacterium. In many flea species, the replicating bacterium forms a blockage in the mid-gut of the flea, starving it and increasing the frequency of feeding. After a blockage forms, the flea is prevented from consuming the bacteria causing it to regurgitate the blood with the bacterium in it. However, the bacterium can also be transmitted shortly after feeding on an infected host, before a blockage is formed (Eisen and Gage 2009). While prairie dog fleas (*Oropsylla spp.*) are efficient transmitters of plague, other flea species do not replicate the bacteria as well or form blockages, reducing transmission efficiency (Gage and Kosoy, 2005). Additionally, length of survival of the mammalian host after infection impacts the spread of the disease. In years with high host and flea populations, even fleas with low transmission rates play a significant role in the transmission of plague (Eisen et al. 2007 and Krasnov et al. 2006).

The black-footed ferret, which feeds almost solely on prairie dogs, is an obligate species to prairie dog colonies (Kotliar et al. 1999). Efforts to reintroduce and restore populations of black-footed ferrets have been slowed by the presence of plague, as both ferrets and their prairie dogs are highly susceptible to plague (Cully et al. 1997, Pauli et al. 2006, Rocke et al. 2008). To restore and maintain populations of ferrets and other species dependent on prairie dog colonies, managers need to maintain the health of prairie dog colonies. Currently two direct strategies to reduce flea impacts on prairie dogs and endangered ferrets are being utilized: vaccines to protect ferrets from infection, and application of deltamethrin insecticides in prairie dog burrows to reduce the flea vector and reduce the probability or severity of a plague outbreak (Jones et al. 2011, Rocke et al. 2004). Deltamethrin is a pyretheroid insecticide that disrupts the nervous system of arthropods and is widely used in both agricultural and household settings. In prairie dog systems, deltamethrin is applied within the burrows as a waterproof powder called DeltaDust™ (0.05% deltamethrin, Bayer Pharmaceuticals). The dusting treatment removes fleas from the burrows and on the associated prairie dogs for at least 84 days and is thought to be effective for up to eight months (Seery et al. 2003). This treatment increases survival of prairie dogs and is thought to have prevented plague outbreaks in observed colonies. Additionally, between outbreaks this treatment increases the survival of prairie dogs and black-footed ferrets (Biggins et. al 2010).

Given the desired effects of deltamethrin treatment on prairie dogs, this insecticide has become widely used to protect and preserve prairie dog colonies to aid in black-footed ferret recovery. However, it is unknown whether deltamethrin treatment also affects non-target small mammals that live on the colonies and may utilize prairie dog burrows. Reducing fleas on these non-target populations could further reduce the effect of the disease. Many small mammal species may play a vital role in the persistence of plague by maintaining the infection and spreading the bacteria between sites (Seery et al. 2003. Additionally, since many rodent species are highly to moderately susceptible to the plague, their populations may be impacted by the introduced disease (Thomas et al. 1988). However, the frequency with which small mammals use the burrows, and therefore are exposed to the insecticide, is unknown. If the small mammals are infrequently exposed to the insecticide, the reductions of the flea populations of non-target small mammals may not be as dramatic as those in prairie dog populations. While prairie dogs are known to be protected for several months, the length of time that these treatments may be effective on small mammals is also unknown. As small mammals play a large role in plague ecology, managers attempting to reduce plague effects in prairie dog towns need a better understanding of the impacts of plague treatment and the process of flea recolonization after dusting (Stapp et al. 2008, 2009).

To determine the effects of prairie dog colony deltamethrin treatment on flea loads of small mammals, we compared rates of flea infestation of deer mice between experimentally treated and untreated populations in western South Dakota (Duckwitz 2001). Deer mice (*Peromyscus maniculatus*) were chosen as the focal species as they are the most commonly found small mammal in prairie dog colonies aside from prairie dogs. Our objectives were to quantify the magnitude and duration of such treatment effects. We expected that after treatment, flea populations on treated grids would be greatly reduced while those on untreated grids would remain constant as mice are expected to interact with prairie dog burrows and come into contact with the insecticide. We additionally expected that treatment effects would still be apparent, but less pronounced, between years as the deltamethrin will degrade from the burrows and may not be at concentrations high enough to impact fleas.

Study Area

We conducted this investigation at Wind Cave National Park and Custer State Park in the summers of 2013 and 2014. Both parks are located in the southern Black Hills of South Dakota and support multiple prairie dog colonies. Following reintroduction of black-footed ferrets in 2007, Wind

Cave National Park began using Deltadust ™ in 2008 to protect prairie dog colonies and reintroduced black-footed ferrets from possible plague outbreaks. In the park, Deltadust is sprayed annually within all prairie dog burrows in colonies where ferret activity is highest. Custer State Park does not dust any of its prairie dog colonies but one colony that is shared with Wind Cave National Park is known to have ferrets. While there have been no outbreaks of the plague in either park, plague has been detected in Fall River and Custer Counties, where the parks are located (Abbott and Rocke 2012). To assess the impact of this treatment, we studied 3 colonies that had not previously been treated, two in Wind Cave National Park and one in Custer State Park (Figure 1). Prairie dog colonies were identified by the presence of prairie dogs, their active burrows, and short grasses from their intense grazing. Primary vegetation species of colonies in these parks included purple three awn (*Aristida purpurea*), large bract vervain (*Verbena bracteata*), Canada thistle (*Cersium arvense*), common hoarhound (*Marrubium vulgare*), western wheat grass (*Pascopyrun smithii*), and grama grasses (*Bouteloua spp.*) (Cogan et al. 1999).

METHODS

Data Collection

Within each selected colony, two pairs of 1.44 hectare units were established, for a total of 12 experimental units. Within each pair, one unit was randomly selected for treatment while the other served as a control. In each treatment area, all prairie dog burrows were dusted with approximately four to six grams of DeltaDust at an intended depth of eight inches into the burrow using an applicator wand. Prairie dog burrows within each treatment unit were treated with Deltadust (0.05% deltamethrin) using standard methods once per year (2013 and 2014) 1-2 days before the second small mammal sampling session in late May or early June. To sample small mammals, an eight by eight grid of 7 cm x 9 cm x 25 cm folding, aluminum, Sherman live traps (H.B Sherman Traps, Tallahassee, FL) were placed within the 1.05 ha core area of each experimental unit. Grid spacing was 15 meters between trap stations, with a single trap placed at each station. All experimental units on each colony were trapped 4 times each year between May and August in 2013 and 2014, at approximate two week intervals between trap sessions. Each of the 8 total trap sessions consisted of four trap nights, with all units within a colony trapped simultaneously. Traps were baited with a mixture of peanut butter and oats and provided with polyester or cotton bedding. Each trap was sheltered from sun and camouflaged with a brown cloth tent (Figure

2). Initially traps were check in both the morning and evening but after it was determined that only nocturnal small animals were captured, traps were checked daily in the early morning.

Upon capture, small individuals were handled in a clear plastic Ziplock™ bag while larger animals that may easily rip a plastic bag were handled in a cloth handling cone. Animals were identified to species using mass, hind foot length, tail length, and coloration. Before release each animal was marked with an individually numbered metal ear tag (National Band & Tag Co., Newport, KY, Monel self-piercing tags, 1005-1).

Fleas were sampled from all captured small mammals at each capture event. Captured deer mice were anesthetized using 0.1-0.05 ml isoflurane. The isoflurane was applied to a cotton ball which was confined in a ball shaped tea infuser to prevent direct contact between the animal and the drug. The infuser was then placed in the Ziplock™ bag with the animal to anesthetize the animal and any fleas. While the animal was unconscious, it was brushed using a cat flea comb over a white sheet of paper to remove all fleas. The use of anesthesia allowed thorough combing and also made fleas drop off the animal into the handling bag, ensuring near perfect detection (Eads et al 2013). Fleas also were collected from the Ziplock™ bag and bedding from the trap. All collected fleas were stored in 90% ethanol. Fleas were sent to the Center for Disease Control in Fort Collins, Co. and the USGS National Wildlife Health Center in Madison, WI. to be identified and tested for plague bacterium following PCR (polymerase chain reaction) methods established by Taylor and others (2010)(Auburn University IACUC protocol 2013-2262).

Analysis

Treatment effect on infestation was analyzed in R (R Development Core Team 2014) with package "lme4" (Bates et al. 2015). For each trap session in which a mouse was combed, the mouse was either considered infested (having fleas on one or more combing occasions) or uninfested. The counted totals of infested or uninfested mice for each trap session were then used in the general linear mixed effects model to determine if treatment impacted the proportion of infested mice. Pair, unit (grid), and pair by session were included as random effects while fixed effects of colony (with 3 colonies sampled, incorporating colony as a random effect was not warranted) and session by treatment were included to examine the variation in treatment effect by session within and between years. A likelihood ratio test was used to compare a model including session-specific treatment effects to one that omitted

treatment to assess evidence for an overall effect of treatment; and session-specific treatment effects were estimated.

RESULTS

In 2013, there were 347 combing sessions of 144 individual *Peromyscus maniculatus* resulting in the collection of 167 fleas. In 2014, 67 fleas were collected from 540 *Peromyscus* combing sessions of 273 individuals (Table 1). Two fleas were collected from one thirteen-lined ground squirrel in 2013.The number of fleas removed from mice ranged from 1 to 16 fleas per combing session. From all combing sessions, 88% resulted in the collection of no fleas. From combing sessions where fleas were collected, 64% resulted in finding 1 flea, 14% in 2 fleas, and 10% in 3 fleas. Fleas counts larger than 3 fleas per combing session were rare with 4,6, and 11 fleas being found 2% of the time, 5 fleas 4% of the time and 7, 10, and 16 fleas being found in less than 1% of combings.

Five species of flea were collected from deer mice*: Aetheca wagerni*, *Malaraeus telchinus*, *Peromyscus hesperomys*, *Stenopia americana*, and *Eiptidea wenmani* (Table 2). *Aetheca. wagerni* was the most widely found flea and most common flea in 2013 (57% of collected fleas) and second most frequently found flea in 2014 (29% of collected fleas). *M. telchinus* was also widely found and the second most common in flea in 2013 with 26% of collected fleas and the most common in 2014 (45%). *P. hesperomys* was not consistently found across all colonies but was frequently collected in the South East colony in both years (2013=14%, 2014=22%). I found single specimens of *E. wanmani* each year and a single *S. americana* (in 2013). All fleas were tested for plague with no positive results.

In both years, the South East colony had relatively high flea numbers and the greatest diversity of fleas. Across all grids, fewer fleas were collected in 2014 than in 2013 (Table 1), with fleas declining on the South East and Highland Creek colonies. Similarly, the rate of infestation (infested mice/total mice) was lower in 2014 (7.1%) than in 2013 (18.6%). Relative to South East and Highland Creek colonies the Custer colony had low flea numbers in 2013 (4) but had a large increase in 2014 (28).

Dusting treatments reduced fleas in 2013: infestation rates on treated sites were reduced after treatment (1=0.09, 2=0.02, 3=00.03, 4=0.13) while infestation increased, compared to pre-treatment levels on untreated sites (Session 1=0.16, 2=0.21, 3=0.27, 4=0.42). In 2014 this decline was only apparent for the first sampling session after treatment(1=0.11, 2=0.01, 3=0.08, 4=0.09) and infestation on untreated sites remained low throughout the summer (1=0.04, 2=0.03, 3=0.06, 4=0.08)(Table 4).

In binomial logit models fit to infestation data, a model with a treatment by trap session interaction (df = 21, log likelihood = -95.6) was supported over the equivalent model with no effect of treatment included (df = 13, log likelihood = -111.3; P <0.001 for likelihood ratio test testing null hypothesis that the model with no treatment effect incorporated was adequate compared to treatment by session model). As expected, the dusting significantly reduced infestation; however, this effect was evident only during 2013. Based on model coefficients (Table 5) and resulting odds ratios (Figure 3), compared to mice on treated grids, those on untreated grids were 2 times, 3 times, and 4 times as likely to be infested during post-treatment 2013 trap sessions 2, 3, and 4, respectively, with estimated effects strongest during the first 2 trap sessions after treatment. However, infestation rates were similar between treated and untreated units throughout 2014, with very high uncertainty in 2014 treatment effects likely due to the low levels of fleas across all sites.

DISCUSSION

All flea species collected were typical mouse fleas which all have the capacity for carrying the plague (Gage 1998). The presence of these fleas indicates that plague can be spread within the mouse populations at Wind Cave National Park when flea, rodent, and plague populations are high. Although these flea species have low transmission efficiency, mice and their fleas could still play a significant role in plague systems (Stark 1958). Rodent and other small mammal species have carrying roles in the spread and maintenance of plague depending on population size, susceptibility, behavior, and habitat (Gage and Kosoy 2005). Small mammals, particularly grasshopper mice, are often considered enzootic hosts and play a role in maintaining plague and even promoting the progression of plague into an epizootic outbreak (Salked et. al 2010). These epizootics were often triggered in years with high levels of grasshopper mice as they acted as alternate hosts *for O. histura* (Stapp at al 2009). While deer mice are not thought to directly contribute to the maintenance of plague, it has been hypothesized that they could play a significant role in areas where deer mice are particularly dense and have high flea levels (Salked and Stapp 2008).

While none of the sampled fleas tested positive for plague, plague may still be present in the ecosystem. When sampling rodents in epizootic conditions plague has been found in fleas on the small mammal; however, the bacteria is difficult to detect in small mammals and fleas associated with prairie dog colonies, especially in enzootic conditions (Holdenried and Morlan 1995, and Thiagarajan et al.

2008). Even in cases when a flea is collected from an animal that is infected with *Yersinia,* the bacteria may not be found (Engelthaler and Gage 2000). When prairie dog colonies are in epizootic states, a maximum infection rate of 15% of the entire flea population has been observed, with only a small percentage of those fleas harboring enough bacteria to transmit to a host (Engelthaler and Gage 2000).

While flea populations vary dramatically between years and seasons depending on a variety of conditions, I observed a strong effect of treatment in year one. The first year data shows that the deltamethrin treatment was effective in reducing flea infestation when compared to the initial population of fleas before treatment as well as in comparison untreated sites. After treatment, the flea infestation rate on untreated colonies increased for the rest of the summer while the number of mice with fleas on treated sites dropped to very low levels. This reduction shows that burrow based insecticide application does impact fleas on non-target small mammals and that dusting may help to reduce plague in the entire system, not just within prairie dog communities. However, in the second year, a treatment effect was not apparent. Instead, I observed low flea numbers across all colonies and sites regardless of treatment. This dramatic reduction in of flea numbers was seen at other sites in the park that had never been dusted and was likely due to the dry conditions experienced the previous year, leading to the desiccation of many juvenile fleas (Eads 2014). Therefore, deltamethrin treatment may have little effect on flea infestations in years with low flea numbers. This suggests that managers should focus on treating colonies treatments after wet years when flea, small mammal, and prairie dog populations are high and may forgo treatments following dry years when fleas are naturally reduced. This strategy could save managers time and money spent on yearly dusting while also reducing secondary impacts that an insecticide may have on the ecosystem.

Given the length of trapping and the dramatic drop in flea populations throughout all study sites by the start of second summer, I could not fully determine the duration of the effects on deltamethrin. However, the effects of deltamethrin on non-target small mammals were seen throughout the first summer and lasted for at least seven weeks. No reduction was seen between years, but this was likely due to the overall weather-related reduction of fleas. However, the small size of my treatment units (1.15 ha) could allow for fleas to more easily re-populate than when an entire colony is treated. This study focused on differences in treatment and control plots within prairie dog colony instead of comparing between colonies because differences in flea and small mammal populations between colonies were uncertain and only a few large, stable colonies that had not been dusted were available.

Studies on whole colony level would be more realistic as plague impacts entire colonies and treatments occur on a colony level.

Deltamethrin was found to have a strong negative effect on mouse flea populations in 2013, indicating that this treatment is effective at reducing flea vectors on non-target animals. Since the ways that plague is spread and retained within prairie dog colonies is still unsure, it is important to understand the impacts on potential carriers. As all flea species found in this study have been shown to be carriers for plague (Stark 1958), this treatment may help in reducing the overall prevalence of plague within the park and the likelihood of a plague outbreak. The reductions of small mammal fleas could slow the movement of plague between colonies by preventing the infection of predators that carry plague, such as coyotes. This re-affirms the effectiveness of deltamethrin treatment of prairie dog colonies as it acts to mitigate the effects of plague across the prairie dog ecosystem instead of within one species. The reduced flea populations increase the overall health of the prairie dog colonies ensuring prairie dogs continue to support a healthy prairie and populations of black-footed ferrets.

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TABLES AND FIGURES

Figure 1.1. Study colonies in Wind Cave National Park (black boundary) and adjacent Custer State Park in western South Dakota (inset). Trapped prairie dog colonies are gray; sampling grids are indicated with a black dot.

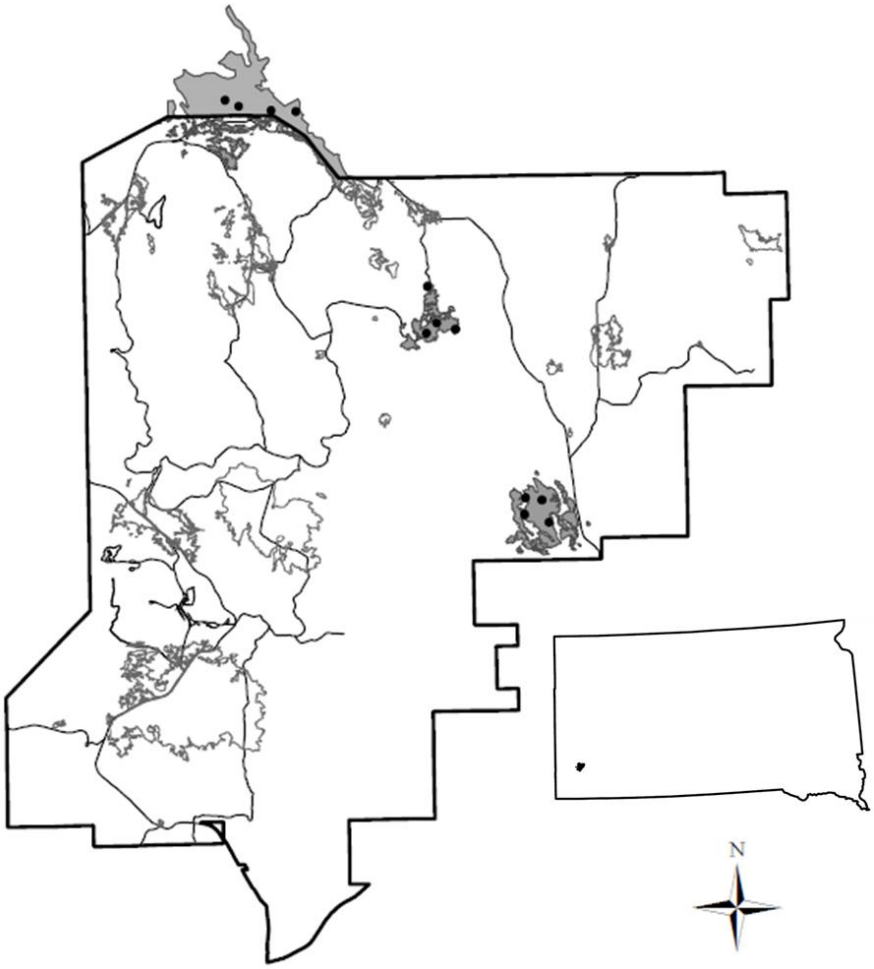


Figure 1.2. Sherman trap used to capture small mammals with a cloth cover.

Table 1.1. Total number of infested and uninfested (i.e. no fleas) deer mice for each prairie dog colony by year at Wind Cave National Park (South East, Highland Creek) and Custer State Park, SD.

Year	Colony	Infested	No Flea	Percent Infested
2013	South East	41	149	21.5
	Highland Creek	23	91	20.2
	Custer	2	49	3.9
2014	South East	20	233	7.9
	Highland Creek	4	143	2.7
	Custer	15	135	10.07

Table 1.2. Fleas collected from deer mice (*Peromyscus maniculatus*) in summers of 2013 and 2014 from prairie dog colonies at Wind Cave National Park and Custer State Park, South Dakota.

Year	Colony	Species	Male	Female	Total
2013	South East	*Aetheca wagerni*	18	22	40
		Malaraeus telchinus	10	30	40
		Peromyscopsylla hesperomys	7	16	23
		Stenopia Americana	1	0	1
	Highland Creek	*Aetheca wagerni*	16	38	54
		Epitidea wenmani	1	0	1
		Malaraeus telchinus	2	2	4
	Custer	*Aetheca wagerni*	1	0	1
2014	South East	*Aetheca wagerni*	3	1	4
		Malaraeus telchinus	2	4	6
		Peromyscopsylla hesperomys	5	8	13
		Epitedia wenmani	0	1	1
	Highland Creek	*Aetheca wagerni*	0	1	1
		Malaraeus telchinus	2	6	8
		Peromyscopsylla hesperomys	1	0	1
	Custer	*Aetheca wagerni*	4	9	13
		Malaraeus telchinus	4	10	14

Table 1.3. Number of fleas collected from each sampling grid during each trapping session in prairie dog colonies at Wind Cave National Park (SE = South East, HC = Highland Creek)and Custer State Park (CSP) during the summers of 2013 and 2014. Annual deltamethrin treatment is indicated by a red line and treated grids are highlighted in grey.

Year	Site	Grid	Session			
			1	2	3	4
2013	SE	1A	25	39	11	5
		1B	1	1	0	0
		2A	7	7	2	
		2B	4	0	0	0
	HC	1A	1	1	0	1
		1B	3	1	41	9
		2A	0	0	3	0
		2B	2	0	0	
	CSP	1A		0	0	
		1B	0		2	0
		2A	0	0	1	
		2B	0	0	0	1
2014	SE	1A	0	2	1	0
		1B	1	0	0	2
		2A	2	1	0	2
		2B	3	0	7	3
	HC	1A	0	0	0	0
		1B	8	0	0	1
		2A	0	0	0	0
		2B	0	0	0	0
	CSP	1A	0	0	0	0
		1B	0	0	0	2
		2A	1	0	3	1
		2B	15	0	5	1

Table 1.4. Percent of infested deer mice for each grid during each sampling session from prairie dog colonies at Wind Cave National Park and Custer State Park in 2013 and 2014. Grids treated with Deltamethrin are highlighted in grey. Sessions where no mice were collected are recorded as N/A.

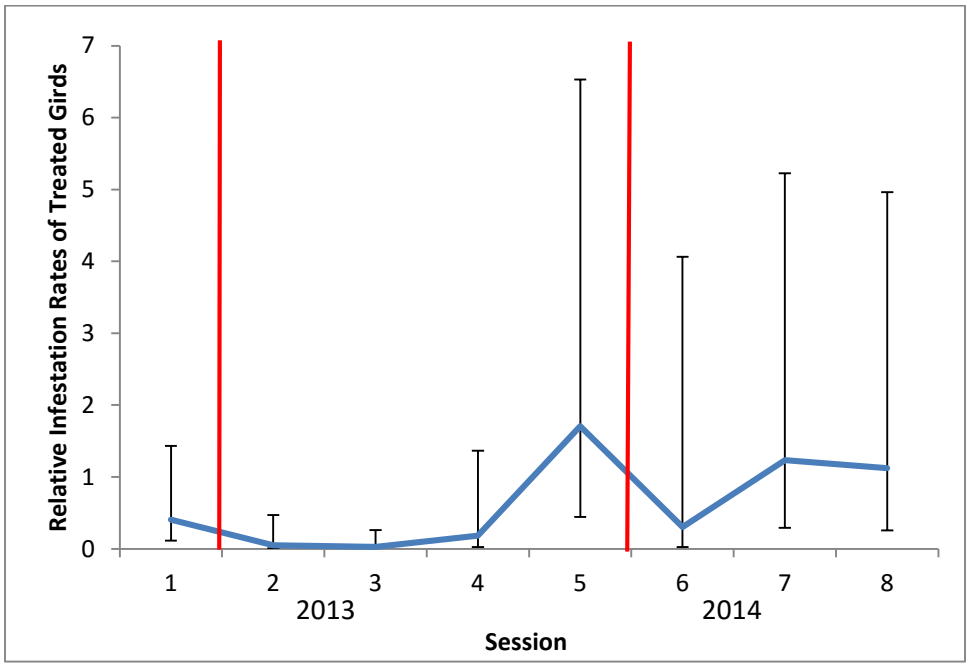
	Trap Sessions: 2013				Trap Sessions: 2014			
Site	1	2	3	4	5	6	7	8
CSP1A	N/A	0.00	0.00	N/A	0.00	0.00	0.00	0.00
CSP1B	0.00	N/A	0.00	N/A	0.00	0.00	0.00	0.20
CSP2A	0.00	0.00	0.20	N/A	0.00	0.00	0.23	0.06
CSP2B	0.00	0.00	0.00	0.33	0.50	0.00	0.29	0.14
HC1A	0.09	0.09	0.00	0.33	0.00	0.00	0.00	0.00
HC1B	0.16	0.17	0.67	0.50	0.13	0.00	0.00	0.06
HC2A	0.00	0.00	0.20	0.00	0.00	0.00	0.00	0.00
HC2B	0.13	0.00	0.00	N/A	0.00	0.00	0.00	0.00
SE1A	0.39	0.53	0.50	0.33	0.00	0.18	0.14	0.00
SE1B	0.20	0.00	0.00	0.00	0.09	0.00	0.00	0.09
SE2A	0.26	0.33	0.25	N/A	0.09	0.00	0.00	0.18
SE2B	0.17	0.00	0.00	0.00	0.10	0.06	0.22	0.33
Average Treated	0.09	0.02	0.03	0.13	0.11	0.01	0.08	0.09
Average Untreated	0.16	0.21	0.27	0.42	0.04	0.03	0.06	0.08

Table 1.5. Estimated odds ratios of infestation for deer mice in relation to colony, session, and treatment. Session-specific treatment effects are estimated odds-effect of deltamethrin treatment compared to untreated grids. Odds ratios for colonies and session are relative to the first session at the Custer State Park colony. Estimates are back-transformed (exponentiated) from logit-scale estimates and 95% confidence interval bounds from a binomial generalized linear mixed effects models.[a]

	Estimate	-95% CI	+95% CI
Intercept	0.21	0.07	0.63
Highland Creek	0.68	0.22	2.09
South East	1.52	0.55	4.21
Session 2	1.54	0.58	4.11
Session 3	2.70	1.03	7.08
Session 4	2.31	0.60	8.96
Session 5	0.26	0.08	0.86
Session 6	0.13	0.03	0.67
Session 7	0.31	0.08	1.12
Session 8	0.37	0.11	1.23
Session 1:Treatment	0.41	0.12	1.43
Session 2:Treatment	0.05	0.01	0.47
Session 3:Treatment	0.03	0.00	0.26
Session 4:Treatment	0.18	0.024	1.36
Session 5:Treatment	1.70	0.45	6.53
Session 6:Treatment	0.30	0.023	4.06
Session 7:Treatment	1.23	0.29	5.23
Session 8:Treatment	1.12	0.25	4.96

[a] Random Effects Variance Components (Standard Deviations)
$\sigma_{Pair} = 0.01$, $\sigma_{unit\_in\_pair} = 0.50$, $\sigma_{Pair*Session} = 0.12$

Figure 1.3. Estimated odds ratio of flea infestation for mice on deltamethrin-treated sites compared to untreated sites with 95% confidence intervals from binomial generalized linear mixed model. Redlines indicate treatments of grids. Session 1-4 occurred in 2013 and sessions 6-8 in 2014 at Wind Cave National Park and Custer State Park.



CHAPTER 2

Deltamethrin Impacts on Arthropod Abundance and Consumption by Small Mammals in Prairie Dog Colonies.

INTRODUCTION

The landscape of western North America has changed dramatically over the last century as grasslands and areas supporting prairie dog (*Cynomys spp.*) colonies were converted to rangelands and agricultural fields, reducing the range of prairie dog ecosystems by up to 99% (Luce 2002, Proctor et. al. 2006). High levels of biodiversity in these ecosystems make them important areas of conservation (Agnew et al.1986, Kotliar et al. 1999, and Dinsmore et al. 2001). Prairie dog systems provide a preferred habitat for many wildlife species by creating a highly disturbed ecosystem through heavy grazing and continual burrowing (Miller et al. 2000, Caro 2007).

Simultaneously, the populations of prairie dog colonies have been further reduced by the introduced bacterium *Yersinia pestis*, i.e. plague. This bacterium is spread between mammals by fleas (Siphonaptera), and, during an outbreak, causes entire prairie dog colonies to die off (Simond 1898, Thomas et al. 1988, and Biggins and Kosoy 2001). These outbreaks are of particular conservation concern as they have slowed the recovery of the endangered black-footed ferret (*Mustela nigripes*) which feeds almost entirely on prairie dogs (Pauli et al. 1996, Kotliar et al. 1999, Rocke et al. 2008). In many areas where black-footed ferrets have been reintroduced, prairie dog colonies are treated with deltamethrin, a pytheroid insecticide that reduces flea populations and therefore reduces the spread of plague (Seery et al. 2003). Although this treatment has been successful at increasing survival of ferrets and prairie dogs and preventing outbreaks of the disease, little is known about the secondary effects of this treatment on the prairie dog colonies (Jones et al. 2010). There is particular concern about the impacts that this treatment may have on other arthropods that utilize prairie dog colonies and on species that feed heavily on these arthropods (Biggins et al. 2010).

While the effects of deltamethrin on prairie dog colonies are still unknown, its wide use in agricultural systems demonstrates its ability to alter the diversity and structure of arthropod communities. In agricultural applications deltamethrin is commonly spread over crops to control herbivorous pests. This broad application of deltamethrin over the landscape creates disproportionate declines within arthropod and arachnid taxa (Schoenly et al. 1996, Badji et al. 2004). The largest impacts have been found in Hymenoptera (insect order containing wasps, bees and ants), Coleoptera (beetle order), Heteroptera (true bugs) and Araneane (spider) populations (Rodriquez et al. 2003). These impacts can alter the composition of the arthropod community. In many cases abundance of predatory arthropods is reduced, allowing herbivorous arthropods to increase (Longley et al. 1997). Additionally sub-lethal effects impacting movement, foraging, and reproduction could further change the abundance of various families of arthropods or alter their impacts on the ecosystem (Desneux et al. 2007). After these agricultural applications, arthropod communities take 20-30 days to return to their previous levels (Schonely et al. 1996).

In prairie dog systems, deltamethrin is sprayed only locally in prairie dog burrows unlike the broad-scale above-ground application used in agricultural systems. However, when used as a plague control in prairie dog colonies, deltamethrin can reduce the abundance of several families of arthropods (Karhu and Anderson 2000, D. E. Biggins, U.S. Geological Survey unpublished data). Arthropods play important roles in prairie dog systems and are found in greater diversity and abundance on active colonies than on neighboring grasslands (Davidson and Lightfoot 2007). Small mammals such as deer mice (*Peromyscus maniculatus*) rely on arthropods as a food source, particularly in prairie dog colonies where beetles, the most heavily consumed order, can be almost twice as abundant compared to surrounding areas (Agnew et al. 1987, Bangert and Slobodchikoff 2004). Because small mammals act as first level predators for arthropods, their reproduction and survival can be readily impacted by a decline in arthropod food sources (Schauber et al. 1997). As mice are a low-level prey item for other species, a change in their abundance can have a far greater impact on the ecosystem (Grant and French 1980). Additionally arthropods act as important players in maintaining nutrient cycling processes (Whiles and Charlton 2006). As both active and inactive prairie dog colonies

have diverse arthropod communities, distinct from the arthropods found in the neighboring grasslands, prairie dog colonies contribute significantly to the overall arthropod diversity of the landscape (Bangert and Slobodchikoff 2006).

To understand the impacts of deltamethrin treatment on the abundance of arthropods and their role in the prairie dog system I compared arthropod abundance and their consumption by small mammals between sites experimentally treated with deltamethrin and control sites in prairie dog colonies of western South Dakota. Our objectives were to determine the magnitude and duration of any changes in ground dwelling arthropod assemblages and to examine whether such changes impact the diet of omnivorous small mammals. I expected that deltamethrin treatments would reduce arthropod abundance but that the magnitude of reduction would vary between families, similar to what was seen in agricultural settings. I additionally expected that these reductions will be short term and the effect of an individual treatment would not last into the following year. Finally, I expected that these declines would impact the diet of small mammals, reducing the amount of arthropods that small mammals consume.

Study Area

Arthropods were sampled from prairie dog colonies at Wind Cave National Park and Custer State Park in the summers of 2013 and 2014. Both parks are located in the southern Black Hills of South Dakota and support multiple prairie dog colonies. Wind Cave National Park began using DeltaDust (0.05% deltamethrin, Bayer Pharmaceuticals) in 2008 to protect prairie dog colonies and reintroduced black-footed ferrets from possible plague outbreaks. However Custer State Park does not treat any colonies. However, at Wind Cave, DeltaDust is annually sprayed within all prairie dog burrows in colonies where the largest populations of ferrets are found. Although there have been no outbreaks of plague in either park, plague has been detected in Fall River and Custer Counties, where the parks are located (Abbott and Rocke 2012). Recently, fleas collected from Wind Cave National Park have been found to harbor the plague bacterium however, infection rates were low and varied across colonies (Mize and Britton 2014).

To assess the impact of deltamethrin treatment, my study focused on 3 colonies that had not previously been treated with insecticides, two in Wind Cave National Park and one in Custer State Park (Figure 2.1). Prairie dog colonies were identified by the presence of prairie dogs and their active burrows, and by the distinctive heavily grazed grasses and disturbed soils they produce. Primary vegetation species include purple three awn (*Aristida purpurea*), large bract vervain (*Verbena bracteata*), Canada thistle (*Cersium arvense*), common hoarhound (*Marrubium vulgare*), western wheat grass (*Pascopyrun smithii*), and grama grasses (*Bouteloua spp.*) (Cogan et al. 1999).

METHODS

Experimental Design

Within each selected colony, two pairs of 1.82 hectare experimental units were established, resulting in 12 units. Within each pair, one unit was randomly selected for DeltaDust treatment while the other was left as a control. In a treatment area, all prairie dog burrows were dusted with approximately four to six grams of DeltaDust at an intended depth of eight inches into the burrow using an applicator wand. Burrows were dusted once annually in late May or early June.

Arthropod Collection

Arthropods were collected from the experimental units using arrays of pitfall traps (Distributions Solida, Quebec, Canada, Multipher I trap, 26cmx26cmx24cm, 40b-001). Within each unit, four 10 x 10 m arthropod sampling sub-plots were established inside each corner, approximately 18.5 meters from the border. The subplots consisted of nine arthropod pitfall traps arranged in an "x" formation forming a 10 m x 10 m array (Figure 2.2). Inside the cup of the pitfall trap, I placed a smaller cup partially filled with diluted propylene glycol (propane-1,2-diol) based anti-freeze to prevent insects from crawling out of the traps and help to preserve them before collection. In 2013, the pitfall traps were installed and opened after dusting during

May- June and closed at the end of July or beginning of August. Traps on Custer State Park were deployed in late May, before dusting, while deployment of pitfall traps at Wind Cave National Park were delayed until after dusting due to the need for archeological surveys to be conducted before digging could begin. The traps were reopened in May of 2014 before 2014 dusting and removed in the beginning of August. Insects were collected approximately bi-weekly, stored in 70% ethanol, and brought back to Auburn University for identification to family. Initially all collected individuals in a sample were to be identified to family however, due to the length of time to process pitfall trap samples and identify captured arthropods, this proved impossible. Samples from 2013 are still being processed and identified to family while beetles from the families Carabidae, Tenebrionidae, and Scarabaedae were removed and counted during the summer of 2014 as they accounted for close to 50% of insects collected, a majority of the arthropod biomass collected, and thought to be frequently eaten by target small mammals.

Fecal Sample Collection and Analysis

To assess arthropod consumption, fecal pellets from captured small mammals were collected and analyzed (Agnew 1987). Small mammals were sampled on all units in each colony four times each year between May and August in 2013 and 2014 at approximate two week intervals. To capture small mammals, an eight by eight grid of 7 cm x 9 cm x 25 cm folding, aluminum, Sherman live traps (H.B Sherman Traps, Tallahassee, FL) was placed within the 1.1 ha core area of each experimental unit. Grid spacing was 15 meters between trap stations, with a single trap placed at each station. Traps were baited with a mixture of peanut butter and oats and provided with polyester or cotton bedding. Each trap was sheltered from sun and camouflaged with a brown cloth tent (Figure 2.3). After the first trap session on each colony, it was determined that only nocturnal small animals were captured, therefore traps were checked daily in the early morning for the remainder of the study.

A minimum of six fecal pellets were collected from bedding in the Sherman traps after each capture. To ensure that ingestion of bait did not influence the abundance of insect material in the fecal pellets; samples were collected only during the first capture of an individual in each session. Fecal pellets were stored in envelopes and dried in a freezer. To

analyze the samples, two pellets were crushed under a microscope and saturated with water in a 2.5 cm x 2.5 cm area (Agnew et al. 1987). Underlying this area, a grid of 3 mm x 3 mm numbered squares was placed to indicate fields. 30 fields were viewed for each sample and the presence of arthropod exoskeletons was recorded (1=present, 0=absent) for each observed field. This process was repeated with additional pellets for each fecal sample collected for a total of 60 reading per fecal sample (Figure 2.4).

Analysis

Analysis of arthropod captures focused on counts of beetles captured in 2014, with separate analyses for each of three major beetle families: Scarabaedae, Carabidae, and Tenebrionidae. The count data from the three 2014 pit-fall sessions were analyzed in a general linear mixed model with a Poisson distribution in program R (Program R; package lme4, Bates et al. 2015). Grid, pair, and pair by session were included as random effects while fixed effects of colony and session by treatment were included to examine the variation in treatment effect by session before and after the second annual treatment.

To examine if treatment influenced the consumption of arthropods, the proportion of insect remnants within viewed fields were utilized from each mouse fecal sample. Samples were collected from an individual mouse once during a session. Any samples that were collected from mice captured in more than one trap session were treated as independent samples to reduce the complexity of the model and because most mice had only one sample included per individual (33 mice, 69 samples, 18.5% of all tested samples). For this analysis, the proportion of fields that included arthropod remnants were treated similarly to a binomial variable however, the assumption that the 60 readings could be used as 60 independent binomial trials was removed. The proportion of arthropod-containing fields per sample was logit- transformed and the resulting proportion was used as the response variable in a general linear mixed effects model (Warton and Hui 2011). Some samples resulted in proportion of 0.0 or 1.0 which could not be logit-transformed without adjustment therefore all 0.0 proportions were adjusted to 0.01 and 1.0 proportions to 0.99. The model included colony and treatment

effects as fixed effects while pair, grids, session and pair by session were included as random effects.

RESULTS

Pitfall traps were open during the summers of 2013 and 2014, resulting in six sample periods from South East and Highland Creek colonies (three annually) and seven sample periods from Custer State park (four from 2013 and three from 2014). Due to the large number of insects collected during each of these sampling occasions, the arthropods collected are still being processed and identified to family. The majority of 2013 samples have been processed resulting in 56,193 insects from 40 array samples (71.4% of collected samples) from the South East colony that have been identified into 102 families and 9 higher level classification groups(Table 2.1). Highland Creek has resulted in 31,636 insects from 26 samples (53.1% of collected samples) into 99 families and 10 higher classification groups (Table 2.2). Finally, 47 samples (62.5% of total samples) from Custer State Park have resulted in the identification of 68,585 insects into 105 families and 10 higher classifications (Table 2.3). Non- arthropod captures included upland chorus frogs (*Pseudaccris triseriata*)(4), Woodhouse's toad (*Anaxyrus woodhousii*)(4), Great Plains toad (*Anaxyrus cognatus*)(1), blotched tiger salamander (*Ambystoma tigrinum*) (1), and several mice (*Peromyscus maniculatis*).

In 2014, selected Coleoptera families from three sampling periods were chosen to preemptively be pulled from pitfall samples to allow for some comparison between colonies since the entirety of the samples would not be complete in time for analysis. Families were chosen as they were the most plentiful family observed in the environment with the largest body size. Due to these observations and the high rate that Coleoptera are consumed by small mammals these families were presumed to have the largest impact on mouse populations (Agnew 1987). Across colonies, the most beetles were collected from the Southeast colony (7,661) while both Highland Creek and Custer resulted in similar numbers of collected beetles (2,417, 2,343 respectively) (Table 2.4). The difference between the Southeast and the other colonies is largely comprised of an increase in beetles from the family Scarabaedae

(Southeast=5,788, Highland Creek=707, Custer State Park= 748). Beetle numbers for Tenebrionidae (Southeast= 665, Highland Creek= 615, Custer State Park= 445) and Carabidae (Southeast=1208, Highland Creek=1295, Custer State Park= 1453) were similar across all colonies. Analysis of beetles captures showed no differences between colonies for any beetle family. Captures for both Tenebreonidae and Carabidae were the same between treated and untreated grids for all capture sessions. However, captures of Scarabaedae beetles were lower for the first session, before annual treatment, but returned to similar levels as untreated grids in the second two sessions (Table 2.5).

Small mammal trapping resulted in the collection of 373 fecal samples (2013=128, 2014=245) from 337 individual mice. The results from these samples were then tested using models in both frequentist and Bayesian frameworks. After the proportion of samples containing arthropods was logit transformed to be utilized in a linear mixed model, a likelihood test comparing the null model to two alternative models (a fixed effect of treatment and a session specific effect of treatment) was performed. The test found that the null model (df=14, log likelihood= -1.52) was the best fitting model with a constant effect of treatment (df= 15, log likelihood= -0.095) having a similar fit (chi square=1.13, p=0.28) (Table 2.5). The full model with session specific effects of dusting (k=22 parameters) was the least favored model (chi square=2.89, p=0.89) to the reduced model with no effect of treatment. The session specific estimates for consumption of arthropods on both treated and untreated grids showed no difference between treatments (Table 2.6). A similar binomial linear mixed model was analyzed in a Bayesian framework and provided the same conclusion (Appendix 1).

DISCUSSION

While the effect of deltamethrin could not be determined due to the abundance of arthropods collected on the prairie dog colonies, the large quantity and diversity of families found on these colonies after deltamethrin treatment indicates that the system is resilient to this manner or insecticide application. Once all arthropods are identified, comparisons of family level diversity and abundance will be made between treated and untreated areas to determine

if there are any impacts of deltamethrin application. While changes in abundance within certain families or groups of arthropods are expected, the low concentrations applied to the systems and infrequent treatments may allow insect groups to recover between treatments (Schonely et al. 1996). However, high numbers of arthropods among all common families were collected from both treated and untreated grids. While statistical comparisons of diversity and abundance within all families would be inaccurate at this point, the abundance of collected arthropods from all areas is promising of a resilient community. The wide variety of arthropods even within families suggest that impacts may be highly variable and declines would be most likely observed in species that heavily utilize prairie dog burrows.

Of the most frequently found beetle families, Scarabaedae, Tenebrionidae, and Carabidae, there were few changes observed between treated and untreated areas. The only change seen was in the Scarabaedae between years of treatment. While agricultural application of deltamethrin tends to have short term impacts on arthropod colonies, the application solely within burrows was thought to more heavily impact the Scarabaedae family as they were frequently observed collecting prairie dog feces from around burrow entrance. Despite this method of deltamethrin application impacting flea species for several months, any changes in beetle density would still be expected to be observed quickly after treatment (Seery et al. 2003). Since only short term impacts on arthropods were expected, it is unsure why impacts on Scarabaedae abundance would be observed almost a year after treatment. However these changes may be related to the re-excavation of prairie dog burrows in early spring, exposing deltamethrin from the prior year, or seasonal changes in habitat use and foraging methods. As these beetles recover quickly after treatment and were still abundant, dusting appeared to only have a low level negative impact on these species.

While negative impacts on Scarabaedae dung beetles were minimal, continual treatment with deltamethrin may lead to increased negative impacts. As dung dispersers, Scrabidae beetles play many important roles in the ecosystem. Primarily, these beetles are a large component of nutrient cycling, increasing the return of nutrients to the soil and increasing overall soil fertility and plant productivity (Bang et al. 2005). Additionally, the movement of

seed containing feces assists in seed dispersal by both moving seeds horizontally across the landscape and vertically within the soil (Andreson 2002). These species can also have significant impacts on mammalian species by reducing the viability of endoparasites and therefore reducing the parasite load of livestock and wildlife species (Mathison and Ditrich 1999). Given the large impact of this family on the ecosystem, the impacts on Scarabaedae species may be significant to the ecosystem.

This negative impact on Scarabaedae beetles and potential impacts on non-target arthropods did not influence the population of arthropods significantly enough to impact their role as a prey species for small mammals. While the role of arthropods as prey is only one ecological role that these species fill, it may indicate that even if declines are found within arthropod families, they are still found at densities high enough to remain functional within the ecosystem (Whiles and Charlton 2006). Since deltamethrin is applied in a targeted approach, the declines in families that frequently use burrows may be significant however families that do not use these burrows may not be impacted. This could allow for un-impacted families to fill the role of any groups that may be declining, reducing the overall impact on the community and their roles. This, along with few observed negative impacts on arthropod families, indicates that arthropod families are resilient enough to sustain limited application of deltamethrin on prairie dog colonies.

Overall the impacts on deltamethrin on these insects seem to be minimal as few declines were noted and were not significant enough to alter the insect's role as prey. However some insects that heavily utilize prairie dog burrows may not have been adequately surveyed, particularly black widow spider (*Latrodectus spp.*). Before treatment black widow spiders were frequently observed in webs at the entrance of prairie dog burrow and frequently found in the funnel entrances to pitfall traps but rarely captured. The occupancy of burrows by black widow spiders was not examined and their presence in the pit fall traps was not recoded. While any impacts of deltamethrin on their population are unknown, many spiders were directly sprayed with dust during treatment and would likely have died from those treatments. If the burrow entrance is a key habitat component for the black widow spiders, the continual presence of

dust in the burrow would prevent them from utilizing those areas. As a top level arachnid predator, the removal of the black widow from would change populations and behaviors of prey species (Schmitz and Suttle 2001). Therefore the impact of deltamethrin on these spiders, and other species that may not have been captured in pitfall traps, may be highly significant but largely unknown.

As deltamethrin application is an efficient method of reducing flea populations on prairie dog colonies and protecting black-footed ferrets and prairie dogs, it has become an important conservation tool. This is further supported by the minimal negative impacts that this treatment has been shown to have on arthropods and their roles in this system. However, deltamethrin should be applied with caution as continual application may exacerbate the impact of deltamethrin, leading to significant arthropod declines and reduce their ability to restore normal population levels. Additional research into species that may not have been adequately sampled using pitfall traps is still necessary to fully determine the impacts that this treatment may have on the overall arthropod community. Since little is known about how arthropods may utilize prairie dog burrows, it is important to survey prairie dog burrows to better understand their presence and roles in prairie dog systems.

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TABLES AND FIGURES

Figure 2.2. Study colonies in Wind Cave National Park (black boundary) and adjacent Custer State Park in western South Dakota (inset). Trapped prairie dog colonies are gray; sampling grids are indicated with a black dot.

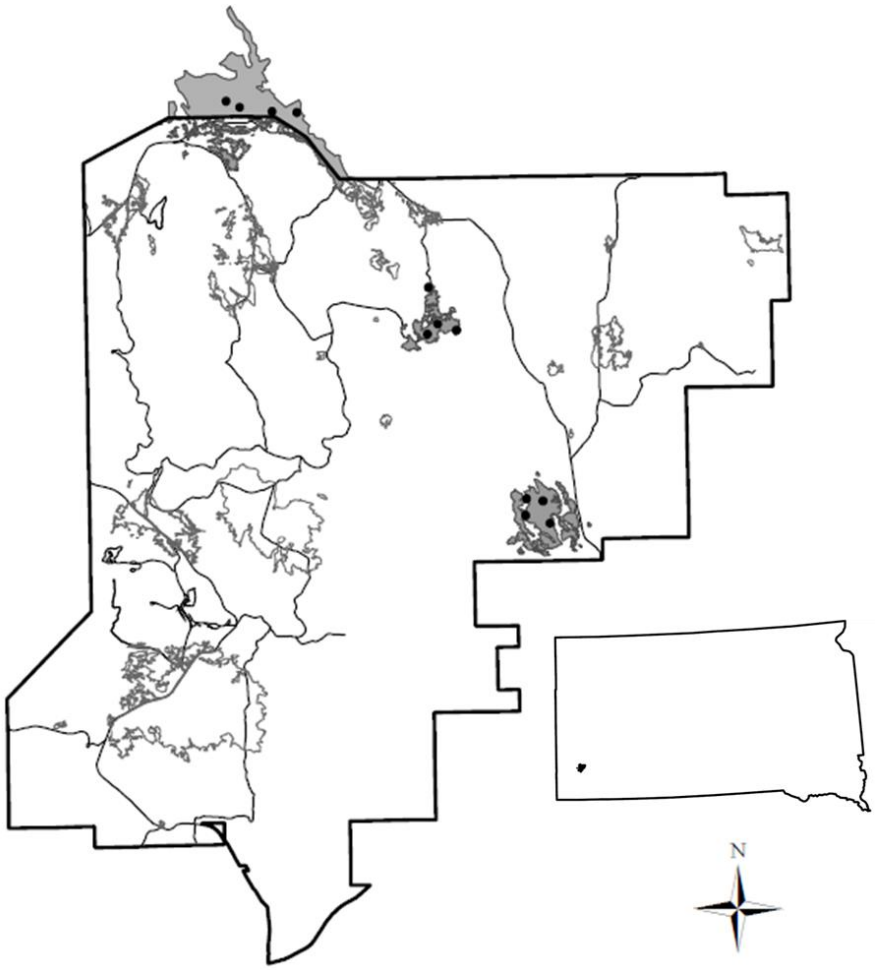

Figure 2.2. Schematic of experimental unit with approximate spacing of small mammal trap grid, arthropod traps, and vegetation transects.

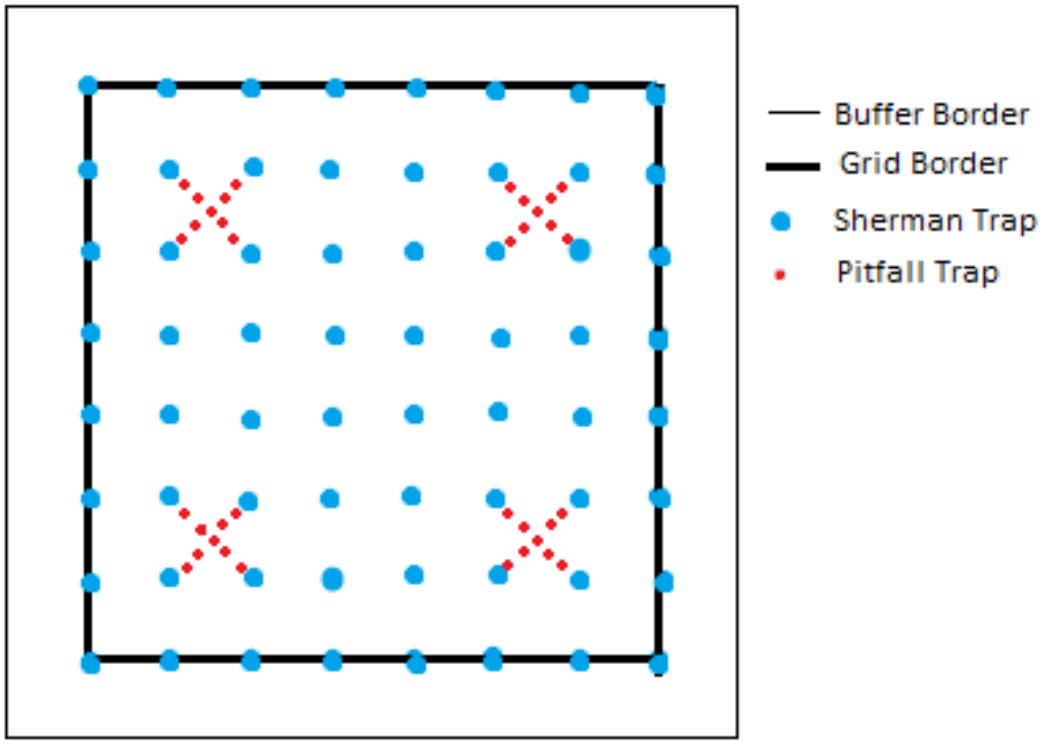

Figure 2.3. Sherman trap used to capture small mammals with a cloth cover.

Figure 2.4. Crushed mouse fecal pellets on a slide, rehydrated and laid over a grid of 3mmx3mm fields.

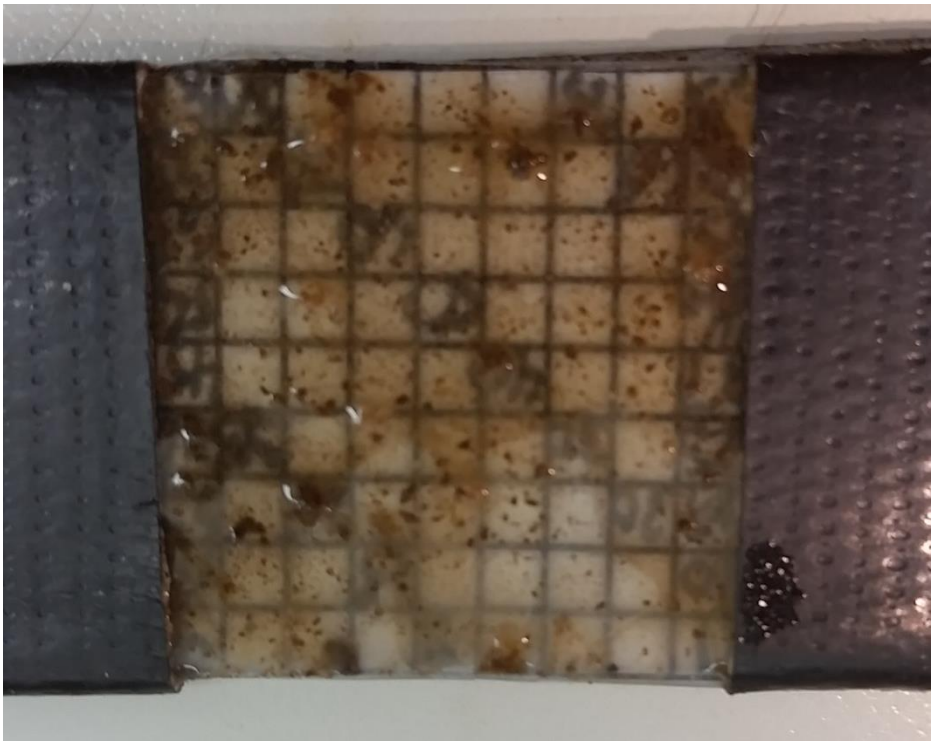

Table 2.1. Arthropod families and counts of individuals collected from pitfall traps on the South East prairie dog colony at Wind Cave National Park in 2013.[2]

Family	Count	Family	Count	Family	Count
Acari*	2716	Cynidae	22	Oecanthinae (gryllidae)	1
Acrididae	489	Dermestidae	39	Pentatomidae	2
Anthicidae	290	Diplopoda*	2	Phalacridae	2
Anthomyiidae	46	Diptera*	17	Phoridae	641
Aphidae	29	Dolichopodidae	20	Piophilidae	2
Araneae	1038	Drosophilidae	1	Platypezidae	29
Asilidae	23	Elateridae	65	Pompilidae	34
Bethylidae	2	Fanniidae	1	Pseudococcidiae	2
Blissidae	1	Figitidae	1	Psocoptera*	1
Bombyliidae	1	Formicidae	10269	Reduviidae	20
Braconidae	6	Gastropoda*	9	Rhaphidophoridae	185
Calliphoridae	13	Geocoridae	869	Rhopalidae	17
Calypteratae	1	Geotrupidae	4	Rhyparochromidae	1101
Carabidae	2123	Gryllidae	709	Sarcophagiade	242
Carnidae	8	Halictidae	117	Scarabaeidae	22437
Cecidomyiidae	10	Heleomyzidae	29	Scathophagidae	3
Cerambycidae	12	Histeridae	131	Scelionidae	6
Ceratopogonidae	11	Ichneumonidae	13	Sciaridae	176
Chalcididae	38	Issidae	6	Scutelleridae	10
Chilopoda*	4	Lathridiidae	7	Sepsidae	34
Chironomidae	1	Lauxaniidae	1	Silphidae	387
Chloropidae	35	Leiodidae	1	Siphanoptera	1
Chrysididae	10	Lepidoptera*	112	Solifugid	100
Chrysomelidae	127	Lygaeidae	2326	Sphaeroceridae	10
Cicadellidae	3883	Megachilidae	1	Sphecidae	42
Cicadidae	8	Melandryidae	1	Staphilinidae	229
Cicindelidae	98	Meloidae	166	Strepsiptera	1
Cleridae	1	Melyridae	12	Syrphidae	1
Coccinellidae	12	Mesoniscidae	1	Tachinidae	22
Coleoptera*	28	Microhymenoptera	145	Tenebrionidae	873
Collembola*	2953	Microhymenoptera	19	Tettigoniidae	1
Colletidae	7	Miridae	10	Therevidae	17
Coreidae	1	Mordellidae	2	Thyreocoridae	10
Corylophidae	12	Mutillidae	17	Tingidae	2
Cryptophagidae	7	Myrmeleontidae	2	Tiphiidae	6
Curculionidae	96	Nabidae	25	Trogidae	65
Cydnidae	149	Nematomorpha	1	Vespidae	19

[2] Asterisk indicates a level of classification higher then family

Table 2.2. Arthropod families and counts of individuals collected from pitfall traps on the Highland Creek prairie dog colony at Wind Cave National Park in 2013.[3]

Family	Count	Family	Count	Family	Count
Acari*	736	Cydnidae	57	Nematomopha	6
Acrididae	244	Cynidae	25	Pentatomidae	3
Alydidae	1	Delphacidae	1	Phalacridae	7
Anthicidae	26	Dermestidae	10	Phoridae	698
Anthocoridea	3	Diplopoda*	10	Piophilidae	1
Anthomyiidae	23	Diptera*	1	Platypezidae	18
Aphidae	107	Dolichopodidae	28	Pompilidae	7
Araneae	1031	Dryinidae	1	Pseudococcidiae	13
Asilidae	4	Elateridae	61	Psocoptera*	1
Bethylidae	5	Formicidae	8570	Psychodidae	1
Caliscelidae	1	Gastropoda*	2	Reduviidae	7
Calliphoridae	13	Geocoridae	100	Rhaphidophoridae	36
Canthyloscelididae	1	Geotrupidae	1	Rhopalidae	2
Carabidae	2075	Gryllidae	622	Rhyparochromidae	1668
Carnidae	133	Halictidae	8	Sarcophagiade	57
Cecidomyiidae	2	Heleomyzidae	12	Scarabaeidae	7549
Cerambycidae	8	Histernidae	45	Scathophagidae	0
Ceratopogoniidae	14	Hydropilidae	1	Sciaridae	151
Chalcididae	1	Ichneumonidae	10	Sciaridae	12
Chilopoda*	11	Issidae	1	Sciaridae	6
Chironomidae	20	Lathridiidae	6	Sciomyzidae	1
Chloropidae	67	Leiodidae	2	Scutelleridae	3
Chrysomelidae	173	Lepidoptera*	114	Sepsidae	82
Cicadellidae	567	Lygaeidae	432	Silphidae	56
Cicadidae	4	Megachilidae	4	Solifugae	24
Cicindellidae	1	Meloidae	10	Sphaeroceridae	5
Clusiidae	2	Melyridae	2	Sphecidae	8
Coleoptera*	33	Membracidae	1	Staphilinidae	50
Collembola*	2452	Microhymenoptera	284	Tenebrionidae	509
Coniopterygidae	13	Microlepidoptera	17	Tettigonidae	3
Coreidae	5	Milichiidae	1	Therevidae	5
Corylophidae	3	Mutillidae	7	Thyreocoridae	8
Cryptophagidae	11	Mymaridae	3	Thysanoptera*	1
Cucujidae	0	Myrmeleontidae	4	Tingidae	1
Curculionidae	86	Nabidae	12	Tiphiidae	8
				Trogidae	63

[3] Asterisk indicates a level of classification higher then family

Table 2.3. Arthropod families and counts of individuals collected from pitfall traps Custer State Park in 2013.[4]

Family	Count	Family	Count	Family	Count
Acari*	7030	Curculionidae	427	Phalacridae	44
Acrididae	638	Cydnidae	37	Phlaeothripidae	11
Alydidae	1	Delphacidae	1	Phoridae	1303
Andrenidae	1	Dermestidae	46	Piophilidae	6
Anobiidae	3	Diplopoda*	82	Platypezidae	75
Anthicidae	204	Diptera*	210	Platystomatidae	1
Anthocoridea	32	Dolichopodidae	51	Pompilidae	20
Anthomyiidae	80	Drosophilidae	8	Proctotrupidae	1
Aphidae	312	Dryinidae	2	Pseudococcidiae	92
Apidae	3	Elateridae	396	Psocoptera*	22
Apoidea	1	Empididae	3	Reduviidae	26
Araneae	3771	Ephydridae	2	Rhaphidophoridae	546
Asilidae	1	Formicidae	26841	Rhopalidae	18
Bethylidae	11	Gastropoda*	5	Rhyparochromidae	1764
Braconidae	22	Geocoridae	590	Sarcophagiade	234
Byrrhidae	4	Gryllidae	605	Scarabaeidae	13081
Calliphoridae	10	Halictidae	15	Scathophagidae	1
Carabidae	3998	Heleomyzidae	106	Sciaridae	170
Carnidae	445	Histernidae	21	Scutelleridae	4
Cecidomyiidae	13	Hydrophilidae	1	Scydmaenidae	10
Cerambycidae	5	Ichneumonidae	72	Sepsidae	9
Chalcididae	1	Lathridiidae	68	Silphidae	887
Chilopoda*	44	Leiodidae	3	Silvanidae	1
Chironomidae	2	Lepidoptera*	518	Solifugae	1
Chironomidae	6	Lygaeidae	2759	Sphaeroceridae	18
Chloropidae	180	Meloidae	32	Sphecidae	8
Chrysomelidae	292	Melyridae	53	Staphilinidae	1760
Cicadellidae	1879	Microhymenoptera	1251	Strepsiptera	1
Cicadidae	26	Miridae	45	Tachinidae	14
Cicindellidae	2	Monotomidae	1	Tenebrionidae	1207
Coccinellidae	39	Mordellidae	11	Therevidae	9
Coleoptera*	271	Mutillidae	20	Throscidae	1
Collembola*	6565	Myrmeleontidae	9	Thyreocoridae	35
Coniopterygidae	4	Nabidae	50	Thysanoptera	11
Coreidae	1	Nematomopha	8	Thysanoptera*	9
Corylophidae	123	Nitidulidae	5	Tingidae	22
Cryptophagidae	32	Opiliones	1	Tiphiidae	16
Culicidae	1	Pentatomidae	2	Trogidae	14
				Vespidae	4

[4] Asterisk indicates a level of classification higher then family

Table 2.4. Counts of pitfall captures of major Coleoptera families from 2014 from each grid from two prairie dog colonies at Wind Cave National Park and one at Custer State park. Grey rows indicate the grids was treated with deltamethrin and the red line indicated timing of the treatment.

Colony	Date	Grid	Scarabaedae	Tenebrionidae	Carabidae
South East	5/14-5/28	1A	59	7	12
		1B	1	13	19
		2A	0	16	11
		2B	60	36	42
	5/28-6/22	1A	652	104	132
		1B	208	36	56
		2A	76	92	109
		2B	34	42	91
	6/22-7/9	1A	1346	118	206
		1B	3064	84	175
		2A	110	76	179
		2B	178	41	176
Highland Creek	5/18-6/5	1A	11	66	75
		1B	2	17	52
		2A	16	22	60
		2B	2	27	43
	6/5-6/26	1A	2	37	76
		1B	4	15	17
		2A	3	20	46
		2B	5	62	67
	6/26-7/18	1A	382	26	155
		1B	72	100	62
		2A	170	92	214
		2B	38	131	228
Custer State Park	5/27-6/9	1A	0	1	29
		1B	21	0	35
		2A	1	10	46
		2B	3	11	46
	6/9-7/5	1A	22	12	177
		1B	17	17	173
		2A	18	86	193
		2B	148	108	232
	7/5-7/22	1A	53	20	99
		1B	29	47	123
		2A	356	13	140
		2B	80	120	160

Table 2.5. The proportional effect of deltamethrin treatment, relative to untreated grids, on abundance of three beetle families captured with pitfall traps on two prairie dog colonies at Wind Cave National Park and one at Custer State Park during the summer or 2014. Highland Creek and South East colony effects are relative to the Custer State Park Colony. Estimates are odds ratios from Poisson distributed generalized linear mixed models utilizing counts of captured arthropods.

Family	Session	Estimate	-95% CI	+95% CI
Scarabaedae[5]	Highland Creek	0.81	0.09	7.02
	South East	4.35	0.51	36.83
	Session 1	0.07	0.01	0.34
	Session 2	3.32	0.81	13.67
	Session 3	0.68	0.17	2.72
Tenebronidae[6]	Highland Creek	2.20	0.93	5.21
	South East	1.92	0.81	4.54
	Session 1	1.24	0.55	2.80
	Session 2	0.86	0.47	1.58
	Session 3	1.01	0.54	1.88
Carabidae[7]	Highland Creek	0.76	0.40	1.42
	South East	0.68	0.37	1.28
	Session 1	1.05	0.67	1.65
	Session 2	1.20	0.81	1.78
	Session 3	1.05	0.71	1.56

[5] Random Effects Variance Components (standard deviations): $\sigma_{Pair} = 0.00$, $\sigma_{grid} = 1.05$, $\sigma_{Pair*Session} = 1.37$

[6] Random Effects Variance Components (standard deviations): $\sigma_{Pair} = 0.00$, $\sigma_{grid} = 0.44$, $\sigma_{Pair*Session} = 0.51$

[7] Random Effects Variance Components (standard deviations): $\sigma_{Pair} = 0.00$, $\sigma_{grid} = 0.25$, $\sigma_{Pair*Session} = 0.45$

Table 2.6. Odds ratio estimates of the effects of time, location, and treatment on arthropod consumption by deer mice (*Peromyscus maniculatus)* from two prairie dog colonies at Wind Cave National Park and at Custer State Park in 2013 and 2014. Estimates are from Poisson distributed generalized mixed models utilizing binomial counts.[8]

Fixed Effects	Estimate	2.50%	97.50%
Intercept	1.60	1.43	1.78
Highland	1.15	1.05	1.27
Custer	1.11	1.00	1.22
Session 2	1.18	1.02	1.38
Session 3	1.27	1.07	1.49
Session 4	0.96	0.73	1.23
Session 5	1.04	0.92	1.19
Session 6	1.21	1.06	1.39
Session 7	1.34	1.15	1.53
Session 8	1.36	1.19	1.54
Session 1:Treatment	1.05	0.91	1.22
Session 2: Treatment	0.96	0.82	1.09
Session 3: Treatment	0.96	0.81	1.15
Session 4: Treatment	0.87	0.64	1.20
Session 5: Treatment	0.94	0.85	1.04
Session 6: Treatment	0.95	0.83	1.10
Session 7: Treatment	1.02	0.90	1.17
Session 8: Treatment	0.98	0.86	1.11

[8] Random Effects Variance Components (standard deviations): $\sigma_{Pair} = 0.05$, $\sigma_{grid} = 0.00$, $\sigma_{Pair*Session} = 0.00$

CHAPTER 3

Deltamethrin Impacts on Non-target

Deer Mice (*Peromyscus maniculatus*) in Prairie Dog Colonies

INTRODUCTION

Conservation of prairie dogs (*Cynomys spp.*), and the ecosystem they support has become a difficult process for managers in the presence of introduced diseases, minimal public support, and increasingly utilized lands (Van Putten and Miller 1999, Hoogland 2006, Miller et al. 2007). Prairie dogs are a keystone species in the American West (Kotliar 2000, Miller and Cully 2001). As herbivorous burrowers, prairie dogs alter soil conditions and vegetation creating a unique niche for many species of birds, plants, insects, and mammals (Weltzin et al. 1997, Graber et al. 1998, Kretzer and Cully 2001, Bangert and Slobodchikoff 2006). However, as ranching spread through the West, prairie dogs were thought to directly compete with cattle for food resources (Merriam 1902). This led to many poisoning and reduction programs, shrinking the range of prairie dogs by an estimated 99% (Luce 2002, Proctor et al. 2006). As prairie dog populations dwindled, so did many of the species that rely on that habitat, including the black-footed ferret (*Mustela nigripes*), burrowing owl (*Athene cunicularia*), and American badger (*Taxidea taxus)* (Dinsmore et al. 2001). Due to the unique habitat of prairie dog colonies, conservation of these lands is an essential component to conserving the biodiversity of North American grasslands.

One of the most notable species reliant on the prairie dog ecosystem is the endangered black-footed ferret. The black-footed ferret is an obligate to prairie dog colonies, as prairie dogs account for more than 90% of their diet and provide burrows for shelter (Miller at al. 1996). As prairie dog colonies shrank and became increasingly fragmented, black-footed ferret populations also declined to the point that the species was considered extinct (Clark 1989, Miller et al. 1996). However, a small population was found and was taken into captivity (Dobson and Lyles 2000). After multiple breeding efforts, the ferrets have been reintroduced into the wild and their populations have grown, creating several self-sustaining populations (Jachowski et al. 2011). As a success story of the Endangered Species Act, the black-footed ferret has become a flagship species for North American conservation efforts (Lockhart et al. 2004).

However, the recovery of the black-footed ferrets is continually threatened by the plague (*Yersinia pestis*). Both prairie dogs and black-footed ferrets suffer close to 100% mortality when infected with plague, so a single epizootic outbreak can eradicate an entire colony (Godby et al. 2006, Pauli et al. 2006,). The intensity of plague epizootics and additional reduction and fragmentation of colonies from eradication efforts has led to reduced immigration of new individuals that could recolonize the area after an outbreak (Augustine 2007).

As an introduced disease, there is still very little known about native reservoirs of plague and triggers of a plague epizootic (Abbot and Rocke 2012). The plague bacterium is vectored by several species of fleas (Siphonaptera). In the flea, the bacterium multiplies in the mid gut and creates a blockage, starving the flea and causing more frequent feedings during which the plague bacteria are transmitted to the vertebrate host (Einsen et al. 2006). Meso-carnivores such as coyotes (*Canis latrans)* and swift foxes (*Vulpes velox)* are to believed transport plague-infected fleas between colonies (McGee et al. 2006). Other small mammal species that live in prairie dog colonies such as grasshopper mice (*Onychomys spp.*) and deer mice (*Peromysucs maniculatus*) are also thought to play a role in spreading or maintaining plague (Stapp et al. 2009).

As much is still unknown about plague cycles and outbreak triggers, plague control efforts have been focused on vector control and preventing infections. Currently, the most common plague prevention method focuses on reducing fleas by using Deltadust, an insecticide powder containing deltamethrin ([(*S*)-Cyano-(3-phenoxyphenyl)-methyl] (1*R*,3*R*)-3-(2,2-dibromoethenyl)-2,2-dimethyl-cyclopropane-1-carboxylate). These efforts focus on the importance of flea to host ratios, and the increasing ratio seen before an outbreak, in the dynamics of plague epizootics (Tripp et al. 2009). Deltadust powder is distributed by a hand duster at the entrance of prairie dog burrows, where the highest numbers of fleas are found. As an insecticide, it reduces the flea populations both in the burrows and on prairie dogs to non-detectible levels for at least three months (Seery et al. 2003). Annual dusting in the summer protects against plague, which is most often contracted during the warmest 4-5 months of the year. Dusting efforts to date may have prevented epizootic events (Seery et al. 2003). The application of deltamethrin reduces the flea load on prairie dogs and black-footed ferrets, but with a widespread application, this treatment also has potential to reduce flea loads and presence of plague in other species that utilize the prairie dog burrows.

While no direct effects of deltamethrin on wildlife have been noted in field conditions, arthropod declines in broad-application scenarios have impacted many species that prey on insects,

affecting body weight and reproduction in several bird species (Martin et al. 1998, Dinsmore 2012). In prairie dog systems, deltamethrin is only sprayed in prairie dog burrows rather than being applied broadly above ground but has still been shown to reduce the number of several families of arthropods when used as a plague control (Karhu and Anderson 2000, D. E. Biggins, U.S. Geological Survey unpublished data). Small mammals, such as deer mice, rely on arthropods as a food source, particularly in prairie dog colonies where beetles can be almost twice as abundant compared to surrounding areas (Agnew et al. 1987, Bangert and Slobodchikoff 2004). This change in the food source could impact the abundance of deer mice by altering reproductive output (Glazier 1985).

However, deltamethrin also has the potential to positively affect deer mouse populations. Deer mouse populations are closely tied to prairie dog colonies, appearing in significantly higher densities on prairie dog colonies than in surrounding areas (Duckwitz 2001). Deer mice are able to host numerous flea species and have been found carrying fleas that are associated with other species (Davis et al. 2002). This can make them susceptible to plague-carrying fleas and plague infection. As deer mice suffer high mortality from plague, living in a colony with enzootic or epizootic plague can depress populations of susceptible species (Holdenried and Quan 1956). Application of deltamethrin has already been associated with increased survival of prairie dogs and black-footed ferrets by reducing susceptibility to plague (Biggins et al. 2010, Matchett et al. 2010). Similarly, the application of deltamethrin may protect mice from plague existing in prairie dog colonies while also reducing deer mouse fleas. A reduction of ectoparasites could reduce the amount of time spent grooming and parasitic blood consumption, potentially increasing the health, and therefore reproduction, of the mice (Hawlena et al. 2007, Devevey et al. 2008, Zwolak et al. 2013).

At Wind Cave National Park in South Dakota, prairie dog colonies have been treated with Deltadust since 2008 to prevent plague outbreaks. Currently, the park focuses its dusting efforts on colonies that support black-footed ferrets re-introduced to the park in 2007. While prairie dog colonies have not suffered from any plague outbreaks, recent research has found the bacteria in fleas collected from several colonies in the park (Mize and Britton 2014).

While managers at Wind Cave National Park and other locations are using deltamethrin for reducing the risk of plague outbreak, there has been growing concern about the secondary effects of the insecticide on small mammals. Because these animals have short life spans, their populations can quickly reflect changes in the environment (Schauber et al. 1997). Small mammals act as a prey base for many species and feed on many arthropod families. Therefore, changes in their populations could impact

many other species. As deer mice are the only small mammal, other than prairie dogs, appearing consistently and in high densities in prairie dog towns of Wind Cave National Park (Duckwitz 2001), they are the focus of this study.

To determine how these mixed effects of deltamethrin may be altering the prairie dog system, I examined changes in deer mouse populations due to deltamethrin application and attempt to explain mechanisms of observed changes. I assessed effects of treatment by comparing abundance and survival of deer mice on paired treated and untreated areas. Given the predicted reductions of plague carrying fleas and arthropod abundances, it was expected that small mammal populations would be altered. Deltamethrin applications are associated with increased survival of prairie dogs and would likely have similar effects on deer mice populations (Biggins et al. 2010). Conversely, the insecticide is also associated with reduced arthropods leading to reduced reproduction in animals that rely upon them for food. Since these effects are conflicting and the extent of both flea and food source reduction are unknown, the level and direction of change cannot be predicted (Figure 3.1). However, since deltamethrin has been shown to have long term effects on the ecosystem, it is expected that any changes in small mammal populations will be cumulative over the two years of treatment examined in this study.

Study Area

I conducted this investigation at Wind Cave National Park and Custer State Park in the summers of 2013 and 2014. Both parks are located in the southern Black Hills of South Dakota and support multiple prairie dog colonies. Wind Cave National Park began using Deltadust in 2008 to protect prairie dog colonies and reintroduced black-footed ferrets from possible plague outbreaks. In the park, Deltadust is sprayed annually within all prairie dog burrows in colonies where ferrets are most densely populated. While there have been no outbreaks of the plague in either park, plague has been detected in Fall River and Custer Counties, where the parks are located (Abbott and Rocke 2012).

To assess the impact of this treatment, I studied 3 colonies that had not previously been treated, two in Wind Cave National Park and one in Custer State Park (Figure 3.2). Prairie dog colonies were identified by the presence of prairie dogs, their active burrows, and short grasses from their intense grazing. Primary vegetation species of colonies in these parks included purple three awn (*Aristida purpurea*), large bract vervain (*Verbena bracteata*), Canada thistle (*Cersium arvense*), common hoarhound (*Marrubium vulgare*), western wheat grass (*Pascopyrun smithii*), and grama grasses

(*Bouteloua spp.*) (Cogan et al. 1999). Within each selected colony, two pairs of 1.82 hectare units were established, for a total of 12 experimental units. Experimental units were chosen at sites that contained active prairie dog burrows and paired based on apparent similarities in vegetation, prairie dog densities, and topography. Within each pair, one unit was randomly selected for treatment while the other was left as a control. In each treatment area, all prairie dog burrows were dusted with approximately four to six grams of DeltaDust at an intended depth 20 cm into the burrow using an applicator wand. Burrows were dusted once per year in in late May or early June. Prairie dog burrows within each treatment unit were treated with Deltadust (0.05% deltamethrin) 1-2 days before the second small mammal sampling session annually.

METHODS

Small Mammal Field Methods

To assess small mammal populations, all experimental units on each colony were sampled 4 times each year between May and August in 2013 and 2014, at approximate two week intervals between trap sessions. Each of the 8 total trap sessions consisted of four trap nights, with all units within a colony trapped simultaneously. To sample small mammals, an eight by eight grid of 7 cm x 9 cm x 25 cm folding, aluminum, Sherman live traps (H.B Sherman Traps, Tallahassee, FL) were placed within the 1.05 ha core area of each experimental unit. Grid spacing was 15 meter between trap stations, with a single trap placed at each station. Traps were baited with a mixture of peanut butter and oats and provided with polyester or cotton bedding. Each trap was sheltered from sun and camouflaged with a brown cloth tent (Figure 3.3). After it was determined that only nocturnal small animals were captured, traps were checked daily in the early morning.

Upon capture, small individuals were handled in a clear plastic Ziplock™ bag while larger animals were handled in a cloth handling cone. Animals were identified to species using mass, hind foot length, tail length, and coloration. Before release each animal was marked with an individually numbered metal ear tag (National Band & Tag Co., Newport, KY, Monel self-piercing tags, 1005-1).

Habitat Assessment Field Methods

To examine the efficiency of pairing for capturing within-colony variation in habitat structure, I measured gross vegetation structure using a simplified Daubenmire method (Coulloudon et al. 1999). Within the core 1.05 ha portion of each unit, three 40 m transects were established 30 meters apart, running approximately North-South, and parallel to trap lines (Figure 3.3). Along each transect, every other meter was measured using a 20 cm x 50 cm Daubenmire frame. Within each quadrat, percent cover by category (grass, forb, woody, moss, bare ground, thatch, and rock) was estimated using the six Daubenmire cover classes (1=0-5%, 2=5-25%, 3=25-50%, 4=50-75%, 5=75-95%, 6=95=100%). Additionally, the tallest plant within each quadrat was measured using a meter stick. Vegetation was measured once per summer at the end of the season to ensure all species were fully grown.

In addition to vegetation measurements, I also counted prairie dog burrows within each core sampling area. Counts of active prairie dog burrows have been shown to be correlated with prairie dog density and can be used as a rough index of density (Biggins et al. 1993, Biggins and Kosoy 2001, Johnson and Collinge 2004). Additionally, counts of active and inactive burrows can be used to quantify total burrow density, which may act as an important habitat structure for *Peromyscus spp.* and other small mammals. Transects approximately 15 m apart were walked within the 1.05 hectare core sampling area and all burrows were counted and classified as either active or inactive. Active burrows were defined as burrows with fresh scat, disturbed soil, and/or vegetation clippings. Inactive burrows were those that are overgrown with vegetation, have a blocked entrance, or spider webs within burrows (Biggins et al. 1993). Burrows where level of activity could not be determined were alternately classified as active or inactive.

Analysis

To determine the validity of pairing the grids and ensure there were no strong pre-existing differences between treatment and control sites, habitat cover metrics were analyzed in Program R (R Core Team 2014) with package "lme4" using generalized linear mixed effects models (Bates et al 2015). Each cover class was analyzed separately in two models normally distributed models; one with random effects of gird, pair, and colony and fixed effects of treatment and year while the second excluded a treatment variable. A likelihood ratio test was used to compare models to assess evidence of systematic difference between treatments. Vegetation height and burrow counts were analyzed using the same models except in a linear mixed effects format.

To assess effects of deltamethrin treatment on deer mouse abundance, I performed 3 alternative analyses. First, I analyzed raw capture counts of unique individual mice captured on each grid during a session. These counts were used in a generalized linear mixed effects model with a Poisson distribution to determine if abundance was influenced by time and treatment. Random effects of pair, grid, and grid by session and fixed effects of colony and treatment by session were included to examine treatment changes in abundance within and between years and determine session specific treatment effects. A likelihood ratio test was used to compare a model including session-specific treatment effects to one that omitted treatment to assess evidence for an overall effect of treatment.

In a second abundance analysis, I independently estimated abundance for each grid-session combination, and analyzed abundance estimates using the same model as used with capture counts. Capture histories were broken up into 96 individual groups, one for each grid and session combination, to estimate the mouse population in program CAPTURE using the jackknife estimator (White et al. 1982). Jackknife population estimates were used in a general liner mixed effects model to determine session-specific effects of treatment expected abundance, using library lme4 in R. This model included random effects of pair, grid, and grid by session as well as fixed effects of colony, and treatment by session.

A third analysis used grid x session capture histories for the 96 grid-session groups as the response variable in Bayesian hierarchical model, following the approach of Converse and Royle (2012). The Bayesian hierarchical model integrated mark-recapture estimation of abundance and Poisson generalized linear mixed effects modeling to estimate effects of treatment and other factors on expected abundance. The model for expected abundance included random effects of pair, grid, pair by session, and an observation level effect. Additionally, fixed effects of year and treatment by session were estimated. Mark-recapture capture probabilities were modeled as a logit-scale additive function of colony x session, colony x session trap night, gird x session, grid x session x trap night and individual random effects. Recapture probability with a trap session was allowed to be different from initial capture probability within a session, to account for behavioral responses to previous capture within a trap session. Thus, the mark-recapture model for each grid-session was a form of model M_{tbh} (Otis et al. 1978). Uniform priors were specified as Unif(0,10) for effects of colony-session, grid-session, colony-session-night, grid-session-night, and recapture probability while the individual heterogeneity random effect prior was Unif(0,15). Priors for log scale parameters utilized a normal distribution with B0 intercept specififed as (2.5,0.1), year 2 as (0,0.1), colony 2 and 3 as (0,0.001), and session, pair, grid, pair

x session and the residual at (0,10). Analysis was run in WinBUGS (Gilks et al. 1996) using the R2WinBUGS package (Sturtz et al. 2005) in Program R (R Development Core Team 2011).

Capture histories of individual mice were analyzed in program MARK to determine if there are effects on mouse survival (White and Burnham 1999). Initial analyses combined abundance and survival analyses in a robust-design framework; however, currently the extension of hierarchical approaches modeling variation in abundance across space and time as well as survival in a multi-site robust-design approach is a research need, not an available approach. Several biologically sound models were run in a Cormack-Jolly-Seber framework to determine the effects of time and treatment on mouse survival (Lebreton et al. 1992). Therefore the models were formatted to reflect a robust design format by constraining survival (Phi) to 1 during trap sessions (secondary periods), while allowing the estimate to be unconstrained in between trap sessions (primary periods). To account for any preexisting differences, covariates for pair and colony were included. Additionally, a trap night level variable was included to account for increasingly large numbers of closed but empty traps that were seen throughout the season. An AIC (Akaike's Information Criterion) was preformed to determine informative variables and select the best fitting model. Estimates from the top model were used to determine the effects of treatment on survival (Burnham and Anderson 2002).

RESULTS

Measured habitat metrics were similar between treatments (Table 3.1). From 2013 to 2014, vegetation height and woody vegetation cover increased while burrow counts and bare ground decreased. Habitat analysis determined that randomization within pairs of treated and untreated grids ensured that there were no differences between treated and untreated grids (Table 3.2).

I captured 146 deer mice (359 total captures, including recaptures) in 2013, and 280 individual mice (564 captures) in 2014. No mice from 2013 were recaptured in 2014. Additionally, in 2013, five thirteen-lined ground squirrels (*Ictidomys tridecemlineatus*), one hispid pocket mouse (*Chaetodipus hispidus*) and one black-tailed prairie dog (*Cynomys ludovicianus*) were captured in Sherman traps. In 2014, 20 thirteen-lined ground squirrels, one black-tailed prairie dog, and one prairie vole *(Microtus ochrogaster*) were captured. Twenty two ground squirrels were caught on the Custer State park grids, two on Highland Creek, and one at South East. A prairie dog was captured on both Highland Creek

(2013) and South East (2014). The pocket mouse was captured at South East while the vole was captured in an insect pitfall trap at Custer State Park.

In both years the South East colony had the highest number of individual mouse captured (86 and 127 individuals making up 59% and 45% of captures respectively). In 2013, Highland Creek had higher numbers of individual captured (39, 27%) then Custer State Park (21, 14%), however these numbers were similar in 2014 (Highland Creek= 75, 27%, Custer =78, 28%) (Table 3.3). Across all colonies and in both years, more males were captured then females (Table3. 4).

Of the general linear mixed effects models fit to mouse capture data, the model with effect of treatment by trap session interaction (df=21, log likelihood= -224.91, 16 parameters) was not supported over the equivalent model with no effect of treatment (df=13, log likelihood=-228.91, 10 parameters; p=0.431 for likelihood ratio test testing null hypothesis that the model with no treatment effect incorporated was adequate compared to treatment by session model). Contrary to the hypothesis that dusting would impact deer mouse populations, treatment appeared to have no effect. This conclusion was supported as the model coefficients (Table 3.5) and the resulting odd ratios (Figure 3.5)showed no significant differences in mouse abundance on treated grids compared to untreated grids.

General linear mixed effects models of Jackknife estimates of mouse abundance revealed similar results to the model utilizing capture counts. The model with no effect (df=13, loglik=-272.58, 10 paramete) was supported over the model including an effect of treatment (df=21, loglik=-268.33; 16 parameters; p=0.384 for likelihood ratio test testing null hypothesis that the model with no treatment effect incorporated was adequate compared to treatment by session model). These results were supported as treatment estimates (Table 3.6) and resulting odds ratios showed no significant effect of treatment (Figure 3.6).

Bayesian analysis was run with three independent Markov chains for 50,000 iterations, discarding the first 20,000 for a total of 90,000 samples from the posterior distribution from each parameter. The MCMC chains showed satisfactory convergence ($\hat{R}$= 1.001-1.079) based on the Brooks-Gelman-Rubin statistic (<1.10) (Gelman et al. 2004). Population estimates from the jackknife estimates and Bayesian models were compared to capture counts for each colony (Tables 3.7-3.9). Capture counts ranged from 0 -20 and corresponding estimates ranged from 0-37 (Jackknife) and 2-28 (Bayesian). Average expected detection for Bayesian estimates was 0.20 (0.17-0.24). Population estimates between models were generally similar however differences ranged from 0.14 to 10.57 with the average

difference being 2.56. Estimates from both models were generally higher for treated grids compared to untreated grids, however no differences were significant within pairs. The average proportional treatment effect was 0.98 (treated grids relative to untreated)(95% Crl 0.72-1.28). Bayesian estimates of treatment showed no influence of treatment on mouse abundance except in the last session of year two when the population of mice on treated grids was significantly lower than on untreated grids (Table 3.10, Figure 3.7).

Model selection in Program Mark showed that models including a group effect of treatment were preferred over those without however, the increase in model fit was not significant (Table 3.11). The top model constrained the first primary period to be equal between treated and untreated groups as no effect of treatment was expected to be seen just days after treatment. After the first primary period, mice in the treated group showed higher survival then the untreated group but high standard error determined that these differences were not significant. Between years (primary period 4), survival was zero for both groups (Table 3.12).

DISCUSSION

Overall the effects of deltamethrin treatment on populations of deer mice seem minimal, with effects only being seen in one analysis in one session after two years of treatment. However, as a decline was noted on treated grids this may be cause for concern. This may indicate a cumulative effect of deltamethrin impacting the mice populations or their arthropod food sources. Since this was a short study, relative to the length of time a particular colony may be dusted for, it is important to note that this decline was seen in the second year. While these declines may indicate that consecutive treatment of the same colonies may lead to increasing declines in deer mouse populations, they were only noted in one of the models used. All methods employing maximum likelihood methods showed no treatment effects on survival of abundance on deer mice. While these methods were increasingly complex, accounting for the additional sources of variation, they are unable to account for all variation within the system. The complexity of the Bayesian models would allow them to be more heavily weighted, however the decline was seen in only one session. Additionally, the average effect of treatment showed no change, so a negative population change is not well supported.

In 2014, flea populations on mice were low compared to those in 2013 (Chapter 1). This decline reduced the benefits deltamethrin provides by removing ectoparasites, leaving only the potential

negatives of reducing food populations. However, as no increases in mouse populations were seen in 2013, when deltamethrin did have significant impacts on flea populations, any benefits that may be provided by reducing grooming times and parasitic blood consumption were minimal. Additionally, arthropod food sources that may have been impacted were readily abundant throughout both treated and untreated grids. Only one short term decline was noted and abundance on treated grids quickly returned to levels similar to untreated areas. However, no difference was seen in the amount of arthropod consumption by mice. Therefore all changes in mouse populations from this study are related to flea parasitism levels. Since mouse and flea populations are so variable between years and seasons, long-term monitoring of small mammal populations both on and off treated colonies is important to better understand cumulative impacts of deltamethrin.

As these prairie dog colonies had a relatively simple small mammal community compared to other areas, the impacts of deltamethrin should be further studied on colonies with a more diverse community (Brinkeroff et al. 2008, Pruett e al. 2010). Since other small mammals such as shrews, voles, and ground squirrels may have different ecologies and roles on prairie dog colonies, deltamethrin could impact their populations differently (Lomolino and Smith 2003). If these small mammals do not utilize prairie dog burrows, they may not interact with the deltamethrin and their fleas would not be impacted. This could allow for plague to maintained and spread through the colony leading to potential outbreaks. This may be especially significant for species such as grasshopper mice whose populations are thought to be closely related to plague outbreaks (Stapp et al 2009). Grasshopper mouse populations quickly develop a resistance to plague, making them excellent disease reservoirs (Thomas et al. 1988). Additionally, grasshopper mice are heavily carnivorous compared to deer mice, making them more reliant on arthropod food sources (Flake 1973). If deltamethrin causes declines in arthropod food sources there may be a greater potential for negative effects on those populations that feed heavily on arthropods. Therefore the fluctuations in food source arthropods may have larger impacts on grasshopper mouse populations, leading to additional impacts on the plague cycle on prairie dog colonies. Further research is still needed to determine the effects of deltamethrin on additional small mammal species. As this research continues, it will further the understanding of interactions between small mammals and plague on prairie dog colonies, allowing us to better understand its dynamics.

The populations of small mammals on these prairie dog colonies, aside from prairie dogs themselves, are almost entirely der mice. The low diversity of animals found on these colonies adds additional importance to the role of deer mice and small mammals as they often have large impacts on

their ecosystem and act as an important prey base for many predators (Gashweiler 1970, Wall 2001). While deer mice were expected to be dominant on this ecosystem, additional species were expected to be captured on prairie dog colonies. Duckwitz (2001) found high abundance of thirteen-lined ground squirrels present on prairie dog colonies and were commonly captured on prairie dog colonies in 2012 (Licht). During the study thirteen-lined ground squirrels were frequently seen on prairie dog colonies, within trap grids, heard while checking traps, and their scat was present by traps. Therefore, while present, ground squirrels exhibited a low trap rate. Utilizing larger traps, such as a small cage trap, may have allowed for additional individuals to be captured. However, as thirteen-lined ground squirrels were found to be patchily distributed across Wind Cave National Park and are so closely tied to grazing pressure and vegetation height, their populations may not have been. Changes in precipitation may influence captures of ground squirrels and other small mammals, therefore we would expect ground squirrel captures to increase in drier years when food is scarcer (Shipley and Reading 2006). While this assumption held true when comparing ground squirrel capture rates between this study and the study conducted by Licht in 2002 when precipitation was lower, it does not explain the increase in captures between 2013 and 2014. This increase ground squirrel captures is likely related to an increased population caused by higher precipitation, or an element of social learning that reduced trap shyness (Galfe and Laland 2005). At Wind Cave, further study of ground squirrel population should utilize several trap methods and longer trap sessions or pre-baited traps.

The populations of deer mice in these systems are highly driven by observed changes in precipitation and related food sources, making the overall population highly variable between years (Mills 2005). Increased vegetation and precipitation play a large role in the impact deer mice have as disease vectors (Luis et al. 2010). Higher densities of mice leads to increased interaction between individuals increasing the transmission rate of diseases or disease vectors (Hu et al. 2013). Additionally, higher densities cause more intense competition and therefore increased rates of dispersal, potentially further spreading disease (Matthysen 2005). Since deer mice are dominant in this small mammal community, the complexity of the plague system is greatly reduced. As deer mice are highly susceptible to plague, they do not have a high potential for transmitting and maintaining plague within this system compared to species that are prone to infection but have low mortality from the disease (Salked and Stapp 2008). A plague outbreak would quickly amplify within deer mouse populations and could quickly remove all small mammals from this system. In the event of an outbreak, the entire small mammal population would be decimated, removing a large prey base for animals such as rattlesnakes and

burrowing owls that are frequently found on prairie dog colonies but may be too small to eat prairie dogs.

Understanding the changes in deer mouse population relative to climate and habitat variables is an important component to deterring plague in the prairie dog system. As deer mice populations are highly influenced by precipitation, managers can use this information of better predict years of higher plague risk (Stenseth et al. 2006). Years with high precipitation lead to higher small mammal and flea densities and therefore higher plague risk (Kausrud et al 2007). If precipitation is high for several years, thereby increasing plant and arthropod food sources for deer mice, the population would likely continue to increase, further increasing the rate of disease transmission. Thus, the importance of flea reduction treatments may vary between wet and dry years. During wet years dusting should become a priority in plague areas as infection of a few individuals could quickly spread through the colony. However in years with low precipitation, or after multiple dry years, mouse populations would be low, reducing their capacity to spread fleas and transmit the disease quickly. During these years, deltamethrin would likely have a reduced effect as the likelihood for an outbreak is already low (Coolinge et al. 2005, Stapp et al. 2004). The plague system is driven by multiple factors, such as flea and other mammal populations. Therefore the small mammal populations and precipitation cannot be entirely predictive of the likelihood of plague outbreaks (Cavanaugh and Marshall 1972).

Prior to this study precipitation at Wind Cave was low relative to historic averages, leading to low mouse and flea populations in 2013 (Dan Roddy, Personal Communications). However precipitation increased to high seasonal precipitation in 2013 and 2014 leading to an increase of fleas and mice in 2014. Since both mouse and flea populations increase with increasing precipitation, deltamethrin application likely provides the greatest benefit to mouse populations after wet years (Stapp et al. 2004, Collinge et al. 2005). After several years of high flea numbers, positive impacts of dusting may be visible in mouse populations. As many colonies have been treated annually for several years or longer, any effects of deltamethrin on small mammals may be more pronounced on these areas. In areas where large numbers of fleas harbor the plague bacterium deltamethrin treatment may have a more significant effect. By reducing the probability of contracting disease, the health of the population would increase drastically. This provides a much greater benefit to the mouse populations compared to colonies with low levels of disease.

While precipitation plays a major role in deer mouse and small mammal abundance, other factors that lead changes in vegetation structure play significant roles as well. Wind Cave National Park

and Custer State Park are both home to large populations of elk and bison that preferentially utilize prairie dog colonies (Krueger 1986). During the course of this study, grazing pressures were high at Wind Cave National Park as estimates for elk and bison populations were high or at management objectives. Grazing pressures can change the vegetation structure, leading to changes in deer mouse abundance (Matlack et al. 2001). Additional management objectives indicating timing and frequency of prescribed burns, presence of invasive species, and applications of herbicides can greatly alter the vegetation structure of prairie dog towns and the habitat for small mammals.

While the impacts of deltamethrin to plague within prairie dog populations is known to increase populations and prevent the epizootic outbreaks, the impacts on non-target groups are still being investigated (Seery et al. 2003). From this study, we gained further insight into its impacts on deer mice populations, learning that any population declines were minimal, further supporting the application of deltamethrin. For mouse populations, deltamethrin likely increased the health of the population by removing flea species from individuals while having no effect on arthropod food sources. Deltamethrin is generally not applied in 1-2 year periods, so this study may not be sufficient to determine the impacts of dusting for many consecutive years. Therefore to reduce any potentially detrimental effects on the mouse populations and the ecosystem, managers may avoid annually dusting an area and instead treatment either every other year or every two years may be sufficient to reduce impact to mouse and non-target populations. Since the main goal of treatment is to reduce the flea populations for ferret conservation, treatment should reflect changes in flea populations. Managers could focus on deltamethrin treatments following consecutive years with above average precipitation when flea and mouse populations are high. Conversely, after several below average years of precipitation, flea populations would be reduced reducing the risk of plague and utility of deltamethrin treatment. While low precipitation is closely related to flea densities, the levels of precipitation needed to reduce vector populations to low-risk densities can vary widely between areas. The possibility of forgoing treatment should reflect the manager's focal wildlife species as well as their concerns about plague and non-target arthropod and wildlife impacts. The ability constrain or reduce treatments after dry years could reduce the impact to non-target mammals while increasing the impact of deltamethrin by focusing efforts to years with higher flea populations.

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TABLES AND FIGURES

Figure 3.1. Predicted effects of deltamethrin on the small mammal population with measured variable indicated in exterior boxes.

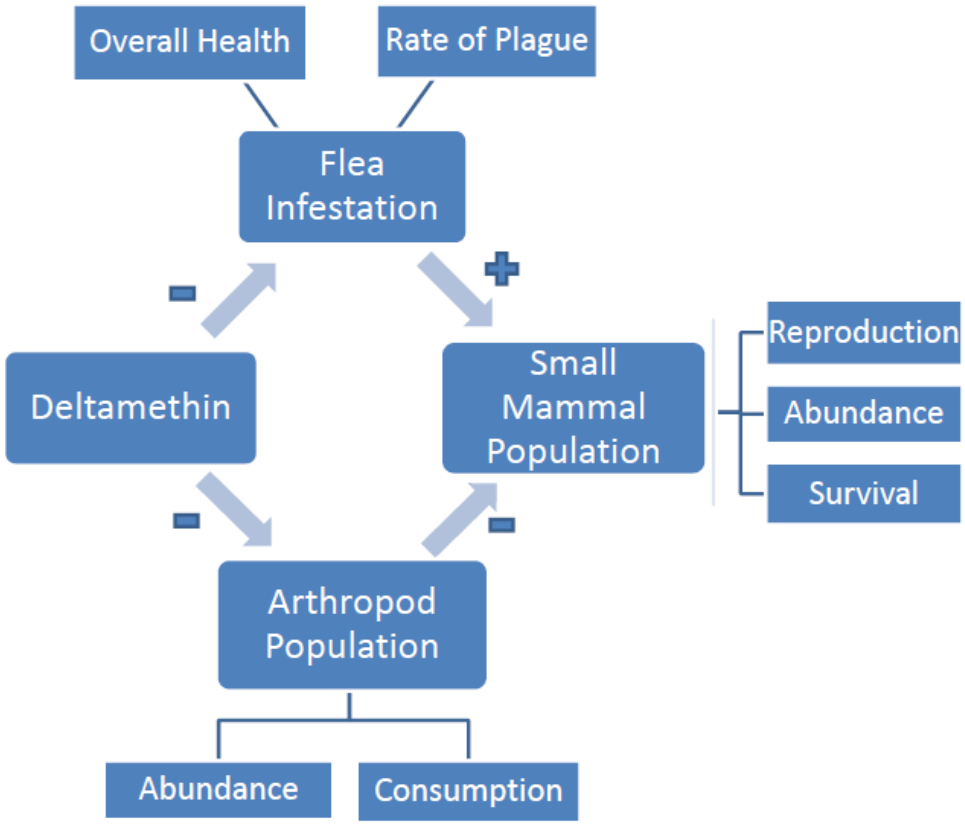

Figure 3.2. Study colonies in Wind Cave National Park (black boundary) and adjacent Custer State Park in western South Dakota (inset). Trapped prairie dog colonies are gray; sampling grids are indicated with a black dot.

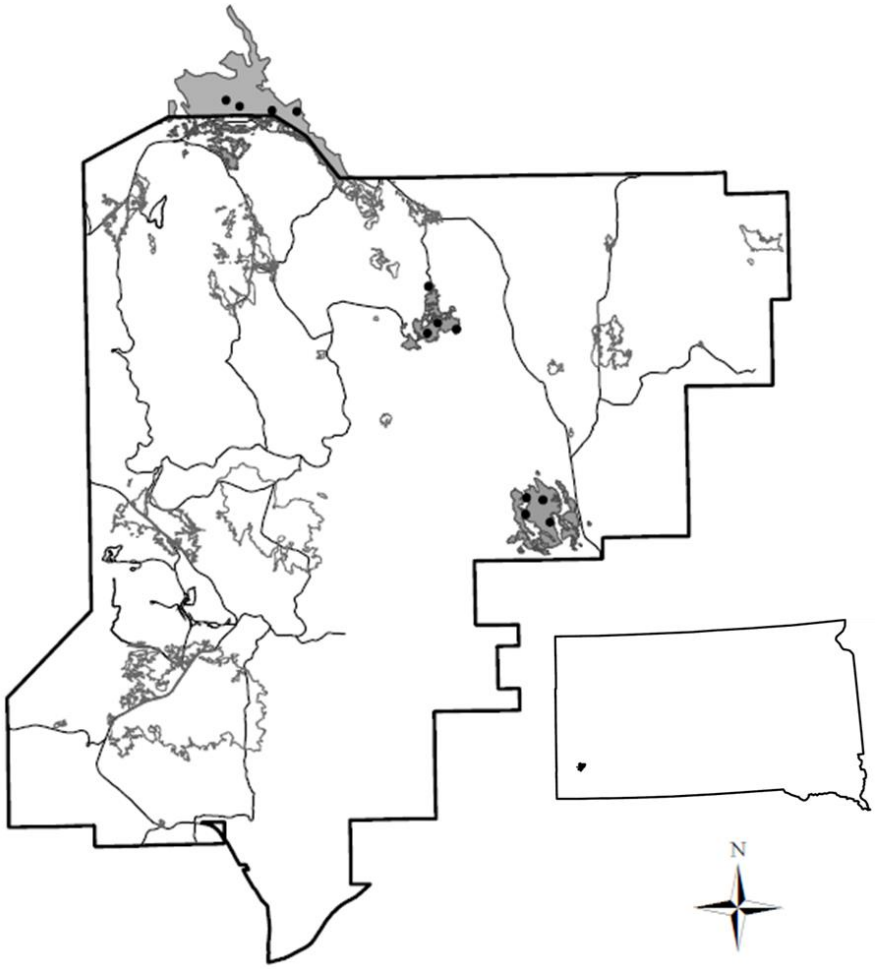

Figure 3.3. Sherman trap used to capture small mammals with a cloth cover.

Figure 3.4. Schematic of experimental unit with approximate spacing of small mammal trap grid, and vegetation transects.

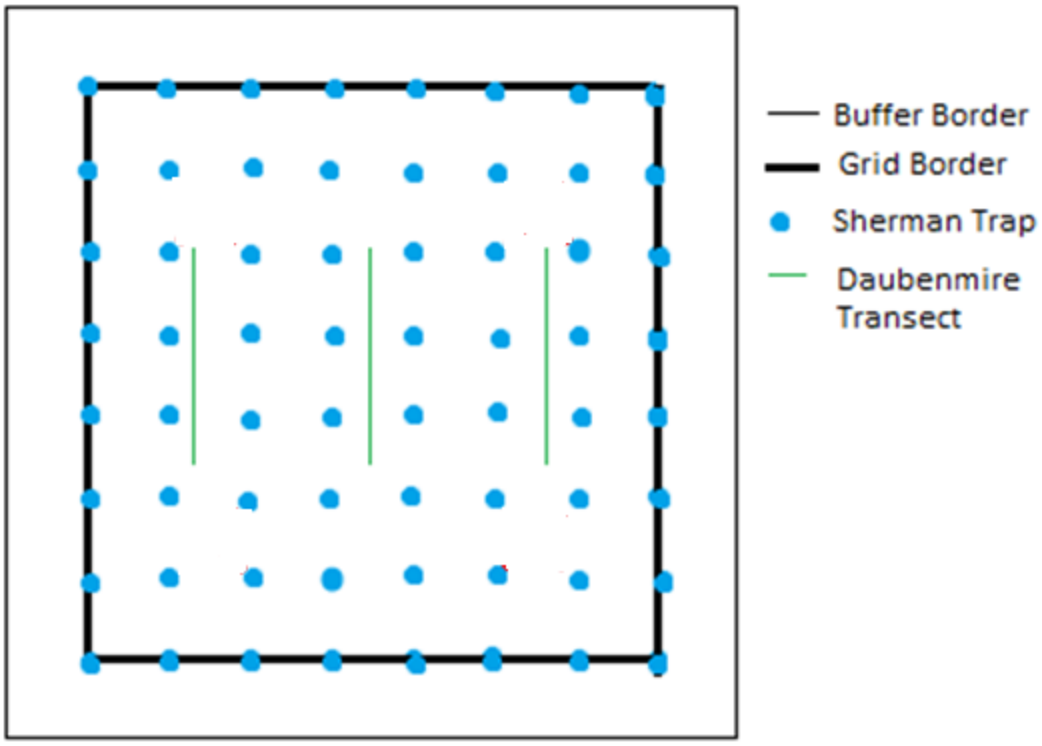

Table 3.1. Means values(SE = Standard Error) for covariates measured on Daubenmire transects from control grids and grids treated with deltamethrin on prairie dog colonies at Wind Cave National Park, SD and Custer State Park, SD in the summers of 2013 and 2014. Herb, grass, woody, bare, and rock are all percentage of ground cover while height is measured in millimeters and burrow is count of burrows on a grid.

			Herb	Grass	Woody	Bare	Rock	Litter	Height	Burrow
2013	Untreated	Mean	26.97	31.10	0.34	20.39	2.74	18.44	23.95	127.50
		SE	4.96	4.33	0.14	1.90	0.60	2.03	1.35	6.48
	Treated	Mean	25.12	26.62	0.04	22.82	3.25	20.31	22.45	126.33
		SE	3.60	3.63	0.04	2.83	0.71	2.96	1.22	9.49
2014	Untreated	Mean	25.45	36.55	8.03	11.97	1.38	16.57	29.87	103.33
		SE	2.64	4.68	1.58	0.90	0.61	1.35	3.35	7.16
	Treated	Mean	25.23	31.20	6.16	15.28	3.42	16.29	26.92	111.83
		SE	3.18	4.15	1.20	2.95	1.32	2.42	2.57	6.84

Table 3.2. Log-scale estimates of differences between control grids and those selected for deltamethrin treatment on vegetation cover attributes, vegetation height, and burrow counts for prairie dog colonies at Wind Cave National Park, SD and Custer State Park, SD in 2013 and 2014. Estimates are from separate linear mixed-effects models for each log-transformed variable. Model included random effects of colony, pair, and grid.

	Fixed Effects				Random Effects (SD)			
	Estimate	Standard Error	-95% CI	+95% CI	Grid	Pair	Site	Residual
Herb Cover	-0.012	0.131	-0.27	0.24	0.04	0.17	0.01	0.07
Grass Cover	-0.095	0.136	-0.36	0.17	0.03	0.19	0.72	0.16
Woody Cover	-0.064	0.105	-0.27	0.14	0.01	0.00	0.00	0.13
Bare Cover	0.045	0.065	-0.08	0.17	0.00	0.00	0.02	0.08
Rock Cover	0.108	0.179	-0.24	0.46	0.07	0.02	0.12	0.18
Litter Cover	-0.033	0.078	-0.19	0.12	0.00	0.000	0.00	0.16
Height (mm)	-2.225	3.025	-8.15	3.70	17.41	18.29	3.36	60.13
Burrow Count	3.667	13.257	-22.32	29.65	312.4	416.9	0.00	429.7
Active Burrow Count	2.75	10.307	-17.45	22.95	0.01	0.04	0.00	0.03
Inactive Burrow Count	0.916	8.399	-15.55	17.38	4.07	0.00	0.00	415.19

Table 3.3. The number of individual deer mice (*Peromyscus maniculatus*) captured in each trap session during the summers of 2013 and 2014. Mice were trapped on four grids in three prairie dog colonies, one located in Custer State Park, SD and two in Wind Cave National Park, SD (Highland Creek and South East). Grey shading indicates grids that were treated with deltamethrin insecticide and the red line shows the timing of the annual treatment.

		2013				2014			
		Session							
Colony	Grid	1	2	3	4	5	6	7	8
Custer	1A	0	2	1	0	2	4	8	5
	1B	1	0	1	0	2	1	8	3
	2A	4	2	2	0	11	3	10	11
	2B	6	2	4	3	8	11	11	6
Highland	1A	6	9	4	3	9	9	6	4
	1B	9	5	7	5	10	6	12	11
	2A	5	3	3	1	8	1	6	5
	2B	5	3	2	0	3	2	1	4
South East	1A	10	9	6	4	8	9	6	4
	1B	4	11	7	5	8	20	11	13
	2A	9	13	7	0	12	15	5	9
	2B	11	13	9	4	19	12	11	6

Table 3.4. Counts of male and female deer mice (*Peromyscus maniculatus*) captured on trapping grids in one prairie dog colony in Custer State Park and two colonies in Wind Cave National Park (Highland Creek and South East) in the summers of 2013 and 2014.

		2013		2014	
		Male	Female	Male	Female
Custer	1A	1	1	9	8
	1B	2	0	8	3
	2A	2	4	18	7
	2B	8	3	18	11
Highland	1A	5	6	14	6
	1B	10	3	16	13
	2A	6	1	11	5
	2B	3	5	7	3
South East	1A	14	7	14	12
	1B	12	7	22	16
	2A	9	9	16	17
	2B	12	16	21	9
Total		84	62	174	110

Table 3.5. Estimated proportional effects of session, colony, and treatment on deer mouse (*Peromyscus maniculatus*) abundance on grids treated with deltamethrin relative to those with no treatment, based on Poisson generalized linear mixed effects modeling of capture counts. Colony estimates are relative to Custer State Park colony; Session estimates are proportional changes compared to Session 1. Session 1-4 occurred in 2013 while sessions 5-8 occurred in 2014. Treatment occurred annually between sessions 1 and 2 in 2013 and between 5 and 6 in 2014.

	Estimate	-95% CI	+95% CI
Intercept	3.81	2.12	6.87
Highland Creek	1.28	0.65	2.52
South East	2.38	1.22	4.66
Session 2	0.83	0.50	1.37
Session 3	0.65	0.38	1.12
Session 4	0.23	0.11	0.50
Session 5	1.20	0.75	1.92
Session 6	0.93	0.57	1.52
Session 7	1.12	0.70	1.80
Session 8	1.11	0.69	1.79
Session 1:Treatment	0.84	0.50	1.40
Session 2:Treatment	1.49	0.73	3.02
Session 3:Treatment	1.32	0.62	2.84
Session 4:Treatment	2.10	0.79	5.60
Session 5:Treatment	1.39	0.71	2.70
Session 6:Treatment	1.89	0.96	3.73
Session 7:Treatment	1.50	0.76	2.93
Session 8:Treatment	1.10	0.55	2.19

Random Effects Variance Components (Standard Deviations)
$\sigma_{Pair} = 0.31$, $\sigma_{grid} = 0.05$, $\sigma_{Gird*Session} = 0.15$

Figure 3.5. Estimated proportional effect of treatment on deer mouse abundance (*Peromyscus maniculatus*), with 95% confidence intervals, on grids treated with deltamethrin compared to controls from Poisson generalized linear mixed modeling of capture counts. Red lines indicate treatments. Session 1-4 occurred in 2013 and sessions 6-8 in 2014. A relative abundance of 1 would indicate no effect of treatment.

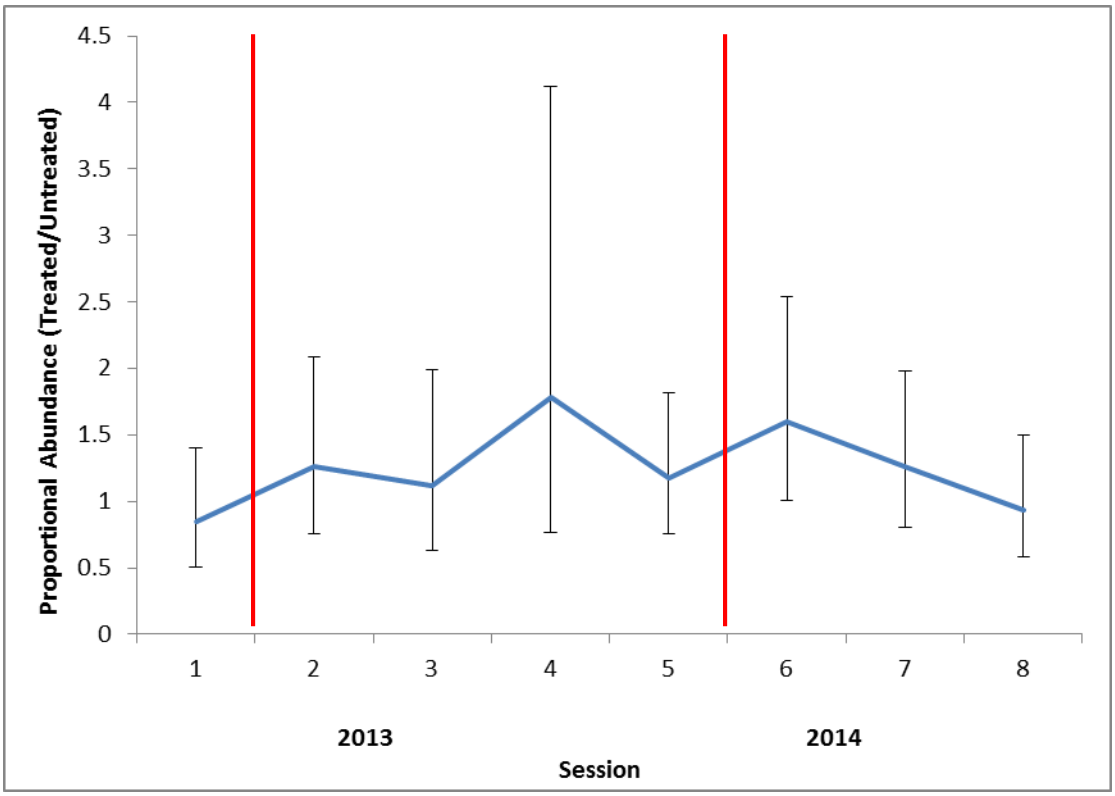

Table 3.6. Estimated proportional effects of session, colony, and treatment on deer mouse (*Peromyscus maniculatus*) abundance on grids treated with deltamethrin relative to those with no treatment, based on Poisson generalized linear mixed effects modeling of jackknife estimates of each grid-session combination. Colony estimates are relative to Custer State Park colony; session estimates are proportional changes compared to Session 1. Session 1-4 occurred in 2013 while sessions 5-8 occurred in 2014. Treatment occurred annually between sessions 1 and 2 in 2013 and between 5 and 6 in 2014.

	Estimate	-95% CI	+95% CI
Intercept	3.86	1.90	7.81
Highland Creek	1.40	0.62	3.20
South East	2.56	1.12	5.83
Session 2	1.07	0.60	1.93
Session 3	0.88	0.48	1.61
Session 4	0.29	0.14	0.60
Session 5	1.58	0.90	2.80
Session 6	1.27	0.72	2.24
Session 7	1.62	0.92	2.85
Session 8	1.51	0.85	2.66
Session 1:Treatment	0.88	0.48	1.61
Session 2:Treatment	1.73	0.76	3.95
Session 3:Treatment	1.11	0.47	2.62
Session 4:Treatment	1.55	0.55	4.39
Session 5:Treatment	1.49	0.67	3.33
Session 6:Treatment	1.90	0.85	4.24
Session 7:Treatment	1.70	0.78	3.72
Session 8:Treatment	1.00	0.44	2.28

Random Effects Variance Components (Standard Deviations)

$\sigma_{Pair} = 0.31$, $\sigma_{grid} = 0.04$, $\sigma_{Gird*Session} = 0.35$

Figure 3.6. Estimated proportional effect of treatment on deer mouse abundance (*Peromyscus maniculatus*), with 95% confidence intervals, on grids treated with deltamethrin compared to controls from Poisson generalized linear mixed modeling of jackknife estimates of abundance for each grid-session combination. Red lines indicate treatments. Session 1-4 occurred in 2013 and sessions 6-8 in 2014. A relative abundance of 1 would indicate no effect of treatment.

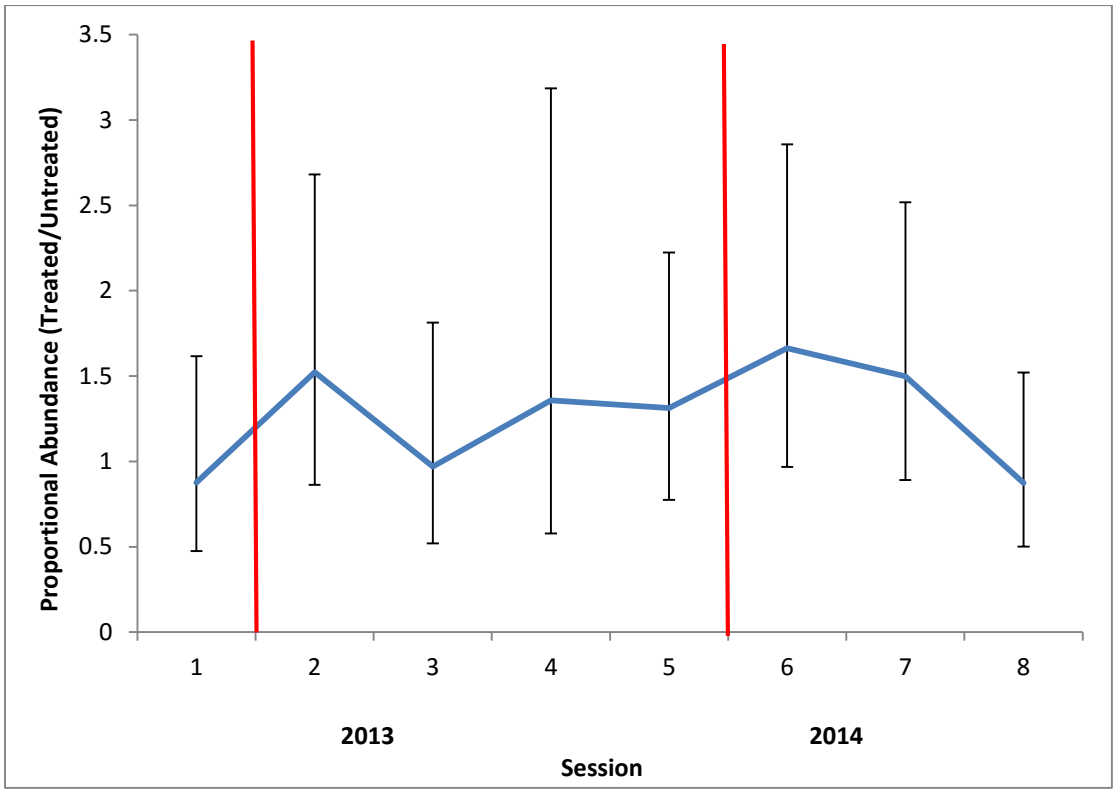

Table 3.7. Population estimates from Bayesian and Jackknife models compared to the number of captured deer mice (*Peromyscus maniculatus)* from 4 sample grids at Custer State Park. Grids shaded with grey indicate treatment with deltamethrin insecticide. Sessions 1-4 occurred over the summer of 2013 while 5-8 occurred in 2014.

			Bayesian Estimates		Jackknife Estimates		
Grid	Pair	Session	Population Estimate	Standard Deviation	Population Estimate	Standard Error	Number of Captures
CSP1A	1	1	2.44	1.53	0		0
CSP1A	1	2	3.8	1.65	2	0.08	2
CSP1A	1	3	3.34	1.36	1		1
CSP1A	1	4	2.58	1.64	0		0
CSP1A	1	5	3.81	1.65	4	2.74	2
CSP1A	1	6	6.99	2.29	5	2.21	4
CSP1A	1	7	12.82	2.56	9	1.18	8
CSP1A	1	8	7.49	1.96	5	2.04	5
CSP1B	1	1	2.7	1.69	1		1
CSP1B	1	2	2.17	1.34	1		1
CSP1B	1	3	2.94	1.75	1		1
CSP1B	1	4	2.62	1.64	0		0
CSP1B	1	5	4.1	1.8	3	1.17	2
CSP1B	1	6	2.85	1.67	1		1
CSP1B	1	7	13.76	3.35	13	3.76	8
CSP1B	1	8	6.07	2.31	4	1.17	3
CSP2A	2	1	7.57	2.5	5	2.21	4
CSP2A	2	2	2.89	1.09	4	2.74	2
CSP2A	2	3	2.81	1.64	2	0.15	2
CSP2A	2	4	2.82	1.66	0		0
CSP2A	2	5	17.71	3.73	26	6.13	11
CSP2A	2	6	5.51	2.01	5	1.67	3
CSP2A	2	7	16.35	3.51	15	3.89	10
CSP2A	2	8	17.05	3.01	14	3.26	11
CSP2B	2	1	8.87	2.13	9	2.91	6
CSP2B	2	2	3.02	1.8	4	2.74	2
CSP2B	2	3	5.77	1.61	6	1.66	4
CSP2B	2	4	6.42	1.96	3	3.35	3
CSP2B	2	5	13.48	3.22	13	3.76	8
CSP2B	2	6	16.53	3.29	21	5.07	11
CSP2B	2	7	16.82	3.38	19	4.54	11
CSP2B	2	8	11.46	3.26	12	3.79	6

Table 3.8. Population estimates from Bayesian and Jackknife models compared to the number of captured deer mice (*Peromyscus maniculatus)* from the Highland Creek prairie dog colony at Wind Cave National Park. Grids shaded with grey indicate treatment with deltamethrin insecticide. Sessions 1-4 occurred over the summer of 2013 while 5-6 occurred in 2014.

			Bayesian Estimates		Jackknife Estimates		
Grid	Pair	Session	Population Estimate	Standard Deviation	Population Estimate	Standard Error	Number of Captures
HC1A	3	1	9.8	2.58	6	2.04	6
HC1A	3	2	12.65	2.93	17	4.47	9
HC1A	3	3	6.2	1.81	5	1.17	4
HC1A	3	4	7.81	2.67	3	2.25	3
HC1A	3	5	13.74	3.35	18	5.03	9
HC1A	3	6	12.69	2.92	17	4.47	9
HC1A	3	7	9.96	2.59	12	3.79	6
HC1A	3	8	7.92	2.6	5	3.87	4
HC1B	3	1	12.14	2.3	10	2.47	9
HC1B	3	2	9.09	2.8	8	2.96	5
HC1B	3	3	11.97	2.66	13	3.72	2
HC1B	3	4	10.12	2.27	7	1.66	5
HC1B	3	5	14.71	2.94	11	1.54	10
HC1B	3	6	9.67	2.54	12	3.84	6
HC1B	3	7	18.44	3.64	16	3.49	12
HC1B	3	8	15.9	3	20	5.04	11
HC2A	4	1	8.13	2.29	5	2.21	4
HC2A	4	2	3.95	1.69	6	2.13	3
HC2A	4	3	5.41	1.97	6	2.20	3
HC2A	4	4	2.25	1.33	1		1
HC2A	4	5	10.03	2.22	14	3.69	8
HC2A	4	6	2.84	1.66	1		1
HC2A	4	7	9.54	2.5	12	3.79	6
HC2A	4	8	6.91	2.16	7	1.66	5
HC2B	4	1	8.3	2.34	5	2.19	5
HC2B	4	2	6.48	0.198	4	1.17	3
HC2B	4	3	3.14	1.25	3	1.17	2
HC2B	4	4	2.5	1.56	0		0
HC2B	4	5	6.46	2.45	4	1.17	3
HC2B	4	6	4.2	1.93	3	1.17	2
HC2B	4	7	2.68	1.58	1		1
HC2B	4	8	8.23	2.34	5	3.87	4

Table 3.9. Population estimates from Bayesian and Jackknife models compared to the number of captured deer mice (*Peromyscus maniculatus)* from the South East prairie dog colony at Wind Cave National Park. Grids shaded with grey indicate treatment with deltamethrin insecticide. Sessions 1-4 occurred over the summer of 2013 while 5-6 occurred in 2014.

			Bayesian Estimates		Jackknife Estimates		
Grid	Pair	Session	Population Estimate	Standard Deviation	Population Estimate	Standard Error	Number of Captures
SE1A	5	1	13.98	2.65	11	2.33	10
SE1A	5	2	15.03	3.04	10	2.35	9
SE1A	5	3	8.92	2.18	6	2.04	6
SE1A	5	4	7.59	2.55	6	1.66	4
SE1A	5	5	14.28	3.61	12	5.48	8
SE1A	5	6	16.81	4.11	17	4.47	9
SE1A	5	7	10.95	3.06	12	3.79	6
SE1A	5	8	7.63	2.49	5	3.87	4
SE1B	5	1	7.6	2.45	5	2.21	4
SE1B	5	2	17.65	3.77	17	6.42	11
SE1B	5	3	10.86	2.61	7	2.05	7
SE1B	5	4	7.39	1.92	5	2.04	5
SE1B	5	5	12.4	2.78	10	2.75	8
SE1B	5	6	27.64	4.05	37	7.10	20
SE1B	5	7	13.42	2.84	24	5.82	11
SE1B	5	8	18.63	3.39	16	3.01	13
SE2A	6	1	14.38	2.88	11	1.67	9
SE2A	6	2	20.76	3.98	23	5.18	13
SE2A	6	3	12.2	3.2	15	4.50	7
SE2A	6	4	2.03	1.27	0		0
SE2A	6	5	19.1	3.88	13	2.34	12
SE2A	6	6	24.62	4.26	21	3.94	15
SE2A	6	7	9.52	2.88	8	2.96	5
SE2A	6	8	15.2	3.59	17	4.47	9
SE2B	6	1	18.31	3.12	13	2.75	11
SE2B	6	2	20.71	4.1	30	6.90	13
SE2B	6	3	13.35	2.79	11	2.75	9
SE2B	6	4	6.62	2.09	5	2.21	4
SE2B	6	5	27.41	4.21	28	4.98	19
SE2B	6	6	21.4	4.26	16	3.26	12
SE2B	6	7	16.29	3.2	20	5.04	11
SE2B	6	8	9.52	2.39	9	4.74	6

Table 3.10. Bayesian hierarchical estimates of treatment by session and random effects of deltamethrin treatment on deer mouse abundance on prairie dog colonies at Wind Cave National Park and Custer State Park. Estimates of year, treatment, residual, pair, grid, session, and pair by session are from Poisson distributed log-scale estimates from abundance models. Remaining estimates for individual, detection, baseline recapture probability, colony by session, colony by session by night, grid by session, recapture, and grid by session by night are from Bayesian logistic generalized mixed models for detecting probability.

	Estimate	Standard Deviation	-95% CrI	+95% CrI
Intercept	2.48	3.16	-3.74	8.63
Year 2	-0.17	0.288	-0.74	0.39
Treatment-Session 1	-0.17	0.28	-0.74	0.37
Treatment-Session 2	0.18	0.27	-0.34	0.72
Treatment-Session 3	0.09	0.24	-0.39	0.57
Treatment-Session 4	-0.1	0.24	-0.59	0.37
Treatment-Session 5	0.24	0.26	-0.27	0.76
Treatment-Session 6	-0.06	0.25	-0.57	0.42
Treatment-Session 7	0.52	0.28	-0.03	1.08
Treatment-Session 8	-0.81	0.33	-1.5	-0.17
Residual	0.1	0.07	0.008	0.28
Pair	0.29	0.25	0.01	0.9
Grid	0.12	0.1	0.006	0.39
Session	0.2	0.17	0.009	0.64
Pair*Session	0.59	0.1	0.41	0.81
Individual	0.65	0.14	0.33	0.92
Detection	0.205	0.016	0.17	0.24
Baseline Recapture	0.88	0.14	0.64	1.18
Colony*Session	0.13	0.09	0.01	0.37
Colony*Session*Night	0.15	0.07	0.03	0.32
Grid*Session	0.23	0.13	0.02	0.522
Recapture	0.68	0.15	0.37	0.99
Grid*Session*Night	0.256	0.105	0.07	0.46

Figure 3.7. Proportional effects of deltamethrin treatment on deer mouse (*Peromyscus maniculatus*) abundance from prairie dog colonies at Wind Cave National Park and Custer State Park. Estimates are from Poisson distributed Bayesian hierarchical models of capture counts. Vertical red lines between sessions indicate the timing of annual treatment. Sessions 1-4 occurred during the summer of 2013 while sessions 5-8 occurred in 2014.

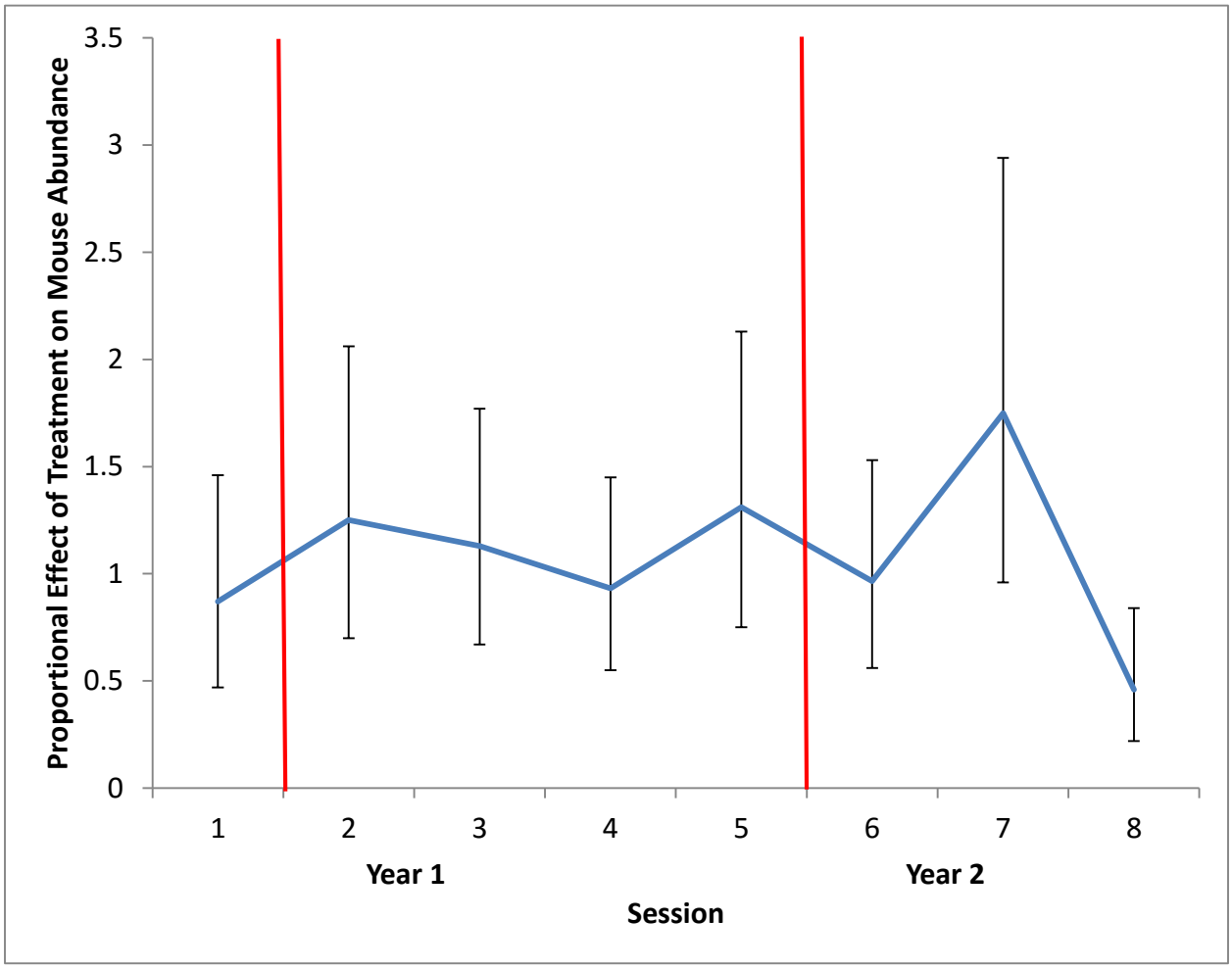

Table 3.11. AICc results of a Cormack-Jolly-Seber survival analyses showing top fitting models of deer mouse survival (Phi) on prairie dog colonies between groups treated with deltamethrin and control groups with variation in treatment group effects (treatment) and session time effects (session). Covariates indicating influence of established pairs and colonies were included as well as a trap night specific variable indicating the number of closed but empty traps. Capture histories of 426 mice from 2013 and 2014 at Wind Cave National Park and Custer State Park were used.

Phi Model	P Model (Random variables)	Delta AICc	AICc Weights	Model Likelihood	Number of Parameters
Treatment*session(2-7)	Treatment*session (trapnight, pairs)	0	0.48	1	20
Treatment*session	Treatment*session, (trapnight, pairs)	1.99	0.17	0.36	20
Treatment*session	Treatment*session, (trapnight, colony)	2.76	0.12	0.25	19
Session	Session (trapnight, pairs)	2.99	0.10	0.22	18
Session	Session (trapnight ,colony)	4.11	0.06	0.12	18

Table 3.12. Between session survival (Phi) estimates from Cormack-Jolly-Seber modeling of deer mouse survival on prairie dog colonies that were treated or controls and Wind Cave National Park and Custer State Park in 2013 and 2014.

Between Session Period	Estimate of Survival	
	Treated	Untreated
1-2	0.609 (0.07)	0.609 (0.07)
2-3	0.525 (0.08)	0.367 (0.07)
3-4	0.409 (0.10)	0.267 (0.08)
4 (2013)-5(2014)	0	0
5-6	0.542 (0.07)	0.384 (0.07)
6-7	0.386 (0.06)	0.234 (0.05)
7-8	0.6 (0.10)	0.441 (0.10)

{Phi(g*t(2-7)) p(g*t) tn, pairs}[9]

[9] Survival (Phi) varied by treatment (g) and session (t) for sessions 2-7. Capture probability (p) varied by treatment and time for all sessions. Random effects of trap night (tn) and pair (pair) were included.

Appendix 1. Bayesian binomial linear mixed effects model to determine the impact of deltamethrin treatment on the consumption of arthropods by deer mice on prairie dog colonies at Wind Cave National Park and Custer State Park.

Analysis Methods

This model utilized the binomial count of fields that contained arthropod remnants for all 60 readings from the fecal sample in a binomial general linear mixed model to determine any effects of treatment (WinBUGS via package R2WinBUGS, Thomas 1994, Ligges and Gleman 2005). The proportion of fields with arthropods was logit transformed and the resulting proportion was used as a response variable. Effects of pair, grid, session, and pair by session were included as random effects while colony and treatment were utilized as fixed effects. The model was run with 3 chains for 200,000 iterations discarding the first 30,000 for a total of 510,000 iterations until chains converged based on the Gelman-Rubin statistic.

Results

Table 2.7. The logit scale effect of deltamethrin treatment on the consumption of arthropods by deer mice (*Peromyscus maniculatus*) on prairie dog colonies at Wind Cave National Park and Custer State Park for each trapping session. Session 1-4 occurred in 2013 while sessions 5-8 occurred in 2014. Annual treatment of deltamethrin occurred after sessions 1 and 5 as indicated by the red line.[10]

	Mean	2.50%	97.50%
B.treat.1	0.29	-1.12	1.74
B.treat.2	-0.45	-1.82	0.97
B.treat.3	0.45	-1.3	2.2
B.treat.4	-0.89	-3.65	1.85
B.treat.5	-0.32	-1.36	0.64
B.treat.6	-0.49	-1.84	0.82
B.treat.7	0.37	-1.02	1.7
B.treat.8	-0.21	-1.59	1.19

[10] Random Effects Variance Components (standard deviations): $\sigma_{Pair} = 0.53$, $\sigma_{grid} = 0.24$, $\sigma_{Pair*Session} = 0.35$