How much effort is required to accurately describe the complex ecology of a rodent-borne viral disease?

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Abstract

We use data collected on 18,1-ha live trapping grids monitored from 1994 through 2005 and on five of those grids through 2013 in the mesic northwestern US to illustrate the complexity of the deer mouse (*Peromyscus maniculatus*)/Sin Nombre virus (SNV) host-pathogen system. Important factors necessary to understand zoonotic disease ecology include those associated with distribution and population dynamics of reservoir species as well as infection dynamics. Results are based on more than 851,000 trap nights, 16,608 individual deer mice and 10,572 collected blood samples. Deer mice were distributed throughout every habitat we sampled and were present during every sampling period in all habitats except high altitude habitats over1900 m. Abundance varied greatly among locations with peak numbers occurring mostly during fall. However, peak rodent abundance occurred during fall, winter and spring during various years on three grids trapped 12 mo/yr. Prevalence of antibodies to SNV averaged 3.9% to 22.1% but no grids had mice with antibodies during every month. The maximum period without antibody-positive mice ranged from one month to 52 months, or even more at high altitude grids where deer mice were not always present. Months without antibody-positive mice were more prevalent during fall than spring. Population fluctuations were not synchronous over broad geographic areas and antibody prevalences were not well spatially consistent, differing greatly over short distances. We observed an apparently negative, but non-statistically significant relationship between average antibody prevalence and average deer mouse population abundance and a statistically significant positive relationship between the average number of antibody positive mice and average population abundance. We present data from which potential researchers can estimate the effort required to adequately describe the ecology of a rodent-borne viral system. We address different factors affecting population dynamics and hantavirus antibody prevalence and discuss the path to understanding a complex rodent-borne disease system as well as the obstacles in that path.

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Keywords

Introduction

The study of hantaviruses has attracted increasing attention from ecologists in the last two decades (Schmaljohn and Hjelle 1997, Mills and Childs 1998, Singleton et al. 1999, Escutenaire et al. 2000, Calisher et al. 2002, Murua et al. 2003, Piudo et al. 2005, Jonsson et al. 2010, Mills et al. 2010, Zhang et al. 2010, Vadell et al. 2011), resulting in a proliferation of scientific articles addressing population dynamics of the rodent hosts, the prevalence of infection in their populations and rodent-pathogen dynamics. Many researchers have gone further and have attempted to model some of these aspects based on climate and environmental characteristics (Murúa et al. 2003, Eisen et al. 2007, Luis et al. 2010, Andreo et al. 2011, Loehman et al. 2012). Although modeling attempts have proven to be very useful and have provided valuable information about different rodent-pathogen systems, modeling can be confounded by complexity created by temporally and spatially limited data. Studies conducted over one or two years and in one or two locations such as many of the preliminary efforts to understand hantavirus/rodent systems have the potential to be interpreted as representative of broader temporal and spatial scales while results may only be a product of short term local conditions.

In 1993, a cluster of a human disease, later named Hantavirus Pulmonary Syndrome (HPS), occurred in the southwestern United States. The causative agent was a virus, later named Sin Nombre virus (SNV), and the reservoir host was determined to be the deer mouse *Peromyscus maniculatus* (Nichol et al. 1993, Childs et al. 1994). Because the cluster occurred following an El Niño event, it has been hypothesized that, in at least areas of the arid southwestern United States where deer mice are not always persistent, human risk may be related to a bottom up trophic cascade (Parmenter et al. 1993, Yates et al. 2002). In the trophic cascade hypothesis, increased precipitation results in improved plant productivity, and deer mouse abundance and distribution increases, increasing the number of infected deer mice and prevalence of infection in deer mice, translating to greater disease risk to humans. Though not usually stated as such, this hypothesis has been assumed to be true for other areas within the distribution of deer mice and in other rodent/hantavirus systems throughout the world.

In response to the 1993 HPS cluster, broad scale, long-term field studies were initiated in 1994 in the US to provide ecological and epidemiological data necessary to understand the deer mouse/SNV system and devise mechanisms, including predictive models, to reduce risk of human infection (Abbott et al. 1999, Calisher et al. 1999, Mills et al. 1999, Douglass et al. 2001, Mills et al. 2010). Several host-related factors make the deer mouse/SNV system very attractive for studies of the ecology of a zoonotic disease. Specifically, the deer mouse reservoir is: 1) abundant; 2) sufficiently widespread geographically to make understanding

the disease system broadly applicable; and 3) easy to capture and recapture for both abundance estimates and for collecting blood samples for antibody testing.

It is clear from decades of deer mouse ecological studies that the deer mouse meets the criteria that make it an excellent model for studying the ecology of a zoonotic disease (King 1968). Long before hantavirus studies began, it was well known that deer mice could be abundant (Calhoun and Casby 1958) and intensive research conducted since then has proven the capacity of this species to reach high abundances (Terman 1966, Mills et al. 2010). Deer mice are geographically very widespread in North America and are found across most of North America, from Canada to Mexico, inhabiting a wide range of habitats, including rainforests, deserts, meadows, sage brush, and grasslands (King 1968, Hall and Kelson 1981, Kays and Wilson 2009). Several studies have shown that deer mice are easy to capture (Terman 1966, Douglass et al. 2001). In addition, it has been shown that *Peromyscus* spp. do not have a significant negative response to anesthesia and blood/saliva sampling protocols suggesting they are an appropriate species for hantavirus research (Parmenter et al. 1998, Douglass et al. 2000).

Although much is known about the ecology of SNV in the US, there still is some controversy concerning some aspects, as shown in a review by Mills et al. (2010). Because the US deer mouse/SNV studies have potential to act as models for other rodent-borne diseases in other parts of the world, our intent is to use the results of 19 years of continuous study of the deer mouse/SNV system in the northwestern United States to demonstrate the possibilities of and obstacles to understanding a complex rodent-borne disease system. In doing so we focused on the following aspects of the deer mouse/SNV system:

1.   The potential of deer mouse populations to fluctuate synchronously across the various habitats in which deer mice reside.

2.   The potential for deer mouse populations to clearly respond to changes in climate, particularly temperature and precipitation that can result in changes in plant productivity.

3.   The potential for infection, either prevalence and/or abundance of infected deer mice to vary with deer mouse abundance.

Based on the study of these aspects along 19 years we discuss the possibilities and requirements needed for successfully model the dynamics of a rodent-borne viral system. We believe that a description of realities of the complexity of the deer mouse/hantavirus ecological system in the northwestern US will be useful in planning future research in that system as well as other rodent reservoir/disease systems.

Methods

We based the Montana deer mouse/SNV field study on a large, standard, mark-recapture effort in which monthly blood samples were collected from mice. We include published data and new data collected since 2000 to 2013. Initial results were presented in Douglass et al. (1996) and Douglass et al. (2001). Some data, addressing climate effects on abundance (Luis et al. 2010) and plant productivity effects on abundance (Loehman *et al.* 2012) primarily

from the Cascade site have been used in previous work. Papers on dispersal (Lonner et al. 2008, Waltee et al. 2009) used data from Cascade and Polson. Carver *et* al. (2010) used Cascade data to examine sampling frequency on results and Madhav et al. (2007) and Carver et al. (2011) used data to examine delayed density dependence prevalence. The mice were released to the capture grids and the blood returned to the laboratory for antibody testing. Details of field procedures are in Douglass et al. (1996) and Douglass et al. (2001). The basic sampling units were 1-ha square grids consisting of 100 evenly spaced Sherman live traps. Eighteen grids were constructed, three at each of six locations in western and central Montana (Figure 1, Table 1). One grid at each location was used as a control to determine the effect of the bleeding protocol on deer mouse populations. The other two grids were used to collect blood samples. Control grids were sampled throughout the study even though bleeding was determined to have no significant effect on deer mouse populations (Douglass et al. 2000). Continued sampling on control grids provided additional data from more populations. Grids were placed in sagebrush and grassland habitats as well as forested habitats and a meadow at elevations ranging from 731 m to 2050 m (Table 1). All grids were sampled for three consecutive nights each month from May through October. Grids at Cutbank, Gold Creek, and CM Russell were sampled 70 months each. The high altitude site, Wisdom, was sampled 59 times. Three grids (grids 10, 11 and 12 at Cascade) were sampled every month throughout the study for a total of 232 months. We terminated the major portion of the study in 2005. However, at two locations, Cascade and Polson, we continued sampling through fall 2013 with three grids sampled every month (grids 10, 11 and 12 at Cascade) and two grids sampled from May through October (grids 4 and 5 at Polson) for a total of 112 months.

We used the Minimum Number Alive (MNA) (Chitty and Phipps 1966) for abundance estimates and Minimum Number Infected (MNI; antibody prevalence × MNA) for abundance of infected deer mice. In earlier papers (Douglass et al. 1996, Douglass et al. 2001) data were averaged for all grids. Here, we present the results from each grid separately avoiding averaging which tends to mask important factors that may play a role in the rodent/virus system. We present the months in which high abundances (Month of peak abundance during each year) and prevalence (Month of peak prevalence during each year) were most frequent for each grid. We present the months of peak abundance for each of the eighteen grids of the study while the months of high prevalence are presented for twelve (the other six grids were control grids on which blood samples were not taken).

We investigated the possibilities of a widespread synchrony among populations by comparing population trends in abundance and antibody prevalence in a pairwise fashion. To investigate trends in antibody prevalence we excluded those grids where few or no mice were present. We used a Spearman Correlation index with a P=0.05 significance level to study trends in abundance and infection among grids.

To gain insight into the broad scale relationship between abundance of deer mice and infection with SNV, we performed simple linear regressions between average prevalence of SNV antibodies and average MNA, and between average MNI and average MNA from 10 grids in Montana. We did not include data from Wisdom because of the few number of deer mice captured.

Results

Throughout the 19-yr study there were 16,608 individual deer mice captured and 10,572 blood samples collected with a trapping effort of 851,000 trap nights. Deer mice were captured in all locations and habitats across Central and Western Montana (Table 1, Figs. 2 and 3). At least periodically, deer mice were very abundant, except at high altitude (Wisdom, Fig. 2). The 1994–2005 average MNA ranged from 0.48 on one Wisdom grid to 52.7 on one Polson grid (Table 1). Except for the subalpine location at Wisdom, deer mice were present at all six locations over the entire study. However, SNV antibodies were not present during all months on any of the grids (Figs. 2 and 3, Table 2).

The maximum period without antibody-positive mice ranged from one month (a single trapping session) at Polson (grid 5) to 52 months at CM Russell (grid 18; Table 2). Longer periods without antibodies occurred at the Wisdom grids but that location was at high altitude and deer mice were frequently absent (Table 2, Fig. 2). Even at the location where we sampled monthly and continuously from 1994 through 2013 (Cascade) there were long periods (up to 47 months) with no antibody positive deer mice detected (Table 2, Fig. 3).

There was little temporal synchrony in MNA across the six locations and 18 grids (Figs. 2 and 3). Examples of inconsistent fluctuations are most evident when populations are compared between Polson and Cascade, the two locations we sampled the longest. The large population surge seen at Cascade from 2001–2004 did not occur at other locations and Polson populations periodically and more frequently reached high numbers (Fig. 3). The populations at Polson reached high numbers during 2001–2004 but these numbers were not sustained over winter as they were at Cascade during 2001–2004. Furthermore, there was little synchrony in antibody prevalence for the 12 bleed grids (Figs. 2 and 3). The highest MNAs occurred mostly during the fall but the highest prevalence occurred mostly during spring (Table 1). Similarly, the percentage of times we found no antibody-positive mice in a given month also varied considerably among locations and even among grids within a location (Table 2). However, September and October tended to be the months with the lowest antibody prevalence (Table 2). Deer mouse populations seemed affected by seasonal weather changes (Figs. 2 and 3; Table 1). Highest abundance occurred in late summer/early autumn for every grid except for one grid at Cascade (with high abundances also frequent in late winter) and one grid at Cutbank (with highest abundance more frequent during spring).

Intra-location fluctuations (i.e., grids within the same location) in abundance in this study were inconsistent for every location except for two grids in Wisdom and two grids in Polson where populations fluctuated synchronously (22%; Table 3). Overall, 21/153 (13.7%) of the grids had similar abundance trends (Table 3). Similar habitats in different locations showed similar population trends in 10.7% of the pairwise comparisons (3/28; Table 3).

Intra-location fluctuations in antibody prevalence in this study were inconsistent for every location except for Gold Creek (Table 4). Overall, antibody prevalence correlations were found between 8/45 (17.8%) pairs of grids, two of which were negatively correlated (a pair of grass grids and one grass-forest pair (Table 4).

The relationship between average SNV antibody prevalence and abundance of deer mice appeared to be negative, but was not statistically significant (r=-0.03; p=0.69), while the relationship between abundance and number of antibody-positive mice (average MNI) was positive and statistically significant (r=0.5; p=0.00; Fig. 4).

Discussion

The potential of deer mouse populations to fluctuate synchronously geographically and across the various habitats in which deer mice reside

We found deer mice to be abundant most of the time in Central and Western Montana and demonstrated marked fluctuations in abundance. Unlike deer mouse populations in the southwestern US (Yates et al. 2002, Mills et al. 2010), the only place deer mice were not continuously present in Montana was in high altitude (>2440 m) subalpine forests (Wisdom). The lack of a consistent presence of deer mice at Wisdom probably resulted from this high altitude location having extreme environmental conditions and fluctuations in resource availability (snow cover from early October until the end of June).

When planning to use deer mice as examples for zoonotic disease studies, variable and inconsistent population dynamics that occur among locations must be expected. The complexity presented by this variability is to be expected in other rodent-borne zoonotic disease systems as well, because much of the variability has to do with the complicated population dynamics of many rodent species. While some groups of rodents (e.g., several species of microtines) have fairly regular annual or multi annual cycles, cricetines (e.g., *Peromyscus* spp.) generally have irregular cycles and experience outbreaks that do not seem to respond to a single factor but to a combination of several interacting factors (Jaksic and Lima 2003, Singleton et al. 2010). A good example of this complexity is highlighted by the two different population dynamics of deer mice observed at Cascade versus Polson, the two locations with the highest average abundances. During the 19 years of study, at Cascade there was what appears to be one huge population irruption at the end of 2002, whereas Polson experienced several moderate irruptions. Although the two study areas are only approximately 150 km apart, they have very different vegetation (Cascade is grassland; Polson is sagebrush and forest) and weather. These differences are likely responsible for the different population dynamics.

Data in table 5, in a cursory fashion, show that fairly large differences in deer mice abundance and antibody prevalence also occur over much broader geographic regions than just across Montana. Climates and habitats vary considerably across the western US with dryer climates in the south (New Mexico and Colorado) and more mesic in Montana and the Arizona sites (Arizona sites were located at fairly high altitude).

The potential for deer mouse populations to clearly respond to changes in climate, particularly temperature and precipitation that can result in changes in plant productivity

The bottom-up trophic cascade hypothesis with high rainfall ultimately leading to increased human risk of HPS was proposed in 1993 (Parmenter et al. 1993, Yates et al. 2002). In South America, several hantavirus reservoirs also have irruptive population dynamics, some of

which are of great relevance to human health due not only to the frequency and magnitude of their outbreaks, but to their proximity to human population (Jaksic and Lima 2003, Murúa et al. 2003). In a review of South American rodent outbreaks, Jaksic and Lima (2003) studied more than 60 irruptive events that have been documented since the Spanish conquest in the 16ᵗʰ century. These authors conclude these outbreaks are closely associated with exogenous factors, mainly bamboo blooming and increases in rainfall, being probably the result of the populations closely tracking changes in the environment. However, though exogenous factors associated with outbreaks are sometimes easy to demonstrate (especially in the case of important outbreaks), establishing the exact mechanism by which they affect rodent populations, and the way these interact with regulatory factors intrinsic to rodent populations is exceedingly complex (Krebs and Berteaux 2006). We are faced with very complex interactions among climatic factors, plant resources and abundance of predators and competitors (with different time lags), so that the result is a multifactorial hypothesis that may be easy to visualize but difficult to test. These interactions, of course, result in trustworthy predictions being extremely difficult to obtain. The difficulty is illustrated by our own attempts to predict deer mouse abundance in Montana based on climatic data (Yaffee et al. 2008, Luis et al. 2010) and remotely sensed plant productivity (Loehman et al. 2012).

The modeling attempted by Yaffee et al. (2008) was not successful in improving predictability of deer mouse abundance by adding climate data to simple density-dependent models. On the other hand, Luis et al. (2010) were able to model deer mouse population dynamics (survival, recruitment, abundance etc.) at the Cascade location based on climate data. This was a complex model, dependent on lags of up to four months and the results depended on season. The most obvious factor contributing to the complexity of this model is that increases in precipitation during winter resulted in deep snow cover, which may negatively affect deer mouse activity and survival, whereas increased precipitation in May can result in increased plant productivity later in the season, which could increase deer mouse survival and recruitment. The model constructed by Luis et al. (2010) was not successful for Polson populations or for peridomestic populations at Cascade (A. Luis, *personal communication*). Loehman et al. (2012) constructed models based on weather data and remotely sensed plant productivity at the Cascade location but were unable to predict rodent populations using those data. For the first four years of the study for which remotely sensed productivity data were available, deer mouse populations increased as primary productivity increased. However, during the fifth year, as plant productivity increased, the deer mouse population decreased significantly. As suggested by Mills et al. (2010) the disconnection between plant productivity and deer mouse abundance may have resulted from intrinsic factors in the deer mouse population which will likely vary among locations. Population factors such as survival rates, timing of reproduction, reproductive rates (and their negative density-dependent feedback loops) need to be investigated and included in future predictive models. Some aspects of population dynamics have been included in modeling attempts of the Cascade data from earlier parts of the study. Luis et al. (2010) demonstrated complex climate effects on deer mouse population dynamics at Cascade but not at Polson (Luis, *personal communication*). Later modeling showed interaction between low abundance and disappearance of infection in deer mice at both Cascade and Polson (Luis et al. 2015).

The potential for infection, either prevalence and/or abundance of infected deer mice to vary with deer mouse abundance

Douglass et al. (2001) found what seemed to be a clear negative relationship between deer mouse abundance and current antibody prevalence of deer mice in Montana. However, this relationship, also observed in other hantavirus/rodent systems (Niklasson et al. 1995, Mills et al. 1999), is not so clearly shown in our results. The main difference in past results and our results arose from including in the analyses presented here the zero prevalences, not included by Douglass et al. (2001). A significant negative relationship between antibody prevalence and abundance has been associated with a dilution effect produced by the high percentage of typically non-infected juveniles in periods of high abundance (i.e., fall). This dilution effect was proposed to be part of a three step mechanism in which recruitment of uninfected juveniles during the spring-summer breeding period resulted in high population densities but low antibody prevalence in the fall. Then, after cessation of recruitment, the accumulation of transmission events and over-winter mortality, lead to low density populations with high hantavirus antibody prevalence during spring (Mills et al. 1999). Madhav et al. (2007) built a model to test this hypothesis and found evidence to support a delayed density dependent relationship between prevalence of antibodies in spring and deer mouse abundance the previous fall in Montana. However, four years later, Carver et al. (2011) tested the same hypothesis with a more inclusive (more locations) dataset, and found a significant delayed density dependent relationship at only one of 12 grids analyzed. Delayed density dependence in some cases, together with the lack of statistical significance of the relationships between antibody prevalence and abundance shown here, seem to suggest there are other factors, besides abundance, influencing prevalence of infection. Factors such as differences in vegetation types or rodent biodiversity, or intrinsic characteristics of the population, such as the proportion of adults and juveniles, could be affecting viral transmission (Klein et al. 2002, Linard et al. 2007, Clay et al. 2009). Moreover, this and other factors could also be affecting transmission via changes in the expected seasonal fluctuations in abundance. Figs. 2 and 3 show that abundance in some years increases from autumn to spring implying there can be low winter mortality and/or winter breeding. This deviation from the expected pattern would decrease the juvenile dilution effect on prevalence due to the reduction in mortality in winter causing peaks in both abundance and in hantavirus infection in the following spring.

What does seem clear, however, is that even when prevalence does not increase with current population size, the number of antibody positive mice does increase (Mills et al. 2010, Palma et al. 2012). In terms of human risk the antibody prevalence in deer mice is probably not as important as the number of infected mice in the environment.

Conclusion: Is 10–19 years sufficient to describe/explain the variability in the deer mouse/hantavirus system?

The response of deer mouse populations to climate/weather in Montana is neither clear nor consistent. As the state name indicates, Montana is mountainous and the series of mountain ranges can significantly affect local climate. If deer mouse populations do respond to climate, the response is likely to be local (Douglass et al. 2001, Mills et al. 2010) as it was at Cascade (Luis et al. 2010). The response of vegetation to increased precipitation in arid

southwestern US environments is probably greater than in the mesic environment of Montana and may produce the El Niño effect on plants and deer mice that have been hypothesized. Through two El Niño events, deer mouse habitats seem to have responded with increased plant productivity and particularly seed production and deer mouse abundance and distribution increased for up to three years (Yates et al. 2002, Mills 2005). Other species of rodents in other systems are likely to respond in equally complex ways as do different populations of deer mice across large geographic areas and altitudinal gradients.

Again, deer mice eventually, with frequent sampling (Carver et al. 2010) over years and with sophisticated modeling techniques, may be clearly shown to respond to weather in mesic environments but the response is likely to be local, inconsistent, and will include intrinsic deer mouse population factors. Clear responses to weather may be easier to detect in the southwestern US where El Niño events produce dramatic responses in plant communities where deer mouse populations are not always present.

If other rodent/disease systems are as complex as the deer mouse/SNV system, explanations and models are going to be more local than general as suggested by Douglass et al. (2001) and Mills et al. (2010) and require extended periods of field sampling.

Acknowledgments

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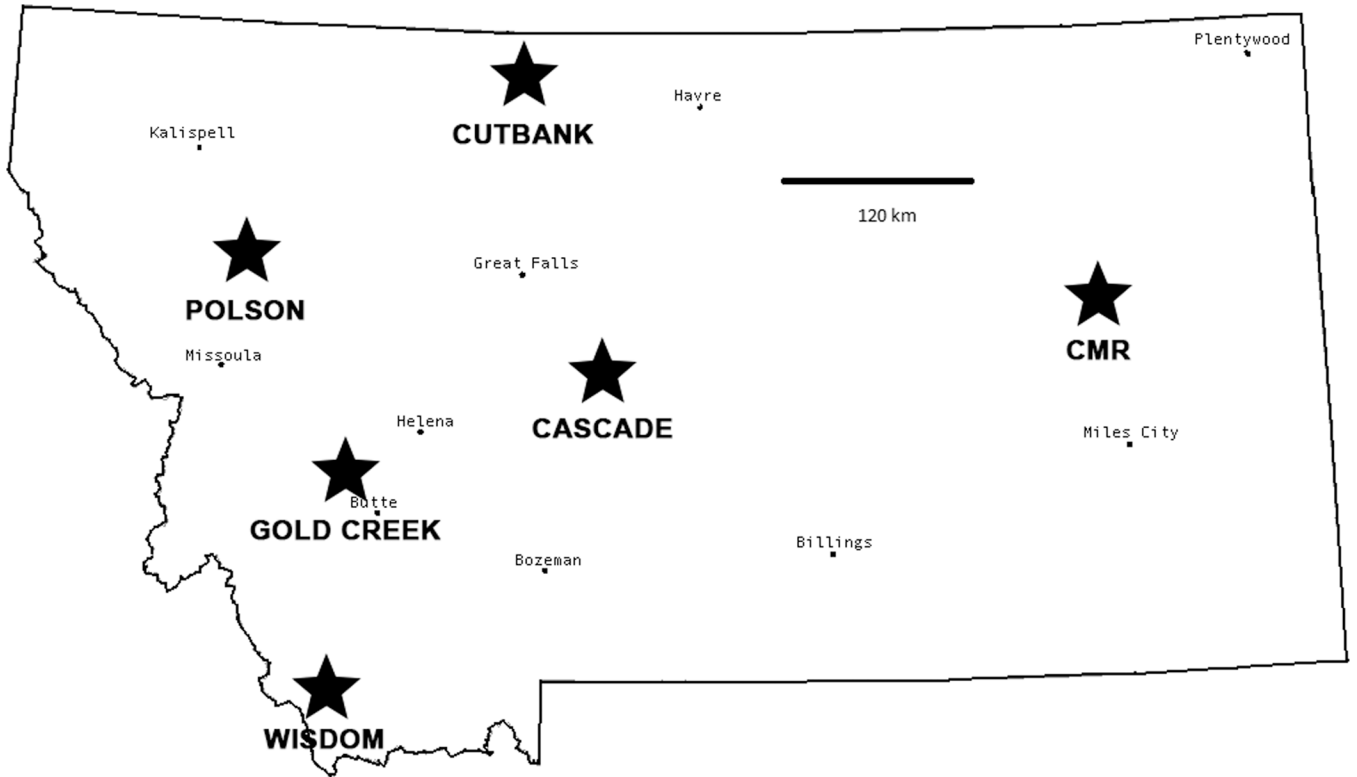
Figure 1.
Six small mammal trapping locations in Montana. CMR = CM Russell Wildlife Refuge.
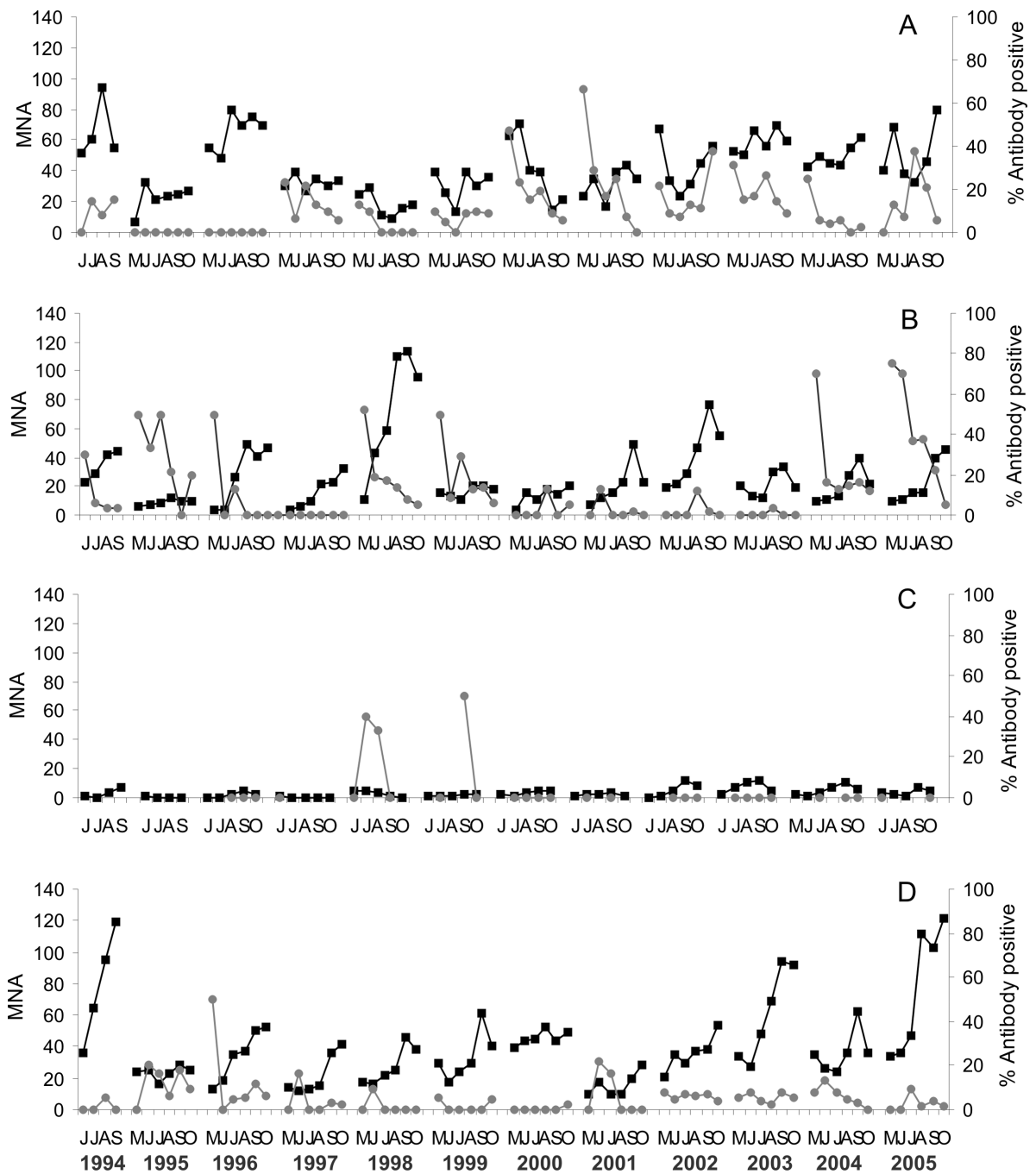
Figure 2.
Deer mouse minimum number alive (MNA) and prevalence of antibodies to Sin Nombre virus from June 1994 to October 2005 in (A) Cutbank, (B) Gold Creek, (C) Wisdom, (D) CM Russell Wildlife Refuge. MNA was calculated on the three grids at each location while the percentage of antibody positive mice was calculated on two grids. Black squares identify MNA; grey circles identify percentage of antibody positive mice.
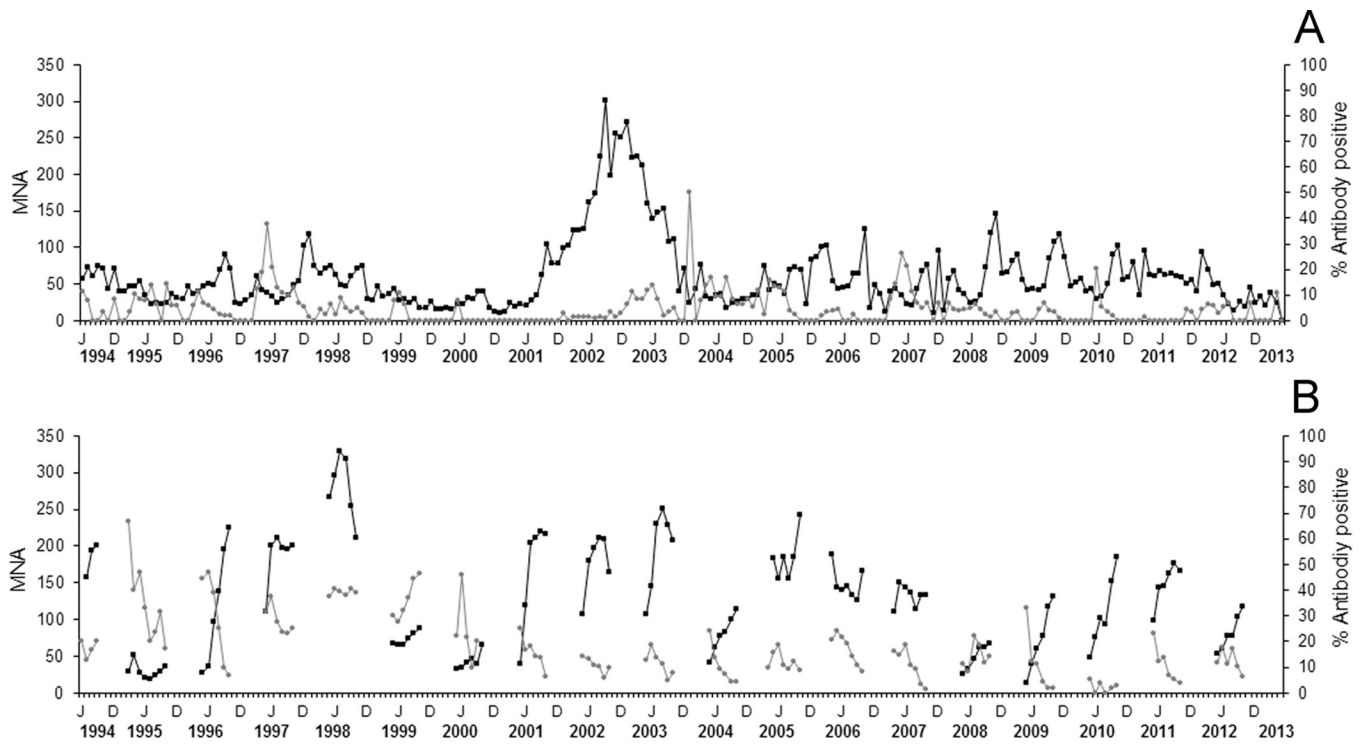
Figure 3.
Deer mouse minimum number alive (MNA) and prevalence of antibodies to Sin Nombre virus in (A) Cascade and (B) Polson from June 1994 to April 2013. In Cascade trapping was carried out continuously throughout the year while in Polson only on those months without snow (from May to October). Black squares identify MNA; grey circles identify percentage of antibody positive mice.
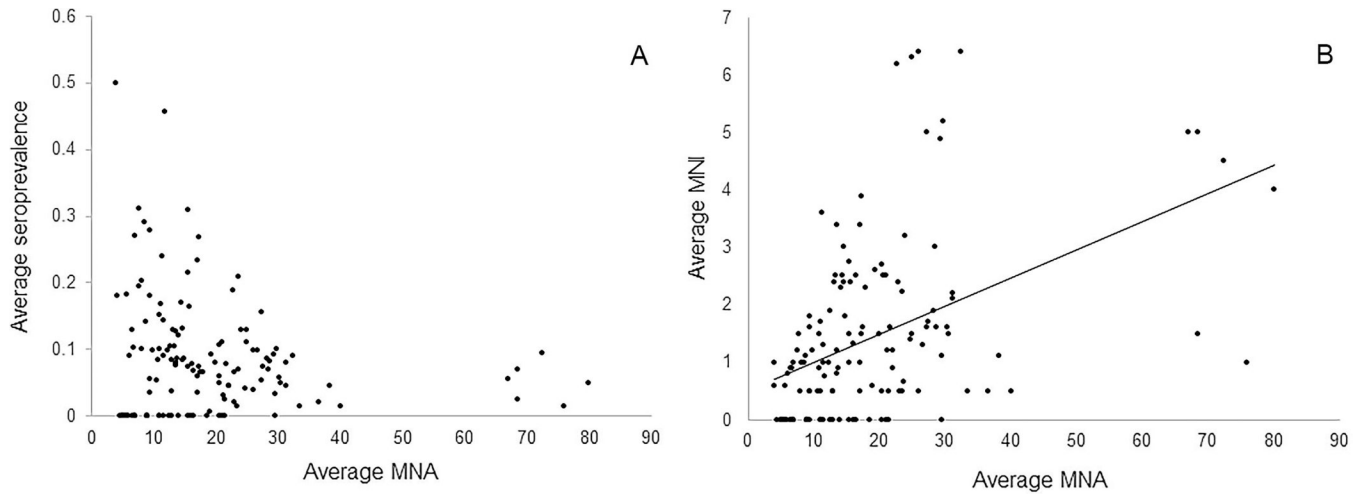
Figure 4.
Relationships between (A) average prevalence of antibodies to Sin Nombre virus in deer mice and average minimum number alive (MNA), and (B) average minimum number of infected mice and average MNA. Data are averages from 10 grids trapped from 1994 to 2005 in central and western Montana.

Table 1

Average minimum number alive (MNA), month of high MNA, average prevalence of antibodies to SNV for deer mice (Av. prev.; expressed as a percentage) and month of highest prevalence, arranged by location, grid, general habitat (Habitat), and elevation (Elev.) in meters.

Location	Grid	Habitat	Elev. (m)	Av. MNA	Month of high MNA	Av. prev.	Month of high prev.
CM Russell	18	Forest	738	8.59	Sep	5.03	Apr
Polson	6	Forest	915	14.90	Aug	15.91	May
Gold Creek	7	Forest	1591	6.69	Sep	Control	…
Gold Creek	8	Forest	1598	11.24	Sep	14.07	May
Wisdom	1	Forest	1957	1.47	Aug/Sep	Control	…
Wisdom	2	Forest	2050	1.20	Sep	3.85	Sep
Wisdom	3	Forest	2146	0.48	Oct	10.23	Aug
Cutbank	13	Grassland	1216	22.42	May/Jun	Control	…
Cutbank	14	Grassland	1256	9.64	Octr	3.83	May
Cutbank	15	Grassland	1299	10.16	Oct	18.03	May
Cascade	10	Grassland	1396	15.30	Oct	Control	…
Cascade	11	Grassland	1402	25.20	Oct/Nov/Dec/Mar	5.69	May
Cascade	12	Grassland	1415	15.20	Oct	4.16	May
Gold Creek	9	Meadow	1591	8.24	Sep	11.55	Jun
Polson	4	Sagebrush	811	43.40	Oct	Control	…
Polson	5	Sagebrush	820	52.70	Oct	22.10	May
CM Russell	16	Sagebrush	905	15.57	Sep	Control	…
CM Russell	17	Sagebrush	927	15.70	Sep	4.39	Jul

Table 2

Summary of sampling periods in which SNV antibodies were not found in deer mice in Montana from 1994 to 2013. A plus sign indicates positive.

Location	Grid	No. months		Percentage of months without +	Max period without + (in months)†	Percentage without +					
		Without +	With tested inds.			May	Jun	Jul	Aug	Sep	Oct
CM Russell	18	50	69	72.46	52	72.73	72.73	83.33	66.67	75.00	77.78
Polson	6	22	69	31.88	37	27.27	27.27	33.33	27.27	41.67	40.00
Gold Creek	8	24	69	34.78	14	40.00	50.00	41.67	33.33	41.67	50.00
Wisdom	2	24	25	96.00	>58	NA	100.00	100.00	100.00	88.89	100.00
Wisdom	3	11	13	84.62	>86	NA	NA	75.00	50.00	100.00	100.00
Cutbank	14	54	69	78.26	50	72.73	0.92	90.91	66.67	66.67	72.73
Cutbank	15	24	69	34.78	17	27.27	36.36	33.33	33.33	50.00	30.00
Cascade	11	96	208	46.15	18	18.18	25.00	25.00	41.67	50.00	50.00
Cascade	12	161	209	77.03	47	54.55	66.67	50.00	83.33	91.67	66.67
Gold Creek	9	39	58	67.24	37	50.00	62.50	72.73	72.73	70.00	72.73
Polson	5	1	70	1.43	1	0.00	0.00	8.33	0.00	0.00	0.00
CM Russell	17	46	69	66.67	13	62.50	58.33	58.33	75.00	66.67	63.64

† May include months without captures.

Table 3

Pearson correlation coefficients (under the diagonal) and p-values (in italics over the diagonal) for deer mouse abundance (MNA) in 18 trapping grids in Montana, 1994–2013. Significant correlation coefficients are shown in bold.

Loc-hab	Grid	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
W-f	1	1.00	*0.02*	*0.56*	*0.01*	*0.21*	*0.03*	*0.75*	*0.39*	*0.05*	*0.00*	*0.00*	*0.00*	*0.34*	*0.09*	*0.09*	*0.69*	*0.15*	*0.01*
W-f	2	**0.30**	1.00	*0.30*	*0.17*	*0.22*	*0.23*	*0.16*	*0.18*	*0.02*	*0.02*	*0.05*	*0.05*	*0.24*	*0.00*	*0.16*	*0.29*	*0.01*	*0.00*
W-f	3	0.09	0.15	1.00	*0.15*	*0.12*	*0.76*	*0.71*	*0.00*	*0.10*	*0.76*	*0.60*	*0.80*	*0.41*	*0.16*	*0.32*	*0.98*	*0.67*	*0.60*
P-s	4	**0.34**	0.18	0.21	1.00	*0.00*	*0.84*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.88*	*0.95*	*0.89*	*0.34*	*0.31*	*0.02*
P-s	5	0.17	0.17	0.23	**0.87**	1.00	*0.04*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.01*	*0.59*	*0.81*	*0.72*	*0.13*	*0.31*	*0.26*
P-s	6	**−0.30**	0.16	−0.05	−0.02	0.25	1.00	*0.06*	*0.02*	*0.00*	*0.27*	*0.99*	*0.08*	*0.21*	*0.61*	*0.22*	*0.28*	*0.74*	*0.57*
GC-f	7	0.04	0.18	0.05	**0.45**	0.47	0.23	1.00	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.79*	*0.42*	*0.61*	*0.53*	*0.41*	*0.09*
GC-f	8	0.11	0.18	**0.43**	**0.48**	0.58	0.29	0.68	1.00	*0.00*	*0.02*	*0.10*	*0.16*	*0.15*	*0.35*	*0.22*	*0.25*	*0.31*	*0.42*
GC-m	9	0.26	**0.30**	0.24	**0.50**	0.58	0.38	0.68	0.84	1.00	*0.00*	*0.01*	*0.01*	*0.26*	*0.43*	*0.86*	*0.61*	*0.01*	*0.06*
C-g	10	**0.46**	**0.30**	0.04	**0.53**	0.33	−0.13	0.48	0.27	0.39	1.00	*0.00*	*0.00*	*0.21*	*0.29*	*0.41*	*0.14*	*0.59*	*0.03*
C-g	11	**0.39**	0.26	0.08	**0.44**	0.30	0.00	0.44	0.20	0.32	0.85	1.00	*0.00*	*0.05*	*0.12*	*0.32*	*0.02*	*0.36*	*0.00*
C-g	12	**0.53**	0.26	−0.04	**0.48**	0.24	−0.21	0.36	0.17	0.31	0.88	0.75	1.00	*0.24*	*0.41*	*0.31*	*0.39*	*0.44*	*0.03*
Cu-g	13	0.13	0.16	−0.12	0.02	0.07	0.16	0.03	−0.18	0.14	0.15	0.23	0.14	1.00	*0.01*	*0.10*	*0.38*	*0.08*	*0.45*
Cu-g	14	0.23	**0.41**	0.21	−0.01	−0.03	0.06	0.10	−0.11	0.10	0.13	0.19	0.10	0.30	1.00	*0.00*	*0.00*	*0.00*	*0.00*
Cu-g	15	0.22	0.19	0.15	0.02	−0.04	−0.15	0.06	−0.15	0.02	0.10	0.12	0.12	0.20	0.66	1.00	*0.00*	*0.00*	*0.00*
CMR-s	16	−0.08	0.20	0.00	−0.16	−0.26	−0.18	0.11	−0.20	−0.09	−0.18	−0.27	−0.10	0.15	0.54	0.53	1.00	*0.00*	*0.00*
CMR-f	17	0.19	**0.34**	0.06	0.12	0.12	0.04	0.10	0.12	0.30	0.07	0.11	0.09	0.21	0.42	0.34	0.64	1.00	*0.00*
CMR-f	18	**0.34**	**0.39**	0.08	**0.28**	0.14	−0.07	0.21	0.10	0.23	0.26	0.35	0.27	0.09	0.56	0.40	0.54	0.63	1.00

Notes: Location-habitat (Loc-hab) codes are: W-f, Wisdom-forest; P-s, Polson-sagebrush; G.C.-f, Gold Creek-forest; G.C.-m, Gold Creek-meadow; C-g, Cascade-grassland; Cu-g, Cutbank-grassland; CMR-s, CM Russell-sagebrush; CMR-f, CM Russell-forest.

Table 4

Pearson correlation coefficients (under the diagonal) and p-values (in italics over the diagonal) for antibody prevalence (MNI) in 10 grids in Montana, 1994–2013. Significant correlation coefficients are shown in bold.

Location-habitat	Grid	5	6	8	9	11	12	14	15	17	18
Polson-sagebrush	5	1.00	0.23	0.34	0.15	0.15	0.96	0.01	0.87	0.40	0.09
Polson-sagebrush	6	0.17	1.00	0.00	0.30	0.69	0.37	0.41	0.00	0.26	0.22
Gold Creek-forest	8	0.13	0.40	1.00	0.00	0.01	0.02	0.63	0.08	0.85	0.93
Gold Creek-meadow	9	0.20	0.15	**0.57**	1.00	0.00	0.30	0.09	0.72	0.73	0.80
Cascade-grassland	11	−0.20	0.06	**0.36**	0.39	1.00	0.85	0.01	0.68	0.14	0.08
Cascade-grassland	12	0.01	0.13	**0.33**	0.15	−0.03	1.00	0.23	0.35	0.10	0.43
Cutbank-grassland	14	**0.34**	−0.12	−0.07	−0.24	**−0.37**	−0.17	1.00	0.30	0.11	0.36
Cutbank-grassland	15	0.02	**−0.46**	−0.25	0.05	0.06	−0.13	0.15	1.00	0.82	0.20
CM Russell-sagebrush	17	−0.12	−0.16	0.03	−0.05	−0.21	0.23	−0.23	0.03	1.00	0.39
CM Russell-forest	18	−0.23	−0.17	0.01	0.04	0.25	−0.11	−0.13	0.18	−0.12	1.00

Table 5

Descriptions of longitudinal hantavirus study sites sampled in the western United States from 1994 through 2006.

Location	Habitats	No. grids or webs	No. trap nights	No. species	No. sp. w/ antibodies	No. deer mice
Arizona	Montane shrub land, pinyon-juniper	3	53,505	10	7	1,756
Colorado	Montane shrub land, pinyon-juniper	4	93,960	17	6	2,907
Montana	Forest, grassland, shrubland	18	429,300	20	7	24,128[†]
New Mexico	Pinyon-juniper, P-J grass, P-J ponderosa	11	500,984	44	9	2,558
All studies			1,077,749			31,349

[†]Includes control grids on which blood samples were not collected