Didactic Lessons Derived from the Shoshone River Skunk Rabies Epizootic

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ABSTRACT Studying the lower Shoshone River Basin's (SRB) striped skunk (*Mephitis mephitis*) rabies 6-year epizootic in northwestern Wyoming has produced four didactic lessons. First, physiographic changes by settlers circa 1900 affected its zoogeography by creating a canal system for irrigating crops originating at Buffalo Bill Reservoir (BBR). The resulting landscape changes increased agricultural lands and skunk habitat eightfold between the valley's steep gravel benches. The valley was historically free of skunk rabies until the epizootic's index case in August 1988. Second, human intervention began when the Bighorn County Predator Board (BCPB) proactively implemented rabies trapping surveillance and depopulation programs in 1989. The epizootic's second case occurred in February 1989. From 1990–1993, the U.S. Department of Agriculture, Animal and Plant Health Inspection Service, Wildlife Services (WS) Wyoming office continued these programs. The epizootic ended in 1993 with over 200 rabid animals diagnosed by the Wyoming State Veterinary Laboratory (WSVL) from about 1,000 skunks tested. Cooperator agreements began in January 1989 and continued throughout the epizootic for trapping and shooting of potential vectors. Third, WS National Wildlife Research Center (NWRC) analyzed the epizootic movements using monthly mean movements and standardized ellipsoids. These analyses demonstrated that rabies dispersed radially from the index case until it reached the Shoshone River. From there, the epizootic spread downstream until stopped by Bighorn Lake (BL) in 1989 and upstream until stopped by BBR in 1992. Fourth, descriptive multivariate movement maps (MMMs) of the epizootic were analogous to fluid wave characteristics describing a swell moving along the surface of a liquid as the "leading edge" and "crest." All rabid animal locations were derived from the first use of global positioning system (GPS) in investigating wildlife disease. These lessons learned should assist others to better understand skunk rabies epizootics.

KEY WORDS epizootic, landscape epidemiology, *Mephitis mephitis,* rabies, Shoshone River, striped skunks, surveillance.

Rabies, a viral encephalomyolitic disease, is usually transmitted by the bite from an infected animal. Its nearly ubiquitous worldwide distribution includes all continents except Antarctica and Australia (Hattwick and Gregg 1975). In the U.S., rabies became a national reportable disease in 1938, becoming one of the oldest disease surveillance databases (Rupprecht et al. 1995). In early records, primary known vectors were the domesticated dog (*Canis familiaris*) and cat (*Felis catus*). However, by 1960, animal vectors changed from domesticated pets to wildlife (McClean 1970). Subsequently, wildlife rabies has occurred primarily in skunks (*Mephitis mephitis*), red (*Vulpes vulpes*) and gray foxes (*Urocyon cinereoargenteus*), raccoons (*Procyon lotor*), and bats (e.g., *Vespertilionidae*) (Baer 1975, Smith 1989a).

Rabid striped skunks have been reported in North America since the early 1800s (Charlton et al. 1991) and in the western United States during the 19th century (Baer 1994). Striped skunks were the major vector in wildlife from 1960 to 1989 in North America; however, since 1989, skunks have remained the major rabies vector only on the Great Plains (Charlton et al. 1991). Smith et al. (1989b) suggested North American skunk rabies likely had two separate origins. The northern strain occurs in the north-central and the eastern U.S. (including Wyoming); the southern strain is located in the south-central states (Centers for Disease Control [CDC] 1985). However, these strains are not geographically static, and the southern strain is advancing northward. In Wyoming, these genomes may soon overlap and potentially increase the chance for emerging viral recombinants with higher pathogenicity and greater potential for vaccine resistance (Barton et al. 2010).

RABIES HISTORY IN NORTHWESTERN WYOMING

In Wyoming, wildlife rabies has been reported in the scientific literature since 1938. It has occurred mainly in striped skunks and bats (*Chiroptera* spp.) and its distribution has generally been limited to eastern Wyoming (Thorne and McLean 1982). Recent epizootics have occurred in the vicinity of Sheridan and Cheyenne, Wyoming, east of the Rocky and Bighorn mountains (Ramey et al. 2010). However, northwestern Wyoming (including the Shoshone River basin [SRB]) had been historically skunk "rabies-free" (CDC 1985, Reid-Sanden et al. 1990, Charlton et al. 1991, and Ramey et al. 2008).

In 1991, the U.S. Department of Agriculture Wildlife Services (WS) Wyoming field office asked the WS National Wildlife Research Center (NWRC) to analyze the skunk rabies epizootic to assist in answering the public's health and safety concerns (W. Rightmire, Wildlife Services, personal communication). We describe methods and analyses that illustrate the skunk rabies epizootic which increased our understanding of what occurred in the SRB.

Lesson Number One—Twentieth Century Changes in Landscape Epidemiology

Twentieth century changes to the SRB have affected its zoogeography and the landscape epidemiology of skunk rabies (Audy 1958). The SRB is a small portion of the Big Horn River basin, lying west of the Bighorn Mountains and just east of Yellowstone National Park in Bighorn and Park Counties. The study area (Figure 1) has been described in Ramey et al. (2008) and includes the towns of Cody, Powell, Byron, Cowley, Deaver, and Lovell. Early settlers began to significantly change the valley's floor using monies from two federal programs, the Carey Act of 1894 and the Newlands Act of 1902. The former act allowed private companies in western, semi-arid states to profit from the sale of water. The latter act led to the establishment of the Bureau of Reclamation and allowed for the construction and maintenance of irrigation projects for the storage, diversion, and development of waters for the reclamation of arid or semi-arid lands. The first federal project funded under these acts occurred here and was locally known as the Cody Canal, named after William Cody (better known as Buffalo Bill). These two acts stimulated the valley's settlement and led to growth of its cities. The Buffalo Bill Dam was completed in 1910; the irrigation distribution network provided the valley with the lands for

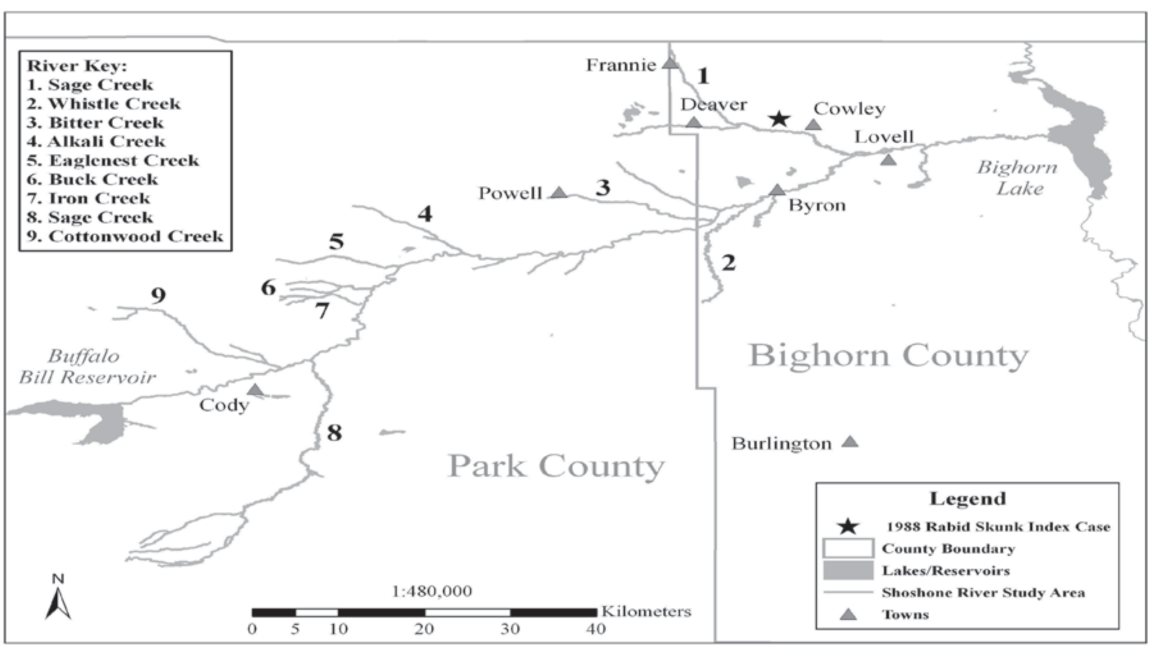

Figure 1: The lower Shoshone River basin study area, Wyoming, USA, during the 1988–1993 striped skunk rabies epizootic illustrating the Shoshone River, major tributaries, towns, and the index case.

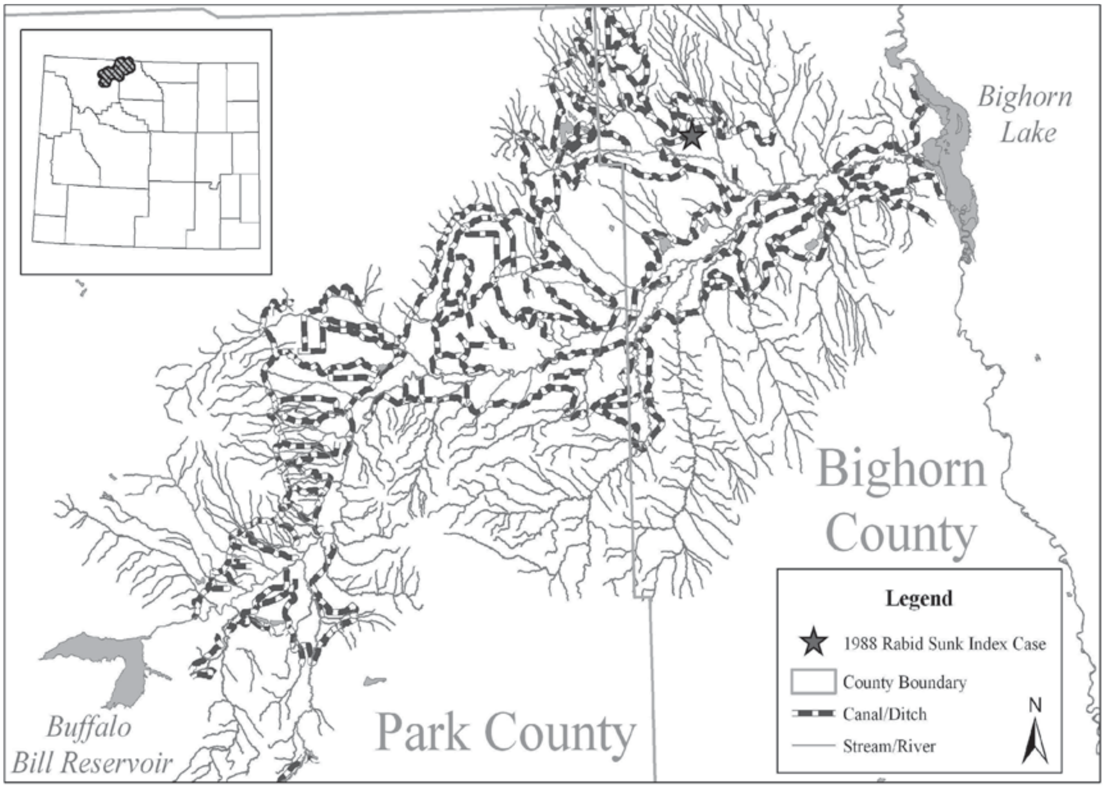

Figure 2. The lower Shoshone River basin, Wyoming, USA, is shown with the lower Shoshone River, and its primary tributaries including creeks and streams as solid black lines. Primary canals are indicated as dashed lines forming the primary irrigation system with water from Buffalo Bill Reservoir. Rabid skunk capture locations are depicted as black dot.

farming and ranching (Figure 2; Bonner 2002). Thus, the lower SRB floodplain became one of Wyoming's most fertile farming regions.

A byproduct of the settler's irrigation activities was an increase in skunk habitat. Similar expansion of striped skunks into crop and pasture lands has been observed in Illinois (Storm 1972). However, in 1988, most of the SRB's irrigated lands were producing alfalfa (*Medicago sativa*). In addition, the actual irrigation canals and ditches provided skunks with dense cover for dens, water, invertebrates and other food sources, and travel corridors. As a result of these landscape epidemiological changes, the SRB's available skunk habitat increased from less than 100 km^2 (10,000 ha) circa 1900 to about 850 km^2 (85,000 ha) in 1989 (Ramey et al. 2010).

The next significant landscape epidemiological feature above the valley's floodplain was the steep and arid slopes leading to gravel benches (Ritter 1975). Skunks were generally absent from both of these areas composed of predominately saltbush fans, flats of sparse desert shrubs, and gravel. Here, the dominant vegetation was Wyoming big sagebrush (*Artemisia* g.). Sagebrush and other western high plains xeric flora may have formed a natural landscape epidemiological barrier contributing to the valley's isolation from skunk rabies until 1988. Thus, geologic and manmade twentieth changes to the SRB produced a skunk population that had significantly increased in size and may have been isolated from Wyoming's skunk rabies.

Lesson Number Two—Direct Human Intervention in the Epizootic

The index case was observed on 15 August 1988 near Cowley. The rabies epizootic radiated from this location and was identified mainly in skunks (~98%), with the remainder in bats. All potentially rabid animals were submitted to the Wyoming State Veterinary Laboratory (WSVL; Laramie, WY) for rabies testing. Over 1,000 skunks were submitted to the laboratory for testing, along with some dogs, cats, coyotes, foxes, and bats. The standardized testing techniques and procedures used the Fluorescent Antibody (FA) Test after McQueen et al. (1960) and others.

Even though no other rabid skunk cases were found in 1988, the Bighorn County Predator Board (BCPB) decided to initiate a proactive strategy to trap potential vectors using methods presented by Ramey et al. 2007. Trapping was initiated in February 1989. The BCPB believed that the index case could have marked the location of a rabies epizootic, and suggested that location as a central point for trapping efforts. The BCPB's supposition was probably correct; the second rabid skunk was identified nearby on Sage Creek in mid-February, although a much larger area was trapped. The BCPB trapper soon captured more rabid skunks, and his trapping activities were given the highest WS priority. The usefulness of this trapping strategy in skunk rabies outbreaks had been suggested by others including Rosatte and Gunson (1984).

In 1990, Wyoming WS was asked to provide a trapping program to monitor the epizootic's locations and to provide depopulation (Davis 1991). WS shared rabies locations with the valley's citizens; however by fall, the epizootic's surveillance and depopulation trapping programs had become so involved that they requested additional analyses from NWRC. Starting in 1991, NWRC provided geographic specific analyses and developed two descriptive concepts analogous to water waves and their swells (explained below) to discuss the rabies' epizootic movements with trappers and the public. Thus, the dynamic "wave front(s)" described rabies outlier locations and "crest(s)" demonstrated area(s) with higher frequencies of rabies cases (Ramey et al. 2010).

Lesson Number Three—Data Analysis Techniques

Although county data met the national reporting requirements for rabies, it was not very useful to the SRB's citizens for two reasons. First, the monthly and annual county summaries did not identify specific rabid skunks' locations and dates. Second, the accuracy of epizootic's movement analyses would be based on the precision of the first known location. This "point of origin" was initially lost in the Bighorn County grouping with a size of 8,181.8 km^2 (i.e., 3,159 sq. miles). Therefore, knowing this location and date was vital for identifying future trapping locations but also in analyzing where the disease was spreading.

In 1991, a NWRC epidemiologist seeking better accuracy from rabies locations had discussions with the U.S. military for permission to use their proprietary global positioning system (GPS) and associated equipment via intergovernmental loan. Eventually, GPS use by the public was approved and the necessary equipment became available in the private sector. Shortly thereafter, NWRC purchased a Sony (Sony Corporation of America, New York, NY) portable GPS unit (Model IPS-360, Park Ridge, NJ). This led to the first use of GPS equipment in wildlife disease surveillance in 1991 (Ramey et al. 2007). The SRB rabies locations were generated with a global positional accuracy of less than 50 meters, depending on the number of satellites available. However with only 7 or 8 satellites deployed (of 24), the time required to set up and initialize this equipment averaged approximately 20 minutes for each potential rabies vector. The trapper(s) believed this process was too time-consuming for use. Thus, only 22 potentially rabid skunks underwent direct GPS locations during the validation process, adding over 7 hours to the trapping time in the field; 5 of these animals tested positive for rabies.

Newer GPS methods (i.e., digitization and geocoding) were employed for the remainder of positive rabies locations. The digitization process generated rabid skunk locations from trapper notes, and when available, locations were plotted on BLM 1987 edition 30 X 60 Minute Quadrangle maps of Cody and Powell, Wyoming. These results were converted to the global GPS latitude and longitude coordinate system, and comprised 91% of the locations. Later, these locations were placed on computer-based topographic maps and were further corroborated with the landowners or leaseholders. Geocoding locations were used whenever BLM rabid map locations, or the trapper's logs were incomplete. They were derived by the placement of the rabid skunk's location in the center of the owner's or leaseholder's lands using computerized maps (Ramey et al. 2007). In some cases, accuracy was improved using information from follow-up telephone calls.

NWRC Databases.—The first of many NWRC geographic information systems (GIS) databases was constructed in 1992, and they have continued through present day. Spatial-temporal data (i.e., GPS location and date caught) is collected for each rabid animal. Using our current context, these data became the first GIS database "layer." The second data layer recorded the SRB's hydrology, and over the years, it has greatly improved in its detail and accuracy. These two data layers formed the first "geographic information system" (GIS) used in computerized mapping of a wildlife disease epizootic (Ramey et al. 2007) and analyses of its movements (Ramey et al. 1995). In later years, the GIS database included the lower SRB's extensive irrigation system and land use features including habitat "bottlenecks" (Ramey et al. 2009). The evolution of the various GIS databases has been chronicled by Ramey et al. (2007). This rapidly evolving area of wildlife disease analysis has made significant progress; for instance, Blanton et al. (2006) developed a GIS-based, real-time Internet mapping tool for rabies surveillance.

Monthly Mean Epizootic Movements.—Using our GIS database with various variables, (e.g., skunk rabies locations, land cover or habitat, hydrology, and topography), we employed a new method of epizootic analysis in 2005 (Ramey et al. 2007), named the epizootic's "monthly mean location" (MML). The MML illustrations from 1989 to 1992 (Figure 3) demonstrate that the epizootic radiated from the index case along Sage and Polecat creeks before progressing into the main stream of the Shoshone River in July 1989. Then it began moving both downstream towards Lovell and the Bighorn Lake and upstream towards Cody (Ramey et al. 2010). During the epizootic (i.e., 1989–1993), the MMLs continued to spread into more streams, creeks, and irrigation canals throughout the lower SRB.

In summary, the MMLs' provided several analytical advantages over our previous individual data locations. First, the MMLs provided a more fluid epizootic movement summary from 1988 to 1993 versus the helter-skelter diversity of locations demonstrated by the daily trapping results. Second, they illustrated the importance of the SRB's entire water system including the smaller streams, creeks, and the extensive irrigation system. Third and most important, the MMLs indicated clearly the directional movements of the epizootic and suggested the areas in harm's way.

Negative aspects of this analytical method were the loss of some of the specific information associated with each rabid location, for example outlier locations. Also, areas with a higher frequency of rabies were not easily discerned. Such information was helpful to the trappers, wildlife and public health officials, and the public. So another method of analysis was tried to demonstrate multiple epizootic attributes in a single illustration.

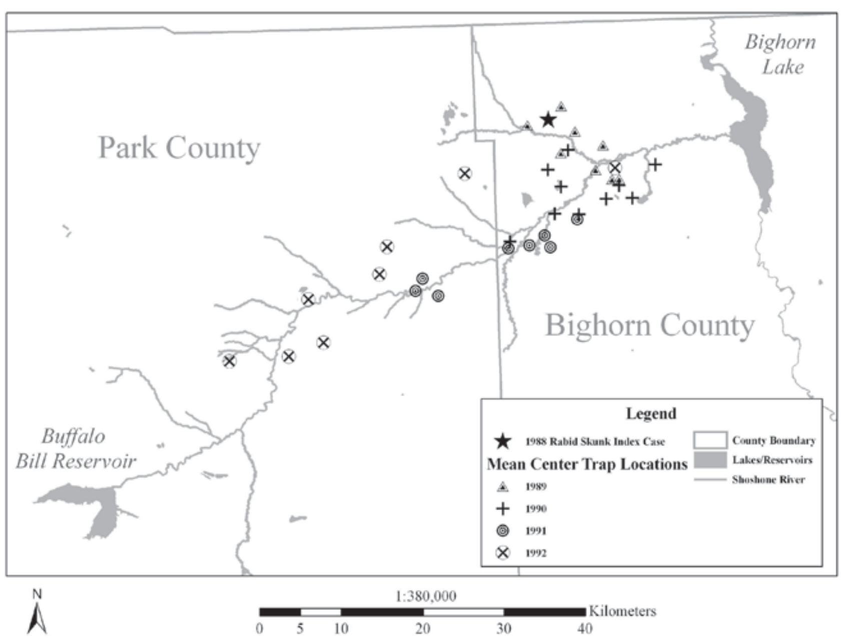

Figure 3. circa 1900**:** The Monthly mean locations of captured rabid skunks along the lower Shoshone River basin, Wyoming, USA, from 1989 to 1992.

Spatial Ellipsoid Movements.—Positive cases were next analyzed in 2008 utilizing the "Directional Distribution (Standard Deviational Ellipse; SDE) (Spatial Statistics, Release 9.1, April 25, 2005)." This was a common way of measuring trends in geographically scattered data points with directional properties. The SDE is calculated using standard distances separately in the x and y directions to define the long and short axes of an ellipse encompassing the data distribution of interest. Our ellipsoids were calculated using ArcGIS 9.2 (ESRI, Redlands, CA). Such ellipses allow the researcher to see if the distribution is elongated or has a directional orientation (Kent and Leitner 2008).

One accepted use of SDEs has been to plot ellipses that demonstrate landscape epidemiology of disease depicting its movements over space and time (Meade and Earickson 2005). For example, mapping distributional trends related to a particular physiographic feature (e.g., habitat) or plotting habitat bottlenecks for the disease over time. Our ellipsoid maps were generated using 1, 2, or 3 standard deviations. By specifying the number of standard deviations (e.g., 1, 2, or 3) different distributional maps were produced which highlighted different epizootic attributes. SDE maps using three standard deviations were more helpful in identifying distributional outliers. In contrast, maps produced using one standard deviation illustrated areas with higher rabies incidences that potentially posed higher rabies exposures for both humans and animals. For example, the 1990 two six-month SDEs are presented in Figure 4. Such analyses and illustrations were also helpful in identifying potential rabies barrier sites to halt the epizootic (Ramey et al. 2009).

However, a drawback in its use was that the area within the ellipsoid seemed to indicate the occurrence of rabies was similar throughout the ellipse, but in reality the highest rabies incidence occurred at the edge of this ellipsoid at any particular time. The interiors of the ellipses tended to have the lowest frequency of skunk rabies probably because of the depopulation effect of trapping and the inferred high virulence of this strain in a previously rabies-free area. These possibilities were indicated by the lack of skunks captured or observed behind the crests. Our need to better understand and illustrate multivariate results led to development of a novel method of analysis, which we named Multivariate Movement Maps (MMM).

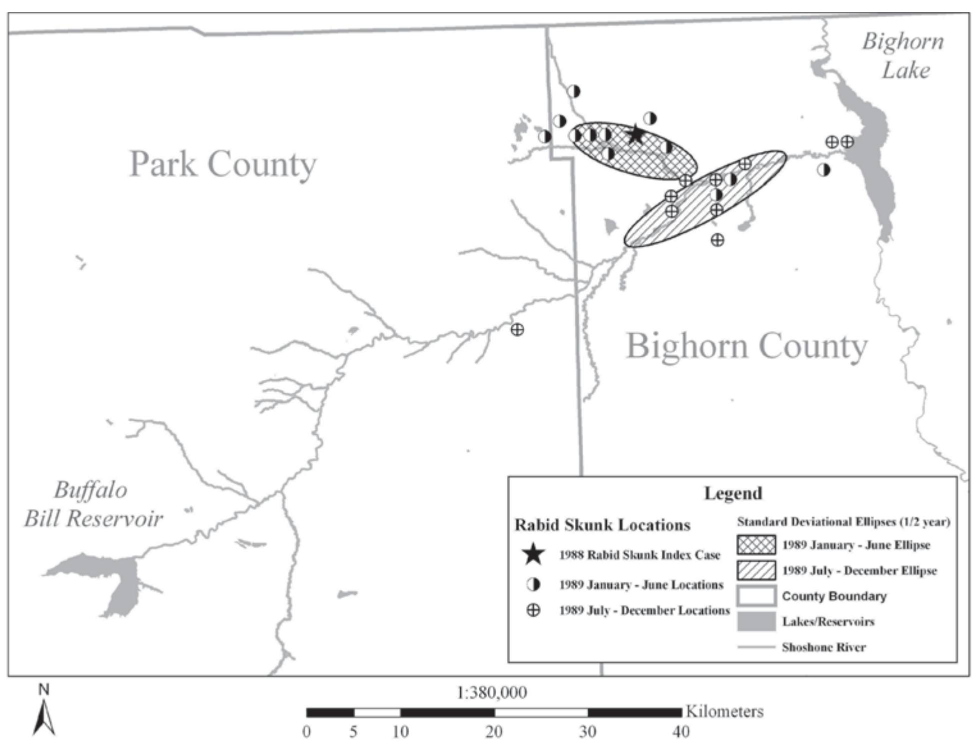

Figure 4. Illustrations of rabid skunk locations from 1989 in the Shoshone River Basin, Wyoming, USA, indicating the two 6-month standard ellipses using one standard deviation.

Lesson Number Four—Descriptive Multivariate Movement Maps

In 2009, we developed this MMMs descriptive approach to analyze the epizootic's movements. These maps illustrated multiple aspects of the skunk rabies epizootic using an analogy of two fluid wave characteristics describing the swell moving along the surface of a liquid as the "leading edge" and "crest." During the SRB's rabies epizootic, the former indicated by temporal sequencing the direction of movement(s) and the latter presented high frequency areas for public health focus. Detailed MMMs methods are being presented in another scientific outlet (Ramey et al. 2010). They have been defined as illustrating the disease front (i.e., leading edge) and crest (i.e., highest density of cases) from the instantaneous and spatially described density of cases and in temporal sequence the directional flow of the spreading disease. MMMs were analyzed for spatial and temporal patterns using general ideas from Carey et al. (1978) and Recuenco et al. (2007). MMMs analyses were generated from a new GIS data layer depicting the frequency of rabies over various time frames in short river segments. The primary baseline for these short river segments was created by tracing the Shoshone River between Buffalo Bill Reservoir and Bighorn Lake. A secondary baseline was added from Sage Creek near the Montana state line to its confluence with the Shoshone River.

These baselines were split into 2.5 km segments, and all rabid skunk locations within each 180^0 segment were summed, and its thickness reflected the number of rabid skunk locations. Although the line segments were arbitrary in size (e.g., length and thickness), the illustration pictured (Figure 5) was selected as a 6-month example that was mindful of the overall rabid skunks locations and skunk habitat. This 6-month MMM illustrates rabid skunk locations from January to June 1990, indicating four rabies wave fronts and one wave crest that demonstrate the instantaneous and spatially described density of rabies cases. Also, when viewed in temporal sequence, they indicated even more clearly the directional path of the rabies epizootic.

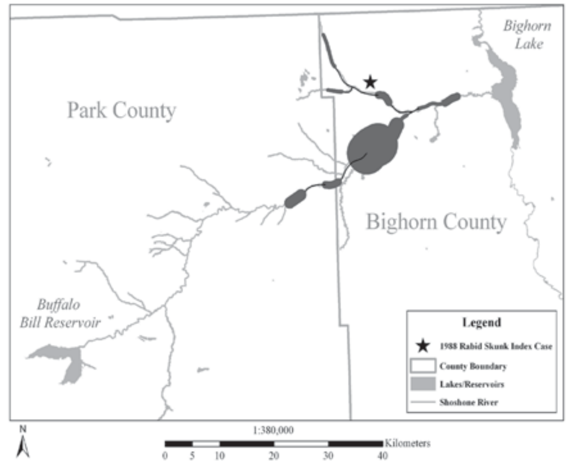

Figure 5: The Multivariate movement map for January–June 1990 from the lower Shoshone River basin's (Wyoming, USA), striped skunk epizootic illustrating the densities at four leading edges and one crest.

SUMMARY AND DISCUSSION

In summary, all of our previous analytical methods could be included in the MMMs. For instance, individual rabid locations and land use were not easily indicated in the black and white illustration published here; however, our coded maps were able to show both of these epizootic traits. Moreover, had these maps been available in real time during the epizootic, the public's requests for epizootic information would certainly have been better answered.

The index case was described by a homeowner and his family as a "friendly" skunk. It was found in their backyard, and after discussions with a veterinarian and several hours of observation, the homeowners killed it. The skunk subsequently tested positive for rabies, sparking public concern. Without a skunk rabies vaccine, the citizens of the SRB were amenable to trapping and shooting for the surveillance and depopulation programs.

Using traditional county surveillance data, it was almost impossible to answer the public's concerns about the epizootic's movements and potential areas of human and domestic animal contact with rabid skunks. The surveillance trapping program provided rabid skunk locations that answered some of the public's epizootic movement questions. However, as the number of rabid skunk locations increased in quantity and distance from the index case, the information they provided became more confusing based on the seemingly haphazard daily trapping results. Increased clarification of the rabid skunk epizootic movements came with the involvement of NWRC in 1991.

Aforementioned NWRC wildlife disease methods include the first use of GPS technology for location data (1991) and its inclusion in GIS databases for the study of wildlife disease spread (1992). In 2007, movements of the monthly mean rabies locations demonstrated epizootic trends that had been unclear while trapping multiple SRB locations. The data were further analyzed for movement trends using standard deviational ellipses (Ramey et al. 2008). SDEs seemed to demonstrate some descriptive wave characteristics, such as "wave fronts" and "crests." In sum, MMMs illustrated multiple aspects of the epizootic wave including the front(s), the density of cases in the crest(s), and the directional flow of spreading disease.

Winkler (1975) suggested that reducing skunk population density would likely be insufficient to curb a rabies outbreak by itself. However, others such as Linhart (1960), Schnurrenberger et al. (1964), Seyler and Niemeyer (1974), and Rosatte et al. (1983) suggested that combining lethal control methods may be sufficient. Combinations of trapping, shooting, night-lighting, and poisoning have been cited as having positive results especially when used early in control. However, the control of rabies by reducing potential vectors continues to be a controversial topic; ultimately, control may await the availability of rabies vaccines for all major terrestrial vectors.

MANAGEMENT IMPLICATIONS

The finding of rabies in the former skunk rabies-free zone of the lower Shoshone River basin caused the Bighorn County Predator Board to foresee several possible epizootic outcomes. Their proactive trapping program, before a second positive case was found, affected the epizootic in a positive way by mobilizing the resources for surveillance and control. However, the skunk rabies epizootic may have been eradicated earlier if a skunk rabies vaccine had been available (Slate et al. 2005). Effective delivery systems such as aerial baiting in rural settings (Johnston et al. 1988) or trap-vaccinate-release program in urban settings (Rosatte et al. 1992) are two examples of currently available management strategies. Today, progress has been made in the development of a skunk rabies vaccine (Dietzschold et al. 2003, Rupprecht et al. 2006), a real-time GIS based mapping tool for rabies surveillance (Blanton et al. 2006), and a national perspective for prevention and control of rabies in the U.S. (Hanlon et al. 1999).

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