State of Wyoming
Department of Transportation

# FINAL REPORT

## WY-18/07F


# Traffic Thresholds in Deer Road-Crossing Behavior


By:

Northern Rockies Conservation Cooperative
Jackson, WY 83001


May 2018

## DISCLAIMER

# TECHNICAL REPORT DOCUMENTATION

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Abstract
Roads have two major effects on ungulate populations: they can cause direct mortality through wildlife-vehicle collisions, and they can create partial to complete barriers to animal movements, cutting animals off fromfood and habitat resources they need. Wildlife-vehicle collisions are also dangerous and costly to the traveling public. The most effective way to reduce wildlife-vehicle collisions and the barrier effects of roads is to install wildlife crossing structures with game fencing; these measures are 80-100percenteffective. However, they are costly, and managers are challenged to make informed decisions about where to prioritize their installation. In this report, we developed two key pieces of information to help inform these decisions. We used a gap-acceptance approach to determine the duration of gap between consecutive vehicles that enables deer to safely and consistently cross roads. We found that 60 seconds' gap is necessary to allow deer to safely cross roads 90percentof the time. We used traffic data to relate this gap duration to hourly traffic volume and to assess the relative degree to which different hotspots of deer-vehicle collisions in Wyoming are permeable or impermeable to deer. We also conducted cost-benefit analyses for six different methods of reducing wildlife-vehicle collisions for the WYDOT road network.

| Key Words: deer-vehicle collisions, Wyoming, mule deer, cost-benefit analysis, traffic | | Distribution Statement<br>This document is available through the National Transportation Library; and the Wyoming State Library. Copyright © 2016. All rights reserved, State of Wyoming, Wyoming Department of Transportation, Northern Rockies Conservation Cooperative, and Corinna Riginos. | |
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# SI* (MODERN METRIC) CONVERSION FACTORS

## APPROXIMATE CONVERSIONS TO SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| in | inches | 25.4 | millimeters | mm |
| ft | feet | 0.305 | meters | m |
| yd | yards | 0.914 | meters | m |
| mi | miles | 1.61 | kilometers | km |
| | | **AREA** | | |
| $in^2$ | square inches | 645.2 | square millimeters | $mm^2$ |
| $ft^2$ | square feet | 0.093 | square meters | $m^2$ |
| $yd^2$ | square yard | 0.836 | square meters | $m^2$ |
| ac | acres | 0.405 | hectares | ha |
| $mi^2$ | square miles | 2.59 | square kilometers | $km^2$ |
| | | **VOLUME** | | |
| fl oz | fluid ounces | 29.57 | milliliters | mL |
| gal | gallons | 3.785 | liters | L |
| $ft^3$ | cubic feet | 0.028 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.765 | cubic meters | $m^3$ |
| | | NOTE: volumes greater than 1000 L shall be shown in $m^3$ | | |
| | | **MASS** | | |
| oz | ounces | 28.35 | grams | g |
| lb | pounds | 0.454 | kilograms | kg |
| T | short tons (2000 lb) | 0.907 | megagrams (or "metric ton") | Mg (or "t") |
| | | **TEMPERATURE (exact degrees)** | | |
| °F | Fahrenheit | 5 (F-32)/9 or (F-32)/1.8 | Celsius | °C |
| | | **ILLUMINATION** | | |
| fc | foot-candles | 10.76 | lux | lx |
| fl | foot-Lamberts | 3.426 | candela/$m^2$ | cd/$m^2$ |
| | | **FORCE and PRESSURE or STRESS** | | |
| lbf | poundforce | 4.45 | newtons | N |
| lbf/$in^2$ | poundforce per square inch | 6.89 | kilopascals | kPa |

## APPROXIMATE CONVERSIONS FROM SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | millimeters | 0.039 | inches | in |
| m | meters | 3.28 | feet | ft |
| m | meters | 1.09 | yards | yd |
| km | kilometers | 0.621 | miles | mi |
| | | **AREA** | | |
| $mm^2$ | square millimeters | 0.0016 | square inches | $in^2$ |
| m | square meters | 10.764 | square feet | $ft^2$ |
| m | square meters | 1.195 | square yards | $yd^2$ |
| ha | hectares | 2.47 | acres | ac |
| km | square kilometers | 0.386 | square miles | $mi^2$ |
| | | **VOLUME** | | |
| mL | milliliters | 0.034 | fluid ounces | fl oz |
| L | liters | 0.264 | gallons | gal |
| m | cubic meters | 35.314 | cubic feet | $ft^3$ |
| m | cubic meters | 1.307 | cubic yards | $yd^3$ |
| | | **MASS** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.202 | pounds | lb |
| Mg (or "t") | megagrams (or "metric ton") | 1.103 | short tons (2000 lb) | T |
| | | **TEMPERATURE (exact degrees)** | | |
| C | Celsius | 1.8C+32 | Fahrenheit | °F |
| | | **ILLUMINATION** | | |
| lx | lux | 0.0929 | foot-candles | fc |
| cd/$m^2$ | candela/$m^2$ | 0.2919 | foot-Lamberts | fl |
| | | **FORCE and PRESSURE or STRESS** | | |
| N | newtons | 0.225 | poundforce | lbf |
| kPa | kilopascals | 0.145 | poundforce per square inch | lbf/$in^2$ |

# TABLE OF CONTENTS

**LIST OF FIGURES**

**LIST OF TABLES**

## LIST OF ABBREVIATIONS AND SYMBOLS

AADT – annual average daily traffic
DVC – deer-vehicle collision
FT – foot
KM – kilometers
M – meter
MI – miles
ML –main line
MP – mile post
MPH – miles per hour
WGFD – Wyoming Game and Fish Department
WVC – wildlife-vehicle collision
WY – Wyoming
WYDOT – Wyoming Department of Transportation

# CHAPTER 1. EXECUTIVE SUMMARY

Wyoming is home to abundant big game, including long-distance migratory species, such as mule deer, elk, and pronghorn. Where these animals' movement patterns intersect with roads, vehicles often hit animals. This poses a threat both to highway safety and to wildlife populations. In addition, roadscan create barriers to animal movements, cutting animals off from food and habitat resources they need. The direct costs of wildlife-vehicle collisions in Wyoming total nearly $50 million per year in vehicle damages, human injuries, and lost wildlife value. The costs of lost wildlife due to the barrier effects of roads are not known, but are likely significant.

The Wyoming Department of Transportation (WYDOT)and its partners continue to work to reduce wildlife-vehicle collisions and increase habitat connectivity in the state. Managers face the challenge of deciding which mitigation measures to use and which locations to prioritize for them. For big game animals, the most effective way to reduce both wildlife-vehicle collisions and the barrier effects of roads is to install wildlife crossing structures (highway under- and/or over-passes) with game fencing; this is 80-100percenteffective at reducing wildlife-vehicle collisions and makes roads permeable to big-game species. However, crossing structures are costly, on the order of $1 million per mile. Other mitigation measures are less costly but less effective.

In this report, we developed two key pieces of information to help inform decisions about where to prioritize crossing structures versus other, at-grade mitigation measures. First, we used a new approach to determine the traffic conditions at which roads become dangerous and difficult for deer to cross. We applied methods used in studies of human pedestrian jay-walking behavior and applied this method to deer crossing. Next, we used thermal video footage of deer-road encounters to determine the duration of gaps between consecutive vehicles that enables deer to consistently, safely cross roads. We foundthat a 60 second gap is necessary to allow deer to safely cross roads 90percent of the time. We then used traffic data to relate this gap duration to hourly traffic volume and to assess the relative degree to which different hotspots of deer-vehicle collisions in Wyoming are permeable or impermeable to deer. Our results indicatethat road conditions with more than 60 vehicles per hour beginto create unsafe and difficult road crossing conditions, and road conditions with more than 120 vehicles per hour create unsafe conditions for both deer and driver.

Second, we conducted cost-benefit analyses for six different methods of reducing wildlife-vehicle collisions: underpasses, under and overpasses, fencing with designated at-grade crosswalks, seasonal message signs to warn drivers, seasonally reduced speed limits, and wildlife warning reflectors.We calculated costs as the costs of installing and maintaining the mitigation, and benefits asthe expected value of avoided collisionsunder the mitigation. We provided maps of the Wyoming highway network showing where benefits are expected to exceed costs for each measure. In general, all mitigations are "worth it" for most major hotspots of wildlife-vehicle collisions as long as they are effective at the level expected.

These tools and maps are useful for (1) deciding where to prioritize wildlife crossing structures based on our understanding of where roads most threaten habitat connectivity for deer, and where human safety is most threatened by unsafe deer road-crossing behavior, and (2) illustrating the economic value of implementing crossing structures or other mitigations.

# CHAPTER 2. INTRODUCTION: ROADS AND WILDLIFE IN WYOMING

Roads and wildlife can come into conflict in a variety of different ways. As road networks expand and traffic volumes rise, in Wyoming and around the world, these conflicts are becoming more frequent and more problematic for transportation and wildlife managers alike. These conflicts typically take the form of either vehicle collisions with wildlife, loss of habitat connectivity for wildlife, or both.[1-3]

Wildlife-vehicle collisions (WVCs) pose a serious threat both to highway safety and to wildlife populations. In particular, collisions involving large ungulates, such as deer (*Odocoileus*spp.), moose (*Alcesalces*), or elk (*Cervuselaphus*), often result in significant damage to the vehicle and injury to its occupants.[4]They also almost always kill the animal involved. In Wyoming, an average of 2,432 WVCs were reported in the last five years, accounting for 14-21 percent of all reported collisions.[5-9]However, this number includes only reported collisions — those with significant vehicle damage and/or human injuries associated with them. Records of animal carcasses removed from roads and road right-of-ways by WYDOT show that an average of about 6,000 wildlife-vehicle collisions occur annually in Wyoming. This number is likely still a significant underestimate of actual large mammal WVCs, as many animals leave the road right-of-way before dying[10], and many carcasses are not picked up before decaying or being scavenged to the point of being difficult to remove. Further, WYDOT's data do not include animals hit in either of the two National Parks, nor animal carcasses picked up by the Wyoming Game and Fish Department (WGFD). The overwhelming majority (>85 percent) of collisions in Wyoming involve mule deer.

These collisions are costly.WYDOT's estimated costs per reported collision are $11,600 in injury and property damage costs, and $4,000 in the unclaimed restitution value of each mule deer that is killed. Taken together, deer-vehicle collisions alone total approximately $24-29 million per year in Wyoming in injury and damage costs, and an additional $20-23 million per year in wildlife costs.

Collision numbers also indicate that roads are having a substantial impact on Wyoming's large mammals. For mule deer, the number of animals killed by vehicles represents approximately 2-4percent of the total population each year. This is a particular concern for a species that is already below its statewide population size management objective,and whose conservation is an extremely high priority in the state.[11]

From a wildlife perspective, an even greater concern, however, is the barrier effects roads have on large mammal movements. Roads that create a partial to complete barrier arelikely having substantial impacts on wildlife populations, particularly migratory and wintering ungulates.[1-3]Most of Wyoming's ungulates are migratory. Ungulates depend on migration to avoid the high elevation deep snows in winter and to benefit from the higher quality forage available at high elevations in summer. Wyoming is home to an extensive network of mule deer migration routes, including the recently-discovered 150-mile Red Desert to Hoback migration, the longest known terrestrial migration in the lower 48 states.[13]Mule deer movements and migrations in Wyoming and across the west are imperiled due to a variety of anthropogenic habitat modifications, including energy and housing developments, fences, and roads.[11-20]

WYDOT continues to work extensively to mitigate wildlife-vehicle collisions; doing so is important to achieving WYDOT's strategic goals of keeping people safe on the state transportation system, and exercising good stewardship of our resources.[21]Working to address these goals is particularly important as the human population of Wyoming continues to grow, with corresponding increases in residential and road development,as well as vehicle traffic.[22]WYDOT has had significant success in reducing conflicts between wildlife and the traveling public through installing road crossing structures (under- and over-passes) at Nugget Canyon west of Kemmerer, Wyoming, at Trapper's Point, west of Pinedale, Wyoming, and north of Baggs, Wyoming; these structures have reduced collisions by more than 80percent and enabled thousands of animals to cross these highways safely.[23-24]

Crossing structures are widely recognized to be the most effective way to reduce wildlife-vehicle collisions and increase habitat connectivity for large mammals.[25-28]However, they are also costly, on the order of hundreds of thousands of dollars per mile. [29] There is a great need to identify where these crossing structures are most needed and most cost-effective. In previous work, we identified locations with the largest numbers and rates of deer-vehicle collisions in Wyoming.[30]In this report, we expand upon this prior work in two ways. First, we use a detailed analysis of deer road-crossing behavior in relation to traffic dynamics to show where deer movements are most impeded by traffic in the state. Second, we conduct a series of cost-benefit analyses to show where different mitigations are more or less cost-effective. Together, these different pieces of information can inform the process of prioritizing locations for different mitigations.

# CHAPTER 3. TRAFFIC THRESHOLDS AND DEER ROAD-CROSSING BEHAVIOR

## Introduction

Roads are widely recognized to create barriers to animal movements.[1-3, 13,20]These barrier effects can range from partial to complete. When roads obstruct animal movements, they prevent animals from accessing habitat and food resources and limit,gene flow.[1] The net consequences of these barrier effects on wildlife populations may be far greater than the effects of wildlife-vehicle collisions and associated animal mortalities.

Traffic volume is generally considered to be one of the main determinants of whether a road acts as a barrier to animal movements or not.[20,32-36] Other factors include road width,vehicle speed, animal movement speed, and animal behavioral characteristics.[32-35]Animal behaviors can be broken down into four general groups of animals: nonresponders, pausers, speeders, and avoiders.[35]Ungulates, such as mule deer, are generally speeders; while they may pause to evaluate the threat of oncoming traffic, they avoid that threat by fleeing from the road or running across the road. When traffic volume is low enough and gaps between consecutive vehicles are large enough, speeders can cross roads by running through these gaps. When gaps become too small, speeders get hit and/or avoid the road all together.[35] Thus at some threshold of traffic volume and associated gaps size between vehicles, roads are thought to become barriers to ungulate movements. Up until this threshold, rates of collisions between ungulates and vehicles are expected to increase with increasing traffic volume, but above this threshold, rates of collisions are expected to decrease with increasing traffic volume — so that the overall relationship between collisions and traffic volume is a downward parabola.[33,35]

Identifying this threshold for species of conservation concern is important to informing decisions about where to site mitigations, such as wildlife crossing structures.[35] Crossing structures are the only effective way to overcome the barrier effect of roads if high traffic volume is the cause of the barrier effect. Thus, crossing structures should be prioritized in places where roads create a partial to complete barrier to animal movements, rather than places where animals can cross roads relatively freely.[35]

To date, there have been few efforts to identify the threshold of traffic volume at which roads become a barrier to animal movements, and these have relied on coarse-scale traffic metrics, such as annual average daily traffic (AADT).For example, moose-vehicle collisions in Sweden were found to have a parabolic relationship with traffic volume that peaked between 2,000 and 6,000 AADT.[33]Similarly, deer-vehicle collisions in Washington state peaked at 8,000 AADT, and a deer movement corridor was found to run parallel to a roads exceeding this number rather than crossing it — suggesting that deer were unable or unwilling to cross it.[20]In a study in the Canadian Rockies, the authors looked at ungulate snow tracks along highways and concluded that ungulates had impaired movements across roads between 500 and 5,000 AADT.[36] While these studies indicate that the threshold effect is real, their authors recognized that AADT may not accurately capture the traffic conditions experienced by animals at the time of attempting to cross and may be skewed by seasonal peaks or dips in traffic volume. Further, carcass and track counts do not tell us anything about the fraction of animals that attempted to cross, succeeded in crossing, or failed to cross given traffic conditions.

Studies of human pedestrian road crossing behavior in relation to traffic volume have focused on the concept of acceptable or critical gaps. Here, pedestrians crossing at locations that are not designated (e.g. not crosswalks or lights) have been found to reject gaps between consecutive vehicles that fall below some threshold number of seconds and accept gaps above this threshold.[37-41] That is, pedestrians choose notto cross when shorter gaps are available but do cross when longer gaps are available. This approach can be used to understand pedestrian decision-making and traffic conditions under which pedestrians do or do not cross roads at non-designated locations.

Here, we apply the same approach to examine deer road-crossing behavior in relation to traffic. Unlike pedestrian studies, our purpose is not to understand why deer accept or reject particular gaps, but rather to understand the gap duration that deer require to safely cross rural two-lane highways. We then use traffic data to suggest how our understanding of acceptable gaps for deer can be used to characterize the relative permeability of different road stretches for deer.

## Methods

### *Deer Behavior Data*

We collected deer behavior data in two general areas: central Wyoming, and southwestern Wyoming. The central area included two stretches of US 20/16, south and north of Thermopolis and between Basin and Greybull. The southwestern area included six stretches of highway: US 189 between Labarge and Big Piney, US 189 from Kemmerer south to Lazeart Junction, US 30 west of Kemmerer to Nugget Canyon, US 30 at Cokeville, US 191 north of Daniel Junction, and WY 89 north of Evanston. All eight sites are stretches of rural two-lane highways. At the time of data collection, the speed limit was 65 mph (104.6 kph) in the central area and 70 mph (112.6 kph) in the southwestern area.

We collected data from central Wyoming from October-February of 2013-14 and 2014-15, as part of a study of the effectiveness of wildlife warning reflectors and white canvas bags in preventing wildlife-vehicle collisions.[31]We collected data from southwestern Wyoming from October-May of 2016-2017, as part of a study of the effectiveness of reduced nighttime speed limit in preventing wildlife-vehicle collisions (ongoing study). For the central Wyoming data set, we included data from deer crossing roads with reflectors, white canvas covering reflectors, or reflectors removed; we accounted for these differences statistically (see Data Analysis, below). For the southwestern Wyoming data set, we included only data from control conditions where the posted speed limit was 70 mph (112.6 kph) and excluded data from experimental conditions where the posted speed limit was 55 mph (88.5 kph).

We observed deer road crossing behavior using automated thermal video recording systems between dusk and dawn, which is the time window when most deer–vehicle collisions occur. Each system consisted of a FLIR® Scout PS32 Thermal Handheld Camera (FLIR Systems, Wilsonville, OR, USA) wired to a laptop and deep-cycle battery for continuous recording. In the field, we mounted the FLIRs to the end of poles placed in the road right-of-ways. We directed the camera parallel to the road, with a field of view that included the road, both shoulders, and right-of-ways. In all eight study sites, we set up three or four automated recording systems at different locations within the site for three to four consecutive nights at a time, with sampling repeated monthly for four months at each site.

We could reliably observe behavior for deer that were less than approximately 328 ft(100 m) from the camera. We scored deer behavior as follows. Each time a deer moved to the edge of the shoulder, within approximately 9.8 ft. (3 m) of the road, and showed intent to cross the road by moving consistently toward the road with head up, we considered this to be a "deer–road interaction." In cases where deer were crossing in a group, we recorded whether the animal was the leader or not and the total group size.For each deer–road interaction, we recorded the deer's behavior in relation to any vehicles present during that interaction, as follows. We recorded the number of seconds between the start of the deer-road interaction and when the first vehicle passed (lag duration) and whether the deer crossed the road during that time. If the deer did not cross during the initial lag, we recorded the number of seconds between the first and second vehicle that passed (gap duration) and whether the deer crossed during that time. We measured the gap regardless of the lanes of vehicle travel, since this is what a deer experiences when trying to cross. We continued this until the deer either completed a crossing or turned away from the road and stopped showing intent to cross. We recorded the duration of lags and gaps up to 5 minutes (central Wyoming) or 2 minutes (southwestern Wyoming) after the start of the deer-road interaction.

For data collected in southwestern Wyoming, we recorded any cases where the deer was hit or nearly hit by a vehicle and labeled these "high risk" crossings. At all sites, we also counted the number of vehicles that passed in the time preceding the start of the deer-road interaction (five minutes preceding the interaction in central Wyoming and three minutes preceding the interaction in southwestern Wyoming).

Observations totaled 489 gaps and lags from 381 deer in southwestern Wyoming, and 773 gaps and lags from 694 deer in central Wyoming.

### *Traffic Data*

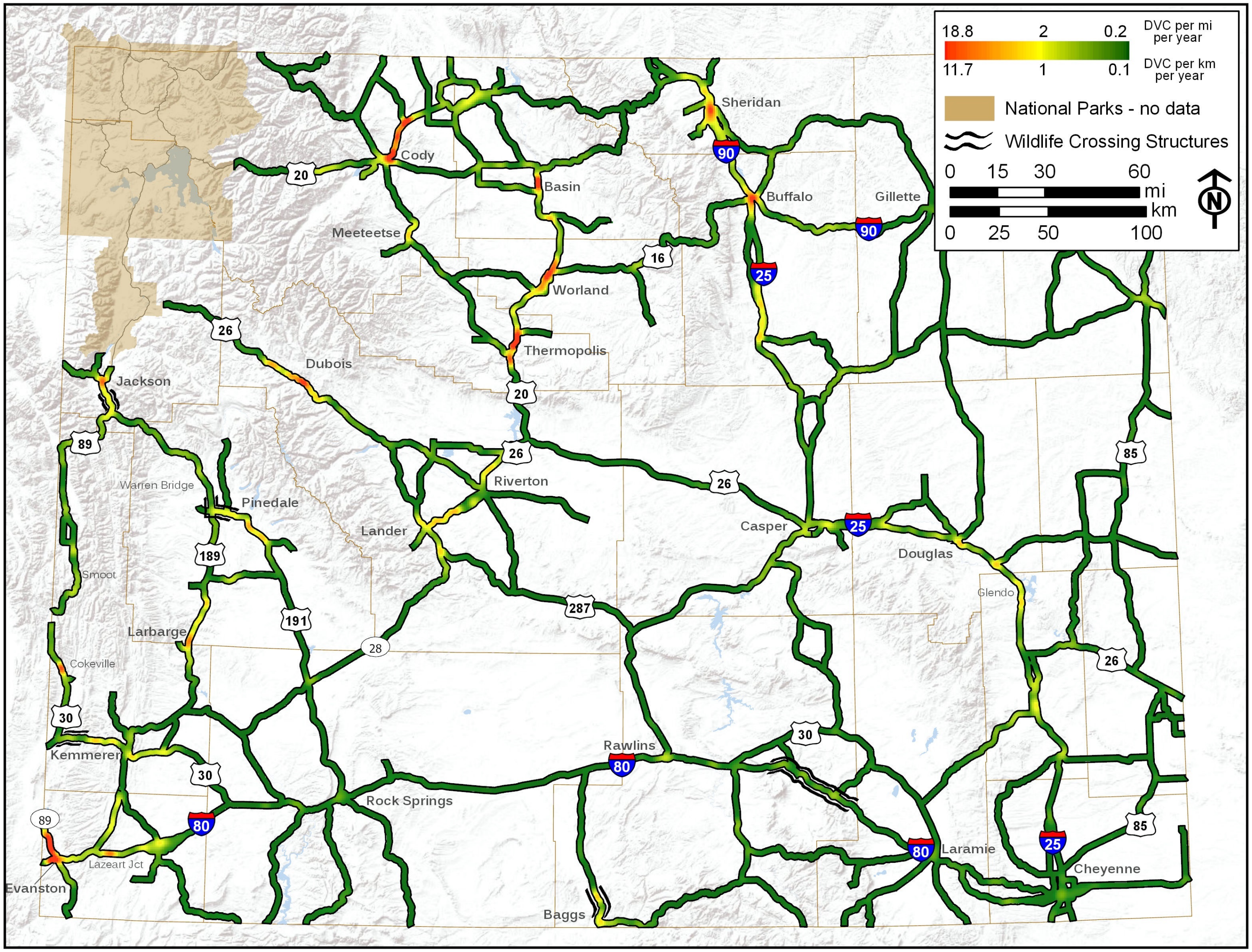
We used two different sources of traffic data. We used traffic data collected as part of the nighttime speed limit study in order to analyze the relationship between total hourly vehicles and gaps between vehicles. These data were collected at the six sites in southwestern Wyoming using automated radar recording systems (JAMAR Technologies, Inc., Hatfield, PA, USA). Radar recording systems were deployed at the same locations and time periods as the thermal video recording systems and recorded the time of each passing vehicle. From this, we calculated the number of seconds between consecutive vehicles and the traffic volume for each hour of recording.

We also used WYDOT traffic counter data in order to apply conclusions from our fine-scale analysis of deer-traffic relationships to hotspots of deer-vehicle collisions across Wyoming. In previous work, we identified the locations within Wyoming with the highest rates of deer-vehicle collisions (Figure 1) and the months of the year in which they tend to occur for each location.[30] For these locations, we obtained hourly traffic counts from 2015 for the months of interest from the nearest WYDOT traffic counter (Table 1).

**Table 1. Locations of hotspots of deer-vehicle collisions, traffic counters, and months of traffic data used.**

| Hotspot name | ML route | Start MP | End MP | Counter # | Months |
|---|---|---|---|---|---|
| Basin | ML34 | 194 | 204 | 6N | Jan-Apr, Oct-Dec |
| Boulder-Pinedale | ML13 | 83 | 104 | 142 | Jan-Apr, Oct-Dec |
| Buffalo-Sheridan | ML90 | 25 | 65 | 3 | May-Nov |
| Cody-Powell-Byron | ML29 | 0 | 43 | 67 | Jan-Dec |
| Cokeville | ML12 | 4 | 10 | 78 | Mar-Apr, Oct-Nov |
| Douglas/Glendo | ML25 | 105 | 117 | 170 | May-Dec |
| Dubois | ML30 | 47 | 73 | 21 | Jan-Apr, Oct-Dec |
| Evanston | ML80 | 3 | 19 | 177 | Jan-Apr, Oct-Dec |
| LazeartJtc. to Leroy | ML80 | 20 | 29 | 26 & 177 | Jan-Apr, Oct-Dec |
| Evanston North | ML50 | 2 | 11 | 113* | Mar-May, Oct-Nov |
| Jackson (N and S) | ML10 | 142 | 159 | 32 | Jan-Apr, Oct-Dec |
| Kemmerer to Nugget | ML12 | 41 | 50 | 178 | Jan-May, Oct-Dec |
| Kemmerer-LazeartJct | ML11 | 4 | 19 | 64 | Jan-Apr, Oct-Dec |
| LaBarge-BigPiney | ML11 | 79 | 104 | 61 | Jan-Apr, Oct-Dec |
| Lander-Riverton | ML20 | 81 | 100 | 63 | Jan-Dec |
| Lander South | ML20 | 72 | 76 | 11 | Jan-Dec |
| Meteetsee | ML33 | 52 | 60 | 161 | Jan-Feb, Jul-Dec |
| Riverton-Shoshoni | ML20 | 100 | 125 | 63 | Jan-Dec |
| Sheridan (N) | ML90 | 15 | 25 | 56 | May-Nov |
| Smoot | ML10 | 65 | 70 | 159 | May-Oct |
| South Pass | ML14 | 60 | 68 | 71 | Jan-Dec |
| Thermopolis (S) | ML34 | 125 | 135 | 135 | Jan-Dec |
| Thermopolis-Worland | ML34 | 135 | 172 | 66 | Jan-Dec |
| Warren Bridge | ML13 | 123 | 127 | 73 | Apr-Jun, Oct-Nov |

*This counter was very far from the road segment of interest.



Source: Esri 2017, ArcGIS ArcPro 2.1.0, revised

**Figure 1.Deer-vehicle collisions per mile per year in Wyoming.**


9

***Data Analysis***

We analyzed deer road crossing behavior separately for the two areas (central and southwestern Wyoming), due to some differences in how the data were collected between these areas. For both areas, we used logistic regression to analyze deer road crossing success versus failure as a function of gap/lag duration. For the southwestern Wyoming data, we separated the data into three outcomes: deer did not enter the road ("failed to cross"), deer entered the road but was hit or nearly hit by a vehicle ("unsafe crossing"), and deer crossed successfully with low risk ("crossed safely"). We examined the effect of gap/lag duration in explaining the likelihood of each pair of outcomes. We also considered whether the deer was a leader versus a follower as a potential explanatory variable.

For central Wyoming deer behavior, we log-transformed the duration of gap/lag to meet assumptions of normality. Because we did not categorize crossings as safe or unsafe, weanalyzed all gaps/lags(hereafter simply "gaps" for simplicity) as a successful versus failed crossing, with the understanding that some "successful" crossings may be unsafe ones. We considered the treatment conditions (reflectors, white canvas, or no treatment) and whether the deer was a leader versus a follower as potential explanatory variables.

We used simple linear regressions to relate duration of gaps/lags with the number of vehicle counted in the five (central Wyoming) or three (southwestern Wyoming) minutes prior to the deer-road interaction. In both areas, we used percentiles to identify the gap/lag duration necessary for 75percent and 90percent of deer attempts to cross to be successful, and for 75percent and 90percent of the deer attempts to cross to fail. This, combined with the logistic regressions, allowed us to define two thresholds: approximately 60 seconds between consecutive vehicles for deer to consistently, safely cross the road (or for drivers to consistently avoid the risk of deer-vehicle collisions), and a minimum of 30 seconds between consecutive vehicles for deer to sometimes safely cross the road (with risk to both drivers and deer). (see Results and Discussion below for more details).

We used these thresholds and our radar data from southwestern Wyoming to characterize the relationship between hourly traffic volume and the percent of the hour in which gaps between vehicles exceed these two thresholds. For each hour of each night of radar data, we extracted the total number of vehicles that passed and the total number of seconds in which gaps between consecutive vehicles (considering both directions of travel at the same time) were less than 60 seconds and less than 30 seconds. The latter two were divided by 3,600 seconds to get the percent of the hour with "unsafe" and "impassable" gaps, respectively. We then regressed these percentages against traffic volume for that hour.

From the results of these regressions (see Results, below) we identified traffic volumes of 60 and 120vehicles per hour to be valuable thresholds. For each hotspot of each hotspot of deer-vehicle collisions, we used WYDOT traffic counter data to calculate the average number of hours of the day in which traffic volumes exceeded 60 and 120vehicles per hour. From this we calculated the percentage of the day in which that hotspot exceeded those thresholds and generated maps indicating these percentages. These maps are intended to show quantitatively what percent of the time (24 hour cycle) each hotspot creates unsafe or impassable conditions for deer.

Finally, we correlated with annual average daily traffic (AADT) for each hotspot with the percent of time with traffic volume exceeding 60 vehicles per hour, to illustrate how these finer and coarser-scale traffic metrics are related. We log-transformed AADT to meet regression assumptions of normality.

**Results**

In the deer behavior dataset from southwestern Wyoming, we found no effect of gap duration on the likelihood of deer failing to cross or making an unsafe crossing ($\beta$=-0.012, $p$=0.22; Figure 2a). In contrast, there was a significant effect of gap duration on the likelihood of deer making an unsafe crossing versus crossing safely ($\beta$=0.06, $p$<0.0001). In other words, there was a strong threshold in gap duration between safe and unsafe crossings (Figure 2b). For unsafe crossings, 90percent had gaps less than 58.5 seconds, and 75percent had gaps less than 33.8 seconds. In contrast, for safe crossings, 90percent had gaps greater than 29 seconds and 75percent had gaps greater than 59 seconds. There was also a significant effect of gap duration on the likelihood of deer failing to cross versus crossing safely ($\beta$=0.04, $p$<0.0001; Figure 2c). Where deer failed to cross, 90percent had gaps less than 63 seconds and 75percent had gaps less than 36 seconds. There were no effects of leader versus follower in any of these cases.

In the deer behavior dataset from central Wyoming, we only distinguished between failed and successful crossings, with unsafe crossings included in the latter category. We found a significant effect of gap duration on the likelihood of deer failing to cross versus crossing successfully ($\beta$=1.83, $p$<0.0001). In other words, there was a strong threshold in gap duration between failed and successful crossings (Figure 3). For successful crossings, 90percent had a gap more than 21 seconds and 75percent had a gap more than 32 seconds; for failed crossings, 90percent had a gap less than 45 seconds and 75percent had a gap less than 26 seconds.

There was also a significant effect of leader versus follower ($\beta$=-0.96, $p$<0.001) in the central WY dataset. This means that for a given gap size, followers were more likely to cross than leaders; put another way, followers accepted smaller gaps than leaders. There were also significant effects of treatment condition such that both reflectors and white canvas treatment conditions were different from the no treatment condition (reflectors versus no treatment: $\beta$=-1.55=6, $p$<0.001; white canvas versus no treatment: $\beta$=-1.68, $p$<0.0001). This means that for a given gap size, deer experiencing no treatment were more likely to cross than deer experiencing reflectors or white canvas along the side of the road. Separate logistic regression curves confirmed that deer experiencing no treatment accepted smaller gaps than deer experiencing reflectors or white canvas along the side of the road.

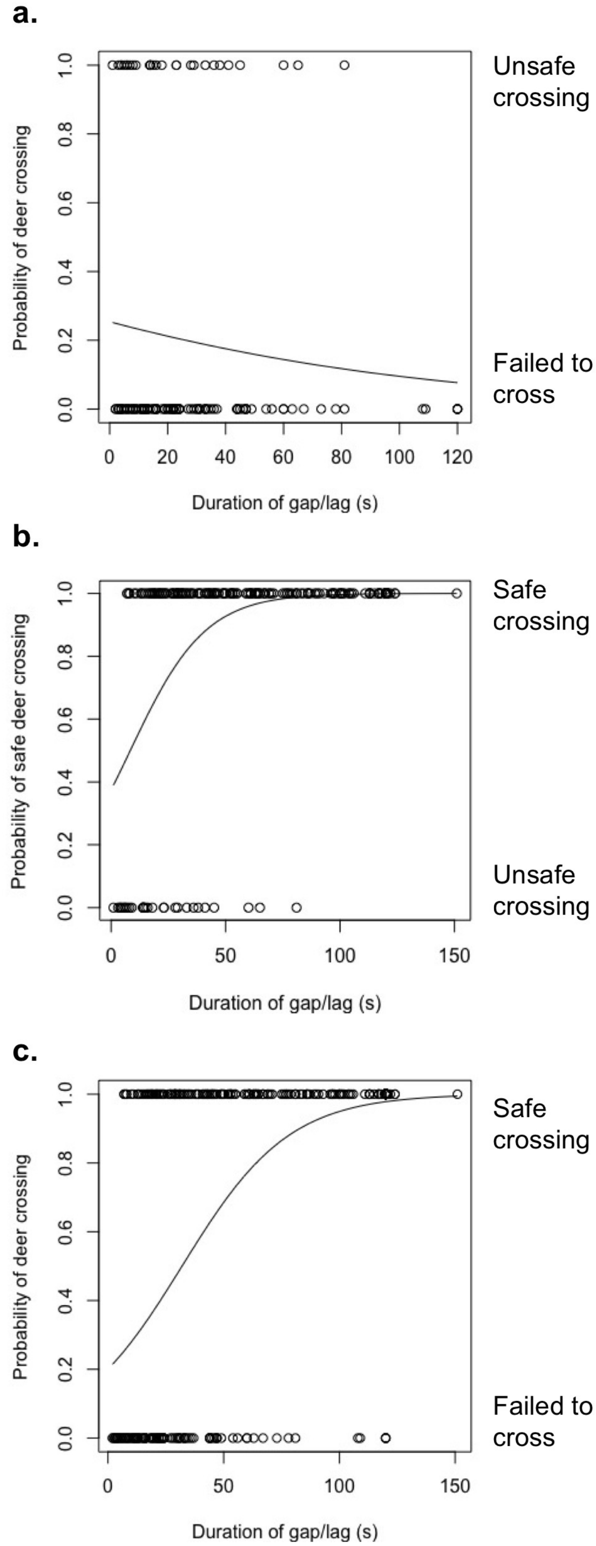



**Figure 2.Logistic regression curves for deer road crossing success in southwestern Wyoming as a function of the duration of gap or lag between vehicles they encountered. Curves compare (a) failure to cross versus unsafe crossing, (b) unsafe versus safe crossing, and (c) failure to cross versus safe crossing.**

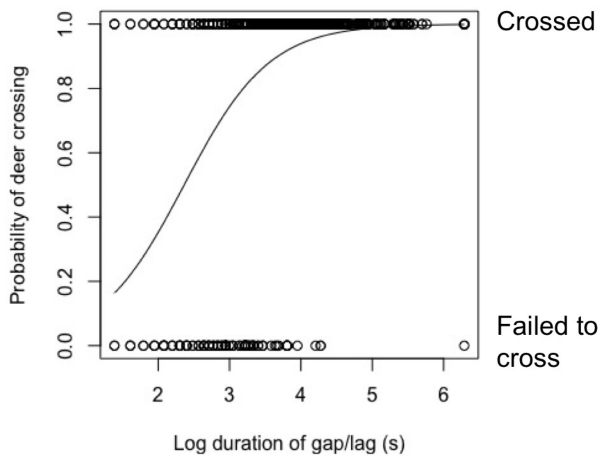



**Figure 3.Logistic regression curves for deer road crossing success in central Wyoming as a function of the duration of gap or lag between vehicles they encountered.**

Based on the results of these detailed analyses of deer road crossing behavior in relation to gap duration, we conclude that deer require approximately 60 seconds between vehicles in order to consistently cross highways safely (>90percent of the time) and in order to avoid deer-vehicle encounters with high risk of collision >90percent of the time. Further, deer require a minimum of approximately 30 seconds between vehicles in order to cross highways, recognizing that some of these crossings may have a high risk of collisions. See Discussion, below, for more discussion of our logic and assumptions in arriving at these thresholds.

In both southwestern and central Wyoming, the number of vehicles on the road in the minutes prior to the deer-road interaction was strongly correlated with the duration of gaps (southwestern: $r^2$=0.19, β=-8.5, $p$<0.0001; central: $r^2$=0.16, β=-0.05, $p$<0.0001). We used traffic data collected in southwestern Wyoming to flesh out this relationship with the specific question of how traffic volume per hour is related to the percent of the hour with gaps between vehicles of less than 60 seconds and less than 30 seconds. We found very strong linear relationships between traffic volume and both of these measures (percent of hour with gaps less than 60 seconds: $r^2$=0.94, β=0.41, $p$<0.0001; percent of hour with gaps less than 30 seconds: $r^2$=0.91β=0.20, $p$<0.0001). From fitted regression lines (Figure 4),a traffic count of 60 vehicles per hour was associated with 20percent of the hour having gaps <60 seconds and 10percent of the hour having gaps <30 seconds. Similarly, a traffic count of 120 vehicles per hour was associated with 50percent of the hour having gaps <60 seconds, and 20percent of the hour having gaps <30 seconds.Based on these numbers, we conclude that a traffic volume of 60 or fewer vehicles per hour is a situation where there is relatively low risk of deer-vehicle collision and deer are able to cross roads relatively freely. A traffic volume of 120 vehicles per hour is at times impassable and is unsafe for 50percent of thathour. The latter conditions may not constitute a complete barrier to deer movements but are a serious concern for both human safety and habitat connectivity for deer.

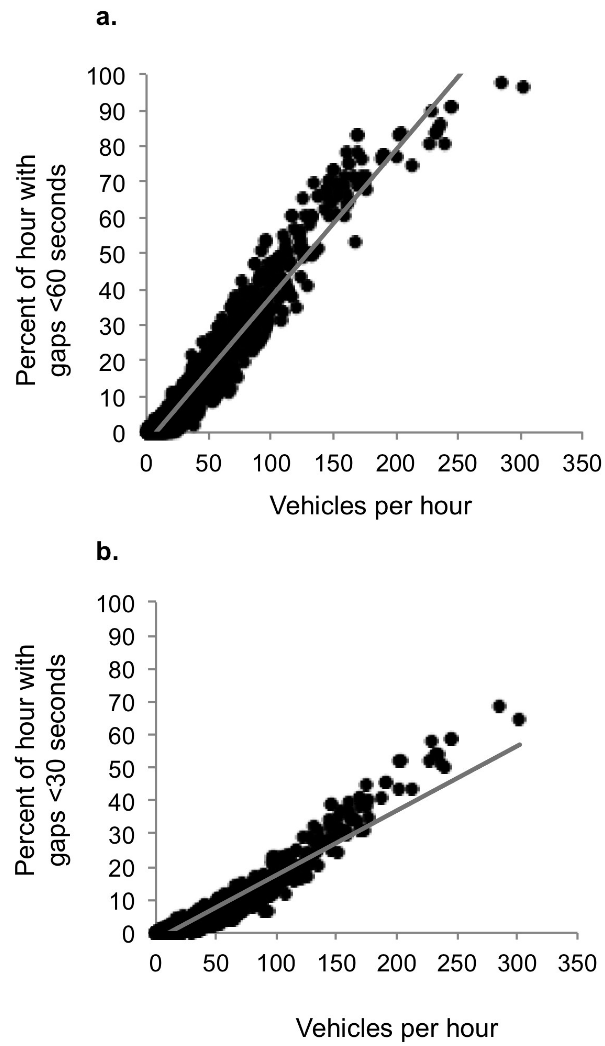
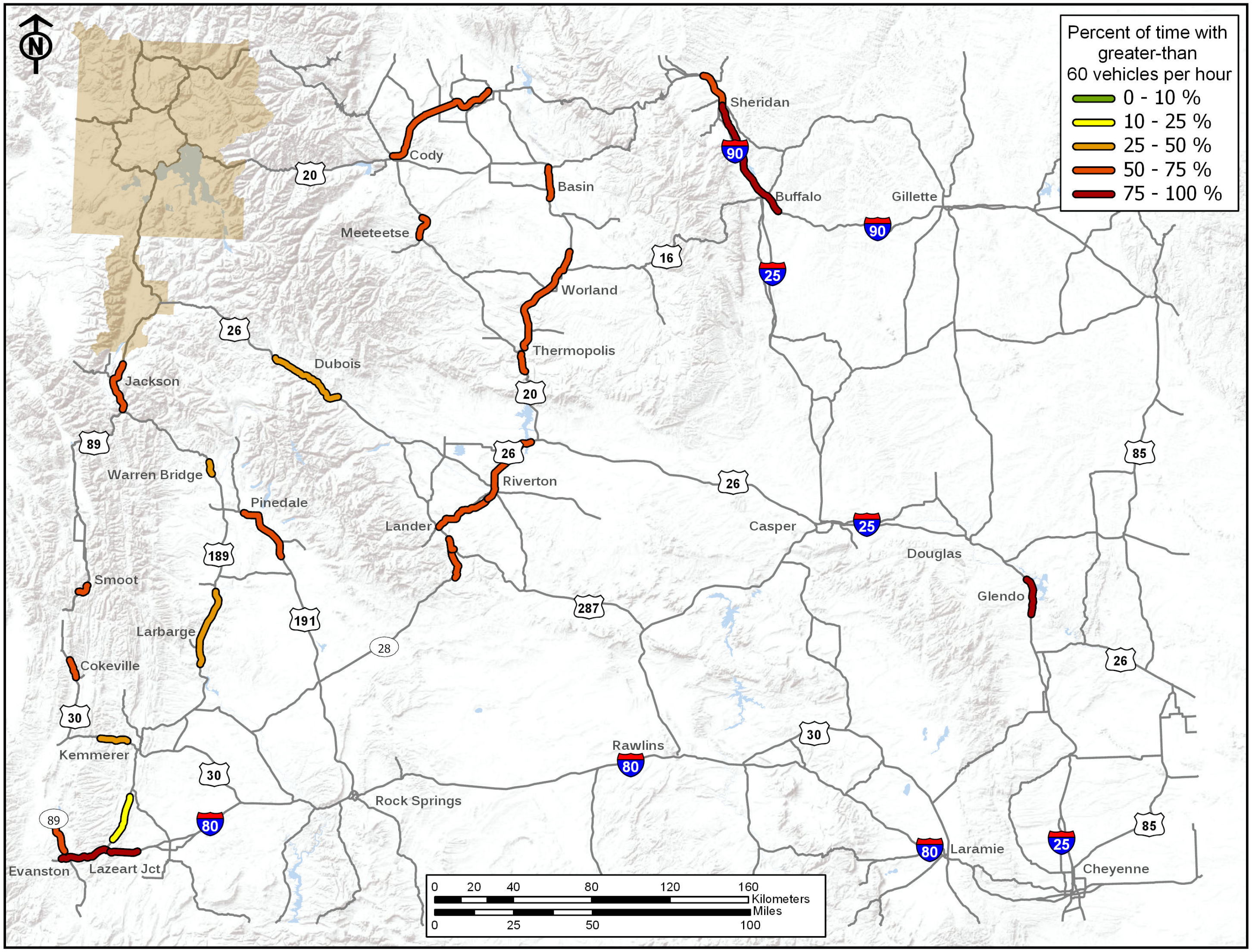



**Figure 4.Linear regressions between number of vehicles per hour and (a) percent of the hours with gaps < 60 seconds, and (b) percent of the hour with gaps <30 seconds.**

Figure 5shows a map of the percent of time when each hotspot of deer-vehicle collisions exceeded 60 vehicles per hour during the months when deer are active in that area. For most hotspots, this is more than 50percent of the time. For hotspots along I-80, I-25 and I-90 (Evanston area, Glendo area, Buffalo-Sheridan areas), these traffic conditions exist nearly 100percent of the time. Figure 6shows a map of the percent of time when each hotspot of deer-vehicle collisions exceeds 120 vehicles per hour during the months when deer are active in that area. Some hotspots, such as in the Dubois, La Barge, and Kemmerer areas, rarely exceeded this threshold; these hotspots have high rates of deer-vehicle collisionsbut are relatively less of a barrier to deer movements than some other hotspots. Hotspots in the Jackson, Lander-Riverton-Shoshoni, Cody-Powell, Evanston, Glendo, and Buffalo-Sheridan areas have traffic volumes greater than 120 vehicles per hour for 50-100percent of the time, and are likely impeding deer movements in important ways.

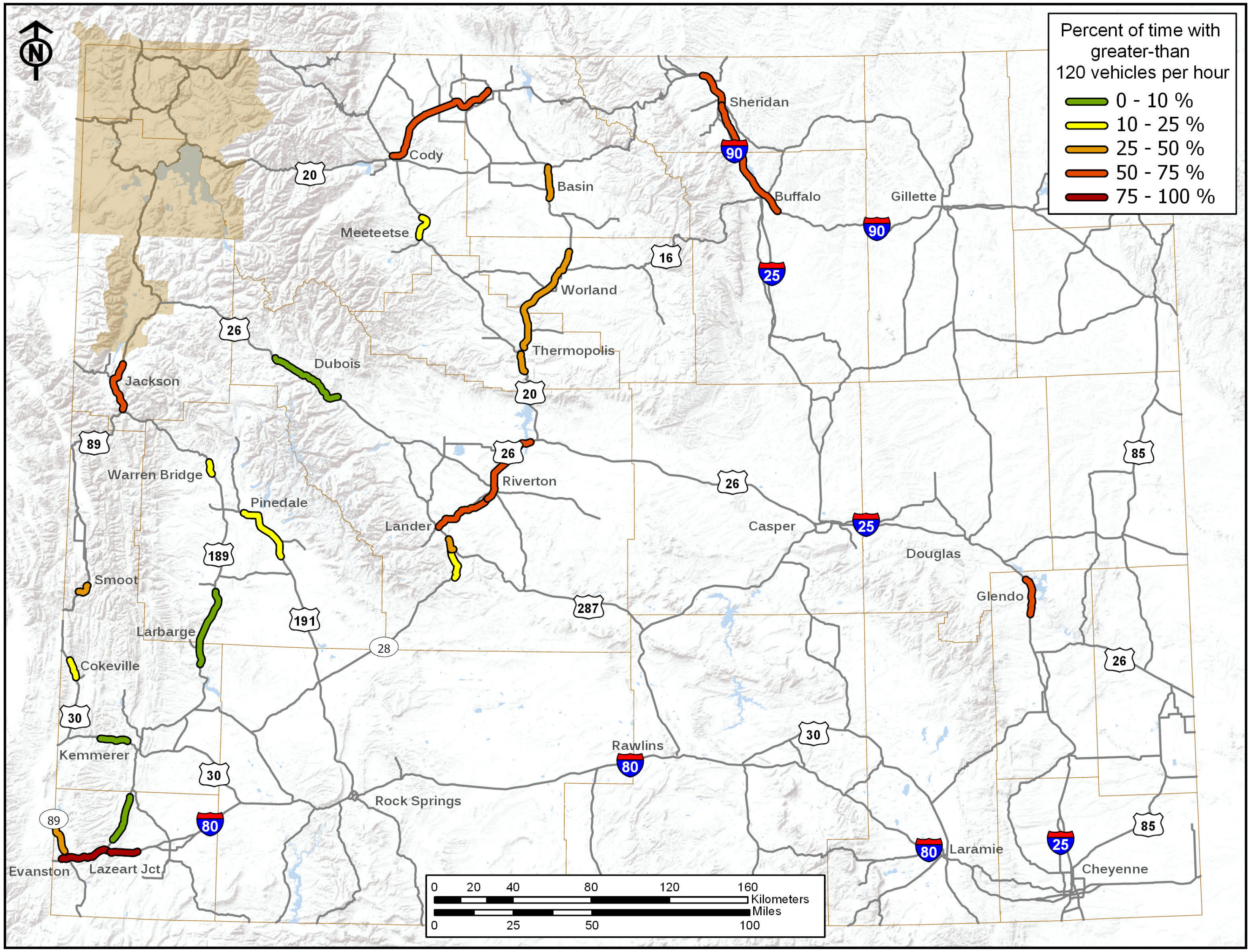
15



Source: Esri 2017, ArcGIS ArcPro 2.1.0, revised

**Figure 5.Map of the percent of time when traffic exceeds 60 vehicles per hour in hotspots of deer-vehicle collisions.**

16




Source: Esri 2017, ArcGIS ArcPro 2.1.0, revised

**Figure 6.Map of the percent of time when traffic exceeds 120 vehicles per hour in hotspots of deer-vehicle collisions.**

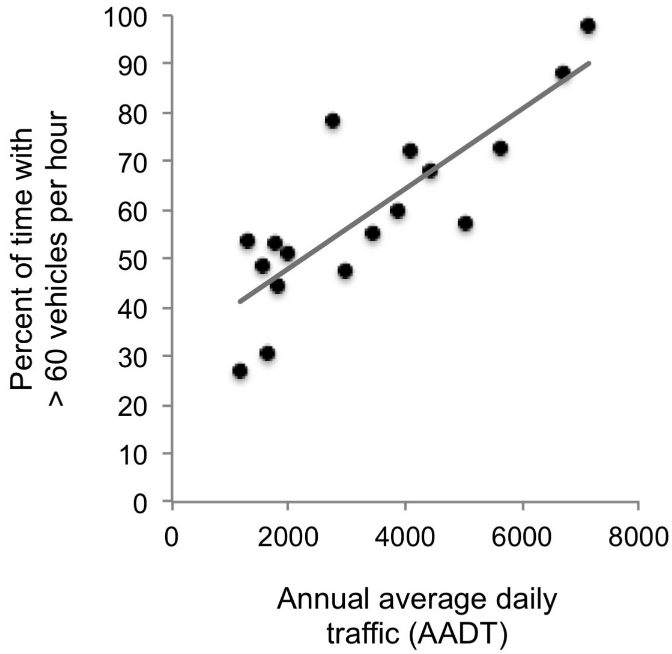



**Figure 7.Relationship between annual average daily traffic (AADT) and the percent of hours, over the whole year, with hourly traffic volume exceeding 60 vehicles.**

Because AADT is the most commonly used and available metric of traffic volume, we correlated the AADT of each of our deer-vehicle collision hotspots against the percent of time when hourly traffic exceeded 60 vehicles per hour during peak deer-vehicle collision seasons. The percent of time with traffic volume exceeding 60 vehicles per hour was significantly correlated with AADT ($r^2$=0.48, β=22.5, $p$<0.001). However, there was substantial variation around this line, which likely has to do with the fact that traffic volumes in Wyoming are much higher in summer than in winter. Hotspots where deer-vehicle collisions are high in the summer but not winter, such as Douglas/Glendo, Smoot, and Buffalo-Sheridan, had a higher percent of hours with traffic >60 vehicles during these months than expected based on AADT. Conversely, sites where deer-vehicle collisions are high in the winter but not summer, such as Jackson, Kemmerer-Lazeart, Labarge-Big Piney, Boulder-Pinedale, and Dubois, had a lower percent of hours with traffic >60 vehicles during these months than expected based on AADT.

A second correlation between AADT and percent of time when hourly traffic exceeded 60 vehicles per hour across the whole year, and excluding Jackson, showed substantially less variation and a linear relationship ($r^2$=0.69, β=0.008, $p$<0.0001; Figure 7). We excluded Jackson because of the very high AADT during summer months, which made this site a statistical outlier. Based on this line, we can infer AADTs necessary to achieve a target percent of the day with hourly traffic less than 60 vehicles per hour. For example, this line indicates that to achieve fewer than 50percent of the hours of the day with fewer than 60 vehicles per hour, AADT should be below 2,000; whereas, at AADT of 6,000, traffic exceeds 60 vehicles per hour about 80percent of the time.

## Discussion

### *Deer gap acceptance*

We found strong evidence that deer show consistent threshold patterns in their decisions about whether to accept or reject a gap between consecutive vehicles. In our southwestern Wyoming dataset, when gaps were less than 30 seconds long, deer did not attempt to cross the road, or crossed in an unsafe way that resulted in either a collision or a narrowly-avoided collision. When gaps were greater than 60 seconds long, deer almost always succeeded in crossing in a safe manner. In our central Wyoming dataset, deer appeared to accept somewhat smaller gaps; however, this data set did not distinguish between safe and unsafe crossings so some fraction of the accepted smaller gaps resulted in unsafe deer-vehicle interactions.

We found some evidence that deer in a group that were following a leader accepted smaller gaps than leaders or single deer. This is consistent with human behavior, where pedestrians in a group have been found to accept smaller gaps than individual pedestrians.[40] We also found evidence that deer encountering a road lined with wildlife warning reflectors, or white canvas covering the reflectors, accepted larger gaps than deer that did not encounter these treatments. This is consistent with our prior observation that deer encountering these treatments are more likely to stop at the edge of the right-of-way before crossing a road and contributes to our understanding of why deer experiencing these two treatments had lower deer-vehicle collision rates than deer experiencing no treatment.[31]However, given prior results that deer in the white canvas treatment were more likely to stop and less likely to be hit than deer in the reflector treatment, it is somewhat surprising that there was no difference in gap acceptance between these two treatments.

One limitation of our data is that they only represent nighttime conditions. It is possible that deer accept smaller gaps between vehicles during daylight hours. However, deer are most active and most likely to cross roads at dusk, night, and dawn, and deer-vehicle collisions are most likely to occur during these times. Thus, from both the perspective of human safety and deer habitat connectivity, our results inform deer-traffic relationships during the most critical times of day.

### *Traffic volume and deer habitat connectivity*

Our findings about deer gap acceptance behavior inform us about the conditions under which roads are permeable or impermeable to deer at very fine time scales. In order to use these findings to indicate how permeable a road is in general, we made a set of reasonable assumptions and judgments. We identified important gaps size thresholds of 30 and 60 seconds; below 30 seconds between vehicles, deer are essentially unable to cross roads, and above 60 seconds between vehicles, deer are consistently able to cross in a way that is safe to both the deer and the traveling public. We found that hourly traffic volume was strongly related to the percent of the hour with gaps below these thresholds, and that at 60 vehicles per hour, deer experience gaps < 60 seconds long 20percent of the time, and gaps 30 seconds long 10percent of the time. We assumed that deer have some tolerance for unsuitable gaps, since they do often wait for vehicles to pass (several too-small gaps) until there is a longer gap. However, at some point, deer likely lose this tolerance and either make an unsafe crossing or abandon their attempt to cross; these patterns are seen in pedestrian gap acceptance behavior.[41] We found that an hourly traffic of 120 vehicles was associated with 50percent of the hour having gaps <60 seconds long, and 20percent of the hour having gaps <30 seconds long. At this traffic volume, we assumed that roads are difficult and/or unsafe for deer to cross, and unsafe for the traveling public.

We used these hourly traffic volumes as a basis to indicate the relative permeability and safety of known deer-vehicle collision hotspots in Wyoming. We used hourly traffic data from these hotspots, focusing on the months in which deer are active and deer-vehicle collisions are common, to calculate the average percent of the 24-hour cycle in which these hotspots exceed the 60 and 120 vehicles per hour thresholds. The results (Figures 5 and 6) show which hotspots are most difficult and/or unsafe for deer to traverse for the largest fraction of the day. Unfortunately, we do not know how many hours of the day a road needs to be difficult to cross for a deer to give up crossing it — in other words, for the road to be a barrier to deer movements. Many roads have low traffic volumes during the middle of the night and may enable partial habitat connectivity for deer, even if they are difficult or impossible to cross during peak traffic hours. Others, such as I-80, have high traffic volumes nearly 24 hours a day and are likely near-complete barriers to deer movements.

We have used a novel approach to understand deer gap acceptance behavior and predict the traffic conditions under which roads are unsafe and impermeable to deer. Our approach takes a much finer-scale and more mechanistic approach than previous efforts to relate traffic volume with the effects of roads on ungulates. This approach also enables us to scale back up to AADT, a coarse measure of traffic volume but one that is readily available and usable to transportation managers and planners. Our results indicate that traffic volumes above 2,000 AADT will be unsafe for deer and the traveling public for more than 50percent of the 24-hour cycle, and higher traffic volumes will incur even higher fractions of the day with unsafe or impermeable road conditions. These results broadly corroborate, but refine, previous estimates, which have indicated barrier effects of roads above 500-8,000 AADT.[20,33,36]

Although we must make several assumptions in using them, our calculations of fraction of time in which roads are permeable and safe for deer provides a way to identify locations within Wyoming where deer habitat connectivity is most imperiled by roads. These are places where deer habitat connectivity would benefit most from wildlife crossing structures, but they are not necessarily the places with the highest numbers of deer-vehicle collision or the highest per-vehicle likelihood of hitting a deer. All of these factors should be considered in decisions about where to prioritize mitigations, such as wildlife crossing structures.

# CHAPTER 4. COST-BENEFIT ANALYSES OF WILDLIFE-VEHICLE MITIGATION MEASURES

## Introduction

Transportation planners are faced with complex decisions about where to prioritize measures to mitigate wildlife-vehicle collisions and the barrier effects of roads, and which measures to choose from. There are many potential mitigation measures available, and these range widely in costs and effectiveness under different circumstances.[27-29] Common mitigation measures include wildlife warning signs (e.g., static icon of a jumping deer), temporary (movable) signs to warn drivers, highway under- and over-passes in conjunction with funnel fencing to guide animals towards crossing structures, wildlife cross-walks (designated locations for crossing, often accompanied by funnel fencing and signage to alert drivers), and animal detection systems. These range in effectiveness from un-detectible effects to >80 percent reductions in WVC, and in cost, from hundreds to millions of dollars.[27-29]

Cost-benefit analysis is one useful tool that can help managers to make informed decisions about which mitigations to consider putting in which locations. A cost-benefit analysis for wildlife-vehicle collisions measures up the costs of installing and maintaining the mitigation for a fixed period of time against the economic benefits of avoiding the costs of wildlife-vehicle collisions that would accrue without the mitigation measure.[27] The costs of collisions include damages to vehicles, medical expenses associated with human injuries and occasional fatalities, and the economic value of lost wildlife. It is not possible to conduct a perfectly accurate cost-benefit analysis, since all of the monetary values involved fluctuate in time. Nevertheless, a cost-benefit analysis can help show where mitigations are most cost-efficient and illustrate to the public that mitigation dollars are money well-spent.

We conducted a series of cost-benefit analyses for six different wildlife-vehicle collision mitigation measures, over each mile of Wyoming's highway network (roads maintained by WYDOT). Here we present the process and the results of these analyses.

## Methods

For the purposes of these cost analyses,we focused on deer, which make up >85percent of all WVC in Wyoming. We used the same general approach for all cost-benefit analyses, following the protocols of Huijser et al.[27] We calculated costs as the total cost of installing and maintaining the mitigation over 75 years, per mile of highway mitigated; this is the "present value cost." The present value cost was then amortized over 75 years at a 3percent interest rate, to get the annual amortized value per mile. This is the "cost" we weighed up against the "benefit" of the mitigation.

We calculated the benefit as the expected average value of avoided collisionsper mile per year under the mitigation. Specifically, this was the average number of WVCs per year in a given mile, from 2011-2015, multiplied bythe estimated percent effectiveness of the mitigation, multiplied by the estimated cost per collision in terms of damage to vehicle, human injury, and deer value. We used the estimated mean cost per collision in damage and human injury from Huijser et al.'s analysis ($6,500)[27]; however, rather than use their value of $100 per deer (a national average that includes areas where deer are less valuable than in Wyoming), we used the Wyoming Game and Fish Department's estimated economic value of $4,000 per deer. Thus, the total benefit per avoided collision was $10,500.

We estimated costs and effectiveness of mitigations using the best information available. For some mitigations, there is good data to indicate effectiveness and average costs; for others, data are scant, with effectiveness results ranging widely. In the latter case, we conducted two separate analyses, one for an average effectiveness and one for a low effectiveness. The specific mitigations we considered are summarized in Table 2.

**Table 2. Estimated costs and effectiveness of the mitigations used for cost-benefit analyses.**

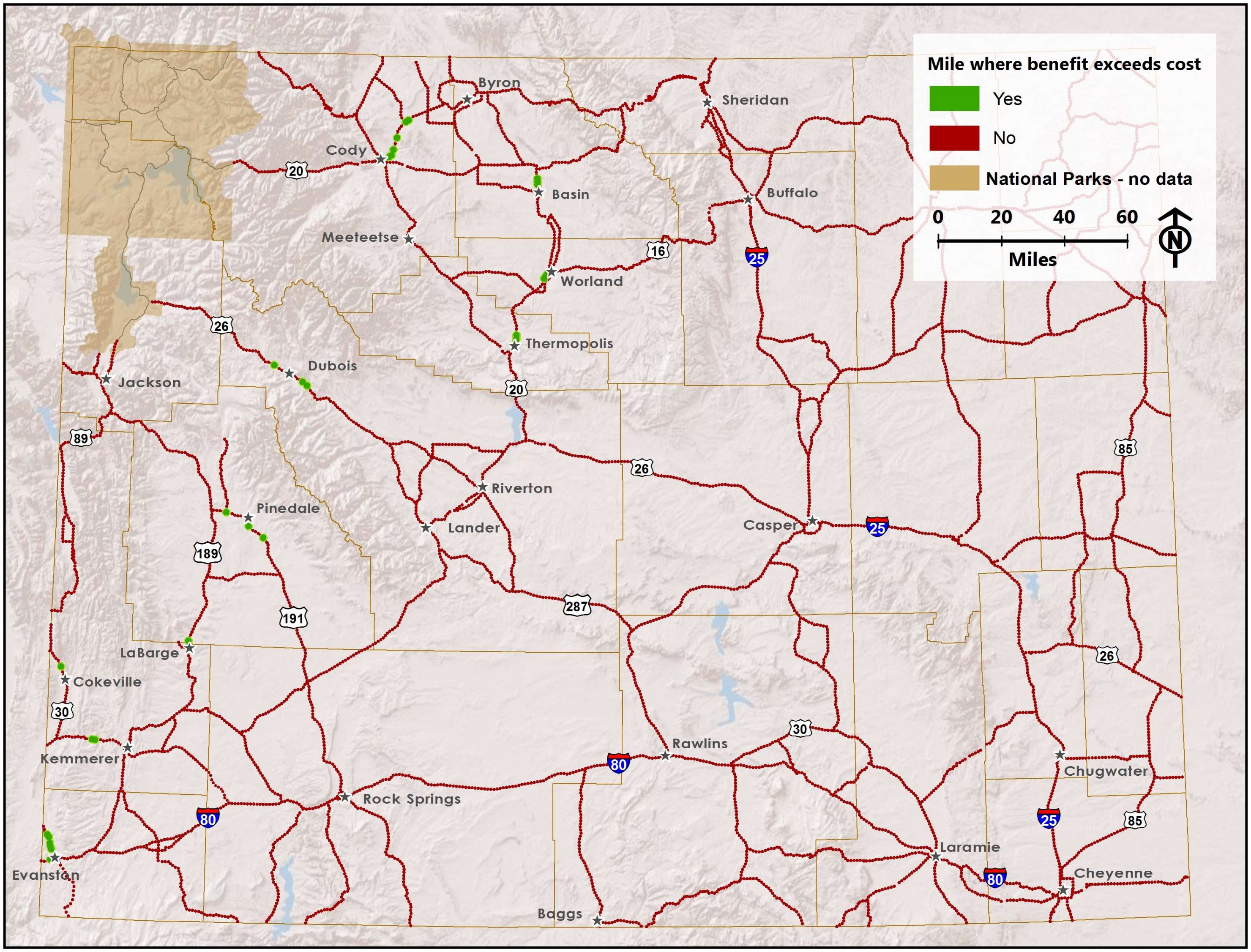
| Mitigation measure | Annual amortized cost | Estimated effectiveness | Sources |
|---|---|---|---|
| Underpasses every 2 km (1.2 mi), fencing, and jump-outs | $18,115 per km ($28,984 per mi) | 86% | Huijser et al. [27] |
| Underpasses every 2 km(1.2 mi), overpasses every 24 km (14.9 mi), fencing, and jump-outs | $24,230 per km ($38,767 per mi) | 86%; allows pronghorn passage | Huijser et al. [27] |
| Crosswalk: fencing with gaps and signs | $10,116 per km ($16,185 per mi) | 40% | Huijser et al. [27] |
| Peak season dynamic message signs | $695 per km ($1,122 per mi) | Average = 26%; low =9% | WYDOT; Huijser et al. [27]; Huisjer et al. [25] |
| Reduced night /seasonal speed limit using electronic, variable speed limit signs | $1,043 per km ($1,683 per mi) | Average = 26%; low =9% | WYDOT |
| Wildlife warning reflectors | $2,760 per km ($4,452 per mi) | Average = 30%; low =10% | WYDOT; Riginos et al.[31] |

For each mitigation, we calculated the ratio of benefit to cost for each of the 6,270 miles of Wyoming's highway network for which WVC data exist; these results are available in tabular form. We also created maps of the road network showing, mile by mile, where the annual benefit of the mitigation exceeded the annual cost. Further, for the first three mitigations (underpasses; under- and overpasses; crosswalks), we created cost-benefit maps with benefit calculated using only the avoided damage and injury costs, only the avoided deer costs, and total avoided costs. These different benefits appeal to different audiences; e.g. transportation managers are mostly concerned about benefit in terms of avoided human injury and damage to vehicles, whereas wildlife managers are mostly concerned about benefits in terms of deer and deer value saved.

**Results**

For the purposes of this report, we present results in map form, showing miles in Wyoming where the benefits of mitigations exceed the costs. However, it is important to note that the ratio of benefit to cost (available in tabular form) is ultimately more informative, and map results showing a simple depiction of where benefits exceed costs should not be viewed as the final word on whether a mitigation is “worth it” or not.

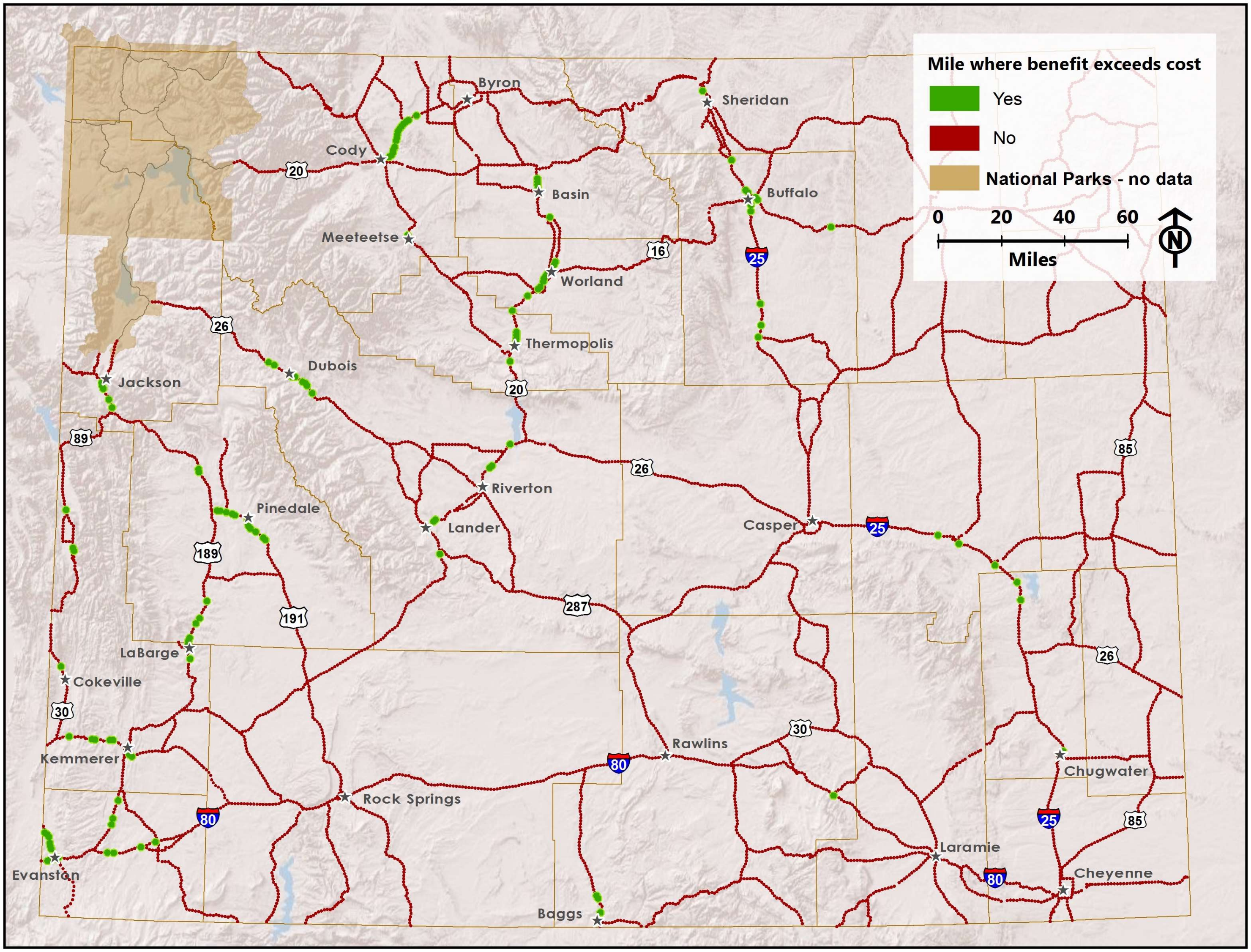
Game fencing, underpasses and jump-outs over 75 years (cost) versus saved deer value (benefit)




Source: Esri 2016, ArcGIS ArcMap 10.5, revised

**Figure 8. Cost-benefit map for underpasses with fencing, with costs versus saved deer value.**

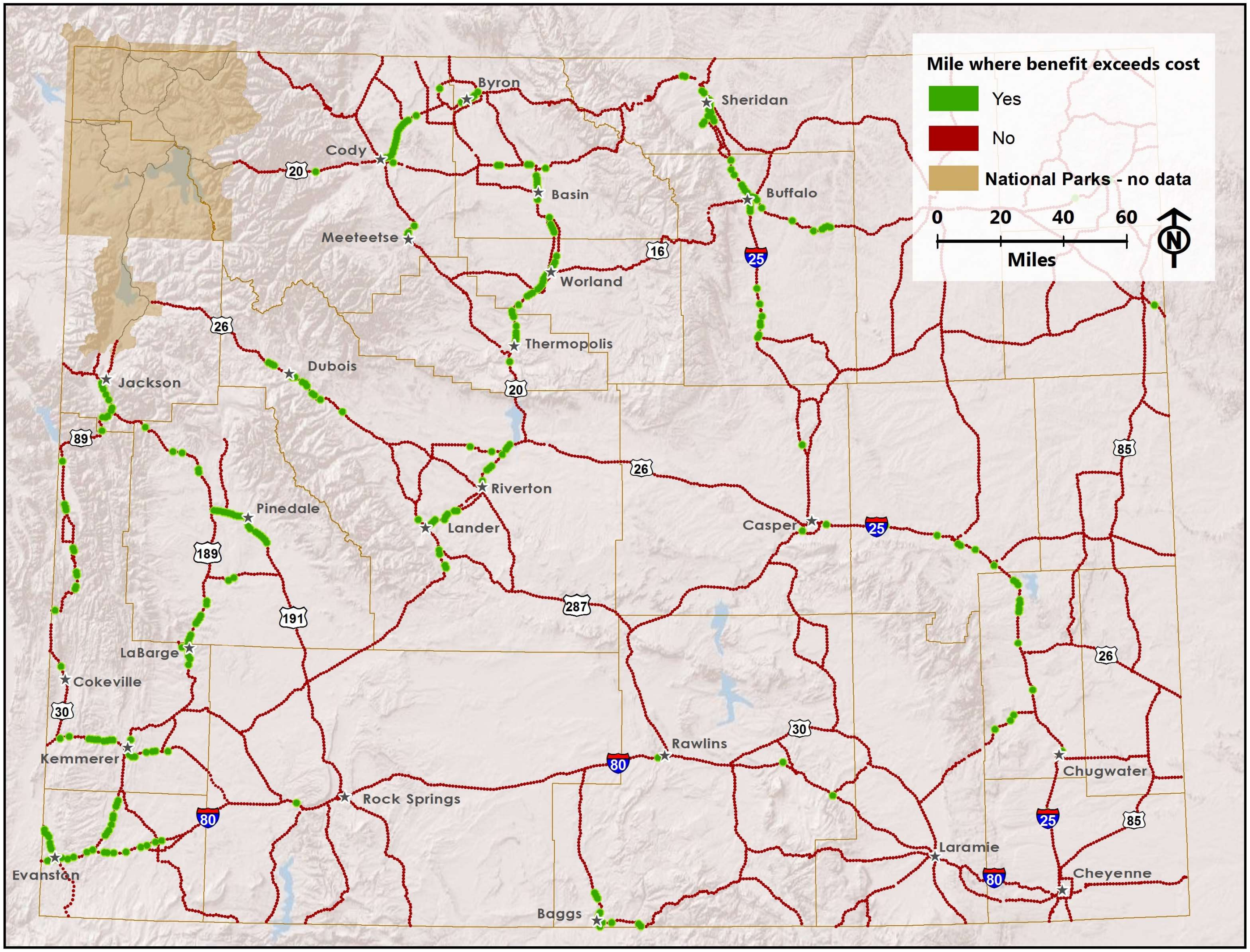
Game fencing, underpasses and jump-outs over 75 years (cost) versus saved injury & damage value (benefit)




Source: Esri 2016, ArcGIS ArcMap 10.5, revised

**Figure 9. Cost-benefit map for underpasses with fencing, with costs versus value of avoided injuries and damage.**

Game fencing, underpasses and jump-outs over 75 years (cost) versus saved deer value and injury & damage value (benefit)



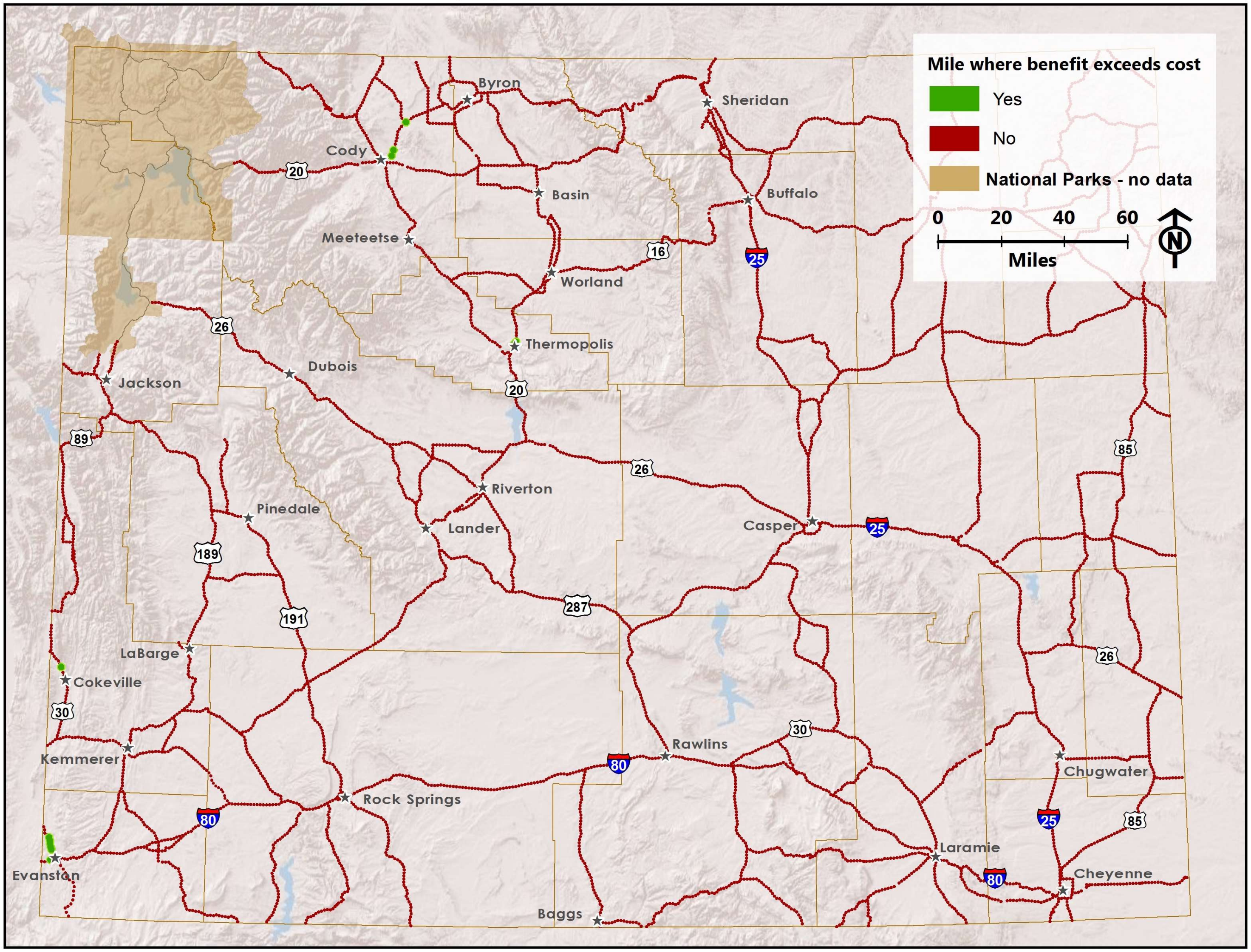

Source: Esri 2016, ArcGIS ArcMap 10.5, revised



**Figure 10. Cost-benefit map for underpasses with fencing, with costs versus value of saved deer and avoided injuries and damage.**

27

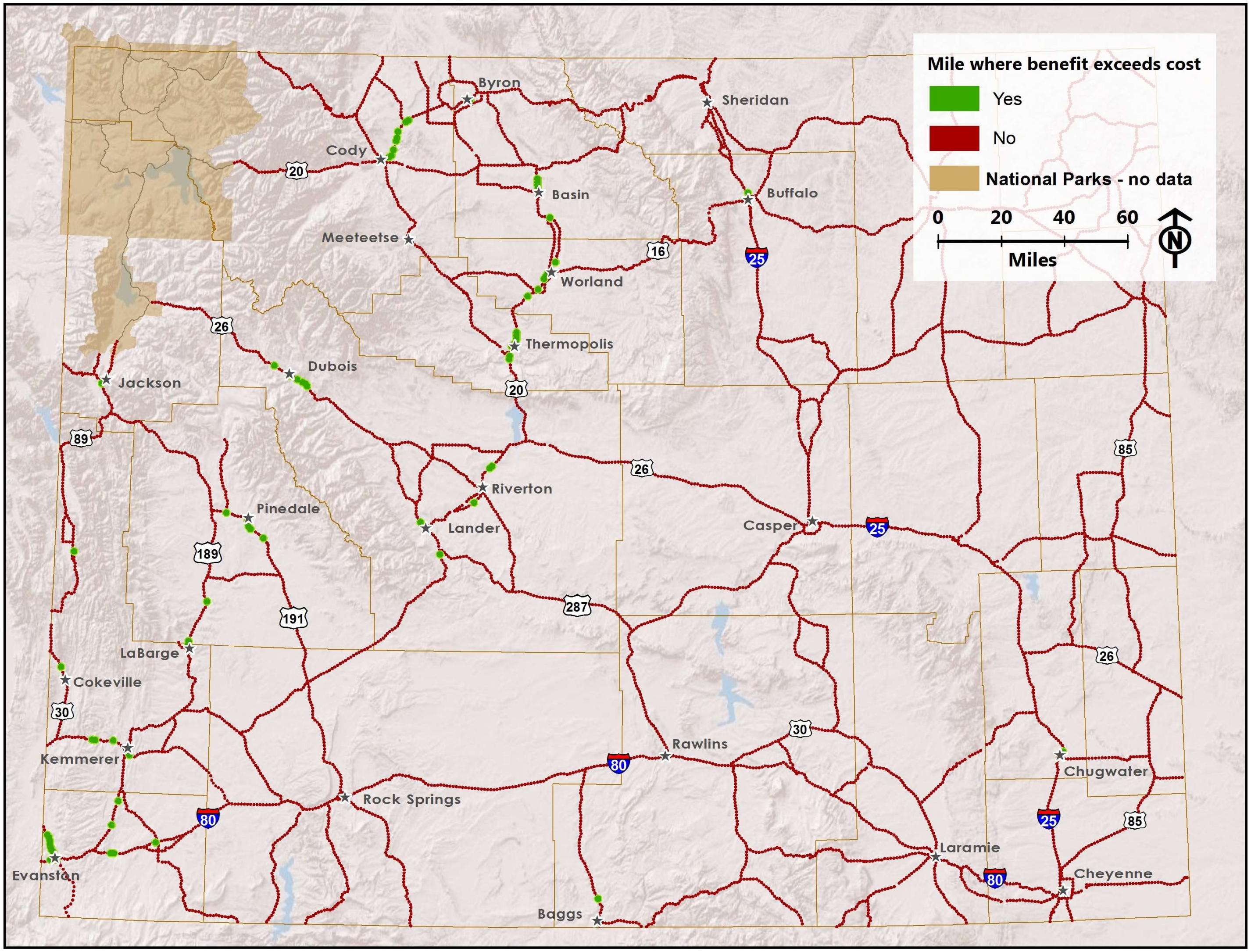
Game fencing, underpasses, periodic overpasses and jump-outs over 75 years (cost) versus saved deer value (benefit)




Source: Esri 2016, ArcGIS ArcMap 10.5, revised

**Figure 11. Cost-benefit map for underpasses and overpasses with fencing, with costs versus saved deer value.**

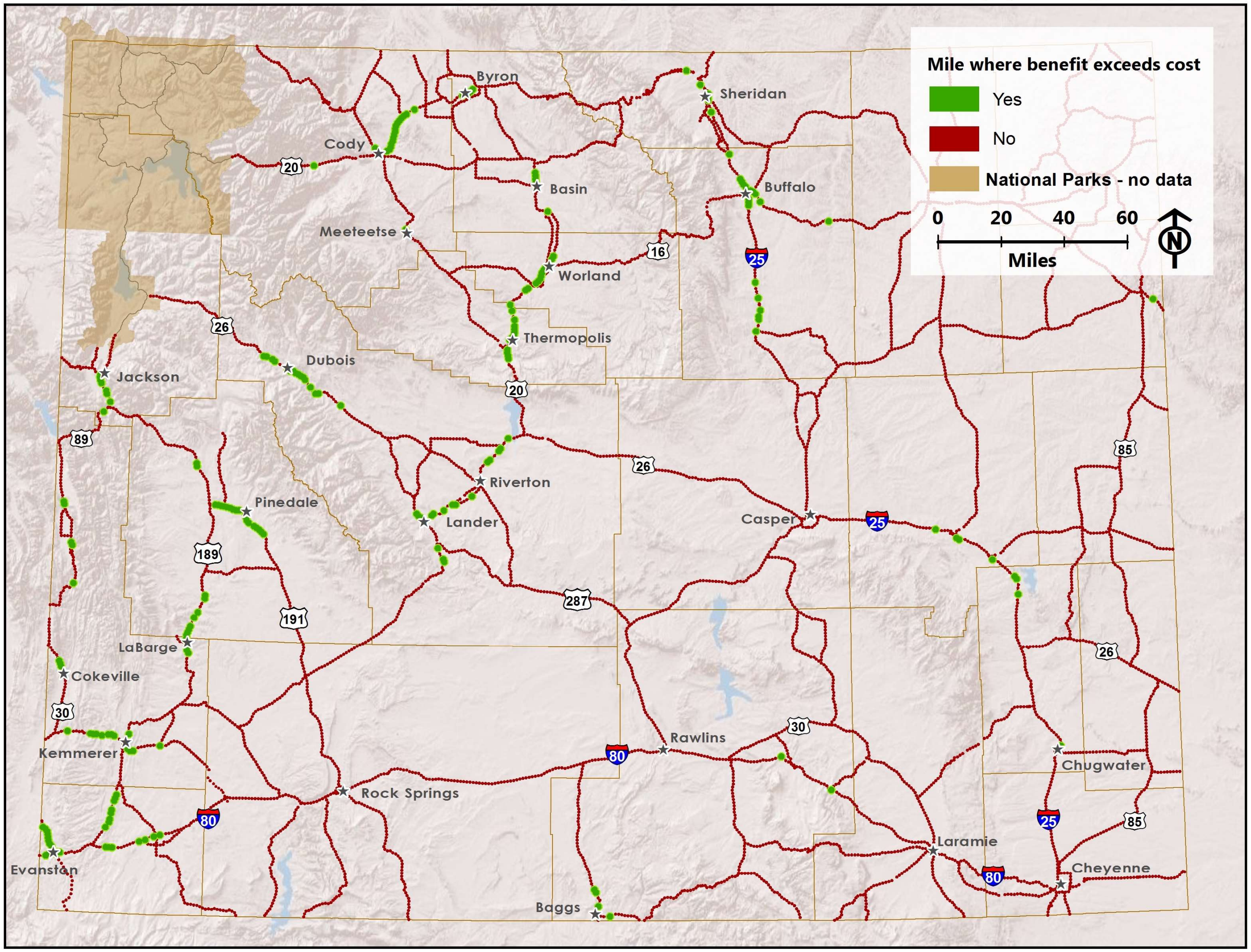
Game fencing, underpasses, periodic overpasses and jump-outs over 75 years (cost) versus saved injury and damage value (benefit)




Source: Esri 2016, ArcGIS ArcMap 10.5, revised

**Figure 12. Cost-benefit map for underpasses and overpasses with fencing, with costs versus value of avoided injuries and damage.**

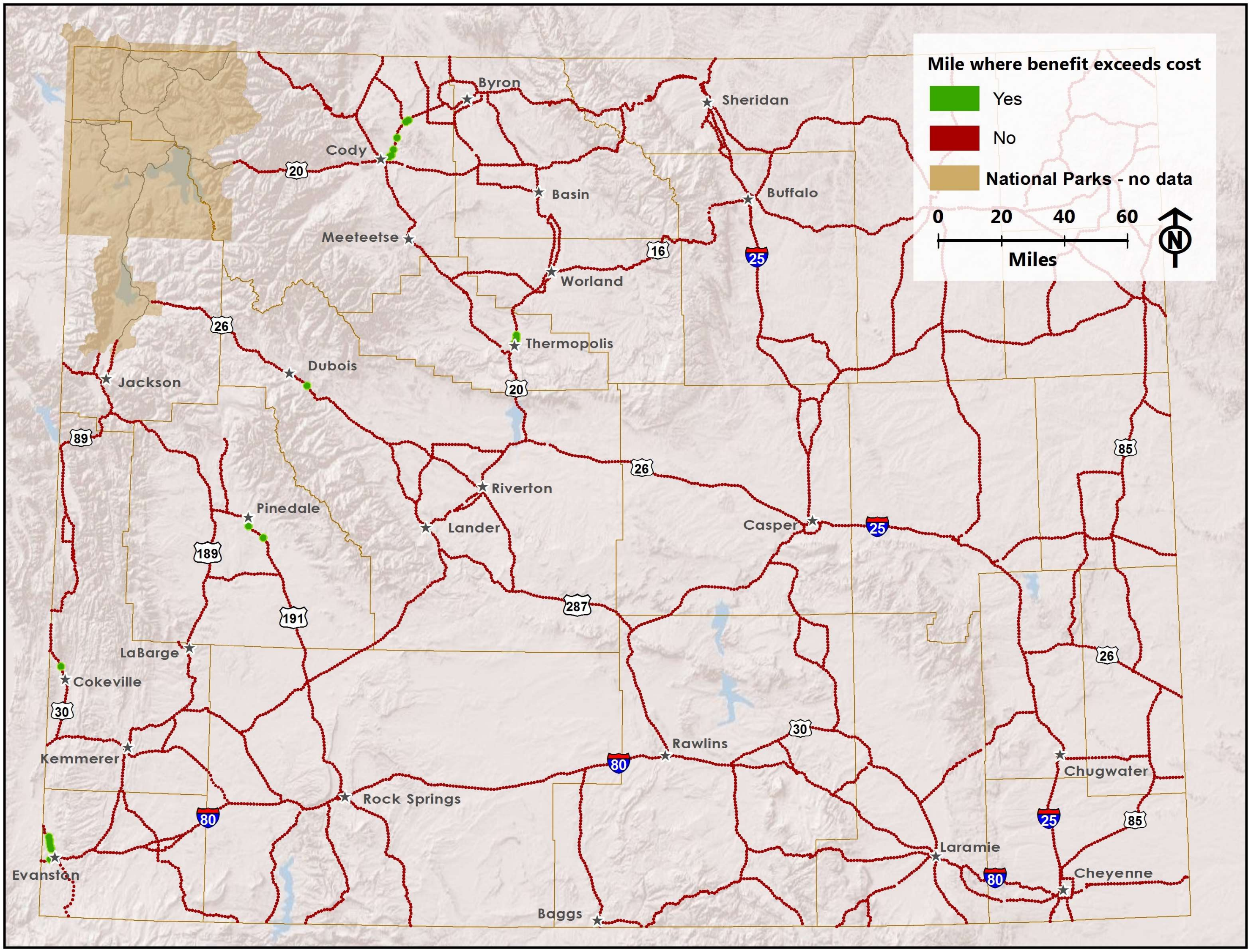
Game fencing, underpasses, periodic overpasses and jump-outs over 75 years (cost) versus saved deer value and injury & damage value (benefit)




Source: Esri 2016, ArcGIS ArcMap 10.5, revised

**Figure 13. Cost-benefit map for underpasses and overpasses with fencing, with costs versus value of saved deer and avoided injuries and damage.**

Game fencing with gaps and crosswalks (cost) versus saved deer value (benefit)

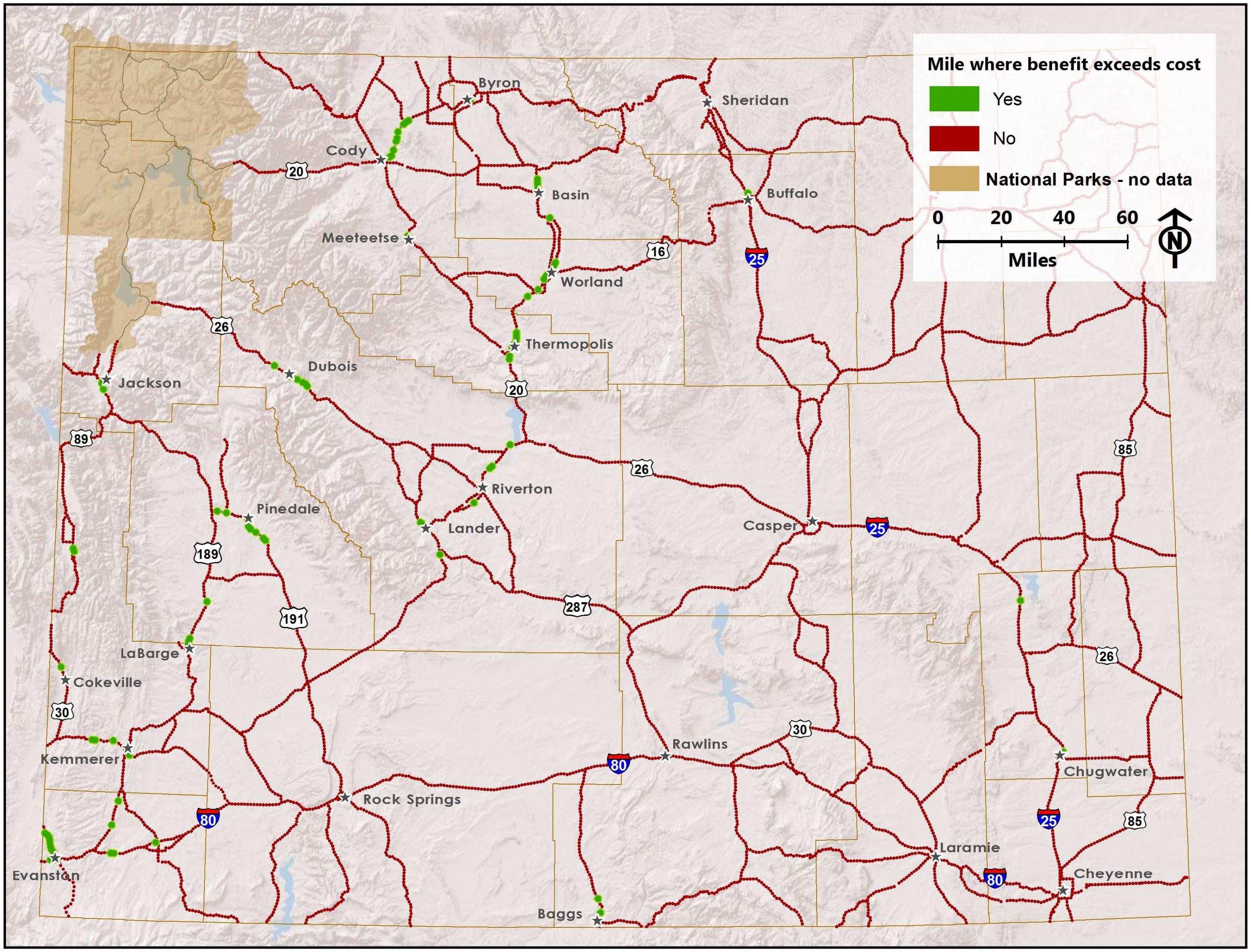



Source: Esri 2016, ArcGIS ArcMap 10.5, revised

**Figure 14. Cost-benefit map for game fencing and crosswalks, with costs versus saved deer value.**

31

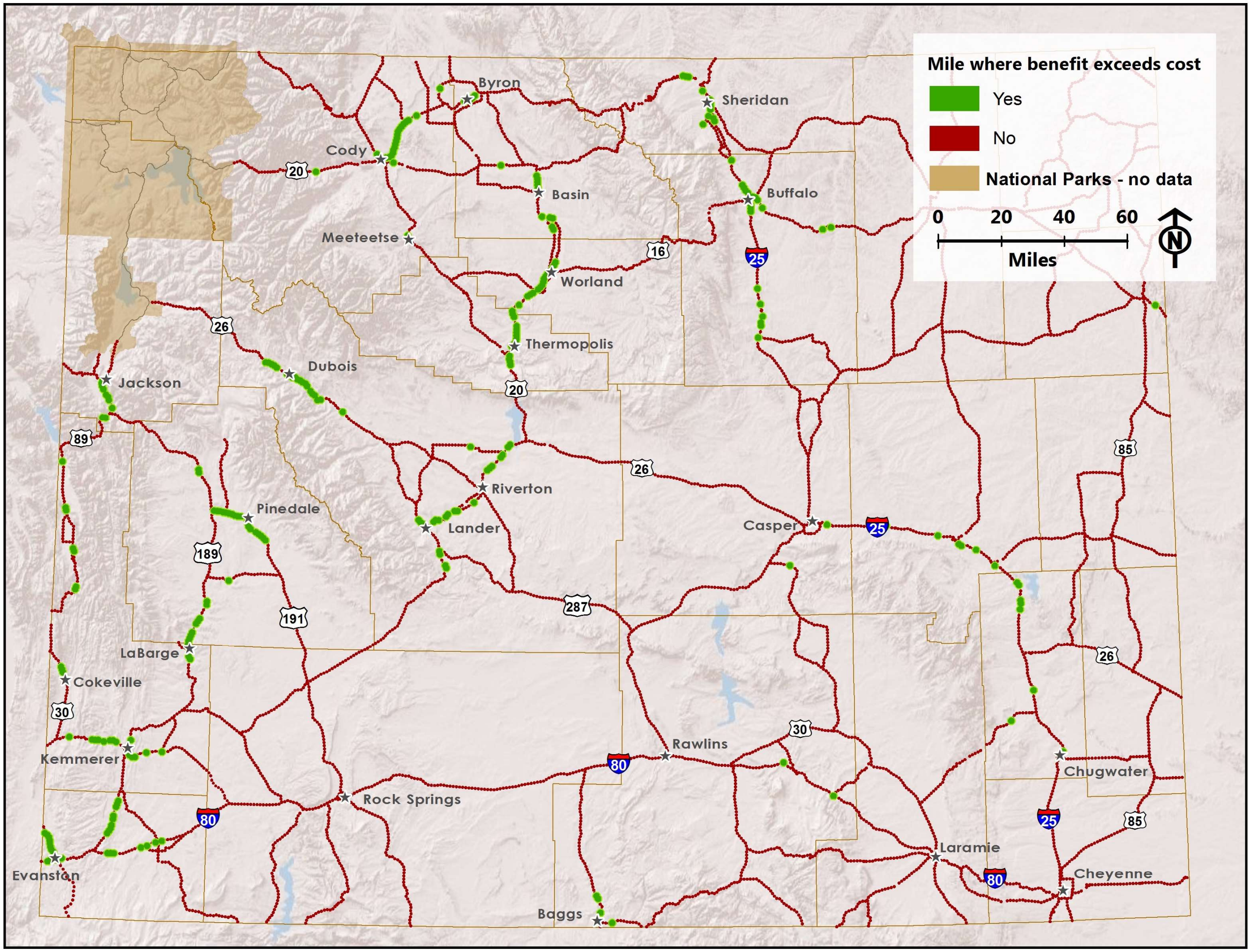
Game fencing with gaps and crosswalks (cost) versus saved injury & damage value (benefit)




Source: Esri 2016, ArcGIS ArcMap 10.5, revised

**Figure 15. Cost-benefit map for game fencing and crosswalks, with costs versus value of avoided injuries and damage.**

Game fencing with gaps and crosswalks (cost) versus saved deer value and injury & damage value (benefit)

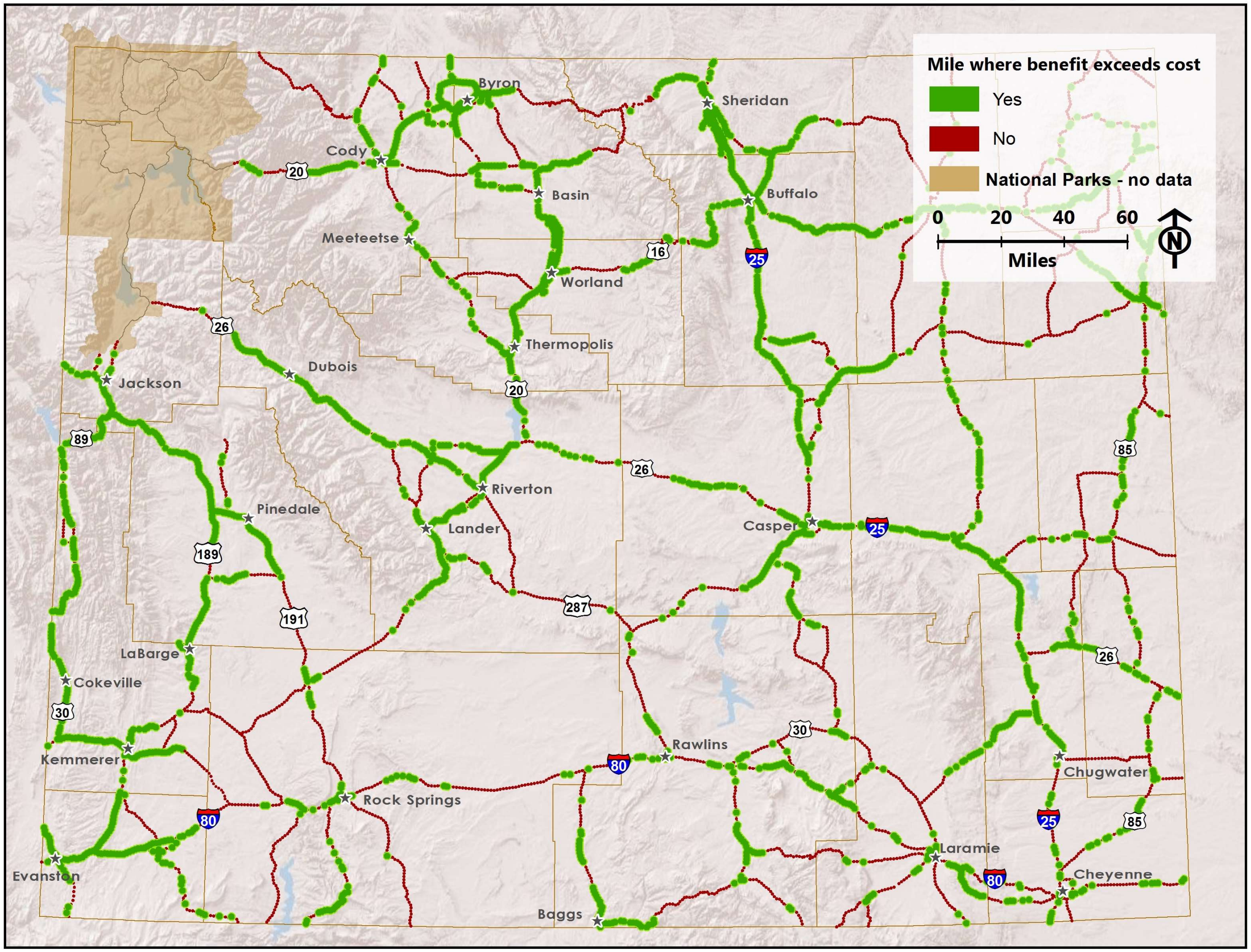



Source: Esri 2016, ArcGIS ArcMap 10.5, revised

**Figure 16. Cost-benefit map for game fencing and crosswalks, with costs versus value of saved deer and avoided injuries and damage.**

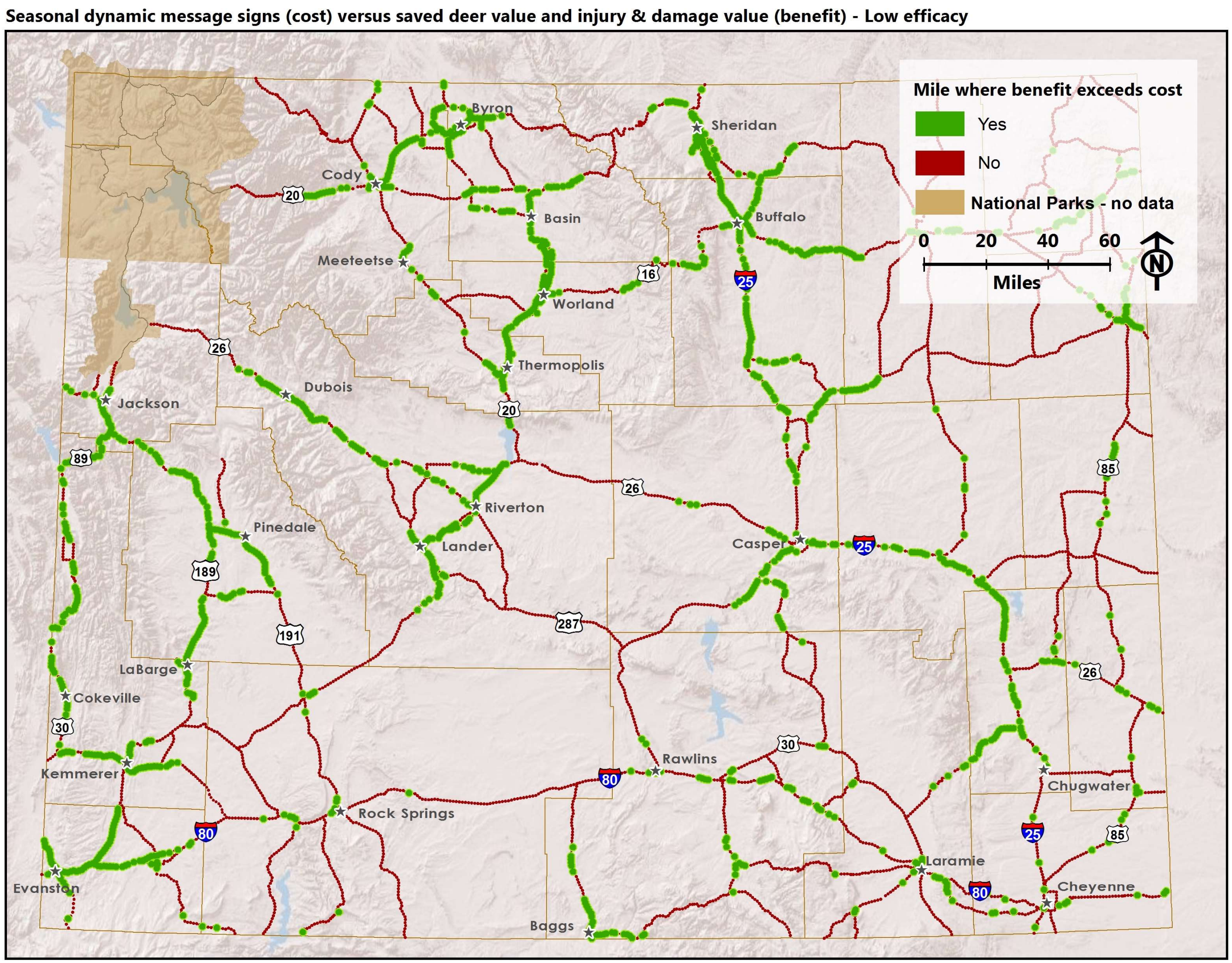
33

Seasonal dynamic message signs (cost) versus saved deer value and injury & damage value (benefit) - Average efficacy




Source: Esri 2016, ArcGIS ArcMap 10.5, revised

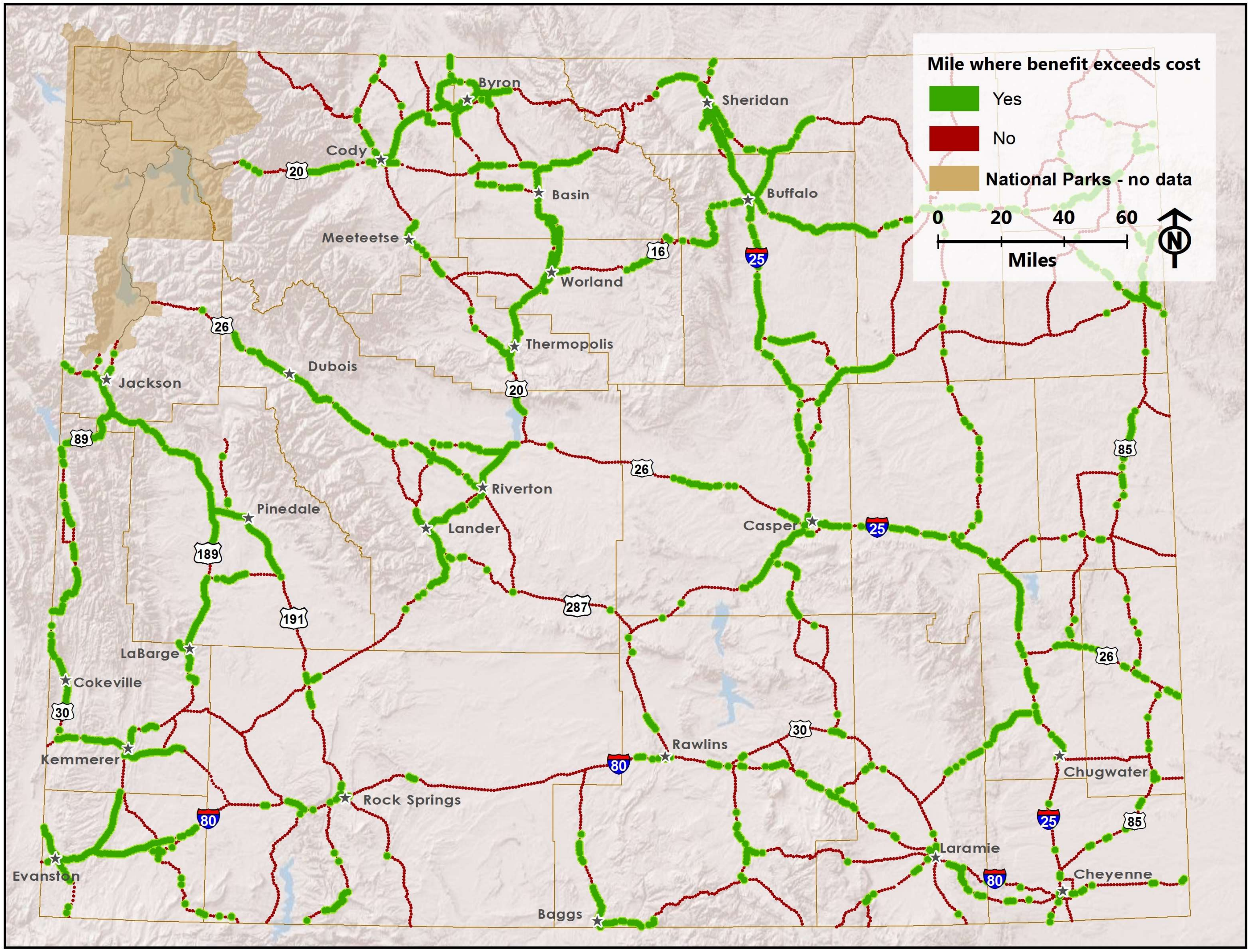
**Figure 17. Cost-benefit map for seasonal dynamic message sign, assuming average efficacy, with costs versus value of saved deer and avoided injuries and damage.**




Source: Esri 2016, ArcGIS ArcMap 10.5, revised

**Figure 18. Cost-benefit map for seasonal dynamic message sign, assuming low efficacy, with costs versus value of saved deer and avoided injuries and damage.**

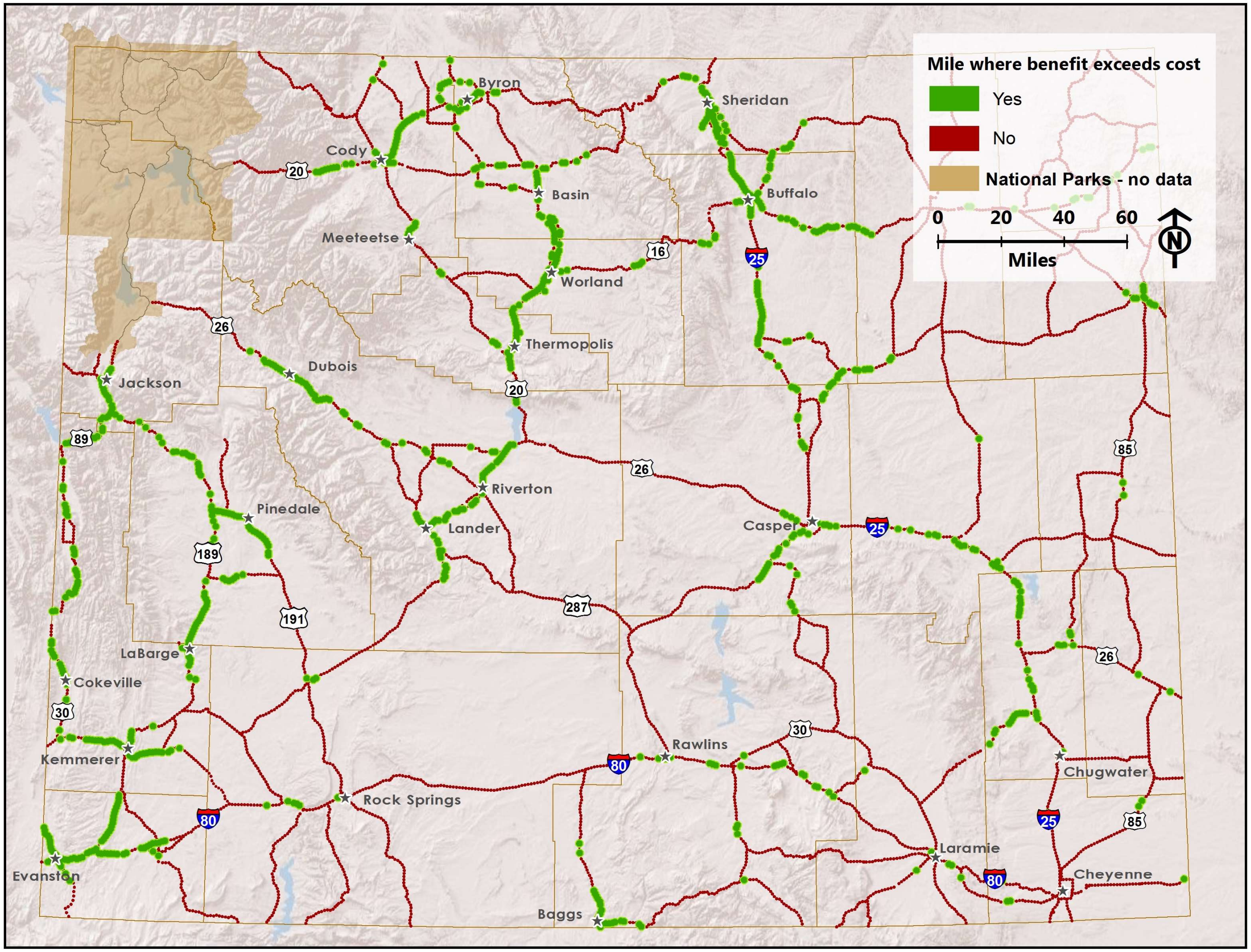
Seasonal speed limit reduction (cost) versus saved deer value and injury & damage value (benefit) - Average efficacy




Source: Esri 2016, ArcGIS ArcMap 10.5, revised

**Figure 19. Cost-benefit map for seasonal speed limit reduction, assuming average efficacy, with costs versus value of saved deer and avoided injuries and damage.**

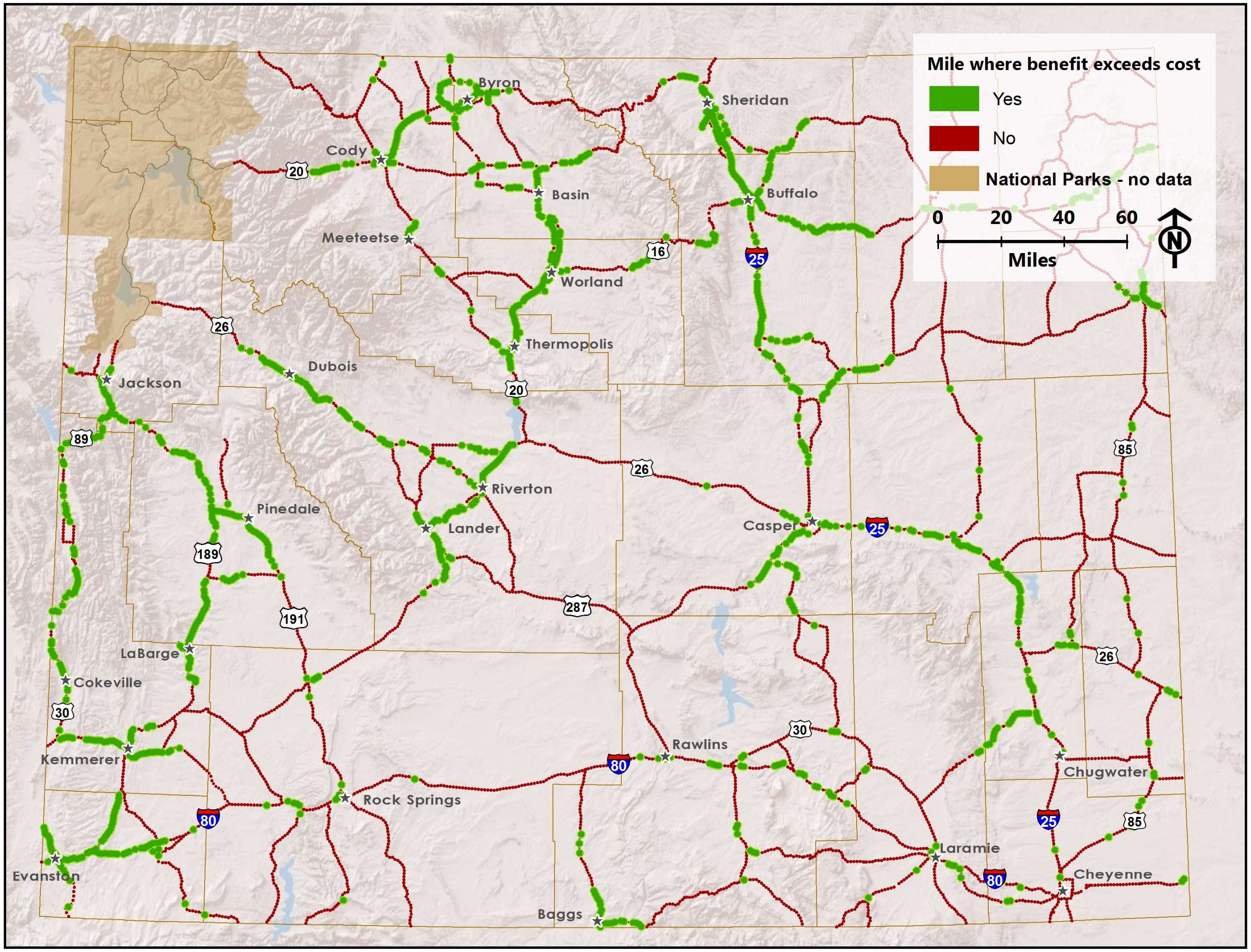
Seasonal speed limit reduction (cost) versus saved deer value and injury & damage value (benefit) - Low efficacy




Source: Esri 2016, ArcGIS ArcMap 10.5, revised

**Figure 20. Cost-benefit map for seasonal speed limit reduction, assuming low efficacy, with costs versus value of saved deer and avoided injuries and damage.**

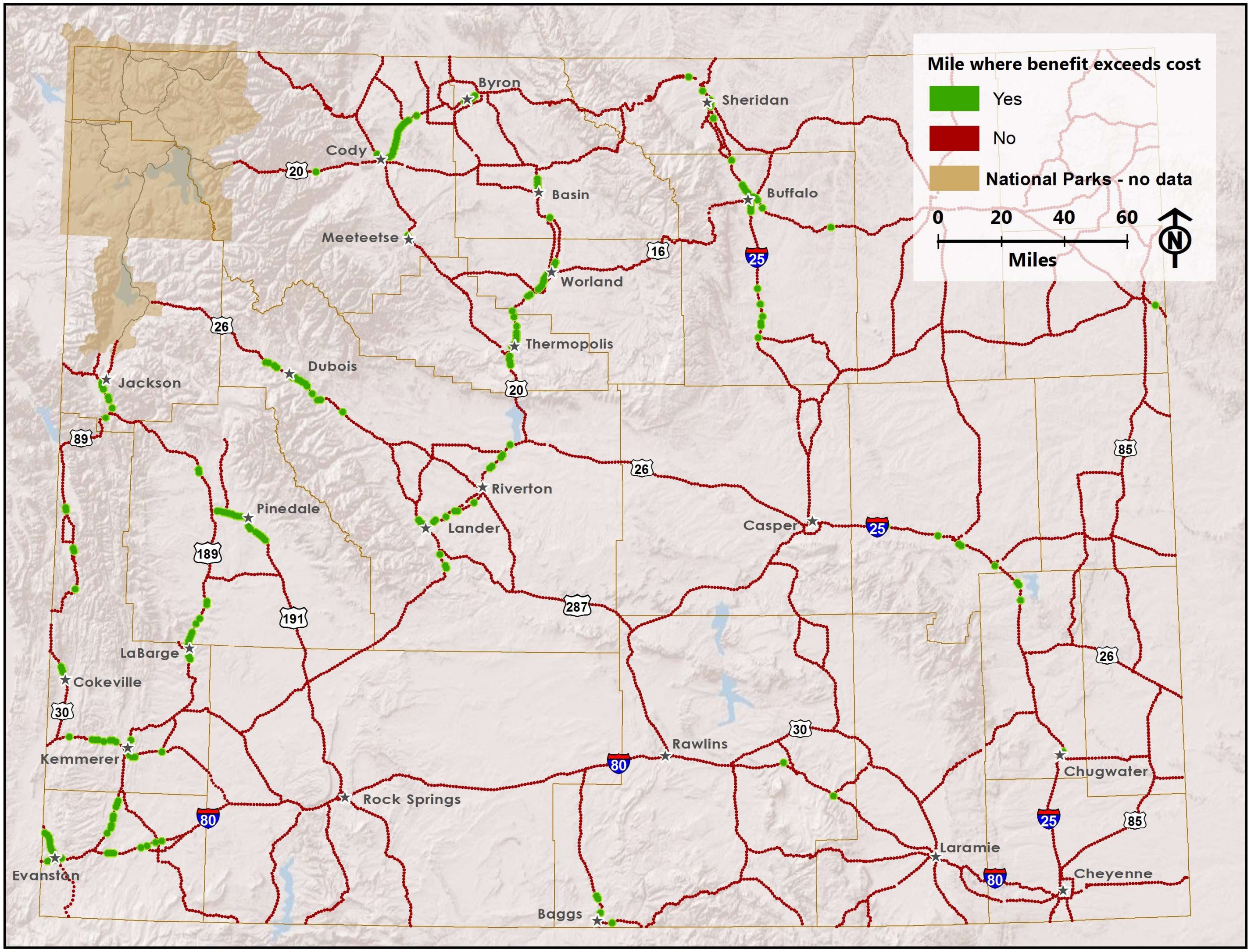
Wildlife warning reflectors (cost) versus saved deer value and injury & damage value (benefit) - Average efficacy




Source: Esri 2016, ArcGIS ArcMap 10.5, revised

**Figure 21. Cost-benefit map for wildlife warning reflectors, assuming average efficacy, with costs versus value of saved deer and avoided injuries and damage.**

Wildlife warning reflectors (cost) versus saved deer value and injury & damage value (benefit) - Low efficacy




Source: Esri 2016, ArcGIS ArcMap 10.5, revised

**Figure 22. Cost-benefit map for wildlife warning reflectors, assuming low efficacy, with costs versus value of saved deer and avoided injuries and damage.**

**Discussion**

For the three most expensive mitigations (fencing with underpasses, fencing with overpasses and underpasses, and fencing with gaps), the cost-benefit maps show that the total benefits exceed the cost for most places in Wyoming that we identified as deer-vehicle collision hotspots. In many of these places, the benefit in avoided injuries and damages alone, and even the benefit in avoided deer losses alone, also exceeds the cost of the mitigation.

For the three less expensive mitigations (dynamic message signs, variable speed limits, and reflectors), the benefits exceeded the costs for extensive portions of the state under the average effectiveness scenarios and for most deer-vehicle collision hotspots under the low effectiveness scenarios. Essentially, these mitigations are “worth it” as long as they are at least somewhat effective; however, given the high degree of uncertainty about their actual effectiveness, these measures should be considered experimental and monitored carefully for effectiveness if implemented.

Our cost-benefit analyses provide valuable tools to support decisions about what mitigations to consider using in different locations in Wyoming. These decisions should also include other considerations such as the number of wildlife-vehicle collisions occurring in different areas, the rate of these collisions per vehicle-mile traveled, and the degree to which a road creates a barrier to animal movements (see Chapter 3, this report).

## APPENDIX 1:TECHNOLOGY TRANSFER AND OUTREACH

The primary means of technology transfer and outreach has been through lead researcher Corinna Riginos' involvement with the Wyoming Wildlife and Roadways Summit and subsequently the Wyoming Wildlife and Roadways Initiative and its Implementation Team. The Summit was held in Pinedale, Wyoming, in April of 2017, and brought together 135 representatives of WYDOT, WGFD, numerous NGOs, legislators, and other interested parties. Riginos helped to plan and organize this Summit, and was one of the key speakers, sharing information contained in this report.

Following the Summit, the Wyoming Wildlife and Roadways Initiative was launched as a broader effort. Riginos was one of the main authors of an action plan emerging from the Summit entitled "The Road Map Forward" along with Daryl Lutz (WGFD) and Kenneth Keel (WYDOT).Following this, WGFD and WYDOT convened the Implementation Team for its initial meeting, in December 2017. This Implementation Team, of which Riginos is a member, has met monthly since then. The Implementation Team is working to develop comprehensive recommendations about top priority locations in Wyoming for crossing structures or other mitigations, and to take steps to begin raising funds for these projects. The findings presented in this report will play an important role in the decisions and public communications of the Implementation Team.

Other outreach activities during the course of this project include:

- Invited publictalk at the AMK Ranch Harlow Seminar Series, in Grand Teton National Park, ~100 members of the public, July 2016
- Conference talk at the Greater Yellowstone Ecosystem Biennial Science Conference, October, 2016
- Conference talk at the Wyoming chapter of The Wildlife Society, November 2016
- Presentation to Mule Deer Working Group and WYDOT partners, November 2016
- Invited public talk at the Jackson Hole Conservation Alliance, ~50 members of the public, March 2017
- Conference talk at the International Conference on Ecology and Transportation, May 2017
- Invited public presentation at the Buffalo Bill Center of the West, ~100 members of the public, October 2017
- Conference talk and poster at the Wyoming chapter of The Wildlife Society, December 2017

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