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EMERGING TECHNOLOGY TO EXCLUDE WILDLIFE FROM ROADS:

ELECTRIFIED PAVEMENT AND DEER GUARDS IN UTAH, USA

By

Joseph P. Flower

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Wildlife Ecology

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Logan, Utah

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ABSTRACT

Emerging Technology to Exclude Wildlife from Roads:
Electrified Pavement and Deer Guards in Utah, USA

by

Joseph P. Flower, Master of Science

Utah State University, 2016

Major Professor: Dr. Patricia C. Cramer
Department: Wildland Resources

Wildlife-vehicle collisions (WVCs) are a persistent problem that threaten public safety and can negatively affect wildlife populations. Wildlife crossing structures in combination with wildlife exclusion fencing can significantly reduce WVC rates. However, these measures can become ineffective if access roads that bisect fencing do not include barriers to deter animals from entering the highway. My objectives were to: 1) evaluate the relative effectiveness of barriers currently used to exclude mule deer (*Odocoileus hemionus*) from highways, and 2) determine whether cattle guards augmented with segments of electrified pavement could reduce wildlife intrusions through fence openings. Currently, transportation departments are seeking innovative methods to cost-effectively upgrade, augment, or replace cattle guards with barriers capable of reducing wildlife access to transportation infrastructure. In chapter 2, I evaluated the effectiveness of existing wildlife barriers at access roads in Utah. I placed camera traps at 14 vehicle access points in wildlife fencing equipped with one of five different barrier designs. Double cattle guards (two adjoining cattle guards) and wildlife guards (steel grates) were $\geq 80\%$ effective in excluding deer. In contrast, electrified mats (plastic planks with embedded electrodes), standard cattle guards, and cattle guards without excavations were $<12\%$, $<50\%$, and $<25\%$ effective for deer, respectively. In Chapter 3, I used camera traps to monitor wildlife intrusions into baited wildlife exclosures. Four exclosures had entrances treated with cattle guards augmented with segments of electrified pavement, and two exclosures were treated with cattle guards alone. Cattle guards augmented with segments of electrified pavement (0.91-m or 1.2-m-wide) were $>80\%$ effective in excluding deer and $>95\%$ effective in excluding elk (*Cervus canadensis*) from wildlife exclosures constructed in a natural area. However, when installed in the road surface in front of an existing cattle guard, a segment of electrified pavement (0.91-m-wide) was 54% effective in preventing deer intrusions into the fenced highway corridor. Electrified pavement appears to have potential as an effective tool to reduce ungulate access to roadways and other protected areas. However, to fully assess the viability of this emerging technology for use in excluding wildlife from highways, results from ongoing long-term monitoring at replicated in-road installations are needed.

(144 pages)

PUBLIC ABSTRACT

Emerging Technology to Exclude Wildlife from Roads:
Electrified Pavement and Deer Guards in Utah, USA

Joseph P. Flower

Vehicle collisions with large wild animals threaten public safety, can harm wildlife populations, and often result in substantial property damage. The most effective way to reduce these collisions is to install wildlife fencing along the roadway and provide structures that enable wildlife to cross roads safely. However, if access roads that bisect fencing do not include barriers to deter animals from entering the highway, these measures can become ineffective. The purpose of my research was to: 1) evaluate the effectiveness of barriers currently used to exclude wildlife from highways, and 2) determine whether cattle guards augmented with segments of electrified pavement could reduce wildlife intrusions through fence openings. Transportation departments are currently seeking cost-effective ways to reduce wildlife access to roads. In chapter 2, I used cameras to evaluate wildlife barriers at access roads along highways in Utah. Of the five barrier designs monitored, two designs consistently prevented mule deer from accessing highways. In chapter 3, I tested cattle guards treated with electrified pavement. I used cameras to monitor wildlife entries into fenced areas and found cattle guards treated with electrified pavement reliably deterred mule deer and elk. However, when tested on the road, a cattle guard treated with electrified pavement had mixed results. Electrified pavement appears to have potential to reduce wildlife access to roadways, but results from long-term monitoring at multiple in-road sites are needed.

DEDICATION

This thesis is dedicated to my family, who supported me throughout the journey. In particular, I thank my wife, Laurén, for showing me what strength looks like. I also thank my father, Richard. We all stand upon his shoulders and reach for our dreams.

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Joseph P. Flower

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CHAPTER I

INTRODUCTION

Modern road networks facilitate the efficient movement of goods and people, enable unprecedented social connectivity, and are central to economic prosperity (Forman et. al 2003, U.S. National Economic Council 2014). The road network in the United States continues to expand and currently encompasses >4.1 million miles of public roads, with >2.9 million miles of those in rural areas (U.S. Department of Transportation [U.S. DOT] 2013). Concurrent with this expansion, traffic volume on America's highways has increased by ~2.0% annually and more than tripled over the 40-year period from 1967 to 2007 (U.S. DOT 2013).

While expanding road networks enhance connections among human populations, they often reduce connectivity among wildlife populations, sever remaining natural habitats, and cause myriad ecological effects (Roedenbeck et al. 2007, Forman and Alexander 1998). For example, roads cover >1% of the total land surface of the contiguous U.S., but affect ≥20% of the land area ecologically (Forman 2000). The ecological effects of roads are diverse and include both indirect and direct effects (Bissonette 2002). Roads indirectly affect ecological systems by reducing habitat availability and quality in areas adjacent to roads, and by increasing landscape fragmentation and edge habitat (Bissonette 2002). Perhaps most importantly, roads often act as barriers to animal movement (Beckman et al. 2010). For example, roads can limit access to habitat and mates and may result in reduced survival and breeding opportunities for wildlife (Forman et al. 2003). When roads obstruct movement between isolated wildlife populations with few individuals, rapid declines in genetic diversity can occur

(Epps et al. 2005, Holderegger and Di Giulio 2010). Roads also directly affect living systems; most notably through road mortality as a result of wildlife-vehicle collisions (WVCs, Bissonette 2002).

With >1 million vertebrates killed each day on America's highways, WVCs are a chronic problem that can threaten the persistence of wildlife populations (Foreman and Alexander 1998). For example, road mortality due to WVCs can be devastating to populations of large-bodied, wide-ranging mammals with low reproductive rates (Rytwinski and Fahrig 2015), or to small or declining wildlife populations (Bennett 1991). Further, road mortality has been identified as a major threat to the survival of 21 federally listed threatened or endangered animal species in the U.S. alone (Huijser et al. 2008). However, road mortality alone does not appear to drive population level declines for some species with high reproductive rates (e.g., most deer [*Odocoileus* sp.] species, Olson 2013).

Vehicle collisions with large wild animals are an increasing problem that threaten public safety and cause substantial economic losses (Hedlund et al. 2004, Fahrig and Rytwinski 2009). In the U.S. alone, an estimated 1 to 2 million collisions with large animals occur annually (Conover 2001). The majority of these collisions involve deer, with deer-vehicle collisions accounting for ≥90% of all WVCs in some U.S. states (Huijser et al. 2008). Moreover, as much as 10% of WVCs result in injuries to drivers and their passengers (Huijser et al. 2008). For example, WVCs cause approximately 29,000 human injuries and 200 human deaths in the U.S. each year (Conover et al. 1995, Huijser et al. 2009). In 2013, 191 people were killed as a result of collisions with animals nationwide (Insurance Institute for Highway Safety 2013). When the collective costs due to vehicle damage, human injuries and fatalities, and loss of animal value are combined, the total economic toll imposed by WVCs in the U.S. exceeds US$8 billion annually (Huijser et al. 2008).

When placed in conjunction with wildlife crossing structures, wildlife exclusion fencing (2.4-m-high) is the most effective method to reduce vehicle collisions with large fauna (Hedlund et al. 2004). Wildlife fencing prevents wildlife access to the roadway and guides animals to crossing structures that facilitate safe passage under or above the road. Bissonette and Cramer (2008) define wildlife crossing structures as any type of structure that was designed or retrofitted specifically to provide wildlife safe passage over or under a roadway or railroad. The main objectives of these structures are to: 1) connect habitats and wildlife populations by providing safe passage for wildlife, 2) increase motorist safety, and 3) reduce wildlife mortality due to WVCs (Beckman et al. 2010). When combined, crossing structures and fencing can reduce collisions with large animals by >85% and are the only widely accepted method to effectively reduce collisions with large fauna (Huijser et al. 2009, Hedlund et al. 2004).

Management of wildlife intrusions at access roads that bisect wildlife fencing is critical to ensure the success of integrated fence-wildlife crossing structure systems (Peterson et al. 2003, Sawyer et al. 2012). For example, if access roads that bisect fencing are not designed with an effective deterrent to exclude ungulates and other wildlife from the road, wildlife crossings and fencing can become ineffective (Peterson et al. 2003, Sawyer et al. 2012, van der Ree et al. 2015). While gates are the best method to exclude large animals from designed openings in wildlife fencing (van der Ree et al. 2015), they can be inconvenient to keep closed and are often left open, permitting unfettered animal access to protected areas (Butchko 2005, West et al. 2007, VerCauteren et al. 2009). Further, the use of gates is impractical on lateral access roads with moderate to high vehicle traffic volumes (van der Ree et al. 2015).

Standard cattle guards (1.8-m to 2.1-m-wide in dimension parallel to vehicle travel) are ubiquitous in the Western U.S. and are common at designed breaks in wildlife exclusion fencing. While cattle guards are generally effective at preventing hoofed livestock from accessing highways, they are largely ineffective as barriers to deer – the species that account for the vast majority of WVCs in the U.S. (Reed et al. 1974, Ward 1982, Huijser et al. 2008, Sawyer et al. 2012). Currently, there is a critical need to upgrade, augment, or replace standard cattle guards with deterrents capable of preventing wildlife – especially deer – from entering fenced highway corridors and other protected areas (Cramer 2012, R. Taylor, Utah Department of Transportation [UDOT], personal communication).

Alternative barriers designed to mitigate openings in fencing specifically for wildlife include double cattle guards (two adjoining standard cattle guards), wildlife guards (steel grates), and electrified mats (composite planks with embedded electrodes). Although previous studies have assessed the effectiveness of some of these or similar designs as barriers to wildlife (U.S. Army 2006, Seamans and Helon 2008, Allen et al. 2013, Siepel et al. 2013), efficacy estimates were derived using widely varying methods, rigor, and sample sizes. Further, depending upon road width, wildlife-specific barriers carry significant costs of $30,000 to $60,000 per application and may become cost-prohibitive when considered across multiple locations (R. Taylor, UDOT, personal communication). For example, transportation departments must spend ~$240,000 to mitigate a single highway interchange with four double cattle guards placed at vehicle entrance and exit ramps (R. Taylor, UDOT, personal communication). Despite the expense and essential role of integrated fence-wildlife crossing mitigation, no study has used consistent methods to directly compare the in-road effectiveness of these barriers for mule deer (*O. hemionus*) across large spatial extents with multiple populations of the target species.

In late 2013, this study was initiated as a joint effort between Utah State University (USU), UDOT, and the Utah Transportation Center at USU. Overall, our aim was to find innovative solutions to reduce wildlife access to fenced highway corridors. Our first objective was to evaluate the relative effectiveness of five different animal barrier designs currently used to control mule deer intrusions through fence openings in Utah. Our second objective was to evaluate whether standard cattle guards augmented with segments of electrified pavement could reduce mule deer and elk (*Cervus canadensis)* intrusions to highway corridors at rates comparable to wildlife-specific barriers, but at reduced cost. Overall, our goals were to: 1) support WVC reduction efforts by determining best management practices in mitigating designed openings in wildlife exclusion fencing, and 2) evaluate a cost-effective retrofit to standard cattle guards that could reduce wildlife intrusions to roads at rates comparable to wildlife-specific barriers.

For decades, researchers have found mixed success with alternative methods to exclude wildlife from designed openings in wildlife fencing (VerCauteren et al. 2009). Under controlled conditions, Reed et al. (1974) found little success with experimental cattle guards constructed of flat mill steel, with 16 of 18 mule deer crossing the guard when released in front of it. Belant et al. (1998*a*) designed a 4.6-m-wide simulated cattle guard with round bars that reduced white-tailed deer (*O. viginianus*) intrusions through openings in chain-link fencing by ≥88% when compared with pre-treatment crossing rates. Silvy and Sebesta (2000) developed a convex-shaped prototype deer guard that was 100% effective with wild-trapped Texas white-tailed deer (*O. v. tenanus*) under experimental conditions. Peterson et al. (2003) tested 3 types of bridge grating and found one design 99% effective at excluding Florida Key deer (*O. v. clavium)* from baited wildlife exclosures. However, in a subsequent field test along the roadway, the guard developed by Peterson et al. (2003) was breached by six deer, although the number of crossing attempts was unknown (Braden et al. 2005). VerCauteren et al. (2009) evaluated an experimental guard with rolling bars that reduced white-tailed deer entries into baited wildlife exclosures, but lost effectiveness over time as deer learned to jump or walk across. Seamans and Helon (2008) tested an electrified mat that was 95% effective at reducing white-tailed deer intrusions into baited wildlife exclosures, although some deer jumped over the mat. However, in a subsequent field test of four electrified mats embedded in asphalt at vehicle access points in wildlife fencing, Siepel et al. (2013) documented mule deer crossing in 54 out of 63 events (85.7% crossing rate). While Siepel et al. (2013) found electrified mats deterred a black bear (*Ursus americanus*) from entering the road corridor, the authors suggested the design should be modified to more effectively exclude deer. Further, Allen et al. (2013) evaluated two wildlife guards (steel grates) deployed along U.S. Highway 93 in Montana, USA. The wildlife guards in the study were >85% effective for mule deer, but less effective for black bears and coyotes (*Canis latrans*, 33% and 55%, respectively).

An alternative approach to enhance the effectiveness of traditional cattle guards for wildlife may be to augment existing guards with an additional deterrent device. However, deterrent devices designed to simply frighten deer are not effective over extended periods because deer habituate to them (Bombford and O’Brien 1990, Hygnstrom et al. 1994, Curtis 1997, Belant et al. 1998*b*, Belant et al. 1998*c*, Beringer et al. 2003). Habituation to these passive devices is likely because animals never receive a negative re-enforcement (J. Berger, Colorado State University, personal communication). For example, deer may respond to a passive deterrent by becoming more alert and may spend less time in an area, but it is likely that animals will continue to occupy an area of established use (Curtis 1997). Current deer deterrence research indicates that without a credible threat or some aspect of pain (e.g., electric shock) deer will not alter established usage or movement patterns (T. Seamans, United States Department of Agriculture [USDA], personal communication).

Electricity may offer the most feasible mode of action to deliver a negative reinforcement to animals that attempt to breach animal barriers. For example, electrified mats were effective in a controlled setting and reduced white-tailed deer intrusions into baited exclosures by as much as 95% (Seamans and Helon 2008). Moreover, Seamans and Helon (2008) suggested that deer could sense electricity and avoided the mats rather than attempting to cross them. Although results from subsequent monitoring of electrified mats on roadways appear mixed (Siepel et al. 2013), the avoidance response observed by Seamans and Helon (2008) indicates that augmenting an existing barrier with an electrical deterrent may minimize the frequency of deer breaching cattle guards.

Utah is a topographically and ecologically diverse state at the nexus of three ecoregions: Colorado Plateau, Central Basin and Range, and the Wasatch and Uinta Mountains (Omernik 1987). Mule deer are the most abundant big game animal in the state, with ~355,000 individuals in the post hunting season 2014 population (Utah Division on Wildlife Resources [UDWR] 2015*a*). Despite fluctuations in abundance driven primarily by severe winters, the mule deer population in Utah has increased on average by ~1.5% annually since 1992 and is currently at its highest level in >20 years (UDWR 2013). Concurrent with increased deer abundance, Utah's human population has grown rapidly, adding >179,000 people from 2010 to 2014 – a 6.5% increase, nearly double the rate of increase in the U.S. population over the same period (3.3%; U.S. Census Bureau 2014). Utah is the 4th fastest growing state in the U.S. (U.S. Census Bureau 2014) and the number of licensed drivers has increased from 1.6 million individuals in 2004 to >2 million individuals in 2013 (UDOT 2013). As a result of more drivers on Utah's roads, vehicle traffic has increased in the state. For example, from 2004 to 2013, vehicle miles traveled in Utah increased by >2 billion miles (24.6 billion to 26.7 billion, UDOT 2013). Utah's public road system includes ~9,440 km (~5,866 miles) of state routes and ~56,700 km (~35,222 miles) of city and county roads (UDOT 2013). Collectively, a network of >73,800 km (>45,880 miles) of public roads span the state (UDOT 2013).

In Utah, deer-vehicle collisions (DVCs) are common, pose serious safety risks to the motoring public, and cause significant economic losses (Romin and Bissonette 1996). For example, 5,582 mule deer carcasses were recorded along Utah's roads in 2014 (UDWR 2015*b*). Though substantial, this figure likely represents only a fraction of the total deer killed in collisions as many animals hit by vehicles wander off the road before dying and are never recorded (Romin and Bissonette 1996). For example, Olson (2013) compared the number of reported wildlife-vehicle accidents with data gathered from wildlife carcass surveys along Utah's highways and found that carcass totals were 526% higher than reported accident totals. Moreover, while he found little effect of DVCs on the long-term population trajectory of mule deer in the state, Olson (2013) estimated that >9,500 mule deer were killed on Utah's roads during the 1-year period from 2010-2011. Bissonette et al. (2008) estimated that the economic value of an average deer in Utah was \$236 in 2001 (\$317 after Consumer Price Index [CPI] adjustment to 2015 dollars). In contrast, the State of Utah requires minimum restitution payments of \$400 for each "non-trophy" deer and \$8,000 for each "trophy" deer illegally harvested in the state (Utah Legislature 1992). However, the value of road killed deer is dwarfed when compared with the combined costs due to property damage, human injury, and human death that can result from DVCs. For example, the overall cost for 13,020 DVCs over a 5-year period (1996-2001) in Utah was >\$45 million, with a mean annual cost of ~\$7.5 million (Bissonette et al. 2008). With the average cost of a single DVC ranging from \$3,834 (Bissonette et al. 2008, CPI adjustment to 2015 dollars) to \$7,593 (Hiujser et al. 2009, CPI adjustment to 2015 dollars), the collective toll of these collisions represents a significant economic burden to the State of Utah and its citizens.

The objective of the second chapter of my thesis was to evaluate the relative effectiveness of five different barrier designs currently used to exclude mule deer from highways in Utah. We used camera traps to monitor wildlife approaches at 14 animal barriers and used generalized linear models to examine explanatory variables associated with events in which deer crossed over the barriers. In our model, we included the categorical predictor of barrier design and the continuous predictors of: 1) number of days that each barrier was monitored by our cameras, 2) traffic volume on the highway adjacent to the barrier, and 3) distance to the nearest safe passage that deer could use to cross beneath the roadway. I hypothesized that the design of the barrier would be the most important predictor of whether deer crossed it and I predicted that the likelihood of deer crossing would be unequal among the five barrier designs.

The objective of chapter 3 was to evaluate whether a standard cattle guard augmented with electrified pavement could reduce mule deer and elk intrusions at rates comparable to wildlife-specific barriers, but at reduced cost. To test cattle guards augmented with electrified pavement, I used a two-part approach that included: 1) a manipulative experiment using augmented cattle guards deployed at entrances to baited wildlife exclosures, and 2) an *in situ* road trial using an existing cattle guard augmented with electrified pavement. We used camera traps to monitor wildlife approaches to the experimental barriers and used generalized linear models to examine predictors of deer crossing. In our model, we used the categorical explanatory variables of treatment level, experimental block, and whether snow was present on the surface of the barrier. We also included the continuous explanatory variable of the number of days that our cameras monitored the barriers. I hypothesized that mule deer and elk would be less likely to breach cattle guards augmented with electrified pavement when compared with untreated cattle guards.

My thesis is written in multiple-paper format. I prepared all chapters according to current style and formatting guidelines used by the Wildlife Society Bulletin.

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CHAPTER II

EVALUATION OF MULE DEER BARRIERS AT ACCESS ROADS IN UTAH, USA

ABSTRACT Vehicle collisions with large animals are an increasing problem that threaten public safety, cause substantial economic loss, and can negatively affect wildlife populations. When placed in conjunction with wildlife crossing structures, wildlife exclusion fencing (2.4-m-high) is the most effective method to reduce vehicle collisions with large ungulates. However, access roads that bisect wildlife fencing must permit continuous vehicle traffic, yet inhibit wildlife from entering the road right-of-way. My objectives were to: 1) evaluate the relative effectiveness of five different animal barrier designs used to control mule deer (*Odocoileus hemionus*) intrusions through fence openings at access roads in Utah, and 2) examine explanatory variables associated with events in which deer crossed the barriers. Double cattle guards (two adjoining cattle guards) and wildlife guards (steel grates) were ≥80% effective at excluding mule deer from fenced highway corridors. In contrast, electric mats (composite boards with embedded electrodes), standard cattle guards, and cattle guards without excavations were <12%, <50%, and <25% for mule deer, respectively. Results from generalized linear models indicated the design of the barrier was the most important predictor of whether mule deer crossed over them. Although double cattle guards and wildlife guards did not entirely eliminate deer access to roadways, both designs were significant obstacles to mule deer and consistently prevented intrusions through designed openings in wildlife fencing for this species.

Vehicle collisions with large animals are an increasing problem that threaten public safety, cause substantial economic loss, and can negatively affect wildlife populations (Hedlund et al. 2004, Fahrig and Rytwinski 2009). In the U.S. alone, an estimated 1 to 2 million vehicle collisions with large wild animals occur annually, resulting in approximately 29,000 human injuries and 200 human deaths *(*Conover et al. 1995, Huijser et al. 2009*)*. When the collective costs due to vehicle damage, human injuries and fatalities, and loss of animal value are combined, the total economic toll imposed by wildlife-vehicle collisions (WVCs) in the U.S. exceeds US$8 billion annually (Huijser et al. 2008). The majority of WVCs involve deer (*Odocoileus* sp.), with deer-vehicle collisions accounting for ≥90% of all WVCs in some U.S. states (Huijser et al. 2008).

In Utah, deer-vehicle collisions (DVCs) are common, pose serious safety risks to the motoring public, and cause significant economic losses (Romin and Bissonette 1996). In 2014 alone, 5,582 mule deer carcasses were recorded along roadways in Utah (Utah Department of Wildlife Resources [UDWR] 2015). Though substantial, this figure likely represents only a fraction of the total deer killed in collisions as many animals hit by vehicles wander off the road before dying and are thus never recorded (Romin and Bissonette 1996). For example, although he found little effect of DVCs on the long term trajectory of the mule deer population in the state, Olson (2013) estimated that >9,500 mule deer were killed on Utah’s roads during the 1-year period from 2010-2011. With the average cost of a single deer-vehicle collision ranging from $3,834 (Bissonette et al. 2008, Consumer Price Index [CPI] adjustment to 2015 dollars) to $7,593 (Hiujser et al. 2009, CPI adjustment to 2015 dollars), the collective toll of these collisions represents a significant economic burden to the State of Utah and its citizens.

When placed in conjunction with wildlife crossing structures, wildlife exclusion fencing (2.4-m-high) is the most effective method to reduce vehicle collisions with large ungulates (Hedlund et al. 2004). Wildlife fencing prevents wildlife access to the roadway and guides animals to crossing structures that facilitate animal passage under or above the road. Bissonette and Cramer (2008) define wildlife crossing structures as any type of structure that was designed, built, or retrofitted specifically to provide wildlife safe passage over or under a roadway. The main objectives of these structures are to: 1) connect habitats and wildlife populations by providing safe passage for wildlife, 2) increase motorist safety, and 3) reduce wildlife mortality due to WVCs (Beckman et al. 2010). When combined, crossing structures and fencing can reduce collisions with large animals by >85% and are the only widely accepted method to effectively reduce WVCs involving large fauna (Hedlund et al. 2004, Huijser et al. 2009).

Management of wildlife intrusions at access roads that bisect wildlife fencing is critical to ensure the success of integrated fence-wildlife crossing structure systems (Peterson et al. 2003, Sawyer et al. 2012). While gates are the most effective method to exclude large fauna from designed openings in wildlife fencing, their use is impractical on lateral access roads with moderate to high vehicle traffic volume (van der Ree et al. 2015). To accommodate vehicle access, but deter livestock, standard cattle guards are commonly used at access roads that bisect fencing adjacent to highways in Utah. Although standard cattle guards are likely ineffective deer barriers (Reed et al. 1974, Ward 1982), they are ubiquitous in the Western U.S. and are commonly integrated with roadside wildlife exclusion fencing.

Alternative barriers currently used to mitigate fence gaps for wildlife along Utah's roadways include double cattle guards (two adjoining standard cattle guards), wildlife guards (steel grates), and electrified mats (composite planks with embedded electrodes). While previous studies have assessed the effectiveness of some of these, or similar designs as barriers to wildlife (U.S. Army 2006, Seamans and Helon 2008, Siepel et al. 2013, Allen et al. 2013), efficacy estimates were derived using widely varying methods, rigor, and sample sizes. Further, wildlife-specific barriers carry significant costs of $30,000 to $60,000 per application (R. Taylor, Utah Department of Transportation [UDOT], personal communication) and may be cost-prohibitive when considered across multiple locations. For example, transportation departments must spend ~$240,000 to mitigate a single highway interchange with four double cattle guards (two on-ramps and two off-ramps, R. Taylor, UDOT, personal communication). Despite their expense and essential role in the function of integrated fence-wildlife crossing mitigation, no study has directly compared the effectiveness of these wildlife-specific barriers as impediments to mule deer movement *in situ* on roadways using consistent methods.

In this field study, my objective was to evaluate the relative effectiveness of five different barrier designs currently used to exclude mule deer from highways in Utah. We used motion activated wildlife cameras to evaluate the effectiveness of the following designs as barriers to mule deer: 1) cattle guards without excavations, 2) standard cattle guards suspended over excavations, 3) double cattle guards, 4) wildlife guards, and 5) electrified mats. We used generalized linear models to examine explanatory variables associated with events in which mule deer crossed over the barriers and gained access to the fenced highway corridor. Overall, our goal was to support WVC reduction efforts by determining best management practices for mitigating designed openings in wildlife exclusion fencing for mule deer.

STUDY AREA

Our study area spans three distinct regions across the State of Utah and includes segments of four major highways: U.S. Highway 91 (Northern Utah), U.S. Highway 6 (Central Utah), and U.S. Highway 89 and Interstate 15 (Southern Utah, Fig. 1). Utah is a topographically and ecologically diverse state at the nexus of three distinct ecoregions: Colorado Plateau, Central Basin and Range, and the Wasatch and Uinta Mountains (Omernik 1987). Accordingly, the topography and biotic communities adjacent to the studied highway segments are heterogeneous and include mountainous areas with high elevation mixed forest (U.S. 91), semi-urban areas interspersed with agricultural fields and sagebrush steppe (U.S. 6), and mixed, sagebrush steppe-pinyon-juniper woodlands (U.S. 89/Interstate 15). Further, annual average daily traffic (AADT) volumes on the studied highway segments vary widely, ranging from 1,850 vehicles per day on U.S. 89, to 21,735 vehicles per day on Interstate 15 (UDOT 2013, Table 1). All barriers are located on lateral access roads that bisect continuous, 2.4-m-high wildlife exclusion fencing constructed on both sides of roadways that range from 2-lane roads to 4-lane interstate highways. Additional wildlife mitigation measures present along the highways include elliptical corrugated metal wildlife underpasses, multipurpose structures (existing culverts and bridges not specifically designed for wildlife), one-way gates in wildlife fencing, and jump-outs (earthen escape ramps that allow animals trapped in the fenced road corridor to escape to safety; see Bissonette and Hammer 2000 for details).

METHODS

Site Selection and Camera Deployment

To determine the effectiveness of the five barrier designs as barriers to mule deer movement, we installed motion activated wildlife cameras (RECONYX Model PC85 or PC800; Holmen, WI) at 14 vehicle access points in wildlife fencing equipped with either cattle guards without excavations (*n*=2), standard cattle guards (*n*=4), double cattle guards (*n*=4), wildlife guards (*n*=2), or electrified mats (*n*=2) in the fall of 2013 (Figs. 2 – 6). We selected monitoring locations in consultation with UDOT personnel and with UDWR biologists familiar with each area. Site selection criteria included: 1) the presence of wildlife exclusion fencing (2.4-m-high) in good condition paired with barriers, 2) similar dimension and condition of barriers within the same design category, and 3) documented wildlife-vehicle collisions on the highway segments adjacent to each barrier.

At each site, we deployed one motion activated wildlife camera on the highway entry side of each barrier to continuously monitor wildlife approaches. We mounted cameras within steel utility boxes to deter theft (Fig. 7 and Fig. 8). With the exception of one camera that was in place prior to the study, all cameras were deployed beginning in September 2013 and most were maintained continuously until late April 2015 (Table 1). We visited monitoring locations on a monthly basis to download images, replace batteries, and ensure proper camera function. We programmed cameras to take 1 to 5 images as fast as possible for each motion trigger. To prevent rapid power loss from repeated vehicle detections, we programmed most cameras to detect motion only during crepuscular and nighttime periods when wildlife were most active.

We used two different camera models in this study (RECONYX Model PC85 or Model PC800; Holmen, WI). Although motion sensing and image quality are nearly identical between the two models, nighttime range differs by ~6-m (15-m [PC85] vs. 21-m [PC800], J. Thinner, RECONYX, personal communication). To test for potential functional differences between the camera models, we exchanged a PC85 model with a PC800 model mid-way through monitoring at one location and found no substantive difference in detection rate or image quality between the two models.

Image Analysis

I examined photographs of animal approaches to the barriers and tabulated data gathered from images in a custom database (Access 2013, Microsoft Corporation, Redmond, WA, USA). A single observer analyzed all images to ensure consistency and limit observer bias. Each record in the database was comprised of an independent event in which one or more animals approached within 2-m of the deterrent. I did not tabulate images of animals that were recorded more than 2-m distant from the barriers, because I did not consider those movements indicative of barrier effectiveness (Allen et al. 2013). Groups of animals that were traveling together or that were present within the same 15-minute interval were treated as a single independent event because movements of individuals within the same group were likely interdependent (Allen et al. 2013, Schwender 2013). For each event, I considered the outcome either a success (no animals in the event breached the barrier) or a failure (at least one animal in the event breached the barrier). The total number of individuals recorded within 2-m of the barrier and the total number of individuals that breached the barrier were also entered for each event. Each individual animal in the event was classified as either: moving parallel to the barrier, repelling from the barrier, or crossing the barrier. Events were classified as including crossing behavior when one or more animals in the event displayed behavior that appeared to indicate an intent to cross the barrier. Qualifying behavior included, but was not limited to: pawing at or stepping on the barrier, stalling at the fence opening, or by animals that placed their nose to the ground in front of, or on, the barrier (Allen et al. 2013). Events were classified as a crossing (failure) when one or more animals completely breached the barrier and gained access to the highway right-of-way (ROW). Where possible, I recorded the method used by each animal to breach the barrier (e.g. jumped, walked, breached at the barrier edge, or unknown).

To examine explanatory variables associated with events in which mule deer crossed the barriers, I also recorded: 1) the annual average daily traffic (AADT) on the highway adjacent to the lateral access road, 2) number of days that each barrier was monitored by our cameras, and 3) the distance (in road miles) to the nearest safe passage deer could use to cross the highway (wildlife crossing structure or multipurpose structure).

Barrier Effectiveness Estimation

I estimated the effectiveness of each of the five barrier designs as an obstacle to deer movement by addressing the following research questions. First, how effective were the barriers as an obstacle to deer that approached them? I answered this question by calculating a distance-based crossing rate; defined as the percentage of events that resulted in crossing compared with the total number of events in which animals approached within 2-m of the barrier (Allen et al. 2013). Because not all of the animals that approached the barriers may have intended to cross them, I also selected a subset of the approach events in which animals displayed behavior to cross the barriers (e.g., by pawing at or stepping on the barrier, stalling at the fence opening, or by animals that placed their nose to the ground in front of, or on, the barrier) and posed a second research question: how effective were the barriers as an obstacle to animals that display behavior to cross them? I answered this question by calculating a behavior-based crossing rate; defined as the percentage of events that resulted in crossing compared with the total number of events in which deer displayed behavioral cues I interpreted as intent to cross the barrier (Allen et al. 2013).

I calculated both a distance-based and a behavior-based crossing rate because, as noted by Allen et al. (2013), each metric had benefits and limitations. For example, while the distance metric had the benefit of being an objective measurement based on distance alone, it may lead to overestimates of barrier effectiveness because not all animals that approached within 2-m of the barriers may have intended to cross them. In contrast, although the behavioral metric avoided possible overestimation of barrier efficacy, it relied on potentially subjective interpretation of animal behavior by the observer.

In addition to calculating the percentage of independent *events* that resulted in crossing, I also considered the total number of *individual animal approaches* within 2-m of the barriers and the total number of those approaches that resulted in crossing. However, I did not base inference of barrier effectiveness on these metrics for the following reasons: 1) there was evidence from image analysis that movement and behavior among individuals was interdependent, 2) because I could not reliably distinguish between individuals, it was often difficult to reliably estimate the total number of individuals that approached the barriers, and 3) inability to distinguish between individuals likely led to overcounting individuals, which led to overestimates of the total number of individual approaches and resulted in efficacy metrics that were biased high.

My null hypothesis was that the likelihood of mule deer crossing over a barrier would be equal among the five barrier designs. That is, no significant difference in barrier effectiveness would exist among the five designs. My alternative hypothesis was that the likelihood of deer crossing over a barrier would differ among the five designs. That is, at least one significant difference in barrier effectiveness would exist among the five designs. To test these hypotheses, and to examine explanatory variables associated with crossing events, we used generalized linear models to perform logistic regression analyses.

Statistical Model

We used generalized linear models with binomial distributions and logit-links to examine explanatory variables associated with crossing events, defined as an event in which one or more deer breached the barrier and gained access to the fenced highway corridor. We performed all analyses using the GENMOD procedure in SAS (Version 9.4; SAS Institute Inc., Cary, NC, USA) and cross-validated model output with model results from R (Version 3.1.1; The R Foundation for Statistical Computing, Vienna, Austria). The response variable was the binary outcome of each event and was assigned as either success (0 = no deer in the event breached the barrier) or failure (1= at least one deer in the event breached the barrier). We used a binary response variable rather than considering the proportion of individuals that breached the barrier out of the total number of individuals that approached the barrier, because it was often difficult to reliably estimate the total number of individuals involved in an event and movement and behavior among individuals was not independent. We used the categorical explanatory variable of barrier design and the continuous explanatory variables of: 1) AADT on the highway segment adjacent to the access road, 2) number of days that our cameras monitored each barrier, and 3) distance (in road miles) to the nearest safe passage that mule deer could use to cross beneath the roadway (wildlife crossing structure or multipurpose structure, Table 2.)

For the logistic regression model, we only considered events that included potential crossing behavior, where one or more deer in the event displayed behavior interpreted as intent to cross the barrier. Events that lacked crossing behavior were defined as events in which animals passed within 2-m of the barrier, but did not display behavior that indicated an intent to cross the barrier. Because these “parallel” movements may not have been directly indicative of deterrent effectiveness, we omitted them from the model (Schwender 2013).

Similarly, we omitted events from the model in which deer breached the barriers when they were snow-covered. Snow coverage negatively affected barrier effectiveness and was a source of variation unequally distributed across the monitoring locations. Omitting these events ensured that only events that were directly indicative of barrier effectiveness were considered in the model.

RESULTS

Effectiveness of Mule Deer Barriers

Across all monitoring locations, I recorded 989 independent events in which mule deer approached within 2-m of the barriers. Of these, 359 (36.3%) independent events were classified as a crossing event, in which one or more deer breached the barrier and gained access to the fenced highway corridor. I was unable to determine whether deer crossed, or did not cross, in 109 (11%) of the 989 events. I incorporated uncertainty from these inconclusive events into an estimate of the upper and lower range of effectiveness for each barrier design. I calculated the lower effectiveness estimate by assuming that all of the inconclusive events resulted in crossing. For the upper estimate, I assumed that none of the inconclusive events resulted in crossing (Table 3).

At cattle guards without excavations, I observed 271 independent events in which deer approached the barriers and 182 (67.2%) events resulted in crossing. Eighty-eight independent events occurred at standard cattle guards suspended over excavations and deer crossed in 48.9% of events. At double cattle guards 9.8% of independent events resulted in crossing. Similarly, 16.3% of events resulted in deer crossing over wildlife guards. In contrast, mule deer crossed electrified mats in 78.8% of events (Table 3).

I then considered only events in which mule deer displayed behavioral cues to cross the barriers, which was a subset of the number of independent approach events. Across all monitoring locations, I recorded 764 independent events in which mule deer approached within 2-m of the barriers and displayed behavioral cues to cross them. Of these, 292 (38.2%) events resulted in crossing and 71 events were inconclusive. Most of the events in which deer displayed behavioral cues to cross cattle guards without excavations, standard cattle guards, or electric mats resulted in crossing (rates of 76.5%, 51.8%, and 88.2%, respectively). In contrast, 13.4% and 19% of events resulted in crossing at double cattle guards and wildlife guards, respectively (Table 4).

In addition to considering the proportion of independent *events* that resulted in crossing, I also considered the total number of *individual* deer approaches within 2-m of the barriers and the total number of those approaches that resulted in crossing. Of the 1,946 individual deer approaches observed across all monitoring locations, 581 (29.9%) deer breached the barriers and gained access to the fenced highway corridor. I observed the greatest total number of deer crossings over cattle guards without excavations (288 crossings) and over electrified mats (143 crossings). At double cattle guards, 5.9% of the deer that approached the barriers crossed over them. Similarly, 12.6% of the deer that approached wildlife guards crossed. However, I did not base inference of barrier effectiveness on these metrics because there was evidence from photographs that behavior among individual deer was not independent. Further, I could not reliably distinguish among individuals during image analysis. As a result, over counting of the total number of individual deer in some events likely led to overestimates of barrier effectiveness (Table 5).

Mule Deer Crossing Methods

Most of the mule deer that breached the barriers did so by either jumping, walking across, or by crossing at the edge of the barrier, where adjacent wildlife exclusion fencing formed a junction with the barrier. Of the 288 mule deer breaches recorded at cattle guards without excavations, 186 (64.5%) crossed by jumping over. Similarly, at standard cattle guards suspended over excavations, 41.3% of deer jumped across. However, nearly

25% of recorded deer breaches at standard cattle guards occurred at the barrier edge, where guard apron wings were common (triangular metal structures installed at the margins of cattle guards). Similarly, most mule deer (52.3%) that breached wildlife guards crossed at the barrier edge, often on a narrow concrete frame exposed between the steel grid and the adjacent wildlife fencing. Most deer that crossed double cattle guards and electrified mats walked across them (52.0% and 97.9%, respectively). Of the 48 recorded deer breaches over double cattle guards, 8 (16.6%) occurred when the barriers were covered in snow. At wildlife guards, ~32% of recorded deer breaches were influenced by accumulated snow on the surface or margins of the barrier (Table 6).

Model Results

Three of the four explanatory variables entered into the logistic regression model were statistically significant at level $\alpha = 0.05$. Significant predictors of whether deer crossed over the barriers included: 1) barrier design, 2) AADT volume on the highway segment adjacent to the access road, and 3) distance to the nearest safe passage that mule deer could use to cross beneath the roadway. Model fit, as measured by the proportion of deviance explained by the fitted logistic regression model (D^2), was 0.415. The residual deviance of 566.46 was less than the 692 deviance degrees of freedom, indicating that model overdispersion was absent (Table 7).

The likelihood of deer crossing over a barrier did not differ significantly at cattle guards without excavations (barrier design 1) when compared with standard cattle guards suspended over excavations (barrier type 2, $P = 0.058$). Similarly, the likelihood of deer crossing did not differ at cattle guards without excavations when compared with electrified mats (barrier type 5, $P = 0.103$). However, deer were significantly more likely to cross standard cattle guards than either double cattle guards (barrier type 3, $P = 0.036$) or wildlife guards (barrier type 4, $P = 0.005$). Further, the likelihood of deer crossing did not differ significantly at double cattle guards when compared with wildlife guards ($P = 0.801$). In contrast, deer were significantly more likely to cross electrified mats than either double cattle guards ($P < 0.001$) or wildlife guards ($P < 0.001$, Table 8). I rejected my null hypothesis that the likelihood of mule deer crossing over a barrier would be equal among the five designs (no significant difference in barrier effectiveness among the five designs) in favor of the alternative that the likelihood of mule deer crossing would differ among the five barriers (at least one significant difference in barrier effectiveness among the five designs).

Barrier Effectiveness for Other Wildlife

In addition to mule deer, I recorded 18 events in which coyotes (*Canis latrans*) approached within 2-m of double cattle guards and 8 (44.4%) events resulted in crossing. I recorded images of, but did not include, the following species in analysis due to insufficient sample size (≤10 events): American badger (*Taxidea taxus*), black-tailed jack rabbit (*Lepus californicus*), bobcat (*Lynx rufus*), cottontail rabbit (*Sylvilagus spp.*), deer mouse (*Peromyscus spp*.), domestic cow (*Bos taurus*), elk (*Cervus canadensis*), gray fox (*Urocyon cinereoargenteus*), gray wolf (*Canis lupus*), mountain lion (*Puma concolor*), raccoon (*Procyon lotor*), red fox (*Vulpes vulpes*), ring-tailed cat (*Bassariscus astutus*), striped skunk (*Mephitis mephitis*), turkey (*Meleagris gallopavo*), and ground squirrel (*Urocitellus spp*).

DISCUSSION

Of the five barrier designs we evaluated, double cattle guards and wildlife guards had the highest potential in excluding mule deer from fenced highway corridors. Although double cattle guards and wildlife guards did not entirely eliminate mule deer intrusions, both designs were ≥80% effective (produced a crossing rate of ≤20%) and consistently prevented deer from accessing the highway ROW. In contrast, electrified mats, standard cattle guards, and cattle guards without excavations were <12%, <50%, and <25% effective, respectively, and each design failed to reliably secure the highway corridor from deer intrusions.

Although double cattle guards were a substantial barrier to mule deer, the design was approximately 55% effective for coyotes, the only non-cervid species for which we had a sufficient sample size (≥10 events). In general, none of the barrier designs we evaluated were significant obstacles to carnivore movement. For example, we recorded an event in which a mountain lion crossed over a double cattle guard and a separate event of a mountain lion breaching a wildlife guard. We also recorded several events in which gray foxes traversed standard cattle guards and we captured one event of a wolf walking over a double cattle guard while escaping the fenced highway corridor. Similarly, we documented several instances of red foxes traveling over double cattle guards and wildlife guards to enter the highway ROW.

Model results supported our estimation of barrier effectiveness based on photographic analysis and suggested the design of the barrier was the most important predictor of whether mule deer crossed. Deer were significantly less likely to breach double cattle guards and wildlife guards when compared with any other barrier design we evaluated. However, we found no significant difference in barrier effectiveness between double cattle guards and wildlife guards.

In addition to the barrier design, annual average daily traffic (AADT) volume on the highway segment adjacent to the access road emerged as a significant predictor of barrier effectiveness. Although the effect was small, we detected a statistically significant effect of AADT on the likelihood of deer crossing over a barrier. Contrary to our expectation, the significant positive relationship between the variables suggested that barriers on access roads adjacent to highways with high traffic volume tended to have a *higher* likelihood of being breached by deer. Rather than representing a causal relationship between the variables however, the effect was likely an artifact of the spatial distribution of the barriers on the landscape. For example, standard cattle guards had a high likelihood of being breached by deer and were concentrated along Interstate 15 - the highway with the greatest AADT volume in the study ($\bar{x}$ > 17,500 vehicles/day). In contrast, double cattle guards were among the most effective barriers we monitored and half of them were adjacent to U.S. Highway 89, which had the lowest AADT volume of any highway in the study ($\bar{x}$ = 1,850 vehicles/day).

Contrary to the positive relationship we found between AADT and the likelihood of deer crossing, several studies suggest that roads with high traffic volume may act as more severe movement barriers to several species than roads with low traffic volume (Hiujser and Bergers 2000, Jaarsma and Willems 2002, Seiler 2003). For example, Rost and Bailey (1979) demonstrated that mule deer and elk appeared to avoid high traffic roads when compared with low traffic roads in Colorado, USA. Moreover, high traffic volume can represent a visual deterrent or “moving fence” to deer (Bellis and Graves

1978) and may exacerbate the barrier effect of a road. Further, models developed by Mueller and Berthoud (1997) suggest that highways with 4,000 to 10,000 AADT are strong movement barriers to wildlife and may become absolute barriers when traffic exceeds 10,000 AADT.

In our model, the distance to the nearest safe passage mule deer could use to cross beneath the roadway also emerged as a significant predictor of barrier effectiveness. We detected a significant inverse relationship between the distance to the nearest safe passage and the likelihood of deer crossing over a barrier. The relationship indicated that barriers closer to potential wildlife crossings had a *higher* likelihood of being breached by deer. This unexpected result was likely driven by the spatial distribution of wildlife barriers and wildlife crossing opportunities in our study area. For example, while the electrified mats adjacent to U.S. Highway 6 had a high likelihood of being breached by deer, the deterrents were also in close proximity to an open passage beneath a highway bridge that deer could use to cross beneath the highway (M. Hanson, UDWR, personal communication).

The modeled inverse relationship between distance to the nearest safe passage and likelihood of deer crossing may also have been influenced by the pattern of deer movement across U.S. Highway 89. For example, although it was directly adjacent to a wildlife underpass, the double cattle guard at milepost 45.5 was ~30% *less* effective than a nearly identical double cattle guard located ~1-km from the nearest wildlife underpass. The observed discrepancy in effectiveness between the barriers on U.S. 89 was likely influenced by factors not accounted for in our model, such as the orientation of the barrier to the highway. For instance, while the more effective guard was *farther* from the wildlife underpass, it was located on the north side of the highway and was generally encountered by deer en route to winter range in Northern Arizona. In contrast, the less effective guard directly adjacent to the underpass was located on the south side of the road and was generally encountered by deer migrating to summer range on the Paunsaugunt Plateau in Southern Utah (P. Cramer, Utah State University, personal communication). Mule deer can be highly motivated to continue migrating to summer range (Reed et al. 1975) and it is possible that deer traveling to summer range may have been more motivated to cross double cattle guards than deer traveling to winter range. In short, these motivational differences may have influenced the observed discrepancy in barrier effectiveness on U.S. 89 and likely contributed to the modeled inverse relationship between barrier effectiveness and distance to the nearest safe passage.

Allen et al. (2013) demonstrated that 93.5% of deer photographed adjacent to U.S. Highway 93 in Montana, USA, crossed through an adjacent wildlife underpass rather than by crossing over a wildlife guard. The authors further suggested that a wildlife crossing structure in the immediate vicinity of a wildlife barrier may increase the effectiveness of the barrier by providing a preferred pathway for wildlife to cross the roadway. Although our model results indicated that wildlife barriers close to safe passages tended to have a *higher* likelihood of being breached by deer, our observations from a double cattle guard paired with an adjacent wildlife underpass on U.S. 89 suggest a similar pattern of deer movement as demonstrated by Allen et al. (2013). For example, although we recorded 26 deer that crossed over the wildlife barrier, we recorded 1178 deer that crossed through the adjacent wildlife underpass during the same time period (P. Cramer, Utah State University, personal communication). These data indicate that the wildlife underpass represents the preferred path for mule deer to cross the highway and suggest that, if presented with the choice, most deer are likely to cross a roadway through an available wildlife crossing structure rather than going over a wildlife barrier.

In addition to AADT and the distance to the nearest safe passage, a suite of secondary factors not accounted for in our model may have influenced barrier effectiveness. For example, factors influencing deer motivation to breach the barriers likely varied across our study area. On Interstate 15 exit 71, resident mule deer in the town of Summit crossed cattle guards to access forage in agricultural fields on the west side of the interstate (T. Abbot, UDOT, personal communication). In contrast, U.S. Highway 89 bisects the seasonal migration route of the Paunsagunt mule deer herd and most animals likely crossed double cattle guards to reach seasonal range on the north and south side of the highway (see Cramer 2015 for details).

Although we were unable to account for it due to a lack of available data, we suspect that the time since the installation of the wildlife barrier may have been an important determinant of efficacy. Based on observations from UDOT staff, electrified mats on U.S. 6 appeared to be effective mule deer barriers in the months immediately following initial installation (D. Babcock, UDOT, personal communication). However, our data indicate that, currently, electrified mats are poor deer barriers and suggest that mat efficacy may have attenuated over time. In contrast, the effectiveness of the double cattle guards we monitored on U.S. 89 may have increased over time. For example, our observations on U.S. 89 were derived during the time period shortly after installation of wildlife fencing in the area (3 to 22 months after installation). Although we recorded several deer crossing over the double cattle guards during this time, few deer have breached either of the double cattle guards on U.S. 89 since the end of our study in late April 2015 (P. Cramer, Utah State University, personal communication). While the number of days that our cameras monitored the barriers did not emerge as a significant predictor of barrier effectiveness, we suspect that the effectiveness of a barrier may attenuate or increase over longer temporal scales as deer learn to defeat or avoid barriers.

Our results from cattle guards along the Interstate 15 corridor corroborate previous findings on the efficacy of cattle guards as deer barriers. Our data suggest that, whether constructed over excavations or not, cattle guards of typical dimensions (1.6-m to 2.1-m-wide) are poor barriers to mule deer. Reed et al. (1974) found little success when evaluating experimental cattle guards constructed of flat mill steel, with 89% of mule deer crossing the guard when released in front of it. Similarly, VerCauteren et al. (2009) evaluated an experimental cattle guard with bearing-mounted rolling bars that reduced white-tailed deer (*O. virginianus*) entries into feeding exclosures, but lost effectiveness over time as deer learned to jump or walk across. Ward (1982) documented 11 vehicle accidents resulting from 18 mule deer that breached cattle guards adjacent to Interstate 80 in Wyoming, USA. Although we did not document any wildlife-vehicle collisions that resulted directly from deer that breached the cattle guards we monitored, we did record an alarming number of mule deer crossings at exit 71 on Interstate 15 near Summit, Utah. At this interchange alone, we observed 288 mule deer breaches into the fenced highway corridor. The cattle guards at this location were not constructed over excavations and were regularly breached by mule deer that traverse the highway to access agricultural fields on the west side of Interstate 15 (T. Abbott, UDOT, personal communication). Due to the high volume of mule deer crossings, there is a current and critical need to fully replace the deteriorating and ineffective cattle guards at this location.

In our study area of Utah, the most common method to increase the effectiveness of standard cattle guards is to install an additional cattle guard adjacent to the existing guard, thereby increasing the total width of the deterrent surface to ≥4.3-m-wide. UDOT and the U.S. Army had each previously monitored one double cattle guard in Utah. Though these short-term monitoring efforts lacked consistent methods and replication, estimates suggested the barriers were 90-95% effective for mule deer and 60-70% effective for elk (D. Babcock, UDOT, personal communication, U.S. Army 2006). A more rigorous, controlled experiment conducted by Belant et al. (1998) found a similar, 4.6-m-wide simulated cattle guard with round bars reduced white-tailed deer crossings through fence openings by >95%. The four double cattle guards we monitored along Utah's highways secured gaps in wildlife fencing from mule deer intrusions in >80% of recorded events (*n* = 337). Our results corroborate previous findings from Belant et al. (1998) and others and suggest that double cattle guards are of sufficient width (≥4.3-m-wide) to represent a significant, though not absolute, barrier to mule deer.

Peterson et al. (2003) tested 3 types of steel bridge grating for deer exclusion efficiency and found one design to be 99% effective at excluding Key deer (*O. v. clavium*) from a baited deer exclosure. More recently, Allen et al. (2013) evaluated two wildlife guards deployed along U.S. Highway 93 in Montana. The wildlife guards consisted of steel bridge grating (6.6-m × 6.8-m) suspended over 45-cm-deep pits. The wildlife guards were >90% effective for mule deer that displayed behavior to cross them (*n*=21 events), but were less effective for black bear and coyotes (33% and 55%, respectively). Although the two wildlife guards we monitored adjacent to U.S. Highway 91 were smaller (4.8-m × 4.8-m) and slightly less effective than those evaluated by Allen et al. (2013), the design was ≥80% effective as a barrier to mule deer (*n*=179 events) and appears to represent a substantial obstacle to deer that attempt to access fenced highway corridors.

Seamans and Helon (2008) evaluated electrified mats consisting of metal electrodes implanted into alternating yellow and black plastic planks. The design was 95% effective at reducing white-tailed deer intrusions into feeding stations, although some deer jumped over the mat. However, in a subsequent field test of four electrified mats along U.S. Highway 101 in California, USA, Siepel et al. (2013) documented mule deer crossing the mats in 54 out of 63 events (14.3% effective). While Siepel et al. (2013) found that electrified mats did deter a black bear (*Ursus americanus*) from entering the road corridor, the authors suggested the design should be modified to more effectively exclude mule deer. Like Siepel et al. (2013), we found two electrified mats deployed along U.S. Highway 6 in Utah to be poor barriers to mule deer movement, with deer crossing the mats in 67 out of 85 events (17.6–21.2% effective). We confirmed that the two electrified mats monitored in this study were operational and we used manufacturer recommended pulse-rate settings (1.5-seconds between electrical pulses). Although Seamans and Helon (2008) found strong effectiveness of electrified mats under experimental conditions using feed bait as a reward, our results corroborate those from Siepel et al. (2013) and suggest limited effectiveness of electrified mats in a real-world setting along a busy roadway.

Although our data suggest that double cattle guards and wildlife guards can limit mule deer intrusions to highways at access roads that bisect wildlife fencing, neither design represents an absolute barrier to mule deer. The majority of deer that breached the wildlife guards did so by walking on a 14-cm-wide concrete frame exposed between the steel grating and the adjacent wildlife exclusion fencing. Installing additional fencing at an angle to obstruct the concrete frame or extending wildlife fencing over the frame may mitigate this problem and enhance the efficacy of wildlife guards (Allen et al. 2013). Additional adaptive management techniques include the installation of rubber "bumper" strips to fence posts or the addition of fence coils that may prevent deer from walking on the concrete frame (P. Basting, JACOBS Engineering Group Inc., personal communication). Similarly, replacing guard apron wings (triangular metal structures installed at the margins of cattle guards) with additional vertical wildlife fencing that overlaps the edge of the cattle guard would likely increase the effectiveness of this design for mule deer. Finally, retrofitting or replacing flat cattle guard rails with round or angular rails may increase the effectiveness of theses barriers for deer (K. McAllister, Washington Department of Transportation, personal communication).

While deer may be capable of running broad jumps of nearly 9-m (Severinghaus and Cheatum 1956), none of the mule deer that breached double cattle guards or wildlife guards in our study did so by jumping over the barriers in a single bound. However, we did observe deer that completely cleared standard cattle guards and electric mats in a single jump. We also recorded instances of deer that became entangled in cattle guards and wildlife guards while attempting to cross and instances of deer landing awkwardly in the guards while attempting to jump across. We documented one deer fatality that resulted from an animal that became entangled in a double cattle guard while attempting to *escape* the fenced highway corridor. Providing additional earthen escape ramps in the vicinity of a wildlife barrier may reduce entanglements by allowing animals trapped within a fenced road corridor to escape safely (see Bissonette and Hammer 2000 for details).

MANAGEMENT IMPLICATIONS

Vehicle access points in wildlife exclusion fencing must often serve dual and conflicting purposes: facilitate continuous vehicle traffic *and* inhibit wildlife from entering highway ROW. Of the five barrier designs we evaluated, double cattle guards and wildlife guards were the most effective mitigation option for these locations, with both designs consistently deterring mule deer from accessing fenced highway corridors. In contrast, electrified mats and cattle guards (whether constructed over excavations or not) were least effective in excluding mule deer from highways. If deer are the primary target of wildlife-vehicle collision mitigation efforts, we suggest replacement of electric mats and standard cattle guards with more robust barriers wherever possible. Further, to facilitate safe passage for deer and other wildlife across the highway, we advise pairing fence gap mitigation measures and wildlife exclusion fencing with wildlife crossing structures (overpasses or underpasses) or with multipurpose structures suitable for wildlife (existing culverts or bridges not specifically designed for wildlife). Often, multipurpose structures can be made suitable for wildlife with minor design or maintenance retrofits (van der Ree et al. 2015).

Although double cattle guards and wildlife guards carry significant costs, each mule deer that breaches a barrier and gains access to the highway has the potential to result in a wildlife-vehicle collision. When costs due to property damage, human injury, human death, and deer loss are combined, the estimated mean cost of a single deer-vehicle collision ranges from $3,834 (Bissonette et al. 2008, CPI adjustment to 2015 dollars) to $7,593 (Hiujser et al. 2009, CPI adjustment to 2015 dollars). Based on these cost estimates, a double cattle guard or wildlife guard that cost $30,000 to $60,000 (R. Taylor, UDOT, personal communication) would need only prevent 4 to 16 deer-vehicle collisions over the life of the barrier to the justify investment. These results demonstrate the need for further research that investigates cost-effective, innovative technologies that could either replace or augment ineffective barrier designs to reduce wildlife access to highways.

Limitations

At some barriers, wildlife cameras were not operational during the entire monitoring period. To prevent rapid power loss from repeated vehicle detections, we programmed most of our cameras to detect motion only during evening and nighttime periods when wildlife were most active. However, due to variation in vehicle traffic volume at the monitoring locations, we varied daily camera on/off schedules across sites. Despite this, we experienced data loss at some sites when cameras lost power between checks. As a result, we likely missed some animal approaches to the deterrents. Additionally, not all cameras were installed for a standard amount of time. That is, there was variation in the date of camera deployment and retrieval. Further, because we could not distinguish between individual animals during image analysis, we could not determine whether movement patterns at the monitoring locations were produced by different groups of animals or by the same groups detected multiple times.

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TABLES AND FIGURES

Table 1. Location, dimensions (m), traffic volume, and distance (miles) to the nearest potential deer crossing of barriers in Utah, USA during the study period (late-Oct 2013 to late-Apr 2015).

Barrier Design	**Location**	**Width**	**Length**	**AADT[b]**	**Days Monitored[c]**	**D to Crossing[d]**	**Crossing Type[e]**
CG[a] (no pit)	I-15 exit 71 NE	1.8	9.7	20,575	231	26.4	multipurpose culvert
	I-15 exit 71 SE	1.9	9.7	20,575	210	26.4	multipurpose culvert
Standard CG[a]	I-15 exit 120	2.1	7.3	17,605	233	3.5	wildlife underpass
	I-15 exit 33	2.1	13.7	21,685	366	3.9	multipurpose culvert
	I-15 exit 31	2.1	11.0	21,675	544	5.4	multipurpose culvert
	I-15 exit 30	2.1	11.0	21,845	234	6.6	multipurpose culvert
Double CG[a]	US91 MP10.8	4.6	7.0	16,460	534	1.3	wildlife underpass
	US6 MP235.8	4.8	26.2	10,980	529	0.6	highway bridge
	US89 MP43	4.3	4.8	1,850	573	0.5	wildlife underpass
	US89 MP45.5	4.4	4.8	1,850	574	0	wildlife underpass
Wildlife Guard	US91 MP5.8	4.8	4.8	17,865	511	0.5	wildlife underpass
	US91 MP9.1	4.8	4.8	16,460	415	0.8	wildlife underpass
Electric Mat	US6/SR139	1.2	12.8	10,980	499	0.6	highway bridge
	US6/Consumer	1.2	10.6	10,980	515	0.9	highway bridge

[a] Cattle Guard

[b] AADT = 2013 annual average daily traffic volume on highway adjacent to access road.

[c] Days Monitored = Number of days barrier was monitored (number of days elapsed from start to end of monitoring period).

[d] D to Crossing = distance (miles) to the nearest crossing that mule deer could use safely pass beneath roadway.

[e] Crossing Type: multipurpose culvert = concrete box or corrugated metal culvert deemed suitable for mule deer use, wildlife underpass = structure beneath highway constructed specifically for wildlife, highway bridge = open passage beneath highway bridge.

Table 2. Measured variables included in the logistic regression model used to examine explanatory variables associated with mule crossings at fence openings adjacent to highways in Utah, USA.

Variable	**Variable Name**	**Variable Description**
Response	Cross Code	0 = success (no deer in the event crossed the barrier)
		1 = failure (at least one deer in the event crossed barrier)
Explanatory	Barrier Design	1 = cattle guard (no pit)
		2 = standard cattle guard
		3 = double cattle guard
		4 = wildlife guard
		5 = electric mat
	AADT	2013 Annual average daily traffic (1,850–21,845 vehicles)
	Monitoring Day	Days since the installation of wildlife camera (4–573 days)
	D to Crossing	Distance to nearest potential deer crossing (0–26.4 miles)

Table 3. Number and percentage of independent events in which mule deer approached (within 2-m) and subsequently crossed, or did not cross, wildlife barriers in Utah, USA, during the study period (late-Oct 2013 to late-Apr 2015).

Location	Approached	Crossed	% Crossed	Inconclusive[b]	% Effective[c]
CG[a] (no pit)					
I-15 exit 71 NE	81	44	54.3	24	16.0 – 45.7
I-15 exit 71 SE	190	138	72.6	36	8.4 – 27.4
Total	**271**	**182**	**67.2**	**60**	**10.7 – 32.8**
Standard CG[a]					
I-15 exit 120	4	1	25.0	0	75.0
I-15 exit 33	7	6	85.7	0	14.3
I-15 exit 31	73	34	46.6	16	31.5 – 53.4
I-15 exit 30	4	2	50.0	2	0 – 50.0
Total	**88**	**43**	**48.9**	**18**	**30.7 – 51.1**
Double CG[a]					
US91 MP10.8	33	8	24.2	14	33.3 – 75.8
US6 MP235.5	41	2	4.9	3	87.8 – 95.1
US89 MP42.3	162	3	1.9	2	96.9 – 98.1
US89 MP45.5	101	20	19.8	3	77.2 – 80.2
Total	**337**	**33**	**9.8**	**22**	**83.7 – 90.2**
Wildlife Guard					
US91 MP5.8	96	20	20.8	1	78.1 – 79.2
US91 MP9.1	112	14	12.5	5	83.0 – 87.5
Total	**208**	**34**	**16.3**	**6**	**80.8 – 83.7**
Electric Mat					
US6/SR139	13	10	76.9	0	23.1
US6/Consumer	72	57	79.2	3	16.7 – 20.8
Total	**85**	**67**	**78.8**	**3**	**17.6 – 21.2**
GRAND TOTAL	**989**	**359**	**36.3**	**109**	**52.7 – 63.7**

[a] Cattle Guard

[b] Inconclusive = Total number of events in which it could not be determined if deer crossed, or did not cross, the barrier.

[c] Effective = Percentage of recorded events in which deer did not cross the barrier. We calculated the lower effectiveness estimate by assuming all of the inconclusive events resulted in crossing. For the upper estimate, we assumed none of the inconclusive events resulted in crossing.

Table 4. Number and percentage of independent events in which mule deer approached (within 2-m) and displayed behavior to cross and subsequently crossed, or did not cross, wildlife barriers in Utah, USA, during the study period (late-Oct 2013 to late-Apr 2015).

Location	Approached	Crossed	% Crossed	Inconclusive[b]	% Effective[c]
CG[a] (no pit)					
I-15 exit 71 NE	168	138	82.1	19	6.5 – 17.9
I-15 exit 71 SE	70	44	62.9	14	17.1 – 37.1
Total	**238**	**182**	**76.5**	**33**	**9.7 – 23.5**
Standard CG[a]					
I-15 exit 120	3	1	33.3	0	66.7
I-15 exit 33	7	6	85.7	0	14.3
I-15 exit 31	69	34	49.3	15	29.0 – 50.7
I-15 exit 30	4	2	50	2	0 – 50.0
Total	**83**	**43**	**51.8**	**17**	**27.7 – 48.2**
Double CG[a]					
US91 MP10.8	29	8	27.6	11	34.5 – 72.4
US6 MP235.5	31	2	6.5	3	83.9 – 93.5
US89 MP42.3	121	3	2.5	1	96.7 – 97.5
US89 MP45.5	66	20	30.3	1	68.2 – 69.7
Total	**247**	**33**	**13.4**	**16**	**80.2 – 86.6**
Wildlife Guard					
US91 MP5.8	85	20	23.5	1	75.3 – 76.5
US91 MP9.1	94	14	14.9	3	81.9 – 85.1
Total	**179**	**34**	**19.0**	**4**	**78.8 – 81.0**
Electric Mat					
US6/SR139	12	10	83.3	0	16.7
US6/Consumer	64	57	89.1	1	9.4 – 10.9
Total	**76**	**67**	**88.2**	**1**	**10.5 – 11.8**
GRAND TOTAL	**764**	**292**	**38.2**	**71**	**52.5 – 61.8**

[a] Cattle Guard

[b] Inconclusive = Total number of events in which it could not be determined if deer crossed, or did not cross, the barrier.

[c] Effective = Percentage of recorded events in which deer did not cross the barrier. We calculated the lower effectiveness estimate by assuming all of the inconclusive events resulted in crossing. For the upper estimate, we assumed none of the inconclusive events resulted in crossing.

Table 5. Number and percentage of individual mule deer approaches (within 2-m) that crossed, or did not cross, wildlife barriers in Utah, USA, during the study period (late-Oct 2013 to late-Apr 2015).

Location	Approached	Crossed	% Crossed	Inconclusive	% Effective[c]
CG[a] (no pit)					
I-15 exit 71 NE	340	216	63.5	47	22.6 – 36.5
I-15 exit 71 SE	135	72	53.3	25	28.1 – 46.7
Total	**475**	**288**	**60.6**	**72**	**24.2 – 39.4**
Standard CG[a]					
I-15 exit 120	8	1	12.5	0	87.5
I-15 exit 33	14	8	57.1	0	42.9
I-15 exit 31	117	47	40.2	20	42.7 – 59.8
I-15 exit 30	5	2	40	2	20.0 – 60.0
Total	**144**	**58**	**40.3**	**22**	**44.4 – 59.7**
Double CG[a]					
US91 MP10.8	55	9	16.4	19	49.1 – 83.6
US6 MP235.5	71	2	2.8	5	90.1 – 97.2
US89 MP42.3	501	11	2.2	3	97.2 – 97.8
US89 MP45.5	186	26	14.0	3	84.4 – 86.0
Total	**813**	**48**	**5.9**	**30**	**90.4 – 94.1**
Wildlife Guard					
US91 MP5.8	159	29	18.2	1	81.1 – 81.8
US91 MP9.1	190	15	7.9	9	87.4 – 92.1
Total	**349**	**44**	**12.6**	**10**	**84.5 – 87.4**
Electric Mat					
US6/SR139	18	15	83.3	0	16.7
US6/Consumer	147	128	87.1	4	10.2 – 12.9
Total	**165**	**143**	**86.7**	**4**	**10.9 – 13.3**
GRAND TOTAL	**1946**	**581**	**29.9**	**138**	**63.1 – 70.1**

[a] Cattle Guard

[b] Inconclusive = Total number of individual deer approaches in which it could not be determined if deer crossed, or did not cross, the barrier.

[c] Effective = Percentage of individual deer approaches that did not cross the barrier. We calculated the lower effectiveness estimate by assuming all of the inconclusive approaches resulted in crossing. For the upper estimate, we assumed none of the inconclusive approaches resulted in crossing.

Table 6. Number of individual mule deer crossings and resulting method of crossing at wildlife barriers in Utah, USA, during the study period (late-Oct 2013 to late-Apr 2015).

Location	Jumped	Walked	Breached Edge[b]	Unknown[c]	Snow[d]
CG[a] (no pit)					
I-15 exit 71 NE	136	61	4	15	0
I-15 exit 71 SE	50	15	1	6	0
Total	**186**	**76**	**5**	**21**	**0**
Standard CG[a]					
I-15 exit 120	0	1	0	0	0
I-15 exit 33	4	3	1	0	0
I-15 exit 31	19	11	13	4	0
I-15 exit 30	1	1	0	0	0
Total	**24**	**16**	**14**	**4**	**0**
Double CG[a]					
US91 MP10.8	0	4	1	4	4
US6 MP235.5	0	2	0	0	0
US89 MP42.3	2	8	0	1	4
US89 MP45.5	5	11	0	10	0
Total	**7**	**25**	**1**	**15**	**8**
Wildlife Guard					
US91 MP5.8	12	3	13	1	8
US 91 MP9.1	1	4	10	0	6
Total	**13**	**7**	**23**	**1**	**14**
Electric Mat					
US6/SR139	0	15	0	0	0
US6/Consumer	2	125	0	1	0
Total	**2**	**140**	**0**	**1**	**0**
GRAND TOTAL	**232**	**264**	**43**	**42**	**22**

[a] Cattle Guard

[b] Breached Edge = Total number of mule deer breaches that occurred at guard apron wings (triangular metal structures at cattle guard edges) or on exposed concrete ledges that framed wildlife guards.

[c] Unknown = Total number of mule deer breaches in which the method of crossing could not be determined.

[d] Snow = Subset of mule deer breaches that occurred when the wildlife barrier was snow covered.

Table 7. Variable coefficients, standard error, z-statistic, and *P*-values for a logistic regression model used to examine explanatory variables associated with mule crossings at fence openings adjacent to highways in Utah, USA.

Variable	**Estimate**	**SE**	**z-value**	***P*-value**
Intercept	29.83	11.64	2.56	0.010
Standard Cattle	-26.28	9.83	-2.67	0.007
Double Cattle Guard	-31.75	11.57	-2.74	0.006
Wildlife Guard	-33.45	11.88	-2.81	0.004
Electrified Mat	-28.35	11.58	-2.45	0.014
AADT[a]	0.0001	0.0001	2.76	0.005
Monitoring Day[b]	-0.0001	0.0008	-0.105	0.916
D to Crossing[c]	-1.17	0.467	-2.53	0.011

Table 8. Differences of barrier types least squares means with adjustment for multiple comparisons (Tukey – Kramer).

Barrier Design*	**Estimate**	**SE**	***z*-value**	***P*-value**	***P*-value (adjusted)**
1 vs. 2	26.28	9.83	2.67	0.0075	0.0581
1 vs. 3	31.75	11.57	2.74	0.0061	0.0479
1 vs. 4	33.44	11.88	2.81	0.0049	0.0392
1 vs. 5	28.34	11.58	2.45	0.0144	0.1030
2 vs. 3	5.47	1.92	2.84	0.0045	0.0364
2 vs 4	7.16	2.08	3.43	0.0006	0.0054
2 vs. 5	2.06	1.85	1.11	0.2672	0.8016
3 vs. 4	1.69	0.76	2.23	0.0260	0.1701
3 vs. 5	-3.40	0.55	-6.18	<.0001	<.0001
4 vs. 5	-5.09	0.60	-8.39	<.0001	<.0001

* Barrier Design: 1 = cattle guard (no pit), 2 = standard cattle guard, 3 = double cattle guard, 4 = wildlife guard, 5 = electrified mat.

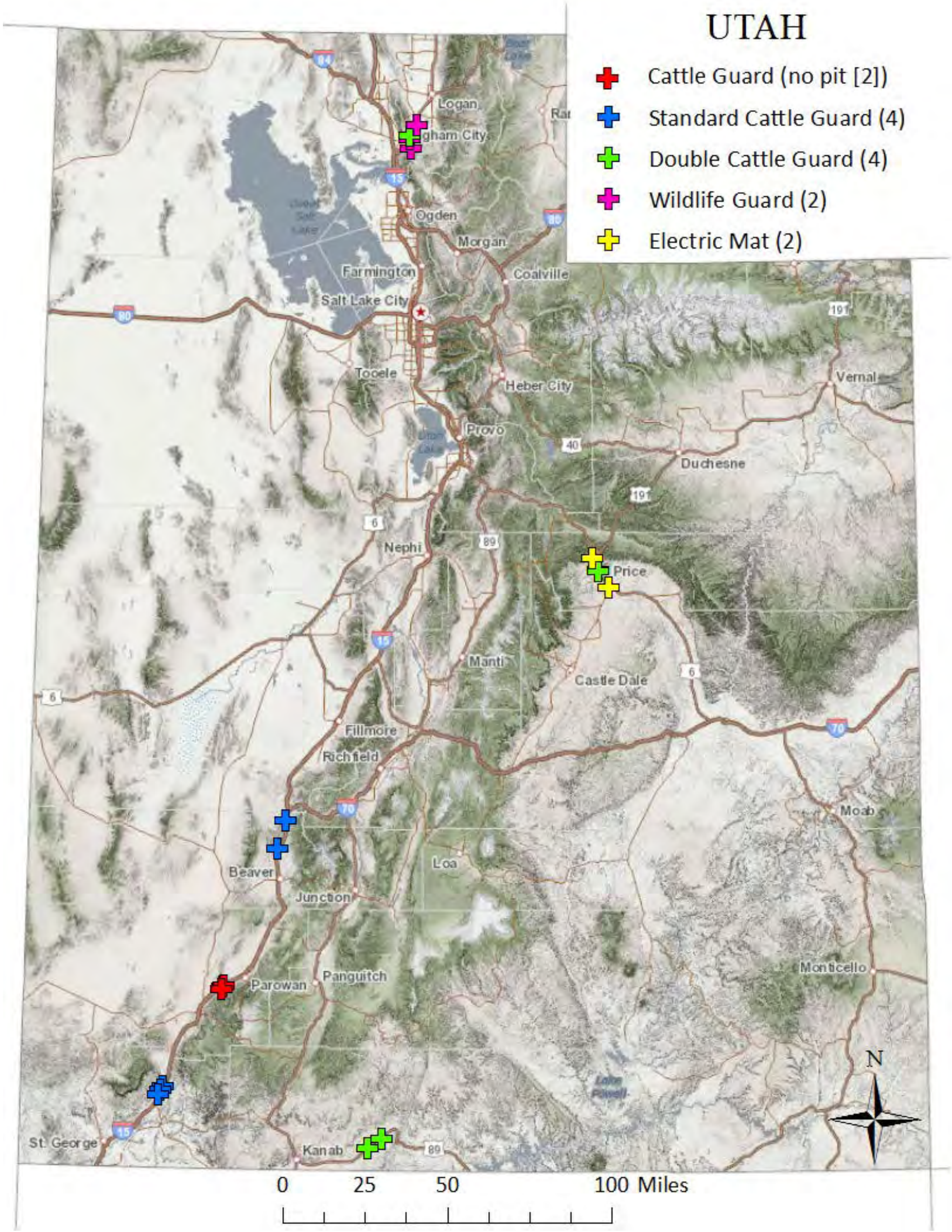

Figure 1. Locations of wildlife barriers (*n*=14) along fenced sections of U.S. Highway 91 (top), U.S. Highway 6 (center), Interstate 15, and U.S. Highway 89 (bottom) in Utah, USA.

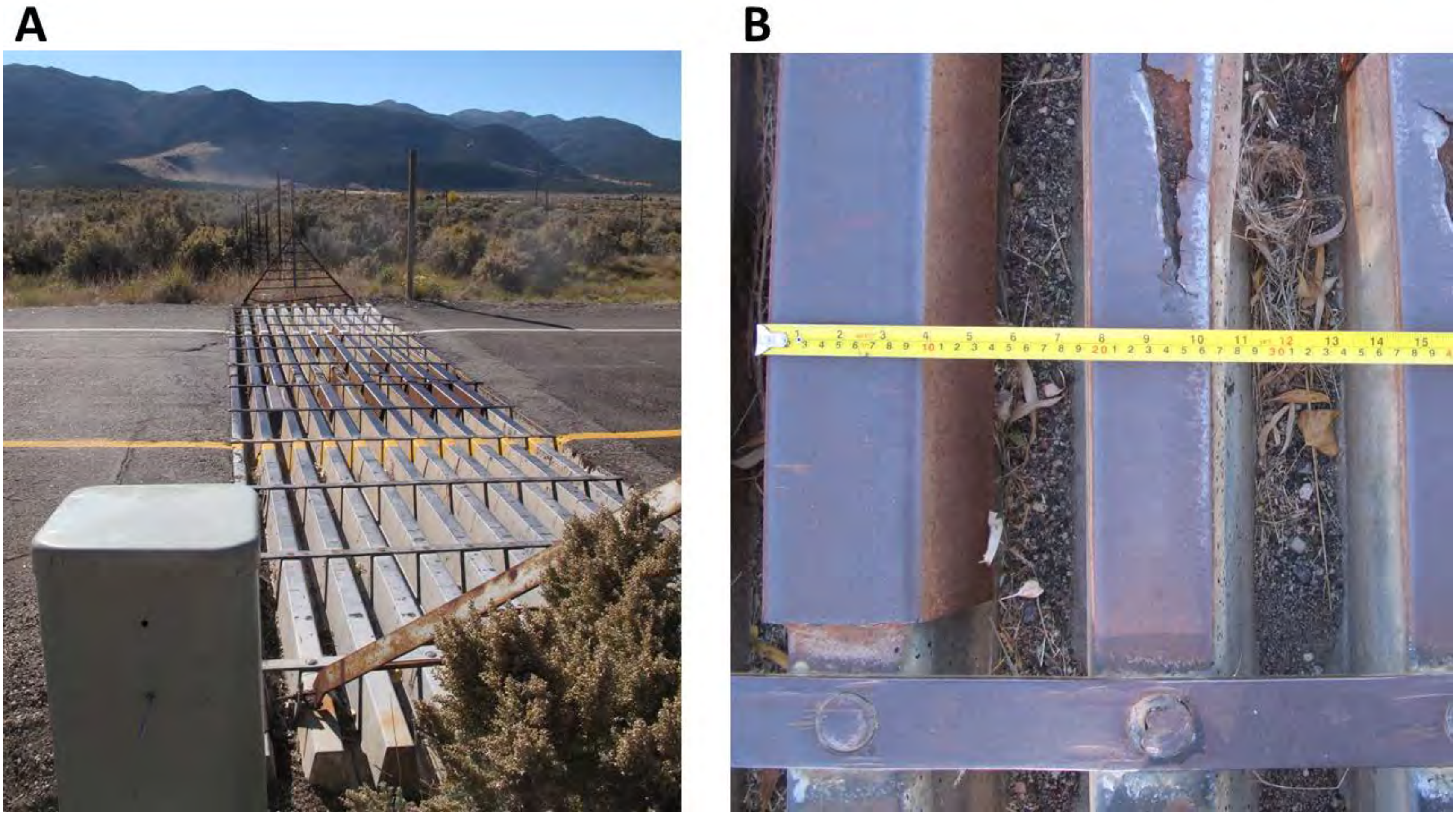

Figure 2. Cattle guard (1.9-m × 9.7-m) not constructed over excavation (A) and close view of cattle guard rails (B) on an access road to Interstate 15, near Summit, Utah, USA.

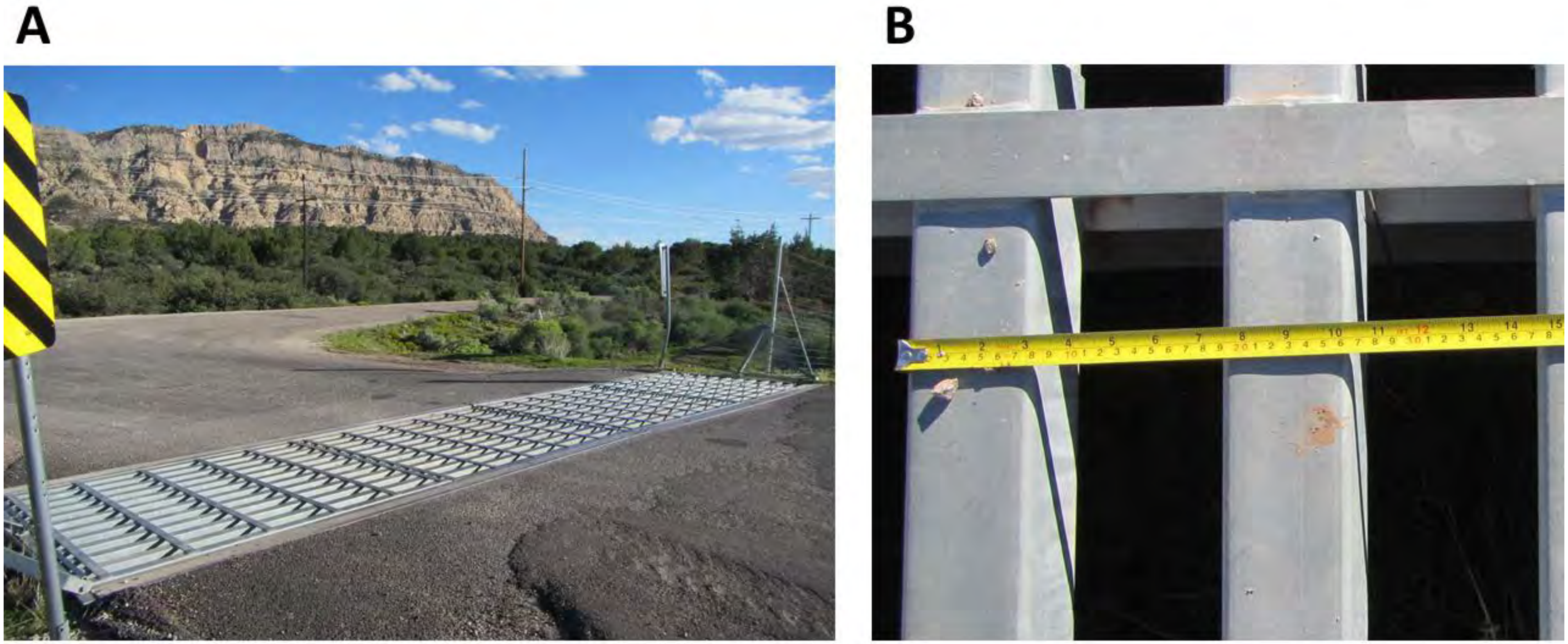

Figure 3. Standard **c**attle guard (2.1-m × 11-m) suspended over excavation (A) and close view of cattle guard rails (B) on an access road to Interstate 15, near Pintura, Utah, USA.

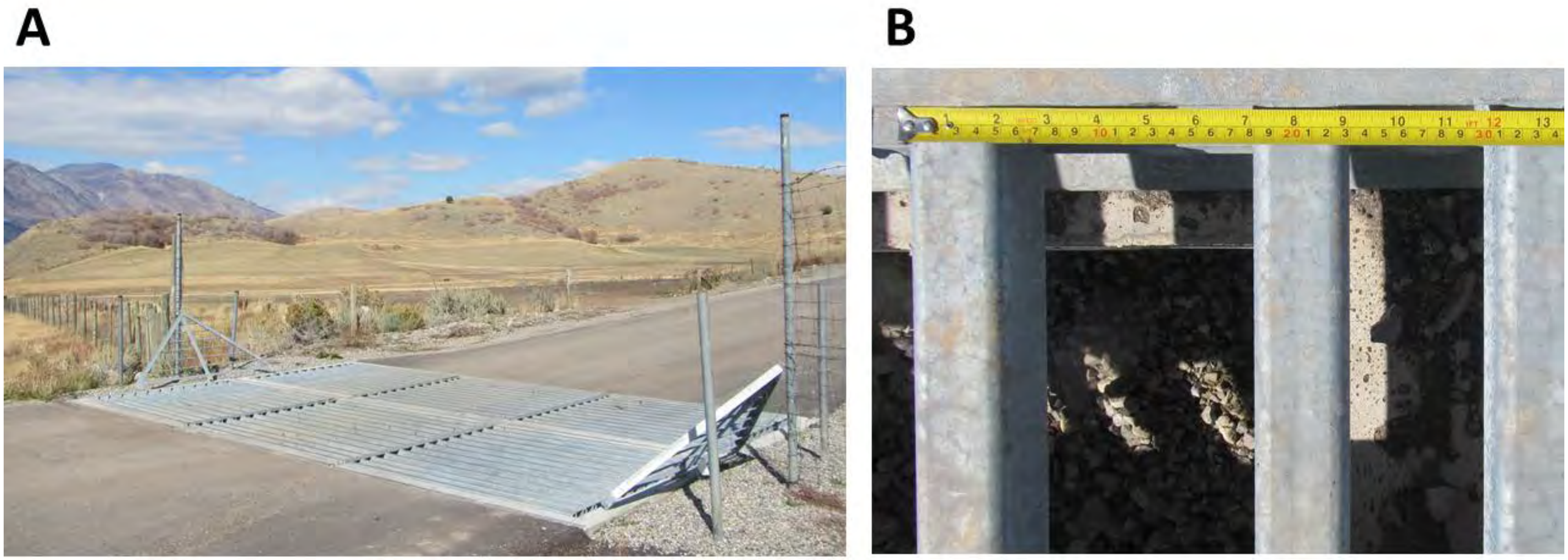

Figure 4. Double **c**attle guard (4.6-m × 7-m) suspended over excavation (A) and close view of cattle guard rails (B) on an access road to U.S. Highway 91, north of Mantua, Utah, USA.

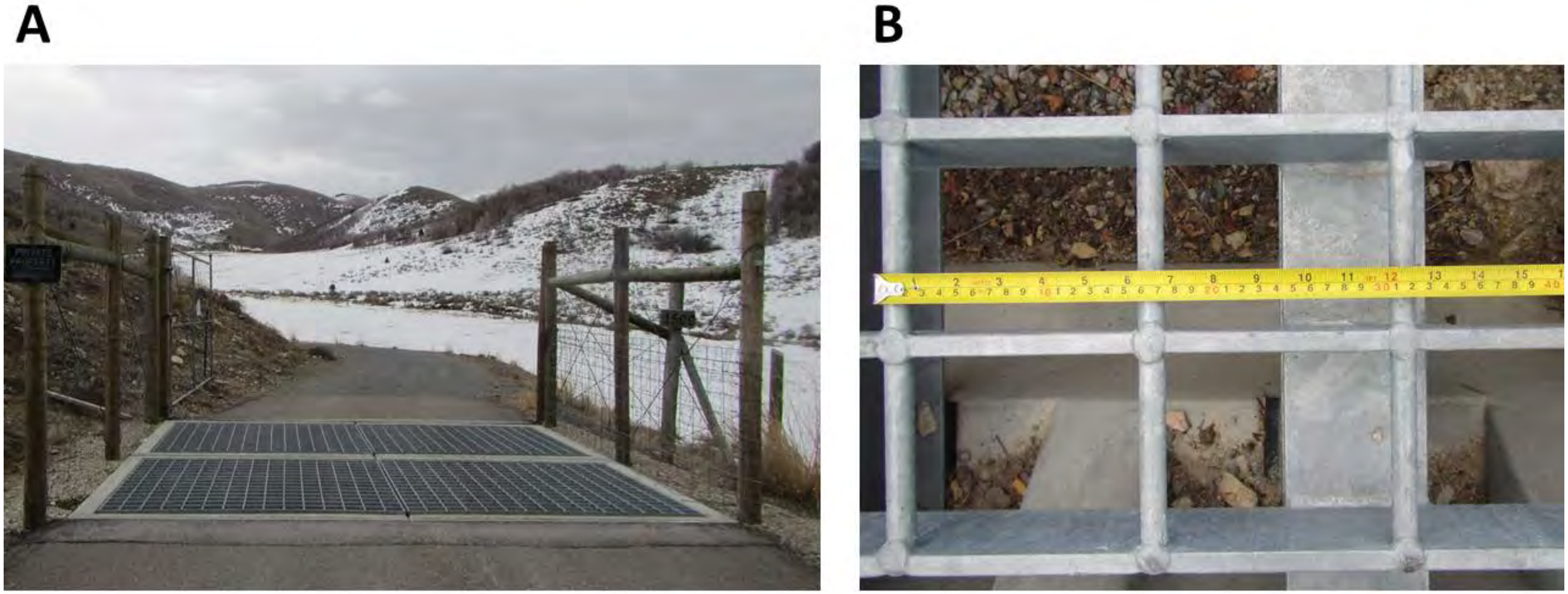

Figure 5. Wildlife guard (4.9-m × 4.9-m) suspended over excavation (A) and close view of steel grating (B) on an access road to U.S. Highway 91, near Mantua, Utah, USA.

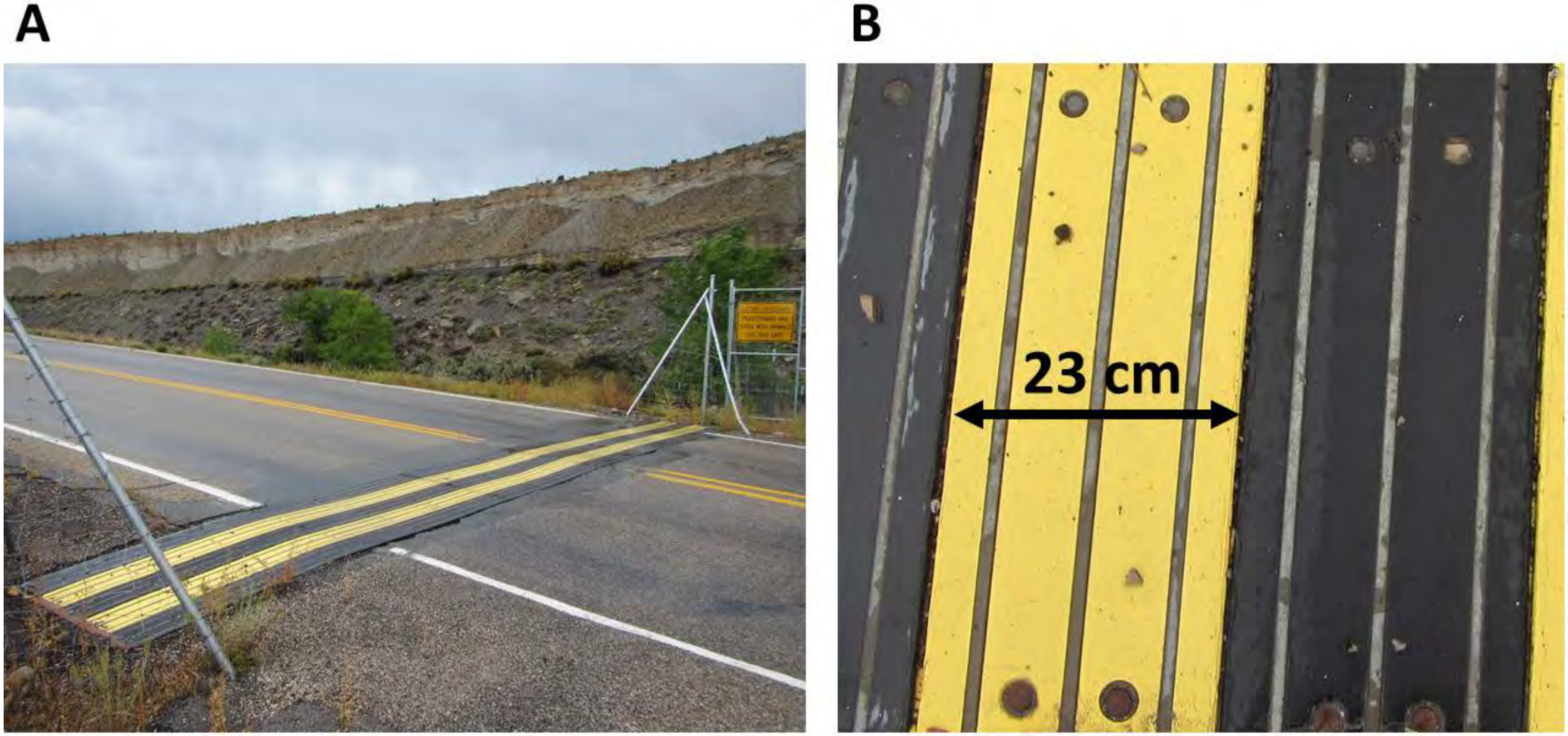

Figure 6. Electrified mat (1.2-m × 11-m, A) and close view of composite planks with embedded metal electrodes (B) on an access road to U.S. Highway 6, near Helper, Utah, USA.

Figure 7. Motion activated wildlife camera (circled) used to monitor wildlife approaches to a wildlife guard on an access road to U.S. Highway 91, near Mantua, Utah, USA.

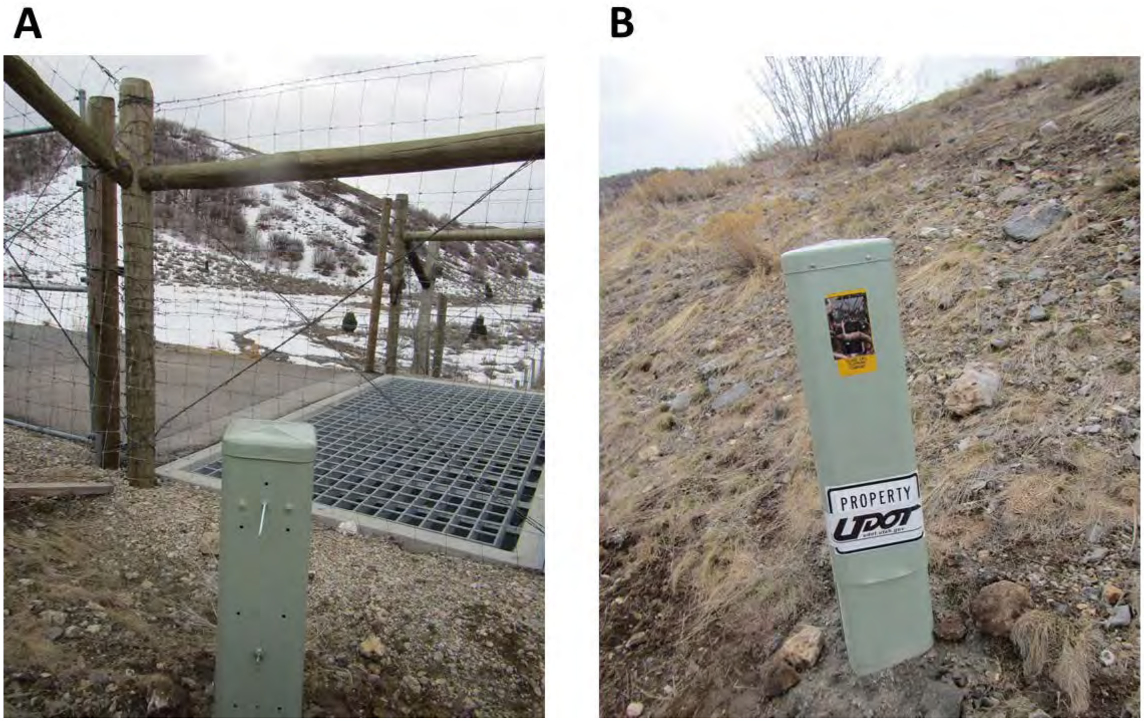

Figure 8. Orientation view (A) and close view (B) of a motion activated wildlife camera used to monitor wildlife approaches a wildlife guard on an access road to U.S. Highway 91, near Mantua, Utah, USA.

CHAPTER III

EFFECTIVENESS OF ELECTRIFIED PAVEMENT IN REDUCING BIG GAME ACCESS TO FENCED RESOURCES

ABSTRACT Deer-vehicle collisions (DVCs) threaten the motoring public, cause substantial economic loss, and can negatively affect deer populations. Wildlife exclusion fencing placed along highways can effectively reduce DVCs, but fencing is often bisected by lateral access roads that animals can use to enter the highway. Although standard cattle guards are common at these locations, they are largely ineffective as barriers to deer (*Odocoileus* sp.). We evaluated whether standard cattle guards augmented with segments of electrified pavement could prevent mule deer (*O. hemionus*) and elk (*Cervus canadensis*) intrusions through fence openings. To test cattle guards augmented with the electrified pavement, we used camera traps to monitor wildlife intrusions into four baited wildlife exclosures with augmented cattle guards and at two exclosures with untreated cattle guards. Cattle guards augmented with segments of electrified pavement (0.91-m to 1.2-m-wide) were >80% effective in excluding deer and >95% effective in excluding elk from wildlife exclosures that were constructed in a natural area away from roads. However, when installed into the road surface in front of an existing cattle guard, a segment of electrified pavement (0.91-m-wide) was 54% effective in excluding deer from a fenced segment of Interstate 15. Based on results derived from baited wildlife exclosures, electrified pavement appears to have potential as an effective tool to reduce ungulate access to roadways and other protected areas. However, to fully assess the viability of this emerging technology for use in excluding wildlife from highways, multi-year monitoring of replicate in-road installations is needed and ongoing.

Roads cover more than 1% of the total land surface of the contiguous United States, but affect ≥20% of the land area ecologically (Forman 2000). While the effects of expanding road networks on living systems are diverse, perhaps none are more direct or conspicuous than wildlife mortality due to wildlife-vehicle collisions (Bissonette 2002). In the U.S. alone, an estimated 1 to 2 million vehicle collisions with large wild animals occur annually, resulting in approximately 29,000 human injuries and 200 human deaths (Conover et al. 1995, Huijser et al. 2009). When the collective costs due to vehicle damage, human injuries and fatalities, and loss of animal value are combined, the total economic toll imposed by wildlife-vehicle collisions (WVCs) in the U.S. exceeds US$8 billion annually (Huijser et al. 2008).

With an estimated 1 million vertebrates killed each day on America's highways, WVCs not only pose a threat to the motoring public, but can threaten the survival of animal populations (Lalo 1987). Although mortality from vehicle collisions may not pose a significant threat to robust wildlife populations, road mortality can be devastating to small or declining populations (Bennet 1991). For example, road mortality has been identified as a major threat to the survival of 21 federally listed threatened or endangered animal species in the U.S. (Huijser et al. 2008). However, the majority of WVCs involve deer, with deer-vehicle collisions accounting for ≥ 90% of all WVCs in some U.S. states (Huijser et al. 2008).

The most effective method to reduce vehicle collisions with large ungulates is the placement of wildlife exclusion fencing (2.4-m-high) in conjunction with wildlife crossing structures (Hedlund et al. 2004). The main objectives of these structures are to: 1) connect habitats and wildlife populations by providing safe passage for wildlife, 2) reduce wildlife mortality due to WVCs, and 3) increase motorist safety (Beckman et al. 2010). When effectively designed and maintained, wildlife exclusion fencing prevents wildlife access to the roadway and guides animals to crossing structures that facilitate animal passage under or above the road. When combined, these mitigation measures can reduce collisions with large animals by >85% and are the only widely accepted method to effectively reduce WVCs involving large fauna (Hedlund et al. 2004, Huijser et al. 2009).

Management of wildlife intrusions at access roads that bisect wildlife fencing is critical to ensure the success of integrated fence-wildlife crossing structure systems (Peterson et al. 2003). If access roads that bisect fencing are not designed with an effective deterrent to exclude ungulates and other wildlife from the road right-of-way, wildlife crossings and fencing can become ineffective (P. Cramer, Utah State University, personal communication). Standard cattle guards (1.8-m to 2.1-m-wide in dimension parallel to vehicle travel) are ubiquitous in the Western U.S. and are common at openings in wildlife exclusion fencing. While cattle guards are generally effective at preventing hoofed livestock from accessing highways, they are largely ineffective as barriers to mule deer – the species most often involved in WVCs in much of the Western U.S. (Reed et al. 1974, Ward 1982, Flower and Cramer unpublished data).

Replacement or upgrade of standard cattle guards with fence-gap mitigation designs that more effectively exclude wildlife can be cost-intensive. Specialized barriers often used to replace or upgrade standard cattle guards, such as double cattle guards (two adjoining standard cattle guards, 3.8-m to 4.8-m-wide) or wildlife guards (metal grates, 4.8-m to 6.6-m-wide) can effectively prevent deer intrusions (Belant et al. 1998, U.S.

Army 2006, Allen et al. 2013, Flower and Cramer unpublished data) but cost approximately $30,000 to $60,000 per application, depending on road width (R. Taylor, Utah Department of Transportation [UDOT], personal communication). These up-front installation costs can be prohibitive when considered at across multiple locations. For example, transportation departments must spend ~$240,000 to mitigate a single highway interchange with four double cattle guards (R. Taylor, UDOT, personal communication).

In this field study, our objective was to evaluate whether a standard cattle guard augmented with a segment of electrified pavement could reduce mule deer (*Odocoileus hemionus)* and elk (*Cervus canadensis)* intrusions through fence openings at rates comparable to specialized barriers, but at reduced cost. To determine the efficacy of the augmented guards as a barrier to wildlife movement, we used a two-part approach that included: 1) a feeding exclosure trial using augmented guards deployed at entrances to baited wildlife exclosures at the Hardware Ranch Wildlife Management Area in Northern Utah, and 2) a road trial *in situ* on an access road to Interstate 15 in Southern Utah. Our goal was to provide a rigorous assessment of a cost-effective retrofit to standard cattle guards that could reduce wildlife intrusions to roadways and other protected areas at rates comparable to specialized guards.

STUDY AREA

We conducted the feeding exclosure trial at fenced wildlife exclosures within the 5,778 ha Hardware Ranch Wildlife Management Area (HRWMA), Cache County, Utah (ranch location ~ 41^{o} 36' N, 111^{o} 33' W). HRWMA is administered by the Utah Division of Wildlife Resources (UDWR) and serves as wintering habitat for mule deer and elk. Since 1947, a winter elk feeding program has operated at HRWMA and was active during the study from 13 December 2014 to 9 February 2015. Although elk are provided supplemental winter feed (grass hay) at the ranch, mule deer are prevented from accessing feed by socially dominant elk that exclude deer from the feeding area (B. Hunt, UDWR, personal communication, Johnson et al. 2000, Stewart et al. 2002). Habitat within HRWMA includes sagebrush communities, grassland, open woodlands, meadows, and riparian corridors. Dominant vegetation includes sagebrush (*Artemisia* sp.), conifers (*Juniperus* sp., *Pinus* sp.), aspen (*Populus tremuloides*), and riparian vegetation (UDWR 2012). Depending on winter severity, the number of wintering mule deer within HRWMA numbers from 500 to 1,000 individuals (8.6 to 17.3/km^2; UDWR 2012). The estimated minimum mule deer population in the immediate study area during the study (fall 2014 – spring 2015) was 200 (D. DeBloois, UDWR, unpublished data). The number of wintering elk within HRWMA ranges from 450 to 650 individuals (7.7 to 11.2/km^2; UDWR 2012). The estimated minimum elk population in the immediate study area during the evaluation was 600 (D. DeBloois, UDWR, unpublished data).

We conducted the road trial *in situ* at mile post 32 on an access road to Interstate 15, near the town of Pintura, Washington County, Utah (town location ~ 37^o 20' N, 113^o 16' W). Standard cattle guards span access roads on each side of the interchange and are located at openings in continuous wildlife exclusion fencing (2.4 m-high). The segment of Interstate 15 adjacent to the test site is a fenced, four-lane highway, divided by an open median with a posted speed limit of 75 miles per hour (120.7 km/hr) and annual average daily traffic of 21,675 vehicles (UDOT 2013).

A concrete box culvert for reservoir overflow is located 8.5 km north of the interchange and prior research found occasional mule deer use of the structure to move beneath Interstate 15 (Cramer 2012). The landscape adjacent to the interchange is heterogeneous, with mule deer summer range in the Pine Valley Mountains on the west side of the interstate, and winter range in low-lying valleys and small agricultural areas on the east side. Ash Creek and the steep volcanic slopes of the Black Ridge formation abut the east side of the highway. The interchange is recognized as an area where mule deer often gained access to the Interstate 15 right-of-way while traveling seasonally between summer and winter ranges (R. Boswell, UDWR, personal communication, Flower and Cramer, unpublished data). Habitat in the area includes sagebrush communities, conifer woodlands, riparian corridors, and small agricultural areas. Dominant vegetation includes sagebrush (*Artemisia* sp.), conifers (*Juniperus* sp., *Pinus* sp.), and riparian vegetation. Public lands adjacent to the interchange are under management of the U.S. Forest Service (west side; Dixie National Forest) and the U.S. Bureau of Land Management (east side; Color Country District).

MATERIAL AND METHODS

Feeding Exclosure Trial

To motivate deer and elk to attempt to cross over the experimental guards, I established six wildlife exclosures at Hardware Ranch and baited each with weed-free alfalfa cubes (Intermountain Farmers Association, Salt Lake City, UT, USA). Wildlife exclosures were constructed of 2-m-high woven wire fencing (10-m/side). I added a single strand of white, braided nylon-copper rope (ElectroBraid Fence Limited, Lititz, PA, USA) to increase the fence height to 2.3-m. At a 3-m-wide opening centrally located on one side of each exclosure, I constructed a 3-m × 2.1-m simulated wooden cattle guard approximately level with the ground (Fig. 9).

I constructed simulated cattle guards according to the design and dimensions of standard cattle guards found on Interstate 15. The cattle guard frame consisted of five, 2.1-m × 8.8-cm × 8.8-cm wooden support beams spaced evenly at 72-cm intervals and suspended over a 1-m-deep excavation. I secured 13 rectangular wooden rails measuring 3-m × 6.4-cm × 3.8-cm evenly at 9.5-cm intervals perpendicularly across the support beams and approximately level with the surrounding ground surface. I installed 9.5-cm × 3.8-cm wooden spacer blocks between the rails to prevent animals from stepping on support beams beneath the rails. I extended the fence line along the edges of the guard to prevent animals from accessing the exclosure by traversing along the sides of the guards. I painted all simulated cattle guards with metallic gray latex exterior paint.

The electrified pavement device (EPD; Lampman Wildlife Services, Ontario, Canada) used to augment the simulated cattle guards was constructed at two different widths to investigate if a difference in effectiveness existed between the two dimensions. The overall dimensions of the two EPD designs tested were 3-m long by either 0.91-m or 1.2-m-wide (dimension traversed by an animal entering the exclosure). The electrified material was contained by a rectangular plastic form constructed of 6.3-cm × 14-cm yellow recycled plastic boards (US Plastic Lumber, Chicago, IL, USA). The plastic form was filled with a black, conductive material impregnated with a matrix of stainless steel that delivered an electrical potential to the entire surface of the pavement-like slab. An additional yellow plastic board installed lengthwise in the center of the form partitioned it into two sections. To insulate the electrified material from earth ground, the bottom of the form was covered with a sheet of 12-mm thick plastic sheeting (Fig. 10).

The EPD was composed of two insulated slabs of conductive pavement. The negatively and positively charged surfaces created a difference of electric potential between the two surfaces meant to deliver a high-voltage (9.9 kV), short duration (< 3/10,000 second) shock to animals in simultaneous contact with both surfaces (Fig. 11). Further, the contrasting yellow and black coloration may have acted as aposematic coloring, providing a visual warning cue to animals that approached it (Seamans and Helon 2008). The EPD was powered by a Stafix X3^{TM} 3-Joule solar-powered energizer (Tru-Test Limited, Auckland, New Zealand), which delivered a maximum output voltage of 11.4-kilovolts to the conductive slabs at approximately 1.5-second intervals. A 40-watt solar panel, solar charge controller, and 12-volt deep-cycle battery were placed within each exclosure and provided continuous power to the system.

I installed one motion activated wildlife camera (RECONYX Model PC800 Hyperfire Professional; Holmen, WI, USA) on a post 1.8-m above the ground at the center of each exclosure to record wildlife approaches and behavioral reactions throughout the feeding exclosure trial. I oriented cameras toward the entrance of the exclosure and programmed each to take 5-10 consecutive photographs as fast as possible each time the camera was triggered and to retrigger immediately after detecting motion. The International Animal Care and Use Committee approved our procedures (Protocol #2432).

I maximized spacing between exclosures to reduce interdependence of deer and elk visitation and behavior among the exclosures (Seamans and Helon 2008, VerCauteren et al. 2009). Average spacing of exclosures at HRWMA was 1.09-km. The minimum and maximum distance between two exclosures was 0.57-km and 1.84-km, respectively. All exclosures were located at similar elevations and within comparable habitat.

We used a randomized complete block design and partitioned the six experimental units into two separate experimental blocks. We then randomly allocated three treatment levels (control = cattle guard, treatment 1 = cattle guard augmented with 0.91-m-wide EPD, treatment 2 = cattle guard augmented with 1.2-m-wide EPD) to the three experimental units within each of the two blocks. Because mule deer tend to avoid areas frequented by elk (Johnson et al. 2000, Stewart et al. 2002), we hypothesized that the three sites within the block closest to the winter elk feeding area (Block 2) would be subject to higher elk visitation rates, and by default, lower deer visitation rates than the three sites farthest from the elk feeding area (Block 1*)*. The putative homogeneity of sites within the same block was imparted by differences in elk presence between the two blocks and lead us to anticipate that sites within the same block may also have similar responses from deer and elk that visited them (Oehlert 2000, Fig. 12).

Prior to the start of the feeding trial, I covered the deterrents at all sites with untreated sheets of plywood and 2-cm of soil for a 5-week pre-treatment period. The pre-treatment period allowed animals to habituate to the exclosures, find the feed, and establish consistent use of the exclosures (Peterson et al. 2003). I visited sites every other day to maintain a supply of alfalfa cubes on the ground in the center of each exclosure. I used alfalfa cubes as bait because the feed is occasionally used by local wildlife managers during emergency winter feeding of ungulates near the study area. Further, the nutrient-rich feed was recommended as an attractive food source for ungulates during energetically stressful periods (D. DeBlooise, UDWR, personal communication). During pre-treatment, I also distributed feed atop the covered deterrents and adjacent to the fence opening to encourage animals to establish use of the exclosures. Pre-treatment took place over a 5-week period from 13 October to 16 November 2014.

Following the conclusion of the pre-treatment period, I removed the wooden sheets from the deterrents, energized the EPDs, and monitored animal approaches to each site for a 17-week treatment period. During the treatment period, I visited exclosures weekly at minimum to: 1) maintain a constant supply of fresh feed in the center of each exclosure, 2) clear accumulated snow from the surface of the deterrents and solar panels, 3) maintain continuous operation of the electrified material and cameras, 4) ensure no wildlife had become entangled in the fencing or guards, and 5) estimate snow cover and record snow depth atop the deterrents. The treatment period took place between 16 November 2014 and 16 March 2015. In total, I maintained the sites for a total of 22 weeks, from 13 October 2014 to 16 March 2015.

Image Analysis

I examined images of animal approaches to the deterrents and tabulated data gathered from images in a custom database (Access 2013, Microsoft Corporation, Redmond, WA, USA). A single observer analyzed all images to ensure consistency and limit observer bias. Each record in the database was comprised of an independent event in which one or more animals approached within 2-m of the deterrent. I did not tabulate images of animals that were recorded more than 2-m distant from the deterrents, because I did not consider those movements indicative of deterrent effectiveness (Allen et al. 2013). Groups of animals that were traveling together or that were present within the same 15-minute interval were treated as a single independent event because the movements of individuals within the same group were likely interdependent (Allen et al. 2013, Schwender 2013). For each event, I considered the outcome either a success (no animals in the event breached the deterrent) or a failure (at least one animal in the event breached the deterrent). For each event, the total number of individuals recorded within 2-m of the deterrent and the total number of individuals that breached the deterrent were also entered. Each individual animal in the event was classified as either: moving in parallel to the deterrent, repelling from the deterrent, or crossing the deterrent. Events were classified as behavior with intent to cross the deterrent (crossing behavior) when one or more animals in the event displayed behavior that appeared to indicate an intent to cross the deterrent. Qualifying behavior included, but was not limited to: circling the exclosure, pawing at or stepping on the deterrent, stalling at the fence opening, or by animals that placed their nose to the ground in front of, or on, the deterrent (Allen et al. 2013). Events were classified as a crossing when one or more animals completely breached the deterrent and gained access to the exclosure. Because I could not distinguish between individual animals during image analysis, I could not determine whether movement patterns at the exclosures were produced by different groups of animals or by the same groups detected multiple times. For each event, I also recorded the number of days since the start of the treatment period and whether snow was present on the surface of the deterrent during the event.

Effectiveness Estimation

I estimated the effectiveness of each of the three treatments levels as a barrier to animal movement by addressing the following research questions. First, what is the difference in the total number of weekly deer and elk intrusions across the treatments? I answered this question by comparing the total number of deer and elk that crossed over the treatments for each week of the 17-week treatment period. Second, how effective are the treatments as barriers to animals that *approach* them? I answered this question by calculating a distance-based crossing rate for each treatment; defined as the percentage of events in which animals crossed the treatments out of the total number of events in which animals *approached* within 2-m of the treatments (Allen et al. 2013). Because not all of the animals that approached the treatments may have intended to cross them, I selected a subset of events in which animals displayed behavioral cues to cross the treatments and posed a third research question: how effective are three treatments as a barrier to animals that *display behavior* to cross them? I answered this question by calculating a behavior-based crossing rate for each treatment; defined as the percentage of events in which animals crossed out of the total number of events in which animals *displayed behavioral cues* to cross the treatments. Qualifying behavior included animals that circled the exclosure, pawed at or stepped on the treatment, stalled at the fence opening, or by animals that placed their nose to the ground in front of, or on, the deterrent (Allen et al. 2013).

I calculated both a distance-based and a behavior-based crossing rate because, as noted by Allen et al. (2013), each metric had benefits and limitations. For example, while the distance metric had the benefit of being an objective measurement based on distance alone, it may have overestimated the effectiveness of the barrier because not all animals that approached within 2-m of the deterrents may have intended to cross them. In contrast, the behavioral metric avoided potential overestimation of barrier efficacy, but was a subjective measurement based on observer interpretation of animal behavior.

In addition to calculating the percentage of independent *events* that resulted in crossing, I also considered the total number of *individual animal approaches* within 2-m of the deterrents and the total number of those approaches that resulted in crossing. However, I did not base my inference of guard effectiveness on these metrics for the following reasons: 1) there was evidence from image analysis that movement and behavior among individuals was interdependent, 2) because I could not reliably distinguish between individuals, it was often difficult to reliably estimate the total number of individuals that approached the deterrents, and 3) inability to decipher between individuals likely led to overcounting individuals, which led to overestimates of the total number of individual approaches and resulted in efficacy metrics that were biased high.

Our null hypothesis was that mule deer would be as equally likely to cross cattle guards treated with electrified pavement as untreated cattle guards. Our alternative hypothesis was that mule deer would be less likely to cross treated cattle guards than untreated cattle guards. We posed similar hypotheses for elk. To test these hypotheses, and to examine explanatory variables associated with crossing events, we used generalized linear models to perform logistic regression analyses.

Statistical Model

We used generalized linear models with binomial distributions and logit-links to examine explanatory variables associated with crossing events, defined as an event in which one or more mule deer or elk breached the deterrent and gained access to the exclosure. We performed all analyses using the GLIMMIX procedure in SAS (Version 9.4; SAS Institute Inc., Cary, NC, USA) and cross-validated model output with model output from R (Version 3.1.1; The R Foundation for Statistical Computing, Vienna, Austria). The response variable was the binary outcome of each event and was assigned as either success (0 = no animals in the event breached the deterrent) or failure (1= at least 1 animal in the event breached the deterrent). We used a binary response variable rather than considering the proportion of individuals that breached the deterrent out of the total number of individuals that approached the deterrent, because: 1) movement and behavior among individuals was interdependent, and 2) it was often difficult to reliably estimate the total number of individuals involved in an event. We used the categorical explanatory variables of treatment level, block, and whether snow was present on the surface of the deterrent during the event. We also included the continuous explanatory variable of the number of days since the start of the treatment period to determine if the likelihood of crossing varied as the treatment period progressed (Table 9).

For the logistic regression models, we only considered events that included potential crossing behavior, where one or more animals in the event displayed behavior that was interpreted as intent to cross the deterrent and gain access to the exclosure. Events where potential crossing behavior was absent were defined as events where animals passed within 2-m of the deterrent, but did not display behavior that indicated an intent to enter the exclosure. Because these “parallel” movements may not have been directly indicative of deterrent effectiveness, we omitted them from the models (Schwender 2013). Discounting these movements ensured that only events in which animals appeared to attempt to breach the deterrents were considered in the models.

Road Trial

On an access road on the west side of Interstate 15, a segment of electrified pavement (0.91-m × 11-m) was installed along the full length of an existing standard cattle guard (2.1-m × 11-m; Fig. 13). The EPD was installed on the highway-entry side of the guard and was meant to prevent wildlife that originated from outside of the fenced highway corridor from gaining access to the highway. We selected the interchange as a test-site due to high mule deer activity documented in the area during pre-installation camera monitoring in 2013-2014, and low vehicle traffic volume on the access road leading to the interstate. The cattle guard consisted of twelve rectangular steel rails measuring 7.6-cm × 11-m spaced evenly at 10.1-cm intervals. The steel rails were suspended over a 30.4-cm-deep excavation, approximately level with the surrounding pavement. Materials used in the construction of the EPD road trial were identical to those used in the feeding exclosure trial. The width of the EPD was identical to that of the narrower pavement dimension in the feeding exclosure trial (0.91-m-wide, treatment level 1). Installation took place over a six-day period from 12-18 June 2014. The deterrent was energized on 29 July 2014. The EPD was powered by components identical to those used in the feeding exclosure trial (3-Joule solar-powered energizer, 40-Watt solar panel, solar charge controller, and 12-volt deep-cycle battery). To deter theft, components were located inside a steel box within a fenced area adjacent to the EPD. A warning sign was installed advising pedestrians to use an adjacent gate in the fence (Figure 13).

To determine the effectiveness of the experimental guard, I installed one motion activated wildlife camera (RECONYX Model PC85; Holmen, WI) on each end of the guard on 16 June 2014. I oriented cameras to face each other and programmed each to take 3-5 images as fast as possible for each motion trigger. To prevent power loss from repeated vehicle detections, I programmed cameras to be inactive from 10 A.M to 4 P.M at the start of the trial (16 June 2014 to 29 November 2014). After I ensured that cameras would remain powered between checks, I eliminated the inactive period and programmed cameras to be active for all hours (29 November 2014 to 22 April 2015). We visited cameras monthly to download images, change batteries, and ensure operation of the electrified pavement. Cameras continuously monitored wildlife approaches from mid-June 2014 to late-April 2015.

I used identical image analysis methods in the road trial and the feeding exclosure trial. In my final analysis, I only included animal movements that originated from outside of the fenced-highway corridor and omitted animal movements in which animals crossed the guard to escape the highway right-of-way (ROW). I did not consider animals that breached the guard while escaping the ROW as indicative of the effectiveness of the experimental guard for the following reasons: 1) animals that breached the guard while escaping the ROW only encountered the electric deterrent after breaching the cattle guard, 2) animals that attempted to escape the ROW may have been more motivated to cross the guard than animals that attempted to gain access to the ROW (Allen et. al

2013), and 3) the purpose of the guard was to deter animal entry into the ROW, rather than to prevent animal escape from the ROW.

RESULTS

Feeding Exclosure Trial

During the five-week pre-treatment period (13 October to 16 November 2014) at Hardware Ranch when the deterrents were covered, mean ambient temperature was 2.1°C and ranged from -21.4 to 23.8°C. During the pre-treatment period, observed snow cover ranged from 0 – 100% and recorded snow depth ranged from 0 to 8-cm. When the sheeting was removed and deterrents were exposed during the 17-week treatment period (16 November 2014 to 16 March 2015), mean ambient temperature was -1.3°C and ranged from -24.9 to 19.9°C (Utah Climate Center 2015). During the treatment period, observed snow cover ranged from 0 – 100% and recorded snow depth ranged from 0 to 8-cm.

Difference in weekly wildlife intrusions: control vs treatment.—When the deterrents were covered in weeks 1 to 5, I observed limited weekly mule deer intrusions across all sites ($\bar{x}$ = 6.2/week, min. = 0, max. = 13, Fig. 14). During this pre-treatment period, average weekly mule deer intrusions at controls sites ($\bar{x}$ = 2/week) were similar to those at treated sites (treatment level 1, $\bar{x}$ = 2.2/week; treatment level 2, $\bar{x}$ = 2/week). When I exposed the deterrents in the treatment period in weeks 6 to 22, mule deer intrusions were virtually eliminated across all sites until week 12 (late December 2014), when intrusions increased dramatically at the control sites only (Fig. 14). During weeks 12 to 22 of the treatment period, I recorded at least 55 deer intrusions at the control sites every week ($\bar{x}$ = 56.5/week, min. = 55, max. = 139), but never greater than 4 intrusions per week at treated sites during the same period ($\bar{x}$ = 1.0/week, min. = 0, max. = 4). Weekly deer intrusions at treated sites never exceeded weekly intrusions at controls sites and were lower at the treated sites in a total of 12 of 17 weeks during the treatment period (Fig. 14). In total, I recorded 983 mule deer intrusions into all sites during the treatment period. Of these, 967 (98.4%) were into control sites and 16 (1.6%) were into treated sites.

Unlike mule deer, elk regularly entered baited feeding exclosures during the five-week pre-treatment period, with intrusions peaking in week 4 (Fig. 15). During pre-treatment (deterrents covered) average weekly elk intrusions were somewhat lower at sites treated with the narrower pavement dimension (treatment level 1, $\bar{x}$ = 45.2/week) when compared with sites treated with the wider pavement dimension (treatment level 2, $\bar{x}$ = 56.8/week) and control sites ($\bar{x}$ = 60/week). When I exposed the deterrents in the treatment period, weekly elk intrusions were virtually eliminated at treated sites ($\bar{x}$ = 0.35/week, min. = 0, max. = 3) for the duration of the 17-week treatment period. However, elk intrusions at control sites occurred in nearly every week of the treatment period ($\bar{x}$ = 11.76/week, min. = 0, max. = 60; Fig. 15). Weekly elk intrusions at treated sites never exceeded weekly intrusions at controls and were lower in virtually every week of the treatment period (Fig. 15). In total, I recorded 206 elk intrusions into all sites during the treatment period. Of these, 200 (97.1%) were into control sites compared with 6 (2.9%) at treated sites.

Effectiveness of treatments as barriers to approaching animals.—Across all sites treated with electrified pavement (treatments 1 and 2 combined), I observed 166 independent events in which mule deer approached within 2-m of the deterrents during the treatment period (Table 10). Of these, 13 events (7.8%) resulted in a crossing event, in which one or more mule deer completely breached the deterrent and gained access to the fenced exclosure. Of the 13 deer crossing events at treated sites, 7 (53.8%) occurred when snow covered the electrified surface of the deterrents. Across the sites with only cattle guards (controls), there were 533 events in which mule deer approached the deterrents and 424 (79.5%) resulted in crossing. Out of 262 events in which elk approached treated sites, 5 events (1.9%) resulted in crossing, all of which occurred when snow covered the deterrents. In contrast, 130 of the 204 elk approach events (63.7%) resulted in crossing at the control sites.

I also considered the total number of individual wildlife approaches within 2-m of the deterrents and the total number of those approaches that crossed, or did not cross the deterrents (Table 11). Of the 363 total individual mule deer approaches at treated sites, a total of 16 deer (4.4%) crossed. Similarly, of the 1069 total individual elk approaches at treated sites, 6 animals crossed (0.6%). However, I did not base our inference on these metrics for the following reasons: 1) there was evidence from image analysis that movement and behavior between individuals was interdependent, 2) because I could not reliably distinguish between individuals, it was often difficult to reliably estimate the total number of individuals that approached the deterrents, and 3) inability to decipher between individuals likely led to overcounting individuals, which led to overestimates of the total number of individual approaches and resulted in efficacy metrics that were biased high.

Effectiveness of treatments as barriers to animals attempting to cross.—I then considered only events in which animals displayed behavioral cues to gain access to the fenced exclosures, which was a subset of the number of approach events (Table 12). Qualifying behavior included animals that circled the exclosure, pawed at or stepped on the deterrent, stalled at the fence opening, or by animals that placed their nose to the ground in front of, or on, the deterrent. Out of 82 events in which mule deer displayed behavior to access the exclosures, 13 events (15.9%) resulted in animals crossing at the sites treated with electrified pavement. In contrast, 424 out of 488 mule deer events (86.9%) resulted in an intrusion at untreated sites. Of the 199 elk events at the treated sites, 5 events (2.5%) resulted in animals crossing. Across the control sites, 139 out of 204 elk events (69.1%) resulted in crossing. I also considered the total number of individual wildlife approaches that included behavior to access the exclosures and the total number of these approaches that crossed, or did not cross the deterrents (Table 13).

Model results.—For mule deer, we detected a highly significant interaction between treatment level and the number of days since the start of the treatment period ($P < 0.001$; Table 14). There was also a significant block effect when considered at level $\alpha = 0.10$ ($P = 0.073$; Table 14). Model fit, as measured by the proportion of deviance explained by the fitted logistic regression model (D^2), was 0.398. The residual deviance of 376.88 was less than the 564 deviance degrees of freedom, indicating that overdispersion was absent.

When considered across all treatment levels and blocks, mule deer were significantly less likely to breach cattle guards treated with 0.91-m-wide electrical pavement (treatment level 1) than untreated cattle guards ($P < 0.001$; Table 15).

Similarly, mule deer were significantly less likely to breach cattle guards treated with 1.2-m-wide electrical pavement (treatment level 2) than untreated cattle guards (*P* < 0.001). However, the likelihood of deer incursion did not differ significantly between the two electrified pavement dimensions (*P* = 0.571). The likelihood of deer incursion at control sites increased significantly as the treatment period progressed and declined, though not significantly, at treated sites (Fig. 16, Fig. 17, Table 16). We rejected our null hypothesis that mule deer would be as equally likely to enter control sites as treated sites, in favor of the alternative that mule deer would be less likely to enter treated sites than control sites.

For elk, three of the four explanatory variables entered into the logistic regression model were statistically significant predictors of elk incursion at level $\alpha = 0.05$. These included the treatment level, block, and snow coverage (Table 17). Additionally, days since the start of the treatment period was statistically significant when considered at level $\alpha = 0.10$ (*P* = 0.060; Table 17). Model fit, as measured by the proportion of deviance explained by the fitted logistic regression model (D^2), was 0.483. There was no evidence of model overdispersion as the residual deviance of 257.64 was less than the 379 deviance degrees of freedom.

When considered across all treatment levels and blocks, elk were significantly less likely to cross cattle guards treated with electrified pavement than untreated cattle guards (*P* < 0.001; Table 18). However, the likelihood of elk intrusion was not significantly different between the two electrified pavement dimensions (*P* = 0.376). Snow cover was a highly significant predictor of elk crossing (*P* = 0.003) with elk intrusion significantly more likely when deterrents were snow covered compared with snow-free. Days since the start of the treatment period was a marginally significant predictor of elk crossing (*P* = 0.060) with the likelihood of incursion increasing slightly as the test proceeded (Fig. 18, Fig. 19). We rejected our null hypothesis that elk would be as equally likely to enter control sites as treated sites, in favor of the alternative that elk would be less likely to enter treated sites than control sites.

In week 17, the control site in block two was destroyed by two bull elk that jumped the cattle guard and subsequently fought within the exclosure. I censored observations after the exclosure was destroyed and ended data collection at the site six days later. I also documented and repaired damage to fences at control sites on two occasions and on three occasions at treated sites. At the control site in block one, I repaired fence damage on two occasions that indicated deer had jumped the fence to gain access to the exclosure. I did not find any evidence of animals jumping the fence at the other control site or at any of the treated sites. I censored a limited number of observations at one of the control stations when it appeared that deer had jumped the fence to gain access to the exclosures.

At treated sites, weekly voltage readings were 9.8 - 9.9 kV, except on one occasion when the voltage dropped below 7.0 kV at one site due to a faulty solar energizer that I replaced. I also replaced a battery after observing complete power loss at one site after snow obscured the solar array for approximately 60 hours. However, I did not record any wildlife intrusions at the site during this period of power loss. I checked voltage at the treatment sites on two occasions in the pre-dawn hours and observed lower battery voltage, but no decrease in deterrent voltage.

I recorded one event in which a moose (*Alces alces*) approached and displayed behavior to cross a cattle guard treated with 0.91-m-wide electric pavement. The animal was subsequently repelled from the deterrent and did not gain access to the exclosure. I recorded images of, but did not include, the following species in analyses due to insufficient sample size (≥10 events): domestic dog (*Canis lupus familiaris*), common raven (*Corvus corax*), hare (*Sylvilagus* sp.), great horned owl (*Bubo virginianus*), magpie (*Pica hudsonia*), coyote (*Canis latrans*), red fox (*Vulpes vulpes*), raccoon (*Procyon lotor*), striped skunk (*Mephitis mephitis*), domestic cattle (*Bos taurus*), and deer mouse (*Peromyscus* sp.).

Road Trial

Mean ambient temperature during the 38-week road trial was 13.5°C and ranged from -10.0°C to 35.9°C (PRISM Climate Group 2014). Although snow cover ranged from 0 – 100% during the test, I observed no wildlife approaches to the experimental guard when snow was present. Voltage readings were 9.8 – 9.9 kV on every visit except one occasion when the voltage dropped to 7.7 kV.

I observed 61 independent events in which mule deer approached within 2-m of the cattle guard augmented with a strip of 0.91-m-wide electrified pavement. Of these, 37 events (60.7%) resulted in a crossing event, in which one or more mule deer completely breached the guard and gained access to the fenced highway segment (Table 19). However, 31 of 37 (83.7%) crossing events occurred when deer breached though a 20-cm-wide gap between edge of the electrified pavement and the fence that was left unmitigated when the deterrent was installed. Further, I was unable to decipher whether deer crossed, or did not cross, in 24.6% of the events. I incorporated uncertainty from these inconclusive events into an estimate of the upper and lower range of effectiveness of the experimental guard. I calculated the lower effectiveness estimate by assuming that all of the inconclusive events resulted in crossing. For the upper estimate, I assumed that none of the inconclusive events resulted in crossing (Table 19). In total, I observed 91 individual mule deer approaches within 2-m of the guard. Of these, 55 (60.4%) crossed the guard and gained access to the fenced highway segment (Table 20).

I then considered only events in which deer displayed behavioral cues to cross the guard, which was a subset of the number of the approach events. Out of 53 events in which deer displayed behavior to cross the guard, 37 (69.8%) resulted in a crossing event (Table 21). Most crossing events (83.7%) occurred when deer crossed through the unmitigated fence gap on one end of the guard. Eight of the 53 events (15.1%) were inconclusive and were used to calculate an effectiveness range for the guard. In total, I observed 85 individual mule deer approaches that displayed behavior to cross the guard. Of these, 55 (64.7%) crossed the guard and gained access to the fenced highway corridor (Table 22).

Because events in which deer breached the unmitigated gap between the deterrent and the fence may not have been directly indicative of guard effectiveness, I also examined a subset of the 53 events in which deer displayed behavior to cross the guards. Out of the 53 events, there were 13 events in which deer attempted to cross the deterrent surface of the guard directly, rather than by circumventing the deterrent by crossing through the unmitigated fence gap. Of the 13 events in which deer challenged the guard directly, 6 (46.1%) resulted in crossing. Deer jumped the guard in 4 of 6 (66.6%) crossings. The remaining 2 crossings (33.3%) were the result of deer that walked across the deterrent. In total, I recorded 18 individual approaches by mule deer that appeared to challenge the guard directly and 6 mule deer (33.3%) crossed.

In additional to mule deer, I also recorded domestic cats (*Felis catus*), domestic dogs (*Canis lupus familiaris*), raccoons (*Procyon lotor*), and wild turkeys (*Meleagris gallopavo*) cross the experimental guard from the highway entry side while it was energized, but did not include them in the final analysis due to insufficient sample size (≤10 events).

DISCUSSION

Regardless of the dimension of the electrified pavement (0.91-m or 1.2-m-wide), simulated cattle guards augmented with a segment of the material were >80% effective in excluding mule deer and >95% effective in excluding elk from baited wildlife exclosures. However, when applied to an existing standard cattle guard spanning an access road to Interstate 15, a segment of the material (0.91-m-wide) was no more than 54% effective in preventing mule deer access to the highway. Although we demonstrated that cattle guards augmented with electrified pavement were effective barriers to deer and elk movement under the conditions of the feeding exclosure trial, we found the design only marginally effective at securing the highway right-of-way from deer intrusions during the road trial.

While snow coverage emerged as a highly significant predictor of elk intrusion in our feeding trial model, the variable was not a predictor of deer intrusion. The lack of significance was likely the result of numerous deer intrusions across simulated cattle guards at control exclosures in both snow and snow-free conditions. During the feeding exclosure trial, we observed a loss of deterrent effectiveness when snow accumulated on the surface of the electrified pavement. Snow was present on the surface of the electrified pavement in all of the elk crossing events, and in most of the mule deer crossing events. Based on animal reactions documented in photographs, electrified pavement was capable of delivering a shock to animals through a light layer (≤ 1.3-cm) of snow. However, we observed sharp declines in effectiveness when approximately 7-cm of snow accumulated on the electrified surface. At this snow depth, animals appeared to be insulated from the electrified pavement and could stand on the snow-covered deterrent before jumping across the cattle guard. In snowy climates, proactive snow and ice removal would be critical to maintain the effectiveness of electrified pavement. Internal heating elements within the electrified material have already been incorporated into subsequent designs and may mitigate this problem (R. Lampman, Lampman Wildlife Services, personal communication). However, snow melt capabilities would increase the cost of the device and would require either a direct power connection or an on-site electrical generator capable of producing more energy than a typical solar panel.

The highly significant interaction between treatment level and the number of days since the start of the treatment period indicated that the effect of the treatments on the likelihood of deer intrusion depended on the number of days the deterrents were exposed. As the feeding trial progressed, the likelihood of deer crossing untreated guards increased significantly, but declined (though not significantly) at treated cattle guards. This result suggests that as the winter progressed and natural forage availability declined, deer became increasingly motivated to access feed within the exclosures and learned to defeat untreated cattle guards. Simultaneously, deer avoided the electrified pavement at treated guards. Future monitoring of new electrified pavement installations may reveal a similar trend, in which the barrier effect of the deterrent increases over time as animals respond to aversive conditioning. For elk, the marginally significant predictor of days since the start of the test indicated that, when considered across all treatments, the likelihood of elk intrusion increased slightly (though not significantly) as the test proceeded. This result was likely driven by elk intrusions into control exclosures and was not indicative of a decline of treatment effectiveness over time.

The marginally significant block effect indicated that mule deer intrusions were less likely to occur at exclosures within block 2, where elk presence tended to be higher, when compared with block 1, where elk presence tended to be lower. In contrast, the significant block effect for elk indicated that elk were more likely to enter exclosures within block 2, when compared with block 1. These results confirmed our *a priori* designation of blocks during experimental design based on spatial differences in elk presence between the two blocks.

We hypothesize the discrepancy in electrified pavement efficacy between the feeding exclosure trial and the road trial was due to two primary factors. First, animals may have been subject to different levels of motivation to breach the deterrents in the two trials. Animals in the feeding exclosure trial were motivated to access a high-quality food source within our exclosures during winter - the most energetically stressful time of year (VerCauteren et al. 2009, Seamans and Helon 2008). It is possible that elk were less motivated to access feed within our exclosures due to the presence of supplemental grass hay available to them during the winter elk feeding program, which operated during weeks 9 to 18 of the feeding exclosure trial. However, because deer were mostly excluded from supplemental grass hay by elk, deer appeared to remain motivated to access alfalfa within our exclosures throughout the trial, despite the presence of grass hay provided to elk at the winter elk feeding area outside of our exclosures. In contrast, deer in the road trial may have been motivated to cross the deterrent by migration imperatives, to access mates, or to escape predators. When sufficiently motivated, deer can exhibit non-typical behaviors (Reidinger and Miller 2013). In short, the discrepancy in electrified pavement efficacy between the two trials may have been influenced by deer that were more motivated to breach the deterrent in the road trial than in the feeding exclosure trial.

Second, important differences existed between the electrical contexts of the deterrents in the two trials. In the feeding exclosure trial, an electrical potential existed between the negatively and positively charged surfaces of the material (9.9 kV), but also between the negatively charged surface of the material and the soil in front of the deterrent (earth ground, 4-5 kV). Animals in the feeding exclosure trial were shocked under certain conditions when in contact with the negative surface of the material and the soil in front of the deterrent. This effect was absent from the road trial because road pavement insulated animals from earth ground. That is, there was no electrical potential between the negative surface of the deterrent and the surface of the road, and only negligible potential (0.3 kV) between the positive surface of the deterrent and the surface of the road. In the road trial, we observed instances of deer being shocked while in simultaneous contact with the negatively and positively charged surfaces of the deterrent. However, deer did not react when in simultaneous contact with the negative surface of the deterrent and the road pavement in front of the deterrent. Due to the presence of an earth ground (soil) in the feeding exclosure trial, there were multiple routes for animals to complete the circuit and receive a shock. However, there was a single route for animals to receive a shock in the road trial – an animal in simultaneous contact with the negatively and positively charged surfaces of the deterrent. In short, the presence of soil in front of the deterrent in the feeding exclosure trial acted a *de facto* extension of the negative surface of the deterrent, thereby expanding the total width of the active deterrent surface.

Seamans and Helon (2008) evaluated an electrified mat consisting of metal electrodes implanted into alternating yellow and black plastic planks. The design was 95% effective at reducing white-tailed deer (*Odocoileus virginianus*) intrusions into feeding stations, although some deer jumped over the mat. However, in a subsequent field test of four electric mats along Highway 101 in California, Siepel et al. (2013) documented mule deer crossing the mats in 54 out of 63 events (14.3% effective). While Siepel's work found that electric mats did deter a black bear (*Ursus americanus*) from entering the road corridor, the authors suggested the design should be modified to more effectively exclude mule deer. Like Siepel et al. (2013), we found two electrified mats deployed along U.S. Route 6 in Utah to be poor barriers to mule deer movement, with deer crossing the mats in 67 out of 85 events (17.6 – 21.2% effective, Flower and Cramer, unpublished data). The results we present here from cattle guards augmented with electrified pavement suggest a similar pattern of effectiveness as demonstrated in work by Seamans and Seipel. Like Seamans and Helon (2008), we found strong effectiveness of an electrified barrier under experimental conditions using feed bait as a reward. However, like Siepel et al. (2013), we found limited effectiveness of the deterrent in a real-world setting along a busy roadway.

Recently, Allen et al. (2013) evaluated two wildlife guards deployed along U.S. Highway 93 in Montana. The guards consisted of a steel bridge grating (6.6-m × 6.8-m) suspended over 45-cm-deep pits. The wildlife guards were >90% effective for mule deer that displayed behavior to cross them (*n* = 21 events), but were less effective for black bear and coyotes (33% and 55%, respectively). In other work, we found two similar, but smaller wildlife guards (4.8-m × 4.8-m) adjacent to U.S Highway 91 in Utah, to be ≥80% effective for mule deer that displayed behavior to cross them (*n* = 179 events, Flower and Cramer, unpublished data). Under the conditions of the feeding exclosure trial, cattle guards augmented with electrified pavement in this study were slightly less effective for mule deer than the wildlife guards tested by Allen et al. (2013), but were more effective than the wildlife guards we monitored along roadways in Utah. However, when tested under in-road conditions, the augmented cattle guards were approximately 35% less effective in excluding mule deer from the highway than the wildlife guards in Allen's study.

In Utah, the most common method to increase the effectiveness of standard cattle guards is to install an additional cattle guard adjacent to the existing guard, thereby increasing the total width of the deterrent surface to 3.8-m to 4.8-m-wide. The Utah Department of Transportation and the US Army have each monitored one of these double cattle guards and estimated they were 90-95% effective for mule deer and 60-70% for elk, though these unpublished, short-term monitoring efforts lacked consistent methods and replication (D. Babcock, UDOT, personal communication, U.S. Army 2006). Belant et al. (1998) found that a similar, 4.6-m-wide simulated cattle guard with round bars reduced white-tailed deer crossings through fence openings by >95%. In other work, we evaluated four double cattle guards deployed along Utah's highways. The design was a significant barrier to mule deer and successfully secured gaps in wildlife fencing in

>80% of recorded events (*n* = 337, Flower and Cramer, unpublished data). Results from the feeding exclosure trial indicate that cattle guards augmented with electrified pavement excluded mule deer at rates comparable to that of double cattle guards (>80% effective). However, results from the road trial suggest that the augmented cattle guard was substantially less effective for mule deer (54% effective) when compared with a double cattle guard (>80% effective).

In this study, our objective was to evaluate whether a standard cattle guard augmented with a segment of electrified pavement could reduce wildlife intrusions at rates comparable to specialized guards, but at reduced cost. Although results from the feeding exclosure trial suggest that standard cattle guards augmented with electrified pavement can deter mule deer at rates comparable to specialized guards, results from the road trial were mixed. Installing an additional standard cattle guard (2.1-m × 11-m) to an existing cattle guard costs approximately $32,400 ($900/ft., R. Taylor, UDOT, personal communication). In contrast, augmenting a standard cattle guard of the same dimension (11-m-long) with a segment of electrified pavement (0.91-m × 11-m) costs approximately $27,000 ($750/ft., R. Taylor, UDOT, personal communication). Based on these cost estimates, electrified pavement yields a total cost-savings of $5,400 when compared to the cost of installing an additional standard cattle guard. However, these initial cost-savings would likely be offset by costs associated with maintenance of the electrified pavement and electrical components over the life of the barrier. In contrast, double cattle guards and wildlife guards require minimal post-installation maintenance.

Although the cost of electrified pavement is forecast to decrease in the future (R. Lampman, Lampman Wildlife Services, personal communication), at present, a standard cattle guard augmented with a segment of the material does not appear to offer substantial cost-savings when compared with the cost of an additional standard cattle guard. When costs due to property damage, human injury, human death, and deer loss are combined, the estimated mean cost of a single deer-vehicle collision ranges from $3,834 (Bissonette et al. 2008, Consumer Price Index [CPI] Adjustment to 2015 dollars) to $7,593 (Hiujser et al. 2009, CPI Adjustment to 2015 dollars). Based on these cost estimates, a double cattle guard or wildlife guard that cost $30,000 to $60,000 would need only prevent 4 to 16 deer-vehicle collisions over the life of the barrier to justify investment.

MANAGEMENT IMPLICATIONS

The central goal of this research was to provide a rigorous assessment of a cost-effective retrofit to cattle guards that could reduce wildlife intrusions to roadways and other protected areas. Based on strong results from the feeding exclosure trial, electrified pavement appears to have potential as an effective tool to reduce ungulate access to fenced resources when deployed at wider dimensions. Moreover, the material may offer a mitigation option for locations unsuitable for double cattle guards and wildlife guards, such as at end points in wildlife exclusion fencing and/or across roads with annual average daily traffic of greater than 500 vehicles. However, mixed results from the road trial suggest that further research is needed to determine the efficacy of electrified pavement for use in roadway applications. Monitoring replicated installations of electrified pavement over multi-year time spans would likely yield a comprehensive assessment of the material under different roadway scenarios and may improve the essential function of this innovative emerging technology – to reduce risk for motorists and wildlife along our highways.

Limitations

Our feeding exclosure trial was modeled after existing ungulate deterrence research (VerCauteren et al. 2009, Seamans and Helon 2008, Peterson et al. 2003). We believe the evaluation provided a robust estimate of deterrent effectiveness under the conditions in which we tested. However, our in-road results were derived from a limited number of useful events ($n = 13$) from a single field site. Further, we did not evaluate full scale, stand-alone deployments of electrified pavement (≥1.8-m-wide) that could be more effective than the narrower dimensions (0.91-m to 1.2-m-wide) that we used to augment cattle guards. At wider dimensions, electrified pavement may be more effective in excluding ungulates and could offer a method to close the 15-20% effectiveness gap that exists between specialized guards (≥80% effective) and an absolute wildlife barrier (100% effective). Further, electrified pavement may represent a promising mitigation option for wildlife species with non-hoof foot morphology, such as canids, felids, and ursids, which may be more susceptible to electric shock than cervids.

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TABLES AND FIGURES

Table 9. Measured variables included in logistic regression models used to examine explanatory variables associated with mule deer and elk intrusions into experimental feeding stations at Hardware Ranch Wildlife Management Area, Utah, USA.

Variable Type	**Variable Name**	**Variable Description**
Response	Cross Code	0 = non-crossing event, 1 = crossing event
Explanatory	Treatment Level	0 = cattle guard (control)
		1 = cattle guard with 0.91-m-wide electric pavement
		2 = cattle guard with 1.2-m-wide electric pavement
	Block	1 = block 1, 2 = block 2
	Snow	0 = no snow present, 1 = snow present on deterrent
	Day	Days since start of the treatment period (0 – 119)

Table 10. Number and percentage of independent events in which animals approached (within 2-m) and subsequently crossed, or did not cross, deterrents at entrances to baited wildlife exclosures during the 17-week treatment period (mid-Nov 2014 to mid-Mar 2015) at Hardware Ranch Wildlife Management Area, Utah.

Species	**Treatment Level**	**Approached**	**Crossed**	**% Crossed**	**Did not cross**	**% Effective**
Mule Deer	Treatment 1[a]	74	4	5.4	70	94.6
	Treatment 2[b]	92	9	9.8	83	90.2
	Treatments Combined	166	13	7.8	153	92.2
	Control[c]	533	424	79.5	109	20.5
Elk	Treatment 1[a]	130	1	0.8	129	99.2
	Treatment 2[b]	132	4	3.0	128	97.0
	Treatments Combined	262	5	1.9	257	98.1
	Control[c]	204	130	63.7	74	36.3

[a] = cattle guard augmented with 0.91-m-wide electric pavement

[b] = cattle guard augmented with 1.2-m-wide electric pavement

[c] = cattle guard

Table 11. Number and percentage of individual wildlife approaches (within 2-m) that crossed, or did not cross, deterrents at entrances to baited wildlife exclosures during the 17-week treatment period (mid-Nov 2014 to mid-Mar 2015) at Hardware Ranch Wildlife Management Area, Utah.

Species	**Treatment Level**	**Approached**	**Crossed**	**% Crossed**	**Did not cross**	**% Effective**
Mule Deer	Treatment 1[a]	161	4	2.5	157	97.5
	Treatment 2[b]	202	12	5.9	190	94.1
	Treatments Combined	363	16	4.4	347	95.6
	Control[c]	1914	967	50.5	947	49.5
Elk	Treatment 1[a]	432	2	0.5	430	99.5
	Treatment 2[b]	637	4	0.6	633	99.4
	Treatments Combined	1069	6	0.6	1063	99.4
	Control[c]	974	200	20.5	774	79.5

[a] = cattle guard augmented with 0.91-m-wide electric pavement

[b] = cattle guard augmented with 1.2-m-wide electric pavement

[c] = cattle guard

Table 12. Number and percentage of independent events in which animals approached (within 2-m) and displayed behavior to cross and subsequently crossed, or did not cross, deterrents at entrances to baited wildlife exclosures during the 17-week treatment period (mid-Nov 2014 to mid-Mar 2015) at Hardware Ranch Wildlife Management Area, Utah.

Species	**Treatment Level**	**Approached**	**Crossed**	**% Crossed**	**Did not cross**	**% Effective**
Mule Deer	Treatment 1[a]	33	4	12.1	29	87.9
	Treatment 2[b]	49	9	18.4	40	81.6
	Treatments Combined	82	13	15.9	69	84.1
	Control[c]	488	424	86.9	64	13.1
Elk	Treatment 1[a]	96	1	1.0	95	99.0
	Treatment 2[b]	103	4	3.9	99	96.1
	Treatments Combined	199	5	2.5	194	97.5
	Control[c]	188	130	69.1	58	30.9

[a] = cattle guard augmented with 0.91-m-wide electric pavement

[b] = cattle guard augmented with 1.2-m-wide electric pavement

[c] = cattle guard

Table 13. Number and percentage of individual wildlife approaches (within 2-m) that displayed behavior to cross and subsequently crossed, or did not cross, deterrents at entrances to baited wildlife exclosures during the 17-week treatment period (mid-Nov 2014 to mid-Mar 2015) at Hardware Ranch Wildlife Management Area, Utah.

Species	**Treatment Level**	**Approached**	**Crossed**	**% Crossed**	**Did not cross**	**% Effective**
Mule Deer	Treatment 1[a]	52	4	7.7	48	92.3
	Treatment 2[b]	114	12	10.5	102	89.5
	Treatments Combined	166	16	9.6	150	90.4
	Control[c]	1417	967	68.2	450	31.8
Elk	Treatment 1[a]	204	2	1.0	202	99.0
	Treatment 2[b]	401	4	1.0	397	99.0
	Treatments Combined	605	6	1.0	599	99.0
	Control[c]	718	200	27.9	518	72.1

[a] = cattle guard augmented with 0.91-m-wide electric pavement

[b] = cattle guard augmented with 1.2-m-wide electric pavement

[c] = cattle guard

Table 14. Type III test of fixed effects including degrees of freedom, *F*-statistics, and *P*-values from a generalized linear model used to examine explanatory variables associated with mule deer intrusions into baited wildlife exclosures at Hardware Ranch Wildlife Management Area, Utah, USA.

Effect	**Numerator DF**	**Denominator DF**	***F*-value**	***P*-value**
Block	1	564	3.23	0.0731
Treatment Level	2	564	0.19	0.8251
Day	1	564	2.34	0.1265
Day × Treatment Level	2	564	11.95	<0.0001

Table 15. Differences of treatment level least squares means for mule deer. Variable coefficients, standard error, degrees of freedom, *t*-statistic, and *P*-values for a logistic regression model used to examine explanatory variables associated with mule deer intrusions into baited wildlife exclosures at Hardware Ranch Wildlife Management Area, Utah, USA.

Treatment Level	**Estimate**	**SE**	**DF**	***t*-value**	***P*-value**
Control vs. Treatment 1	4.3336	0.6827	564	6.35	<.0001
Control vs. Treatment 2	3.9083	0.4242	564	9.21	<.0001
Treatment 1 vs. Treatment 2	-0.4253	0.7504	564	-0.57	0.5711

Table 16. Variable coefficients, standard error, degrees of freedom, t-statistics, and *P*-values for a logistic regression model used to examine explanatory variables associated with mule deer intrusions into baited wildlife exclosures at Hardware Ranch Wildlife Management Area, Utah, USA. Results from block 1 only. Block 2 results showed similar relationships.

Label	**Estimate**	**SE**	**DF**	**t-value**	**P-value**
Control Intercept	-1.5274	0.4972	564	-3.07	0.0022
Control Slope	0.05441	0.008370	564	6.50	<.0001
Treatment 1 Intercept	-0.9364	1.1480	564	-0.82	0.4150
Treatment 1 Slope	-0.01319	0.01837	564	-0.72	0.4729
Treatment 2 Intercept	-1.0506	0.8667	564	-1.21	0.2259
Treatment 2 Slope	-0.00579	0.01132	564	-0.51	0.6095
Control - Treatment 1 Slope	0.06760	0.02018	564	3.35	0.0009
Control - Treatment 2 Slope	0.06020	0.01408	564	4.27	<.0001
Treatment 1 - Treatment 2 Slope	-0.00741	0.02158	564	-0.34	0.7315

Table 17. Type III test of fixed effects including degrees of freedom, *F*-statistics, and *P*-values from a generalized linear model used to examine explanatory variables associated with elk intrusions into baited wildlife exclosures at Hardware Ranch Wildlife Management Area, Utah, USA.

Effect	**Numerator DF**	**Denominator DF**	***F*-value**	***P*-value**
Block	1	379	6.92	0.0089
Treatment Level	2	379	32.64	<.0001
Snow	1	379	8.84	0.0031
Day	1	379	3.55	0.0603

Table 18. Differences of treatment level least squares means for elk. Variable coefficients, standard error, degrees of freedom, *t*-statistic, and *P*-values for a logistic regression model used to examine explanatory variables associated with mule deer intrusions into baited wildlife exclosures at Hardware Ranch Wildlife Management Area, Utah, USA.

Treatment Level	**Estimate**	**SE**	**DF**	***t*-value**	***P*-value**
Control vs. Treatment 1	5.7198	1.0473	379	5.46	<.0001
Control vs. Treatment 2	4.6931	0.6951	379	6.75	<.0001
Treatment 1 vs. Treatment 2	-1.0268	1.1606	379	-0.88	0.3769

Table 19. Number and percentage of independent **events in which mule deer approached** (within 2-m) and subsequently crossed, or did not cross, a 2.1-m × 11-m cattle guard augmented with 0.91-m × 11-m electrified pavement near Pintura, Utah, USA, during the study period (late-Jul 2014-late-Apr 2015).

Species	**Approached**	**Crossed**	**% Crossed**	**Did not cross**	**Inconclusive**[*]	**% Effective**
Mule Deer	61	37	60.7	9	15	14.8 – 39.3

[*] Inconclusive = events in which it was uncertain if deer crossed, or did not cross, the deterrent.

Table 20. Number and percentage of **individual mule deer approaches** (within 2-m) that crossed, or did not cross, a 2.1-m × 11-m cattle guard augmented with 0.91-m × 11-m electrified pavement near Pintura, Utah, USA, during the study period (late-Jul 2014-late-Apr 2015).

Species	**Approached**	**Crossed**	**% Crossed**	**Did not cross**	**Inconclusive**[*]	**% Effective**
Mule Deer	91	55	60.4	22	14	24.2 – 39.6

[*] Inconclusive = approach in which it was uncertain if deer crossed, or did not cross, the deterrent.

Table 21. Number and percentage of independent **events in which mule deer displayed behavior to cross** and subsequently crossed, or did not cross, a 2.1-m × 11-m cattle guard augmented guard augmented with 0.91-m × 11-m electrified pavement near Pintura, Utah, USA, during the study period (late-Jul 2014-late-Apr 2015).

Species	**Approached**	**Crossed**	**% Crossed**	**Did not cross**	**Inconclusive***	**% Effective**
Mule Deer	53	37	69.8	8	8	15.1 – 30.2

* Inconclusive = events in which it was uncertain if deer crossed, or did not cross, the deterrent.

Table 22. Number and percentage of **individual mule deer approaches (within 2-m) that displayed behavior to cross** and subsequently crossed, or did not cross, a 2.1-m × 11-m cattle guard augmented with 0.91-m × 11-m electrified pavement near Pintura, Utah, USA, during the study period (late-Jul 2014-late-Apr 2015).

Species	**Approached**	**Crossed**	**% Crossed**	**Did not cross**	**Inconclusive[*]**	**% Effective**
Mule Deer	85	55	64.7	21	9	24.7 – 35.3

[*] Inconclusive = approach in which it was uncertain if deer crossed, or did not cross, the deterrent.

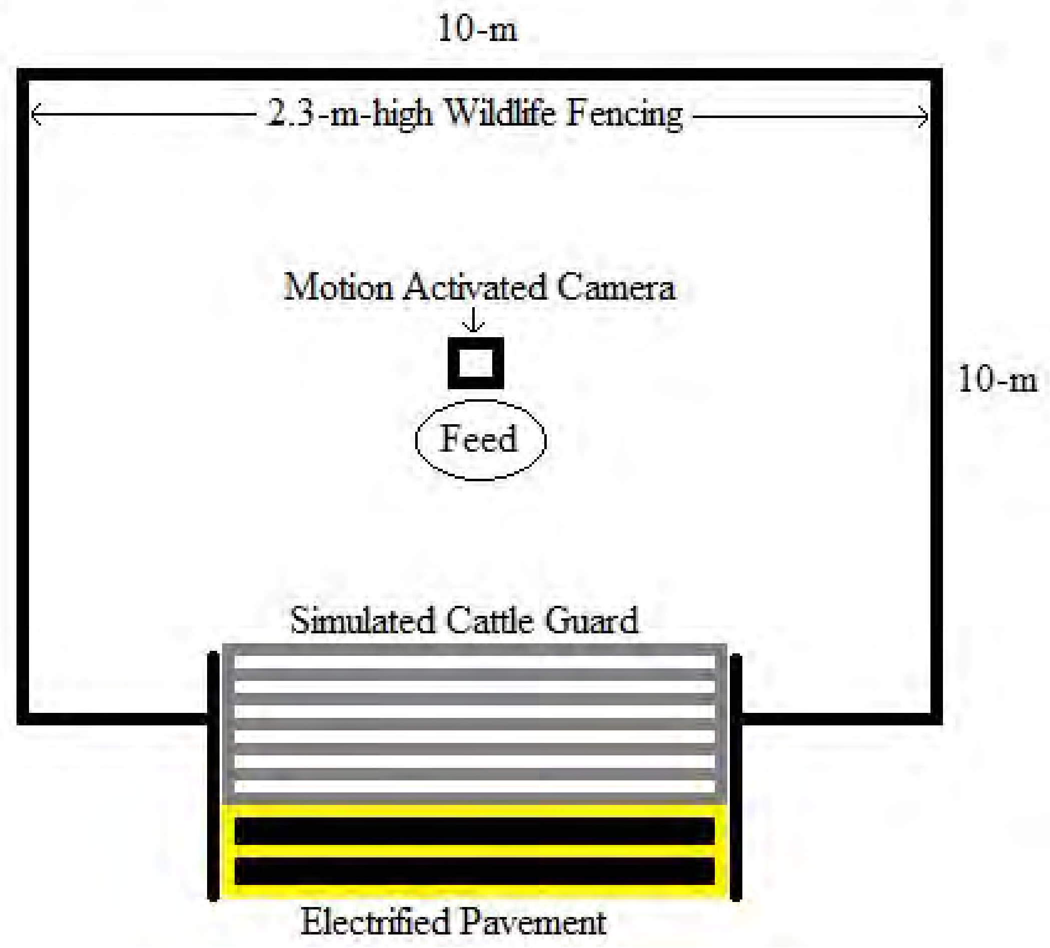

Figure 9. Top view of a 10 × 10-m wildlife exclosure used to test 3 × 2.1-m cattle guards augmented with either 3 × 1.2-m (n = 2) or 3 × 0.91-m (n = 2) electrified pavement as an ungulate barrier at Hardware Ranch Wildlife Management Area, Utah, from mid-Oct 2014 to mid-March 2015. Four sites had cattle guards treated with electrified pavement and two sites had untreated cattle guards.

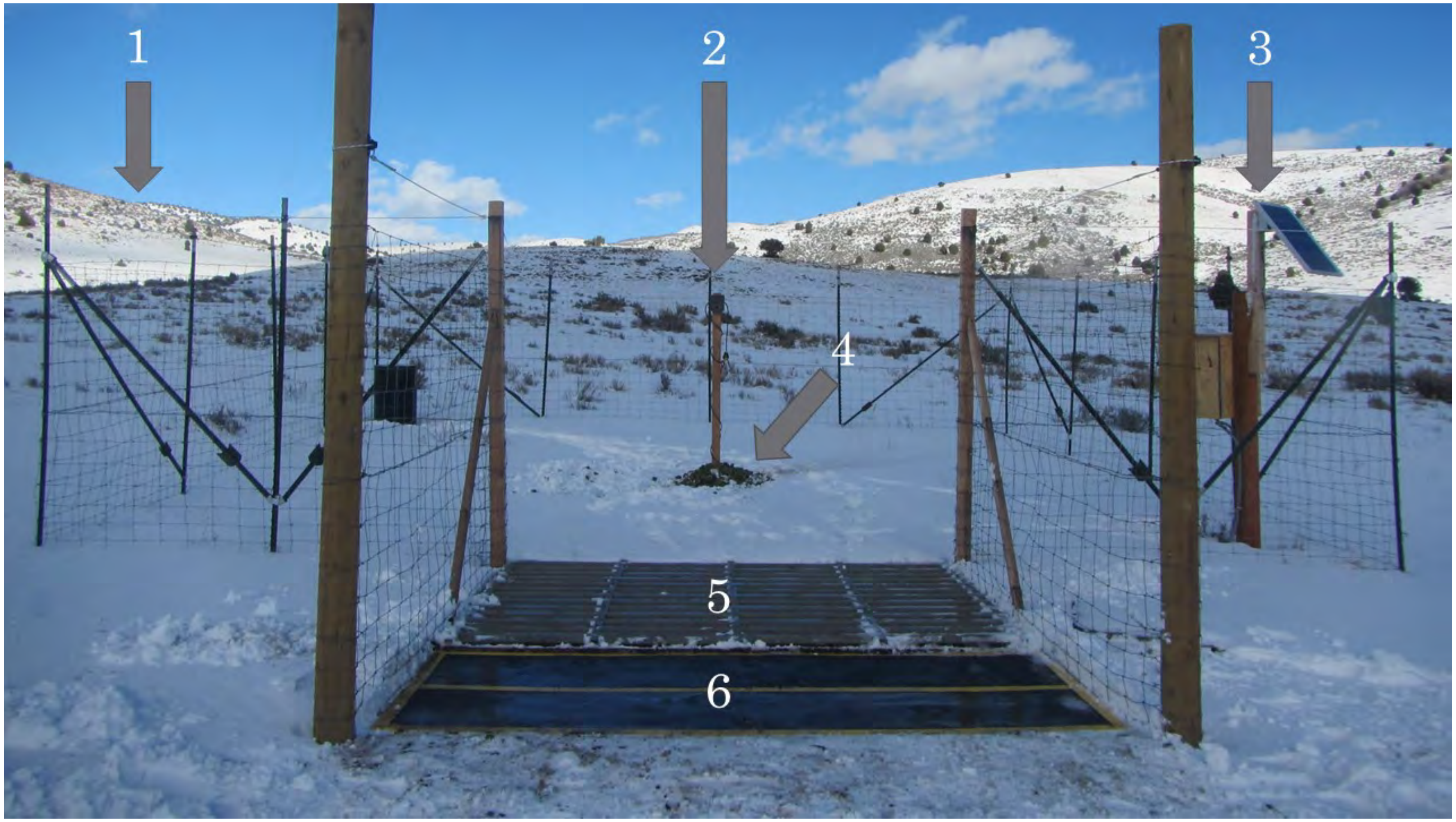

Figure 10. Front view of a 10 × 10-m wildlife exclosure used to test efficacy of 3 × 2.1-m cattle guards augmented with either 3 × 1.2-m (n = 2; pictured) or 3 × 0.91-m (n = 2) electrified pavement as an ungulate barrier at Hardware Ranch Wildlife Management Area, Utah, from mid-Oct 2014 to mid-March 2015. Symbols added to indicate exclosure elements: 1 = 2.3-m-high woven wire fencing, 2 = motion activated camera (Reconyx PC800), 3 = solar panel, 4 = alfalfa feed bait, 5 = simulated cattle guard, and 6 = electrified pavement device.

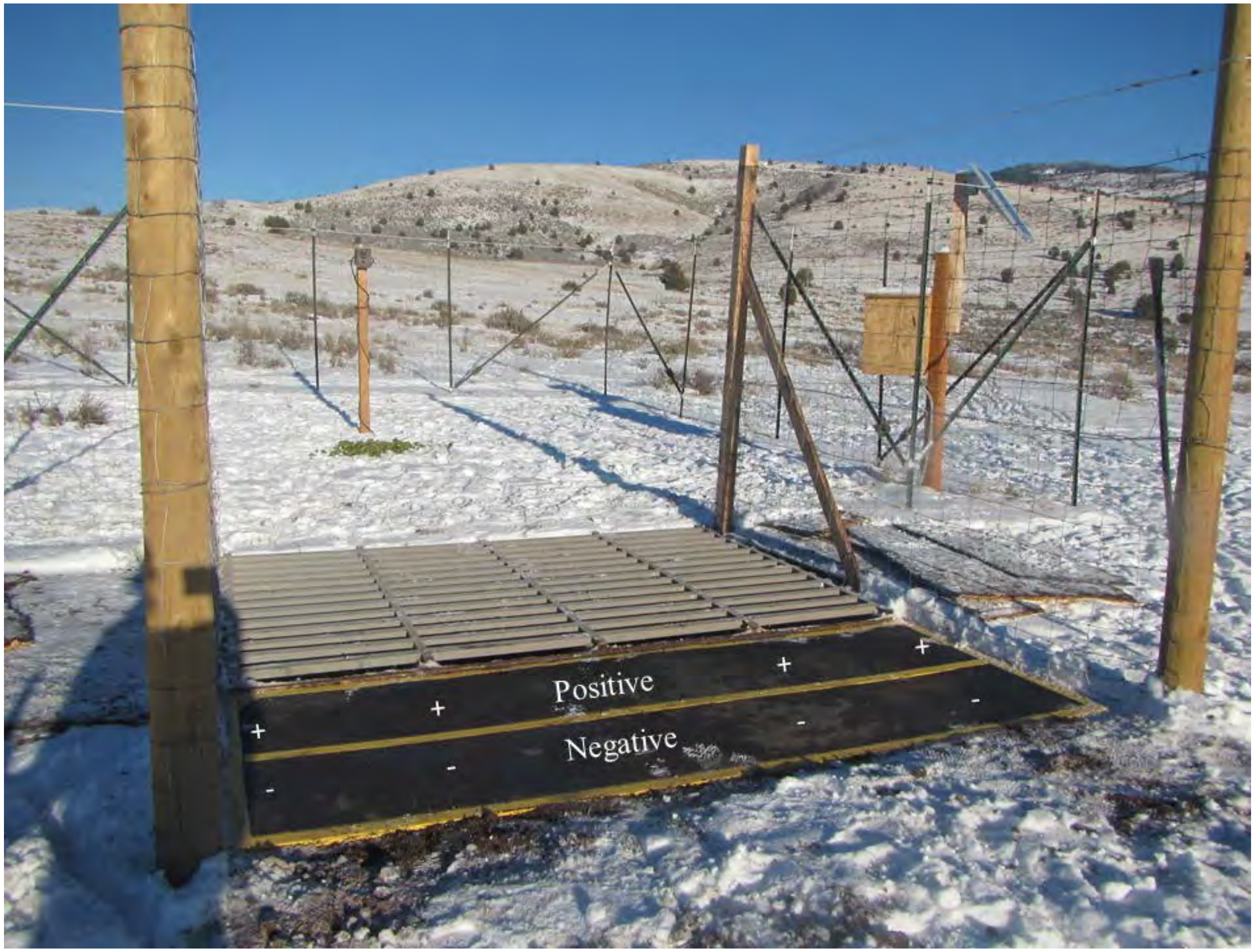

Figure 11. Close view of a 10 × 10-m wildlife exclosure used to test efficacy of 3 × 2.1-m cattle guards augmented with either 3 × 1.2-m (n = 2; pictured) or 3 × 0.91-m (n = 2) electrified pavement as an ungulate barrier at Hardware Ranch Wildlife Management Area, Utah, from mid-Oct 2014 to mid-March 2015. Positive and negative symbols added to indicate polarity of electrified pavement.

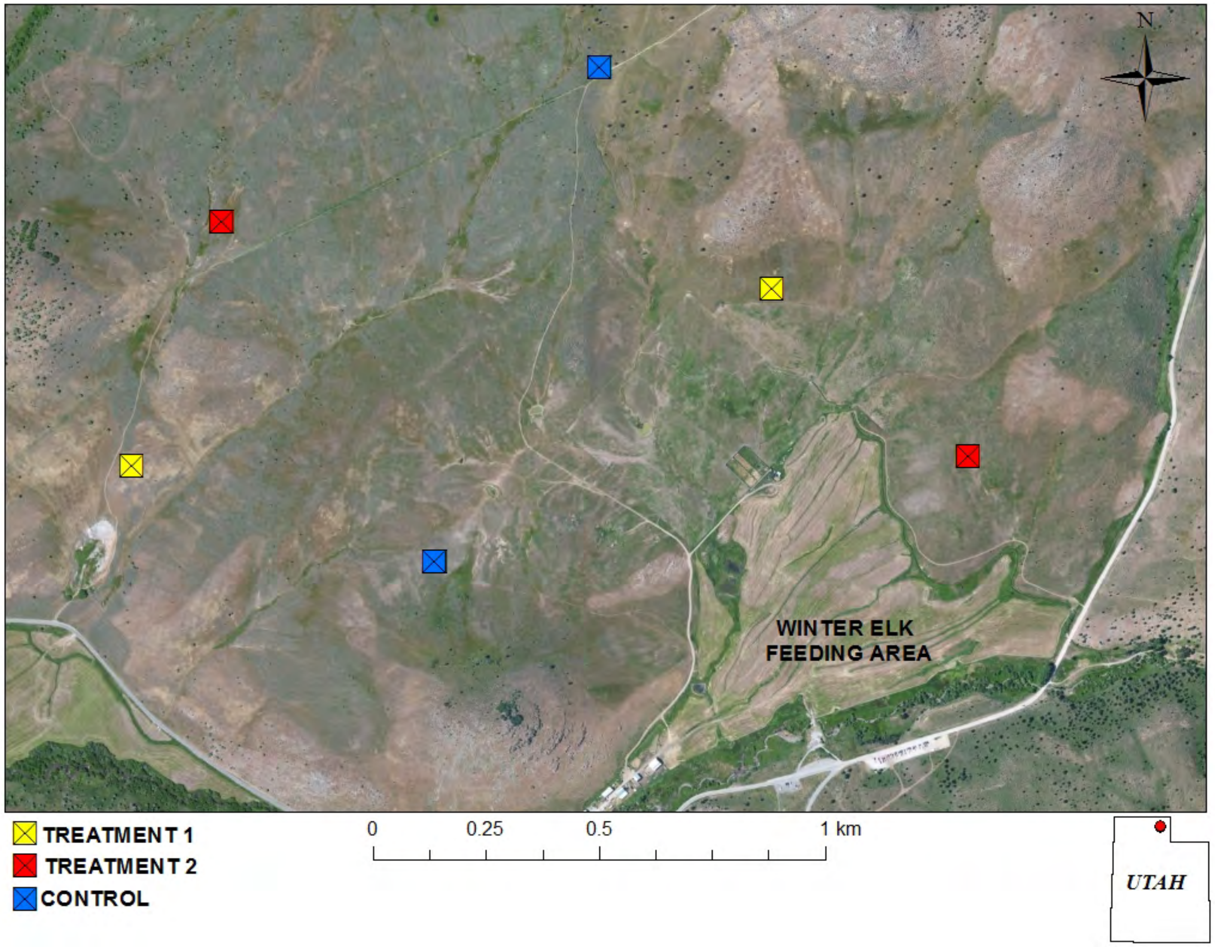

Figure 12. Aerial view of wildlife exclosures with entrances treated with cattle guards augmented with either 3 × 0.91-m electrified pavement (treatment 1, n = 2), 3 × 1.2-m electrified pavement (treatment 2, n = 2), or cattle guards alone (control, n = 2), Hardware Ranch Wildlife Management Area, Utah, USA. Three stations adjacent to the winter elk feeding area were assigned to block 2 and the remaining three stations were assigned to block 1.

Figure 13. Cattle guard (2.1-m × 11-m) augmented with electrified pavement (0.91-m × 11-m) on access road to Interstate 15 (background), near Pintura, Utah, USA.

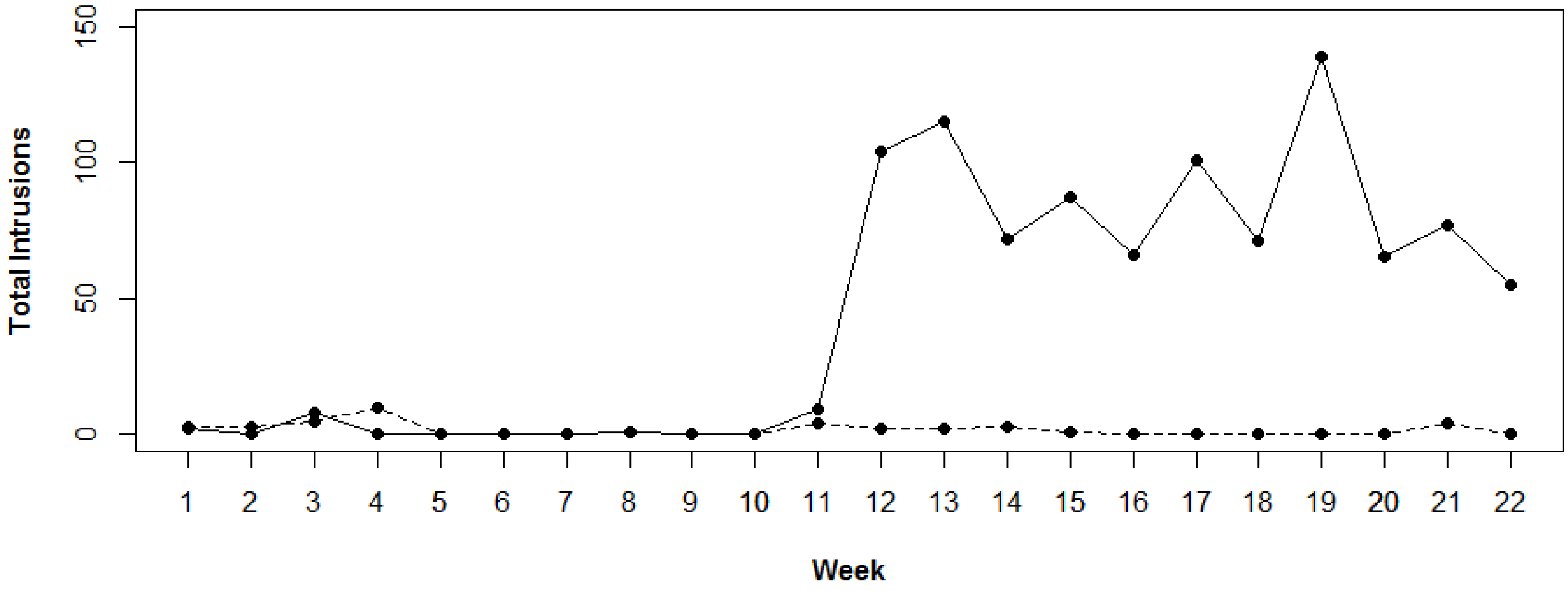

Figure 14. Weekly mule deer intrusions into 2 baited wildlife exclosures with entrances treated with simulated cattle guards (control, solid line) and into 4 exclosures treated with simulated cattle guards augmented with electrified pavement (treatment, dashed line) over the 22-week study period (mid-Oct 2014-mid-Mar 2015) at Hardware Ranch Wildlife Management Area, Utah. Deterrents were covered in weeks 1 to 5 and exposed in weeks 6 to 22. Note that week 12 corresponds to late-Dec 2014.

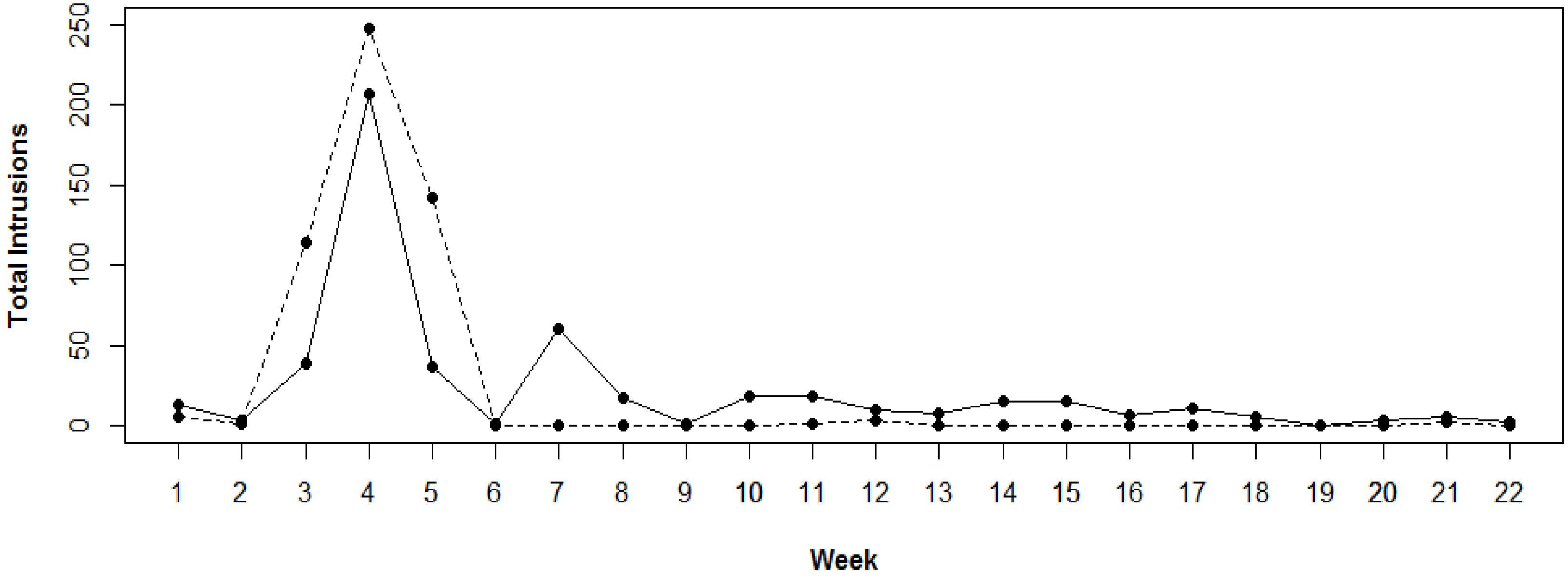

Figure 15. Weekly elk intrusions into 2 baited wildlife exclosures with entrances treated with simulated cattle guards (control, solid line) and into 4 exclosures treated with simulated cattle guards augmented with electrified pavement (treatment, dashed line) over the 22-week study period (mid-Oct 2014-mid-Mar 2015) at Hardware Ranch Wildlife Management Area, Utah. Deterrents were covered in weeks 1 to 5 and exposed in weeks 6 to 22.

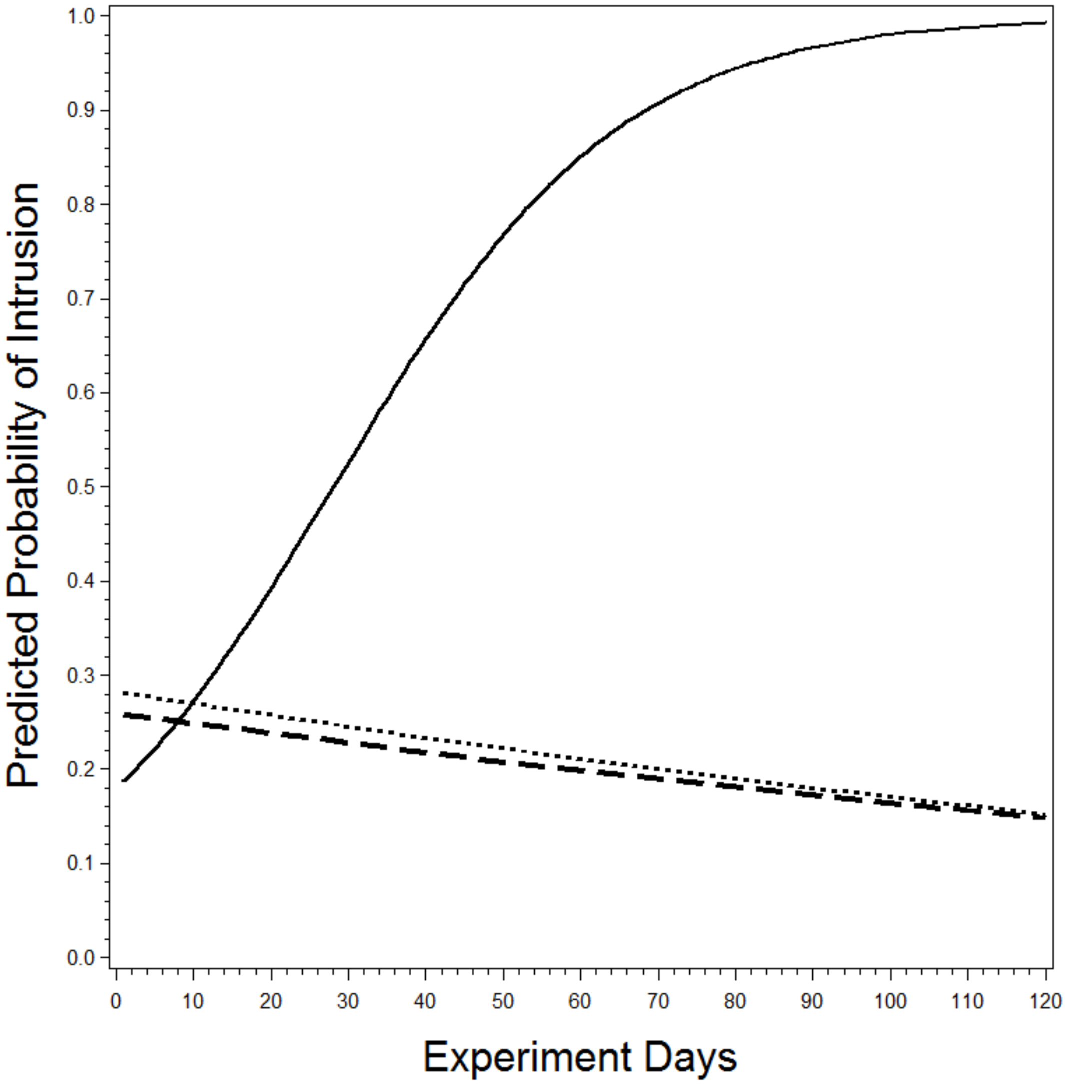

Figure 16. Effect of experiment day on the predicted probability of mule deer intrusion over the 17-week treatment period (mid-Nov 2014-mid-Mar 2015) at Hardware Ranch Wildlife Management Area, Utah, USA. Results from logistic model using observations from exclosures within block 1 during snow and snow-free conditions. As the feeding trial progressed, the likelihood of deer intrusion into exclosures treated with cattle guards increased significantly (control, solid line). Intrusion likelihood declined, though not significantly, at exclosures treated with cattle guards augmented with 0.91-m-wide electric pavement (treatment 1, dotted line) or 1.2-m-wide electric pavement (treatment 2, dashed line). The likelihood of deer intrusion did not differ among treatments 1 and 2, but was significantly higher at controls when compared with either treatments.

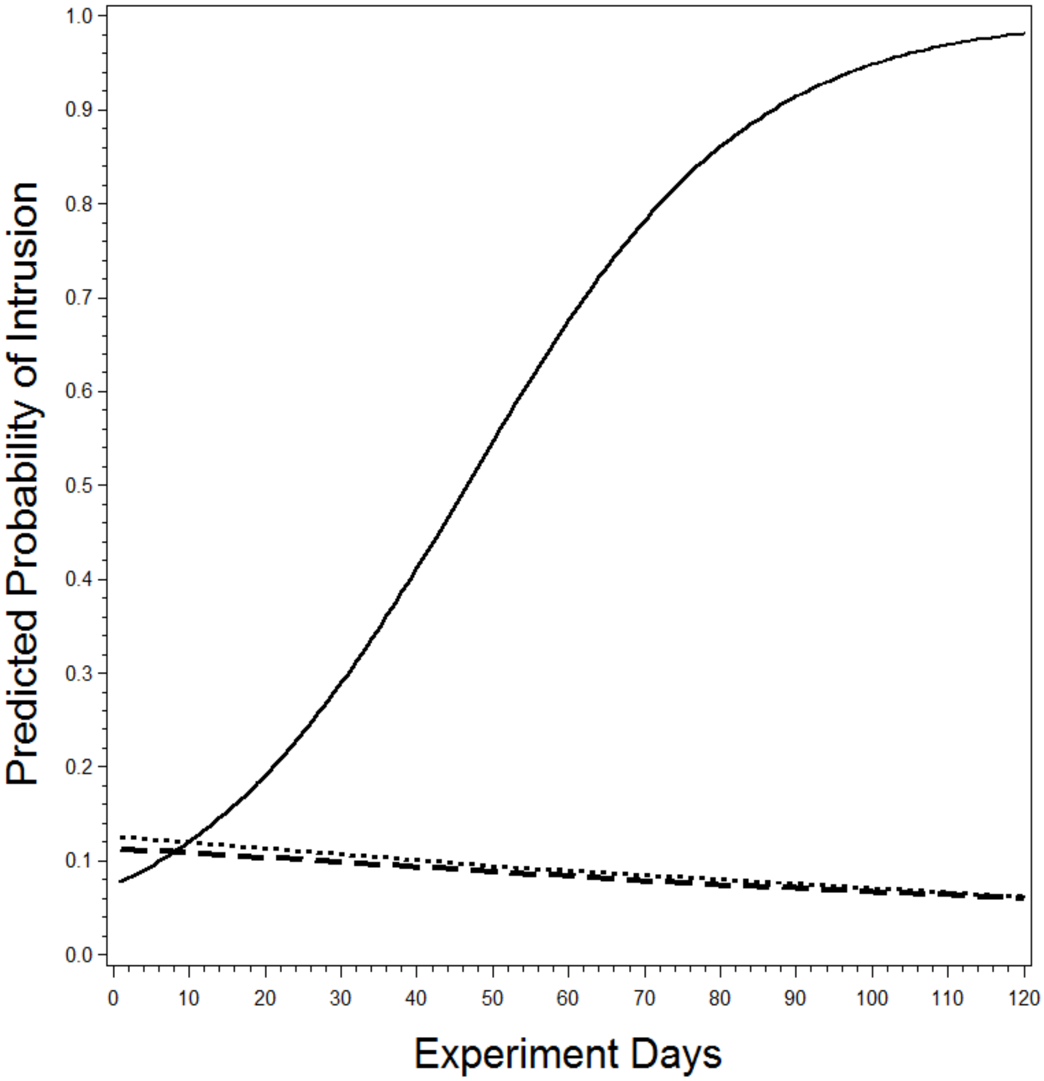

Figure 17. Effect of experiment day on the predicted probability of mule deer intrusion over the 17-week treatment period (mid-Nov 2014-mid-Mar 2015) at Hardware Ranch Wildlife Management Area, Utah, USA. Results from logistic model using observations from exclosures within block 2 during snow and snow-free conditions. As the feeding trial progressed, the likelihood of deer intrusion into exclosures treated with cattle guards increased significantly (control, solid line). Intrusion likelihood declined, though not significantly, at exclosures treated with cattle guards augmented with 0.91-m-wide electric pavement (treatment 1, dotted line) or 1.2-m-wide electric pavement (treatment 2, dashed line). The likelihood of deer intrusion did not differ among treatments 1 and 2, but was significantly higher at controls when compared with either treatments.

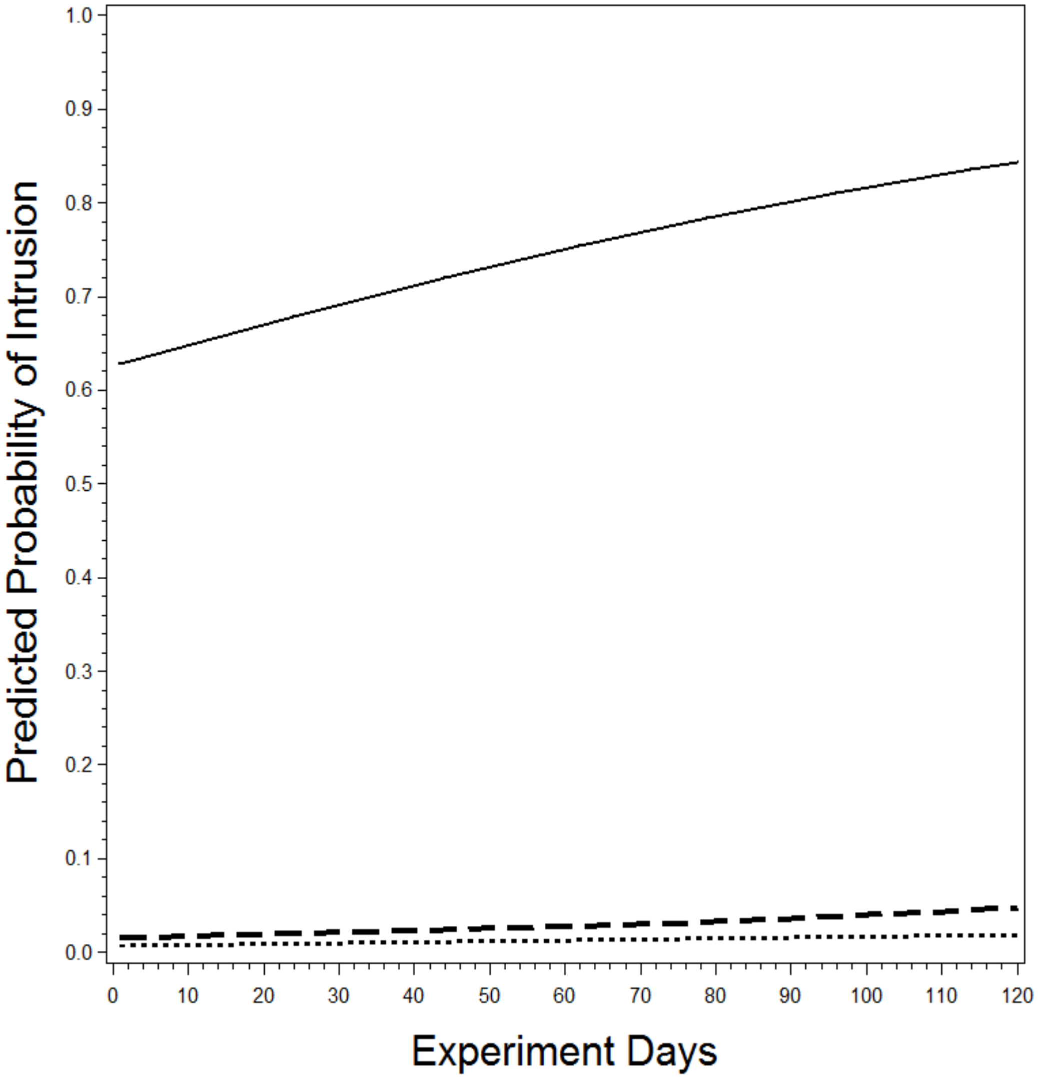

Figure 18. Effect of experiment day on the predicted probability of elk intrusion over the 17-week treatment period (mid-Nov 2014-mid-Mar 2015) at Hardware Ranch Wildlife Management Area, Utah, USA. Results from logistic model using observations from exclosures within block 2 during snow-free conditions. As the feeding trial proceeded, the likelihood of elk intrusion increased, though not significantly, at exclosures treated with cattle guards (control, solid line) and at exclosures with cattle guards treated with either 0.91-m-wide (treatment 1, dotted line) or 1.2-m-wide (treatment 2, dashed line) electric pavement. The likelihood of elk intrusion did not differ among treated exclosures, but was significantly higher at controls when compared with either treatments.

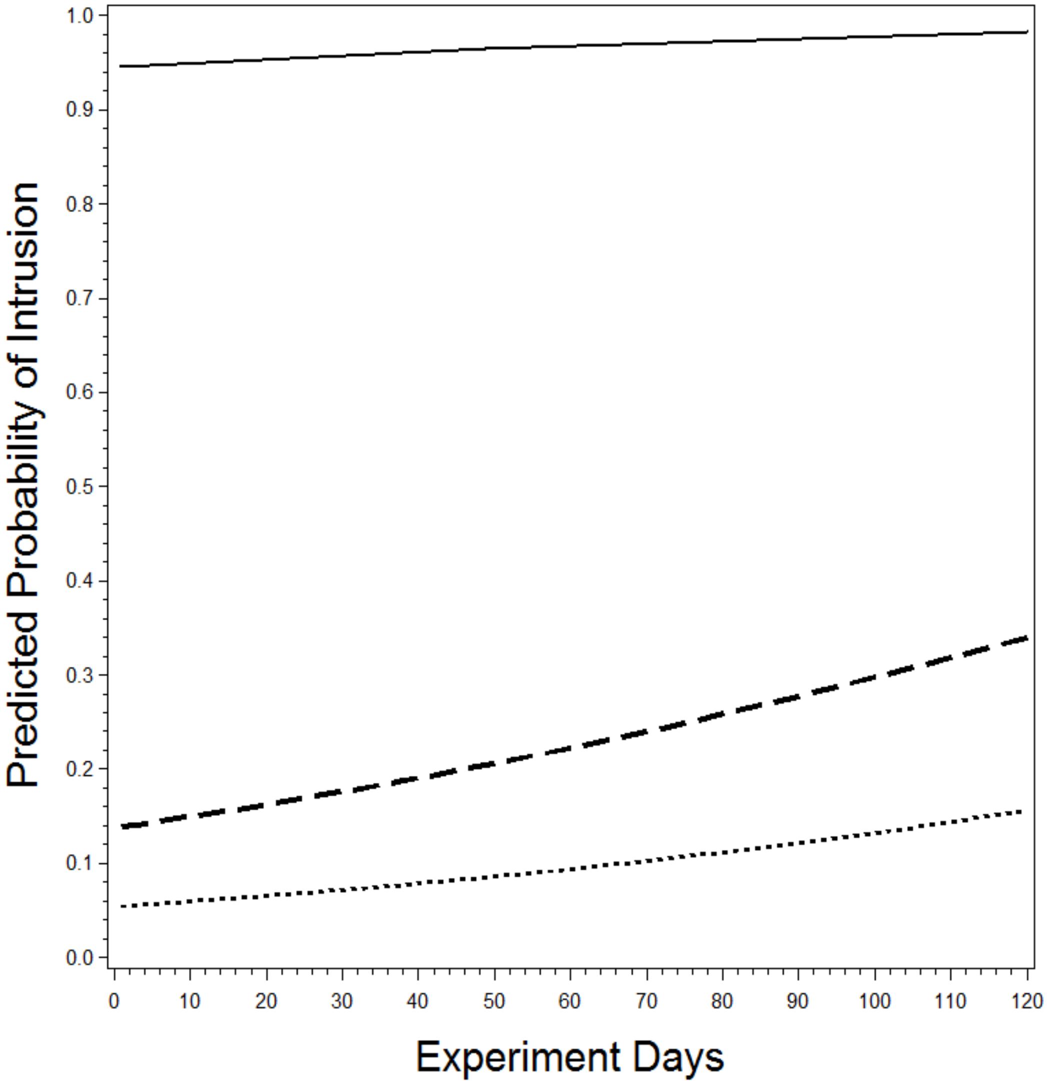

Figure 19. Effect of experiment day on the predicted probability of elk intrusion at Hardware Ranch Wildlife Management Area, Utah, USA over the 17-week treatment period (mid-Nov 2014-mid-Mar 2015). Results from logistic model using observations from exclosures within block 2 during under snowy conditions. As the test proceeded, the likelihood of elk intrusion increased, though not significantly, at exclosures treated with cattle guards (control, solid line) and at exclosures with cattle guards treated with either 0.91-m-wide (treatment 1, dotted line) or 1.2-m-wide (treatment 2, dashed line) electric pavement. The likelihood of elk intrusion did not differ among treated exclosures, but was significantly higher at controls than at either treatments.

CHAPTER IV

SUMMARY

The focus of my research was to find innovative solutions to reduce wildlife access to highways. When combined with wildlife exclusion fencing, wildlife crossing structures represent the “gold standard” of highway mitigation for large mammals. However, the success of this mitigation often depends on its weakest link: openings in fencing at access roads that must permit vehicle traffic, yet deter animals from entering the highway corridor.

The objectives of the second chapter of my thesis were to: 1) evaluate the relative effectiveness of five different barrier designs currently used to exclude mule deer from highways in Utah, USA, and 2) identify predictors of events in which mule deer crossed over the barriers. I hypothesized that the design of the barrier would be the most important predictor of barrier effectiveness and I predicted that the likelihood of deer crossing would be unequal among the five barrier designs. I found that double cattle guards (two adjoining cattle guards) and wildlife guards (steel grates) were ≥80% effective in excluding mule deer from fenced highway corridors. In contrast, electrified mats (plastic planks with embedded electrodes, standard cattle guards, and cattle guards without excavations were <12%, <50%, and <25% effective for mule deer, respectively, and each design failed to reliably secure the highway corridor from deer intrusions.

Model results confirmed the design of the barrier was the most important predictor of effectiveness. Deer were significantly less likely to breach double cattle guards and wildlife guards when compared with any other barrier design we monitored. However, we found no significant difference in barrier effectiveness between double cattle guards and wildlife guards. Although the design of the barrier emerged as the most important predictor of whether deer crossed, additional significant predictors included: 1) the annual average daily traffic on the highway adjacent to the access road, and 2) the distance to the nearest safe passage that deer could use to cross beneath the roadway.

If deer are the primary target of wildlife-vehicle collision mitigation efforts, we recommend the use of double cattle guards or wildlife guards to mitigate designed breaks in wildlife fencing at access roads. We advise replacement of electrified mats and standard cattle guards with more effective barriers wherever possible. Further, to facilitate safe passage for deer and other wildlife across the highway, we advise pairing wildlife barriers and wildlife exclusion fencing with wildlife crossing structures (overpasses or underpasses) or with multipurpose structures suitable for wildlife (existing culverts or bridges not specifically designed for wildlife). Finally, animals may sustain serious injury when attempting to breach wildlife barriers. Providing earthen escape ramps in the vicinity of a wildlife barrier may mitigate this problem by allowing animals trapped within the fenced road corridor to escape safely.

The objective of chapter 3 was to evaluate whether a standard cattle guard augmented with electrified pavement could prevent mule deer and elk intrusions at rates comparable to wildlife-specific barriers, but at reduced cost. I hypothesized that mule deer and elk would be less likely to breach simulated cattle guards augmented with electrified pavement when compared with untreated cattle guards. Simulated cattle guards augmented with segments of electrified pavement (0.91-m or 1.2-m-wide) were $>$80% effective in excluding deer and $>$95% effective in excluding elk from baited wildlife exclosures that were constructed in a natural area away from roads. However, when installed in the road surface in front of an existing cattle guard, a segment of electrified pavement (0.91-m-wide) was 54% effective in excluding deer from the fenced right-of-way of Interstate 15. We suspect that variation in pavement efficacy between the two trials was driven by differences in animal motivation and by exposed soil (earth acts as an electrical ground) in the feeding exclosure trial.

Model results from the feeding exclosure trial indicated that deer and elk were significantly less likely to breach cattle guards augmented with electrified pavement than untreated cattle guards. However, we detected no significant difference in barrier efficacy between cattle guards treated with a 0.91-m-wide segment of electrified pavement when compared with cattle guards treated with 1.2-m-wide segment. We also found snow coverage to be an important predictor of whether animals breached the deterrents, which suggested a decline in electrified pavement effectiveness when the material was snow-covered. Further, as the feeding exclosure trail proceeded, we found that deer became increasingly likely to cross over untreated cattle guards, but slightly less likely to cross over cattle guards treated with electrified pavement.

The central goal of this research was to provide a rigorous assessment of a cost-effective retrofit to cattle guards that could reduce wildlife intrusions to roadways. Based on strong results from the feeding exclosure trial, electrified pavement appears to have potential as an effective tool to reduce ungulate access to transportation infrastructure and other protected areas. Moreover, the material may offer a mitigation option for locations unsuitable for double cattle guards and wildlife guards, such as at end points in wildlife exclusion fencing and/or across high-traffic roads. However, mixed results from the road trial suggest that further research is needed to determine the efficacy and viability of electrified pavement for use in roadway applications. Monitoring replicated in-road installations of electrified pavement over multi-year time spans would likely yield a comprehensive assessment of the material under different roadway scenarios. Further, additional research may lead to improvements in the intended function of this innovative emerging technology – to reduce risk for motorists and wildlife along our highways.