TESTING WILDLIFE FRIENDLY FENCE MODIFICATIONS TO MANAGE WILDLIFE AND LIVESTOCK MOVEMENTS

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THE STATE OF MONTANA
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FEDERAL HIGHWAY ADMINISTRATION

September 2020

prepared by
Erin Landguth[1]
Andrew Jakes[2]
Mark Hebblewhite[1]

The University of Montana[1] | Missoula, MT
National Wildlife Federation[2] | Missoula, MT

RESEARCH PROGRAMS

MDT

Testing ‘wildlife friendly’ fence modifications to manage wildlife and livestock movements

Prepared by

Erin Landguth, Associate Professor, School of Public and Community Health Sciences, University of Montana, Missoula, MT, USA.

Andrew Jakes, Regional Wildlife Biologist, National Wildlife Federation, Missoula, MT, USA.

Mark Hebblewhite, Professor, Wildlife Biology, University of Montana, Missoula, MT, USA.

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7. Author(s)
Erin L Landguth, https://orcid.org/0000-0002-7044-346X
Andrew Jakes, https://orcid.org/0000-0003-1552-554X
Mark Hebblewhite, https://orcid.org/0000-0001-5382-1361

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16. Abstract

Fences are ubiquitous across the landscape, yet there is little understanding on their effects on wildlife. Fences pose both indirect (i.e., access to habitat, energetic costs) and direct (i.e., mortality) consequences to wildlife, and so their effects are an important consideration. Wildlife managers, land managers, and Departments' of Transportation, must explore mitigation options to allow for wildlife connectivity while addressing human concerns (i.e., keeping motorists safe). Fences along roadways serve as safety measures to protect humans from vehicular collisions with wildlife and livestock (i.e., all cattle) by containing animals in appropriate pastures and keeping them off roadways. Our objectives were to test wildlife friendly fence design that allows for daily and seasonal wildlife movements, while simultaneously keeping livestock in desired pastures. From 2012-2016, we tested three various bottom wire modifications to allow for safe wildlife passage which included smooth wire, clip/carabiners of the bottom two wires together, and PVC pipe on the bottom wire. From 2016-2018, we tested two additional fence modifications which were sage-grouse reflectors and PVC pipe on top wires to measure effects to ungulate crossing success from these modifications. Results from field trials indicate the use of either smooth wire or carabineers as a method to clip together the bottom two wires to a height of approximately 18 inches off the ground were two effective modifications at allowing passage by pronghorn, while the commonly proposed goat-bar (i.e., PVC pipe on bottom wire) was ineffective and created a negative behavioral response by pronghorn. In addition, the use of sage-grouse reflectors and PVC pipe on top wires had no substantial unintended consequences on the crossing behavior of pronghorn, mule deer or white-tailed deer, ultimately leading to a plausible multi-species wildlife friendly fence design and providing that the overall height of the fence as comparable/equivalent to adjacent fence lines. Our secondary objective was to test the influence of fence density around highways on species movement and connectivity in conjuncture with maintenance road mortality data through the Hi-Line region of Montana. Our connectivity modeling with highway mortality data show that fences East of Havre, MT are acting as barriers to seasonal migration for pronghorn and individuals are moving to the West of Havre, MT to cross in the fall and spring, but not winter, which indicates that increased fence densities may act as an ecological trap to individuals forced to move through sub-optimal habitat. In addition, we observed increased mortalities for mule deer with higher fence densities during fall and winter. Finally, through local, regional and national presentations, it is our intent to communicate our results to wildlife and habitat managers, as well as private landowners so as to consider these cost effective and prudent recommendations for on-the-ground implementation.

17. Key Words
Connectivity, pronghorn, mule deer, white-tailed deer, transportation corridor, fences, multi-species design, livestock, ungulates, sage-grouse, barriers, wildlife, roadside fauna, animals, bird, safety factors, habitat, landowners, field tests

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1. PROJECT SUMMARY

Fences are ubiquitous across the landscape, yet there is little understanding of their effects on wildlife. Fences pose both indirect (i.e., access to habitat, energetic costs) and direct (i.e., mortality) consequences to wildlife and so their effects are an important consideration. Wildlife managers, land managers and Departments' of Transportation must balance mitigation options that allow for wildlife connectivity, private property rights, and public safety. Fences along roadways serve as safety measures to protect humans from vehicular collisions with wildlife and livestock by containing animals in appropriate pastures and keeping them off roadways. Historically, many in the ranching community have believed wildlife friendly fence designs to be ineffective in holding livestock. Our objectives were to test various wildlife friendly fence design that allows for daily and seasonal wildlife movements, while keeping livestock (i.e., all cattle) in desired pastures. From 2012-2016, we tested three various bottom wire modifications to allow for safe wildlife passage which included smooth wire, clip/carabiners of the bottom two wires together, and PVC pipe on the bottom wire. From 2016-2018, we tested two additional fence modifications which were sage-grouse reflectors and PVC pipe on top wires to measure effects to ungulate crossing success from these modifications. Results from field trials indicate the use of either smooth wire or clips with a bottom wire height of approximately 18 in. were most effective at allowing passage by pronghorn, while the commonly proposed 'goat-bar' (i.e., PVC pipe on bottom wire) was ineffective and created a negative behavioral response by pronghorn. In addition, the use of sage-grouse reflectors and PVC pipe on top wires had no substantial unintended consequences on the crossing behavior of pronghorn, mule deer or white-tailed deer, ultimately leading to a plausible multi-species wildlife friendly fence design. Our secondary objective was to test the influence of fence density around highways on species

movement and connectivity in conjuncture with maintenance road mortality data through the Hi-Line region. Our connectivity modeling with highway mortality data show that fences East of Havre, MT act as barriers to seasonal migration for pronghorn and individuals are moving to the West of Havre, MT to cross in the fall and spring, but not winter, which indicates that increased fence densities may act as an ecological trap for individuals forced to move through sub-optimal habitat. In addition, we observed increased mortalities for mule deer with higher fence densities during fall and winter. Fence modification and connectivity modeling results could be married together by MDT personnel to target areas for fence modification along highways that provide the biggest return on investment. These results can also be used to update the MDT wildlife friendly fence brochure and Right-of-Way manual. However, objective 2 results are from a very broad-scale and as such, site-by-site identification and monitoring is still required while working with landowners in negotiating ROW agreements. Finally, through local, regional and national presentations, it is our intent to communicate our results to wildlife and habitat managers, as well as private landowners so as to consider these cost-effective and prudent recommendations for on-the-ground implementation.

2. PROJECT BACKGROUND

During a preliminary literature search, fourteen studies were identified evaluating structures to facilitate wildlife (mainly ungulates) movements across roadways. Structures include underpasses and overpasses (including fencing associated with these structures), wildlife friendly fencing and cattle guards. The majority of these identified studies investigated the effectiveness of overpass and underpass structures, with associated fencing, on wildlife movements. These structures are used to reduce wildlife-vehicle collisions, keep wildlife off roadways and improve ecological connectivity for targeted wildlife species by facilitating movement across roads. However, underpass and overpass structures can be expensive to build, can be an unwarranted mitigation measure for wildlife within specific ecological systems and in many cases, may be an unwelcomed measure in varying socioeconomic regions. For example, an overpass structure may not be the most reasonably economic or socially acceptable mitigation measure within a flat, prairie landscape. Importantly, none of these fourteen studies reported on the effectiveness of these various mitigation measures in keeping livestock in desired pastures. Therefore, there is a gap in the literature for both analytically assessing and understanding the effects of various ‘wildlife friendly’ fencing modifications on wildlife and livestock (i.e., all cattle) movements. In particular, increased analytical assessment is needed to investigate fence density effects on wildlife movement, especially in relation to navigating federal and state funded highways.

Generally, fences along roadways serve as safety measures to protect humans from vehicular collisions with wildlife and livestock by containing animals in appropriate pastures and keeping them off roadways. However, fences can act as semi-permeable or complete barriers to wildlife movement. As a consequence, through landscape fragmentation, fences reduce landscape connectivity, impede resource selection, and are a direct cause of mortality in ungulates (e.g., pronghorn, elk, deer) and other species (e.g., greater sage-grouse). To combat these effects on wildlife, multiple fence modifications have been recommended by management agencies in the past using the best available science to either facilitate or deter wildlife and/or livestock from crossing fences. To further refine and improve upon previous practices to improve wildlife movement, updated technologies and analytical approaches are now available to assess the effectiveness of recommended 'wildlife friendly' fence modifications. Further, there is not a clear understanding on the effects of fence densities on wildlife movements and large-scale connectivity and where to mitigate wildlife-fence interactions to effectively sustain connectivity across roads and highways. Therefore, agencies need effective approaches, rigorous tools, and reproducible frameworks to identify and prioritize locations to install 'wildlife friendly' fencing when considering mitigation measures for wildlife movement at both small and larger scales, all while addressing landowners needs and keeping livestock in the proper pastures. The Hi-Line area provides an opportunity to assess the impacts of fencing on wildlife connectivity, particularly across a large transportation system (i.e. US HWY 2). In concert, analytically proven wildlife friendly fencing techniques could be used along targeted roadside sections where fencing impedes wildlife connectivity. These targeting approaches and techniques can provide a reproducible framework for other parts of the state where GPS collar information is available for wildlife and where fencing is mapped from a broad-scale. Once models are completed in other areas, MDT can identify appropriate mitigation tools using a similar targeted approach.

The objectives of this project were to:

1) Evaluate effectiveness of various 'wildlife friendly' fence modifications that have previously been recommended by multiple management agencies to assess their

effectiveness in allowing for continued wildlife movements while effectively controlling livestock (i.e., all cattle).

2) Use the outputs of a previously developed and published fence density map (Poor et al. 2014) and the results of the final evaluation of the effectiveness of various "wildlife friendly" fence modifications together, to guide MDT District Biologists and Right-of-Way Personnel in the application of effective "wildlife friendly" fences and other effective habitat connectivity measures on the landscape.
3) Effectively demonstrate and present the importance of developing fence density maps for other important ecological areas, to create scientifically and economically defensible positions for MDT to use, in the justification for and the effectiveness of "wildlife friendly" fences and other habitat connectivity measures on the landscape as a prudent use of their limited resources.

3. METHODS and RESULTS

3.1. *Objective 1: Evaluate effectiveness of various 'wildlife 'friendly' fence modifications*.

Wildlife and livestock-fence interactions are investigated by conducting field tests at The Nature Conservancy's (TNC's) Matador Ranch in North-Central Montana and at Canadian Forces Base (CFB) Suffield in Alberta, using a Before-After-Control-Impact (BACI) experimental design. We measured the response of wildlife and livestock interacting with fences using digital images captured by remote trail cameras (Reconyx$^{©}$ PC650, PC800 or PC900, Reconyx, Holmen, Wisconsin, USA; Bushnell$^{©}$ Trophy Camera, Bushnell Corporation, Overland Park, Kansas, USA, and U-way$^{©}$ Trail Camera-VH200HD, UWAY Outdoors Canada, Lethbridge, Alberta, Canada). At both CFB Suffield in Alberta and the Matador Ranch site in Montana, cattle interacted with barbed wire fences in an open native grass system. However, only at the Matador site did cattle interact with modified fences during the 'After' period. At the Matador site, cattle were present on both the TNC side and private landowner side of the fence. Stocking rates of cattle were variable based on pasture size (approximately several hundred) but were typically year-round on the private landowner side of the fence and from June-September on the TNC side during the study. Livestock fence-interactions from both sides of the fences from the Matador site were included in analyses. In summary, techniques to collect and assess data include: 1) the use of a BACI study design with remote field cameras deployed to capture wildlife-fence interactions; 2) a standardized procedure across study sites to record wildlife-fence interactions and populate into database; 3) the use of statistical approaches (i.e. ANOVA, logistic regression, time-to-event analyses) to identify parameters (including effectiveness of modifications) important to successful wildlife-fence crossings, unsuccessful livestock crossings, and time required for wildlife habituation to proposed modifications.

3.1.1. First field trials (2012-2016)

We deployed approximately 90 remote cameras in Montana and Alberta to capture and process images of wildlife interacting with fencing. We evaluated the effects of three modifications types to barbed wire fencing on pronghorn, deer and livestock movements. These included modifying the lowest barbed wire using either smooth wire, PVC pipe (i.e., goat bars), or with a carabineer clip (Figure 1). These modifications included changing the type of the bottom fence strand to smooth wire, adding PVC pipe (i.e., goat bars) to the bottom wires, and raising the height of the bottom wire by clipping it to the wire above it with a carabineer clip. Standardized procedures across study sites allowed us to collect uniform data on wildlife-fence interactions and assess wildlife and livestock use, which was the first analytical assessment of fence modification use by pronghorn (Jones et al. 2018). Our objectives were to understand 1) differences between bottom wire height at selected versus available fence sites; 2) the change in crossing rates before and after fence modification treatments; 3) the effect of a suite of fence, environmental, and demographic characteristics on group crossing success; and 4) the time lag until pronghorn became habituated to different fence modifications after initiation of treatments.

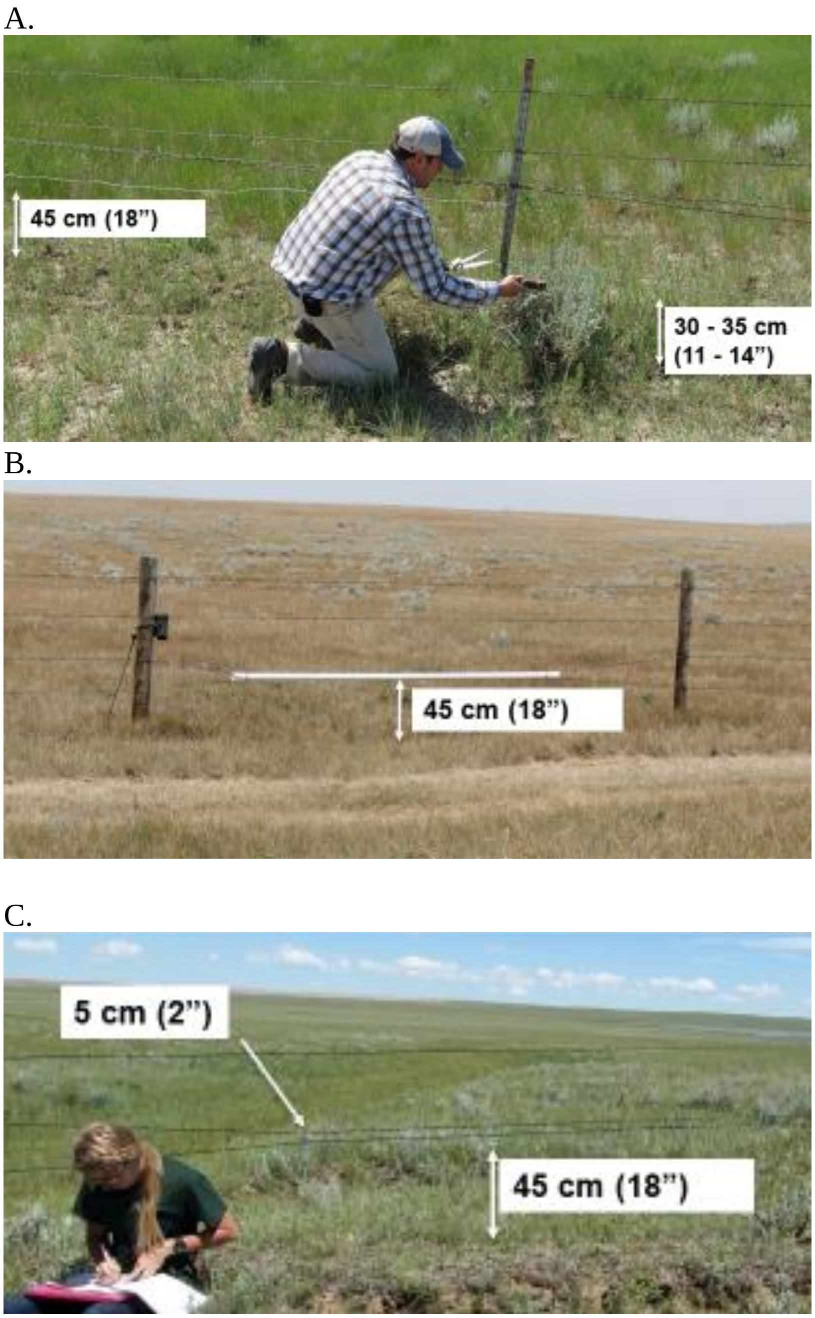


Figure 1. Bottom wire fence modifications: Wildlife friendly fence modifications deployed on the bottom wire of multi-stranded barbed wire fencing during first field trials. These included smooth wire (A.), PVC pipe (i.e., goat bar) (B.) and, carabineer/clips (C.). All bottom wire modifications were at 18" of height.

Detailed Statistical Methods:

Bottom-wire height.—We compared the bottom-wire height at the pronghorn known-crossing sites (selected) to the bottom-wire height at the neighboring (or adjacent) fence panels (available) to test optimal bottom-wire height selected by pronghorn to cross fences. We used an ANOVA to compare the bottom-wire height between selected and available fence panels, where the response variable was bottom-wire height (cm) and the explanatory variables were type (selected and available), study area (Alberta or Montana), and the interaction term of type × study area. We used bottom-wire heights during the before period (unaltered bottom-wire height) at control and modification sites to represent available sites in the analysis. To avoid pseudoreplication with the Alberta data, we randomly selected 1 year of data for known-crossing (and companion) sites for those sites that were used over multiple years, whereas we used all of the sites for Montana in the analysis. If an effect was detected for the type × study area explanatory variable, we used the Tukey honest significant difference (HSD) test to conduct multiple comparisons (Zar 1984).

Crossing success.—We used a mixed-effect ANOVA to compare pronghorn crossing success between the before and after period at each fence panel with modifications, where the response variable was mean actual success and explanatory variables were treatment type (modification type [goat-bar, clip, or smooth wire], control, or known-crossing), study area (Alberta or Montana), the interaction term of treatment × study area, and the random term of set (name assigned to each group of 3 cameras). We used instances of successful crossing as the response variable because we felt it allowed evaluation of overall change in crossing success and provided insight into the use and differences between treatment types and periods. The before and after periods included a maximum of 106 and 419 days of camera monitoring, respectively.

The before period included fewer camera monitoring days than the after period because it was intended to establish baseline rates of crossing before installation of fence-modification treatment. The before and after periods differed in terms of number of days, so we first calculated the mean number of successful crossing instances per day for each camera and then calculated the mean number of successful crossing instances per period (before or after) per camera. We then calculated the actual success as the difference between the mean number of successful crossing instances per day after installation and mean number of successful crossing instances per day before installation. We removed those days from the initial calculation for instances where the camera did not record photos because of the SD card being full, batteries dying, or camera failure. If we detected an effect for any explanatory variable, we used the Tukey HSD test to conduct multiple comparisons (Zar 1984). During the processing of the images associated with the goat-bar sites, we noted some pronghorn not crossing underneath the goat-bar but instead crossing off to the side where the bottom wire was still raised and there was no protection from hair loss and scarring. We classified these instances where pronghorn did not cross directly under the goat-bar as a failed attempt for all analyses because pronghorn appeared to specifically avoid the goat bar. We performed the ANOVA analyses in JMP v13.1.0 (SAS Institute, Inc., Cary, NC, USA).

Factors affecting crossing events.—We used generalized linear models with a logit link function to control for seasonal and demographic factors and estimate the effect of fence modification treatments on pronghorn-group crossing success (Hosmer and Lemeshow 2000). Specifically, we considered season (i.e., winter, summer, or migratory; see Jakes 2015), group size, group composition (i.e., male, female, or mixed), snow presence (i.e., none, partial ground coverage, or full ground coverage at fence panel), and fence modification treatments (i.e., control, clip, smooth, goat-bar, and known-crossing) as explanatory variables. We classified crossing events where >50% of the group successfully crossed as successful (coded as 1) and the remaining events as failed attempts (coded as 0) for our response variable. We considered the >50% group success rate was an acceptable threshold because it produced similar results to >75% and >90% group success rate analysis (P.F. Jones, unpublished data). We standardized continuous variables by subtracting the mean and dividing by 2 SDs, allowing their effect sizes to be comparable to categorical variables (Gelman 2008). We used the antilogit transform and unstandardized coefficient estimates to make predictions on the probability scale. We used Akaike's Information Criteria for small sample sizes (AIC_c) to evaluate the support among models (Burnham and Anderson 2002). We compared all nested models using the dredge function in Program R version 3.3.2 (R Core Team 2016) package MuMIn (Barton 2016). We used $\Delta AIC_c < 2.0$ as a cut-off to compare competing top models. Finally, we evaluated model goodness-of-fit using a likelihood ratio test, but did not report this result unless we found evidence of lack of fit.

Time to event analysis.—We used a time-to-event approach with multiple events to estimate daily crossing rates for pronghorn among fence panel types during the before and after periods (Hosmer et al. 2008). We used days since camera deployment and modification for before and after periods respectively, as the origin for all camera sets, and we interval-censored cameras when they were not available to detect pronghorn crossing a fence (e.g., insufficient battery power). We explored using a recurrent calendar date as the origin, but found no qualitative differences in our results (P.F. Jones, unpublished data). We pooled data across all years and study areas to summarize crossing rates. We estimated cumulative daily crossing rates for the 5 fence panel types (known-crossing, control, goat-bar, clip, and smooth) and 2 periods (before and after) using nonparametric cumulative incidence functions (CIFs; Heisey and Patterson 2006). When competing risks of an event are involved, the incidence of event type k occurring at time t is generally defined as the hazard of event k at time $t[h_k(t)]$ multiplied by the overall probability of survival at $t-1$ just before event k occurs (Kleinbaum and Klein 2012). However, we assumed a survival probability at $t-1$ of 1.0 because cameras did not fail (or die) when they detected pronghorn fence-crossings. Although multiple crossing events could occur within a day at a single fence panel, we restricted crossing rates to a maximum of 1 event/day at each fence panel to eliminate bias due to multiple crossings of the same individual. We modified the R code provided in Eacker et al. (2016) to estimate CIFs and used the R package survival (Therneau 2015). We used the R package bshazard to estimate smoothed daily treatment-specific crossing rates, and conducted all statistical analyses in Program R 3.4.0 (R Core Team 2016).

Overall Results:

In Alberta, we captured images of pronghorn in 1,584 events in 2012–2013, 808 events in 2013–2014, and 2,217 events in 2015–2016; whereas, we captured images of pronghorn in 3,460 events from 2015 to 2016 in Montana. Events can represent multiple individuals as well as multiple behaviors; therefore, events in the Alberta study area included 14,978 instances of paralleling the fence, 5,738 instances of lingering, 3,368 instances of successfully crossing under the fence, and 8,247 instances of failing to cross. We recorded 3 instances of pronghorn jumping over the fence and 4 going through in Alberta. In Montana, events included 1,968 instances of paralleling the fence, 1,024 instances of lingering, 2,148 instances of successfully crossing under the fence, and 3,563 instances of failing to cross. We recorded 1 instance of a pronghorn jumping over the fence and 1 instance of a pronghorn going through the fence in Montana. Both instances of pronghorn going over or through a fence were considered failed attempts. Of the 123 instances of pronghorn using the goat-bar sites at CFB Suffield, there was only 1 instance of a pronghorn actually going under the goat-bar, but 122 instances where they crossed to the side and under barbed-wire. In Montana, there were 9 instances of pronghorn crossing at goat-bar sites with only 5 going under the goat-bar. We recorded 1 cattle (calf) going through the fence at a goat-bar panel and no successful crossings by cattle at a clip or smooth wire site during the after period in Montana; there were no cattle present in the after period in Alberta.

Bottom Wire Height Results.—There was an effect of type ($F_{1,1} = 108.59$, $P < 0.001$), study area ($F_{1,1} = 23.07$, $P < 0.001$), and the interaction between type and study area ($F_{1,1} = 6.20$, $P = 0.01$) on the mean bottom-wire heights between those selected and those available to pronghorn to cross at. The mean bottom-wire height at known-crossing sites ($\bar{x} = 46.75$ cm, SE = 1.51) was 1.7 times greater than at the available sites ($\bar{x} = 27.44$ cm, SE = 1.07), whereas the overall mean bottom-wire height in Alberta ($\bar{x} = 41.55$ cm, SE = 1.29) was 1.3 times greater than in Montana ($\bar{x} = 32.64$ cm, SE = 1.33). The results of the Tukey HSD test revealed that the mean bottom-wire height at known-crossing sites in Alberta and Montana were not different, but both the known-crossing sites in Alberta and Montana were different than the available sites in Alberta and in Montana (Figure 2).

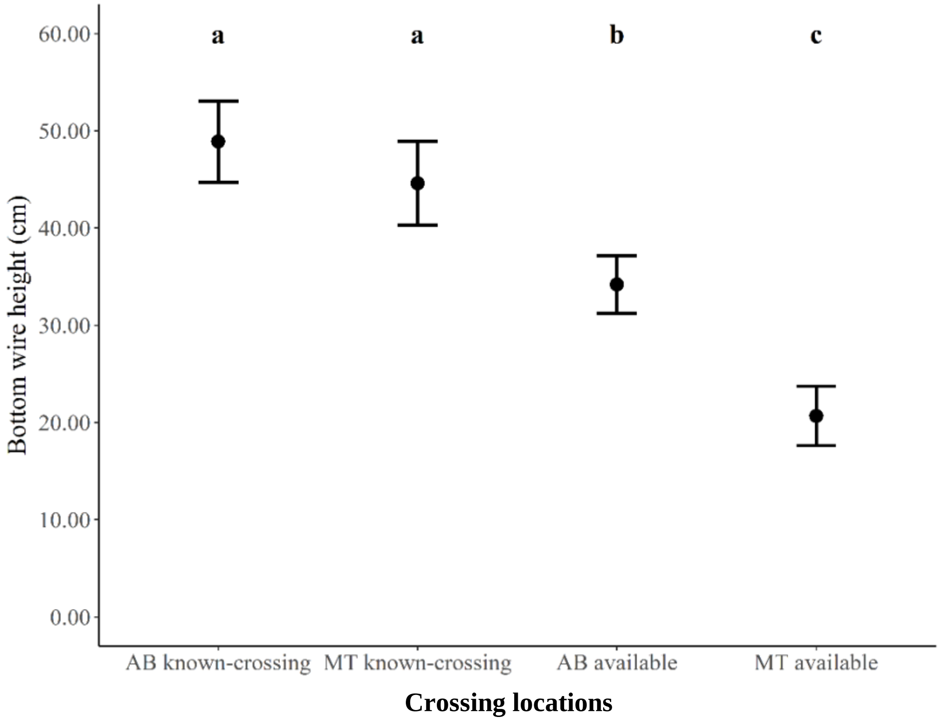


Figure 2. Bottom wire height selection results: Least squared mean and 95% confidence limits for bottom wire height (cm) at fence panels selected and available to cross at by pronghorn in Alberta, Canada, during 2012–2016, and Montana, USA, during 2015–2016. Similar letters above points indicate no differences between means.

Crossing Success Results.—There was an effect of treatment ($F_{4,\,133}$ = 17.63, $P < 0.001$), but not study area ($F_{1,\,89}$ = 0.04, $P = 0.84$) or an interaction between study area and treatment ($F_{4,\,133}$ = 0.61, $P = 0.66$), on the mean daily actual rate of success crossing by pronghorn. The mean actual rates of success crossing at the known-crossing sites differed from the 3 modifications and control sites. The mean actual rate of success crossing at the known-crossing sites was negative, indicating a decrease in successful crossings during the after period, whereas the mean for the 3 treatments were positive. This result highlighted that lowering the bottom wire at the known-crossing fence panels influenced our results, suggestive of the importance of known-crossing sites to pronghorn. Therefore, we redid the analysis removing the known-crossing fence data to allow for interpretation of the effectiveness of the 3 modifications. There was an effect of treatment ($F_{3,\,85}$ = 7.08, $P < 0.001$), but not study area ($F_{1,\,76}$ = 0.65, $P = 0.42$) or an interaction between study area and treatment ($F_{3,\,85}$ = 2.44, $P = 0.07$), on the mean daily actual rate of success crossing when we analyzed the 3 modifications and the control data separately. Smooth wire sites were similar to clip sites, and clip sites, goat-bar sites, and control sites were similar. Smooth wire increased average crossing success by 0.35 crosses/day (or ~1 additional cross every 3 days), clips increased the average crossing success by 0.14 crosses/day (or ~1 additional cross every 7 days), whereas goat-bars decreased the average crossing success by −0.002 crosses/day (or ~1 fewer cross every 500 days).

Factors Affecting Crossing Success Results.—We recorded 2,684 events of pronghorn attempting to cross during the after period. We selected a single top model that had 92.5% of the AIC_c model weight and included the full suite of candidate variables, with the next closest model having a ΔAIC_c of 5.03 and one less parameter (Table 1). The top model was highly supported over a null model (LRT: χ^2_9 = 1,265.1, $P < 0.001$). We found that the clip ($\hat{\beta}$ = 5.44, SE = 0.73,

$P < 0.001$) and smooth-wire ($\hat{\beta} = 4.72$, SE = 0.72, $P < 0.001$) fence modifications had greater relative importance for pronghorn-group crossing success than any environmental or demographic parameter, and had greater group crossing success probability compared with the control group (Table 1; Figure 3a). In contrast to our predictions, we found strong evidence that all-male groups had greater crossing success than all-female groups ($\hat{\beta} = 0.75$, SE = 0.17, $P < 0.001$), but there was no difference between all-female and mixed-group composition ($P = 0.98$). Although the effect size was relatively weak, group crossing success was greater in summer ($\hat{\beta} = 0.95$, SE = 0.30, $P = 0.002$) and lower in winter ($\hat{\beta} = -1.10$, SE = 0.31, $P < 0.001$) compared with the migratory season (i.e., spring and autumn; Figure 3b). After controlling for season, fence treatment, and group composition, we estimated that the odds of a group successfully crossing increased by 1.02 for every additional individual that was in a group (Figure 3), but this effect was marginal—the 95% CI nearly overlapped 1.0 (95% CI = 1.004–1.03%, $P = 0.01$).

Table 1. Pronghorn fence crossing success model: Logistic regression results from the top model of group crossing success (>50%) for pronghorn in the northern sagebrush steppe region of Alberta, Canada, and Montana, USA, during the after period, 2012–2016. For all model parameters, we report the coefficient estimate, $\hat{\beta}$, standard errors, SE, 95% confidence intervals, and P-values. We considered season (migratory, summer, winter), fence modification type (control, clip, goat-bar, smooth, and known-crossing), group composition (all female, all male, or mixed) and group size as explanatory variables for group crossing success. The reference group (i.e., intercept) was female group composition and the control fence modification during the migratory season. We standardized group size by 2 standard deviations to compare relative effect sizes among categorical factors and continuous covariates.

PARAMETER	$\hat{\beta}$	SE	LOWER 95%	UPPER 95%	*P*
INTERCEPT	−4.61	0.78	−6.50	−3.31	<0.001
SEASON: SUMMER	0.94	0.30	0.37	1.55	0.002
SEASON: WINTER	−1.10	0.31	−1.70	−0.48	<0.001
FENCE: KNOWN-CROSSING	1.86	0.72	0.69	3.67	0.010
FENCE: CLIP	5.43	0.73	4.24	7.27	<0.001
FENCE: GOAT-BAR	1.28	0.89	−0.39	3.29	0.15
FENCE: SMOOTH	4.72	0.72	3.55	6.53	<0.001
GROUP: ALL MALE	0.75	0.17	0.43	1.08	<0.001
GROUP: MIXED	0.004	0.22	−0.43	0.44	0.98
GROUP SIZE	0.32	0.13	0.082	0.59	0.01

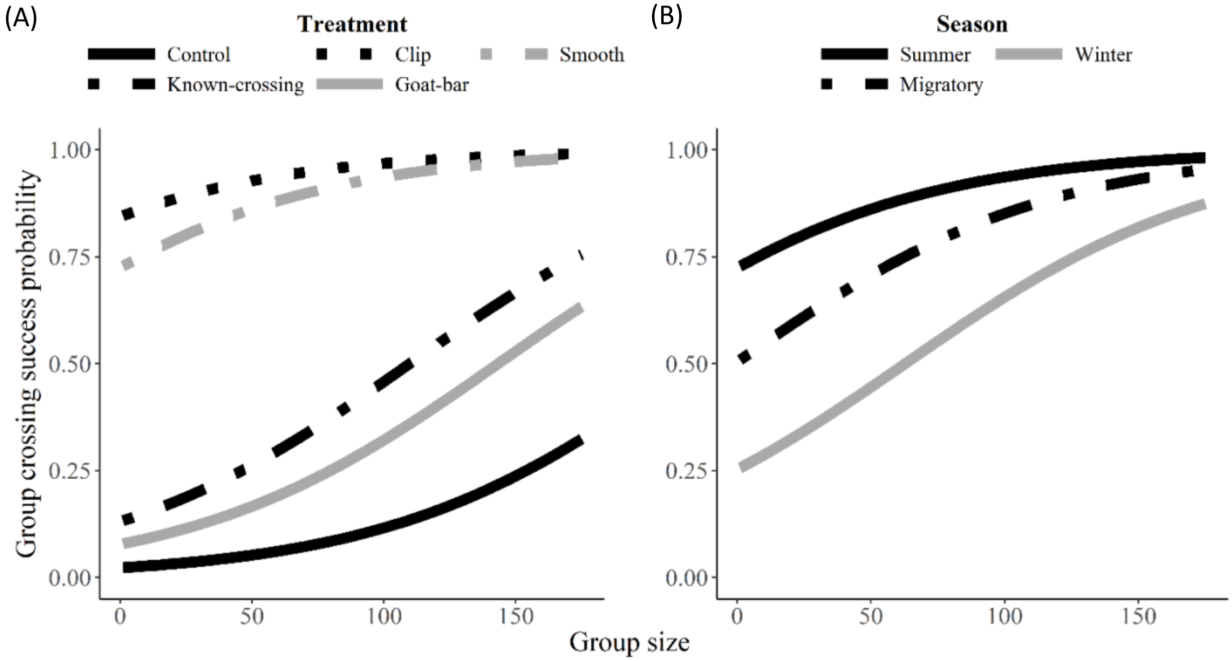


Figure 3. Pronghorn crossing success probabilities (Field Trial 1): Predicted group-crossing success probability from the top logistic regression model for fence modification treatments (A) and seasons (B) over the range of observed group sizes (n = 1–175) for pronghorn in Alberta, Canada, during 2012–2016, and Montana, USA, during 2015–2016. We classified crossing events where >50% of the group successfully crossed as successful (i.e., event = 1). We based our predictions for fence modification treatments (A) on all-female group composition during summer and seasons (B) on all-female group composition and the smooth fence modification treatment.

Time-to-Event Analysis Results.—Our pooled analysis included 9,912 camera-days during the before period and 35,138 camera-days during the after period. We detected 733 and 653 daily crossing events during the before (days 0–106) and after (days 0–419) periods, respectively. Most daily crossing events occurred at the known-crossing sites during the before period, which reached a cumulative rate of 33.76 (95% CI = 21.41–56.96) daily crossings/fence by 106 days since the onset of camera deployment (Figure 4). Consequently, if there were 100 known-crossing sites in the study area, we would expect 3,376 crossing events to have occurred after 106 days (not accounting for multiple crossings events/day/fence). Although none of the treatment groups reached the before crossing rate of known-crossing sites, both clipped (CIF = 29.66, 95% CI = 20.48–44.96) and smooth (CIF = 29.99, 95% CI = 20.37–46.39) wire modifications were of similar effectiveness, and reached comparable rates as before known-crossing sites during the after period by 419 days. However, the steady increase in crossing rates observed around day 270 (see Figure 4) was driven solely by the Montana data because the maximum right-censoring day for Alberta data was day 157. Although clipped and smooth wire modifications appeared as effective as known-crossing sites, this result should be interpreted with caution because the number of cameras was relatively small for the clipped (*n* = 5) and smooth (*n* = 6) wire treatments during days 159–419 in the after period. The control sites had the lowest crossing event rates during the after period (CIF = 0.39, 95% CI = 0.27–0.51), followed by the goat-bar sites (CIF = 1.66, 95% CI = 3.61–4.78), which appeared to be ineffective as a fence modification.

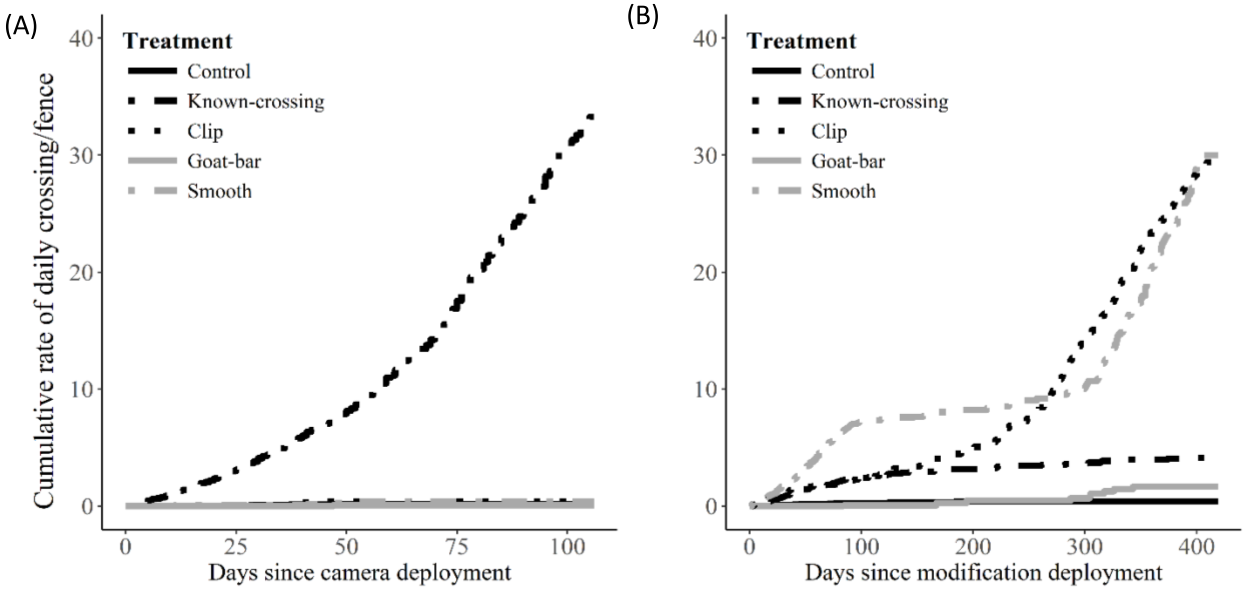


Figure 4. Pronghorn time lag results to modifications (Field Trial 1): Cumulative incidence functions (CIF) for fence modification treatments during (A) before (t = 0–106) and (B) after (t = 0–419) periods for pronghorn in Alberta, Canada (2012–2016), and Montana, USA (2015–2016). Treatments included control, known-crossing, goat-bar, clip, and smooth wire. Although multiple crossing events occurred within a day at a fence, we restricted crossing rates to a maximum of 1 event/day/fence to eliminate potential bias due to multiple crossings of the same individual at a fence.

3.1.2. Second field trials (2016-2018)

We deployed approximately 60 remote cameras in Montana and Alberta to capture and process images of wildlife interacting with fencing. We evaluated the effects of two additional commonly used fence modification/deterrents on pronghorn, deer and livestock movements. During the second field trials, we assessed fence modifications that were placed on the top barbed wire only. These included modifying barbed wire by either placing sage-grouse reflectors on the top and third wires or white PVC pipe on the top wire at fence panels with a known crossing location (Figure 5). Markers to reduce greater sage-grouse strikes have been identified as a useful tool for mortality reduction (Stevens et al. 2012), however no assessment has been conducted on how these markers effect other wildlife (i.e., deer, elk, pronghorn) fence interactions. Standardized procedures across study sites allowed us to collect uniform data on wildlife-fence interactions and assess wildlife and livestock use, similar to those in Jones et al. 2018 and Burkholder et al. 2018. Our objective was to evaluate effects of these two modifications aimed to increase fence visibility on the fence crossing behavior of three sympatric ungulates and assess their potential impacts of livestock interactions in the Northern Great Plains.

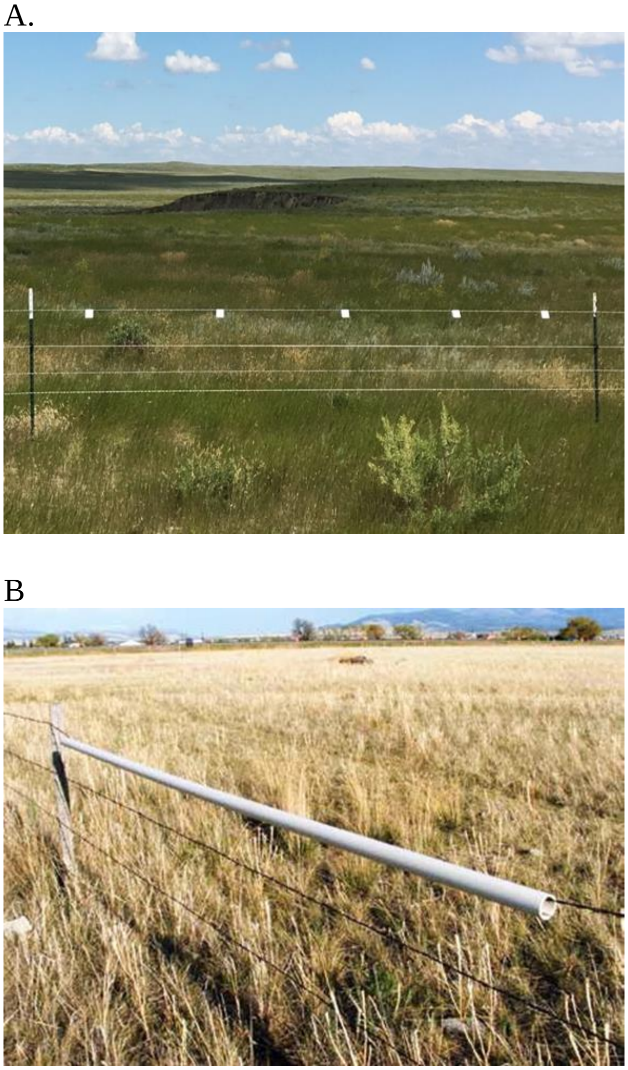


Figure 5. Top wire fence modifications: Wildlife friendly fence modifications deployed on the top wire of multi-stranded barbed wire fencing during second set of field trials. These included sage grouse markers (A.) and PVC pipe (B.). Top wire modifications were placed at known crossing during the after periods of field trials.

Detailed Statistical Methods:

Factors affecting crossing events.—We used generalized linear models with a logit link function (i.e., logistic regression) to evaluate pronghorn group crossing success (Hosmer and Lemeshow 2000). For pronghorn, we classified crossing events where > 50% of the group successfully crossed as successful (coded as 1) and the remaining events as failed attempts (coded as 0) for our response variable. We considered area (Alberta or Montana), group size, group composition (i.e., all male, all female, or mixed), bottom wire height, and treatment-period (control-before, control-after, PVC pipe-before, PVC pipe-after, SAGR reflector-before, or SAGR reflector-after) as explanatory covariates in our models. We used the covariate treatment-period as a surrogate for the interaction of treatment and period as it is easier to interpret the results than the interaction term, does not affect the results of the logistic regression, and provides an easy way to deal with missing combinations of treatment and period. We standardized continuous variables by subtracting the mean and dividing by 2 SDs, allowing their effect sizes to be comparable to categorical variables (Gelman 2008). We first screened for collinearity and eliminated one if there was high correlation (i.e., $|r| \geq 0.7$) between two covariates. Then we explored our data (Zuur et al. 2010) by comparing the single covariate model to the null model and eliminated the covariate from further modelling efforts if $P \geq 0.05$ to reduce global model complexity. We used Akaike's Information Criteria for small sample sizes (AIC_c) to evaluate the support among models (Burnham and Anderson 2002). We compared all possible combinations of covariates from the global model using a best-subsets regression approach (Grueber et al. 2011) achieved with the dredge function in Program R version 3.5.1 (R Core Team 2018) package MuMIn (Barton 2016). We used $\Delta AIC_c < 2.0$ as the initial cut-off to compare competing top models, then examined the covariates in each top model to see if including them improved model performance (Arnold 2010). If we determined that more than one model was competitive, we report the full model averaged β coefficients (Grueber et al. 2011). We calculated the odds ratio values and 95% confidence intervals (CI) using the unstandardized covariates and where there was more than one top model, we report the odds ratios for the unstandardized model averaged β coefficients and associated 95% CI. We evaluated model fit using Receiver Operator Curves (ROC) and used the scores to classify model fit as excellent (> 0.9), good (0.8 – 0.9), adequate (0.7 – 0.79), satisfactory (0.6 – 0.69), or poor (<0.6; Hosmer and Lemeshow 2000).

We used a similar approach to assess factors influencing deer crossing behavior except for two major differences. First, we evaluated the crossing behavior made by individual mule deer and white-tailed deer, as opposed to the group crossing success by pronghorn as noted above. As both mule deer and white-tailed deer groups were relatively small compared to pronghorn, we were able to keep track of individual deer and classify their behavior as to whether they successfully crossed or failed to cross. In instances where we had a deer cross a fence and then turn around and cross back, we recorded the event as one successful crossing. Secondly, in addition to evaluating crossing success we also evaluated crossing decision (see Figure 1 in Burkholder et al. 2018). We evaluated crossing decision by individual deer by subsampling our data for successful crossings, then determined whether the deer crossed the fence by crawling under (coded 1) or jumped over (coded 0). We removed any instances where a deer went through the fence from our decision analysis. We used the same covariates used in the pronghorn analysis except group composition was replaced with the covariate age-sex (adult male, adult female, or fawn unknown), and we included the covariate snow coverage (none, partial ground coverage, or full ground coverage at fence panel) for which there was no evidence of an effect for pronghorn but there was for deer (P.F. Jones, unpublished data). We used a categorical covariate for snow, as opposed to actual snow depth, because we did not have snow measurements for each camera site throughout the winter seasons. We analyzed mule deer and white-tailed deer separately. We conducted all analyses in Program R 3.5.1 (R Core Team 2018).

Multiple comparison analysis. — In logistic regression when categorical covariates are included in the top model, the beta coefficient (direction and size) for each level of the categorical covariate are only in relation to the reference category and do not provide an indication of how the other levels compare to each other. Therefore, for categorical covariates included in the logistic regression top model we used a Tukey-like comparison to account for the proper alpha level when comparing proportions (and not means as used in the standard Tukey comparison) to estimate pairwise-effect sizes among levels of the categorical covariate using the emmeans package (Lenth 2018) on the probability scale. Estimates of the logit (for success/decision) were obtained for each categorical covariate separately, if they were contained in the top model(s) of the logistic regression. Likelihood methods generate an estimate and SE on the logit scale, with the 95% confidence intervals (CI) calculated on the logit-scale by taking the estimate ± 1.96 SE. We then estimated the probability of success / decision as the anti-logit of the logit value and the 95% CI bounds.

Time to event analysis.—We used a time-to-event approach with multiple events to estimate daily crossing rates for pronghorn and deer among fence panel types during the before and after periods (Hosmer et al. 2008, Jones et al. 2018). We used days since camera deployment and modification as the origin for all cameras for the before and after periods respectively, and interval-censored cameras when they were not operable due to insufficient battery power or other issues. We pooled data across all years and study areas to summarize crossing rates. We estimated cumulative daily crossing rates for the 3 fence panel types (control, PVC pipe, SAGR reflector) and 2 periods (before and after) using nonparametric cumulative incidence functions (CIFs; Heisey and Patterson 2006). When competing risks of an event are involved, the incidence of event type k occurring at time t is generally defined as the hazard of event k at time $t[h_k(t)]$ multiplied by the overall probability of survival at $t-1$ just before event k occurs (Kleinbaum and Klein 2012). However, we assumed a survival probability at $t-1$ of 1.0 because cameras did not fail (or die) when they detected crossing events. We restricted crossing rates to a maximum of 1 event/day at each fence panel to eliminate bias due to multiple crossings of the same individual. We modified the R code provided in Eacker et al. (2016) to estimate CIFs and used the R package survival (Therneau 2015). We used the R package bshazard (Rebora et al. 2018) to estimate smoothed daily treatment-specific crossing rates with 95% CI. We conducted the time-to-event analyses in Program R 3.5.1 (R Core Team 2018).

Overall Results:

Combining data for Alberta and Montana, we recorded 7,665 and 1,787 successful crossing attempts for pronghorn and mule deer, respectively (Table 2). We recorded 341 successful crossing attempts for white-tailed deer in Alberta only (Table 2). We did not record any successful or failed fence crossing attempts for white-tailed deer in Montana. Pronghorn successfully crossed a fence 49% of the time and did so predominately by crossing under (99.9%). Mule deer successfully crossed the fence 75% of the time and did so predominately by going under (83%) as opposed to over. White-tailed deer crossed the fence 65% of the time and did so predominately by going under (60%). In Montana, we captured images during the before and after periods of pronghorn and mule deer (no white-tail deer) crossing at further fence panels within a camera’s view, down to the fence panel where the camera was located.

Factors Affecting Crossing Success Results.—For our analysis, the 15,771 crossing attempts (successful and failed) by pronghorn represented 2,394 events, of which 1,520 of the events had > 50% of the group successfully cross and were considered successful (coded 1) for our logistic regression analysis. We removed group composition from our model selection as it was correlated with maximum group size. We selected one top model that included 4 covariates with a model weight of 100%; the next best model had a $\Delta \mathrm{AIC}_c = 34.58$ and was not considered as a competing model. The covariate treatment-period was retained in the final top model for pronghorn crossing success and is discussed below in the Multiple Comparison Analysis section. Bottom wire height was retained in the top model, with the odds of a pronghorn successfully crossing the fence greater for every 1 cm increase in bottom wire height (unstandardized odds ratio = 1.08, 95% CI = 1.07–1.10). In addition, group size was retained in the top model, with the odds of a pronghorn successfully crossing the fence greater for every additional individual in the group (unstandardized odds ratio = 1.06, 95% CI = 1.05–1.08). Lastly, pronghorn had a higher probability of successfully crossing a fence in Montana (unstandardized odds ratio = 2.15, 95% CI = 1.67–2.79). The top model performed adequately with a ROC score of 0.73.

Table 2. **Ungulate fence crossing attempts summary:** Number of successful and failed fence crossing attempts made by pronghorn, mule deer, and white-tailed deer in Alberta, Canada, and Montana, USA, 2016–2018. Crossing attempts were determined from photos captured using trail cameras at fence panels with a crossing site. Note that the attempts by pronghorn are the total number and may include repeated attempts by an individual during the same event due to difficulty keeping track of individuals in groups, whereas the attempts by mule deer and white-tail deer are for individuals as group sizes tended to be smaller and individuals could be kept track off.

SPECIES	NUMBER UNDER	NUMBER OVER	NUMBER THROUGH	TOTAL SUCCESSFUL ATTEMPTS	TOTAL FAILED ATTEMPTS	TOTAL ATTEMPTS
PRONG HORN	7,656	1	8	7,665	8,106	15,771
MULE DEER	1,482	298	7	1,787	610	2,397
WHITE-TAILED DEER	205	135	1	341	184	525

For mule deer we recorded 2,397 individual deer attempting to cross (successful and failed) with a 75% crossing success rate (1,787/2,397). We selected one top model for mule deer crossing success that contained 4 covariates with a model weight of 100%; the next best model had a ΔAIC_c = 15.43 and was not considered as a competing model. All covariates in the top model had a negative relationship except for bottom wire height. The covariate treatment-period was retained in the final top model for mule deer crossing success and is discussed below in the Multiple Comparison Analysis section. The odds of a mule deer successfully crossing the fence were greater for every 1 cm increase in bottom wire height (unstandardized odds ratio = 1.05, 95% CI = 1.04–1.06). Mule deer had a lower probability of successfully crossing a fence in Montana (unstandardized odds ratio = 0.41, 95% CI = 0.32–0.52). Lastly, mule deer adult males and unknown fawns had a lower probability of successfully crossing (male-adult: unstandardized odds ratio = 0.46, 95% CI = 0.38–0.57; fawns-unknown: unstandardized odds ratio = 0.64, 95% CI = 0.47–0.87) compared to females. The top model performed satisfactory with a ROC score of 0.68.

For white-tailed deer in Alberta, we recorded 525 individual deer attempting to cross (successful and failed) with a 65% crossing success rate (341/525). As there were only 8 individual fawns detected during our study, we removed them and the associated females during those events from further analysis resulting in our age-sex composition being either adult female or adult male. We removed the events with fawns from the analysis because the low number created model instability. For our crossing success analysis, we selected one top model containing 4 covariates with a total cumulative model weight of 74%; the next best model had a ΔAIC_c = 2.99 and was not considered as a competing model. The covariate treatment-period was retained in the final top model for white-tailed deer crossing success and is discussed below in the Multiple Comparison Analysis section. The odds of a white-tailed deer successfully crossing a fence increased for every 1 cm increase in bottom wire height (unstandardized odds ratio = 1.05, 95% CI = 1.02–1.08), while the odds decreased if the individual was an adult male (unstandardized odds ratio = 0.44, 95% CI = 0.30–0.65) than if it was an adult female. The odds of successfully crossing a fence increased if the snow coverage was patchy (unstandardized odds ratio = 5.31, 95% CI = 1.45–34.33) or full (unstandardized odds ratio = 1.31, 95% CI = 0.63–2.88) compared to no snow coverage. The top model performed satisfactorily with a ROC score of 0.68.

Factors Affecting Crossing Decision Results.—For mule deer we recorded 1,482 individual deer deciding to cross under a fence, resulting in 83% (1,482/1,780) of the individual deer deciding to cross under as opposed to jumping over. We removed the 7 individual instances of a deer crossing between the wires for the decision analysis. For our crossing decision analysis, we selected 3 top models that had $\Delta AIC_c < 2.0$ with a total cumulative model weight of 88%. The next best model had a $\Delta AIC_c = 2.56$ and was not considered as a competing model. The covariate treatment-period was retained in the final top model for mule deer crossing decision and is discussed below in the Multiple Comparison Analysis section. We model averaged the beta coefficients and determined that bottom wire height, group composition, area, and group size were important covariates in the top model. The odds of a mule deer successfully crossing under a fence increased for every 1 cm increase in bottom wire height (unstandardized odds ratio = 1.16, 95% CI = 1.13–1.19). The odds of a mule deer crossing under a fence increased if the individual was an unknown fawn (unstandardized odds ratio = 2.74, 95% CI = 1.20–6.27) and decreased if the individual was an adult male (unstandardized odds ratio = 0.09, 95% CI = 0.06–0.13) than if it was an adult female. Lastly, the odds of a mule deer crossing under a fence decreased for every additional individual in the group (unstandardized odds ratio = 0.97, 95% CI = 0.89–1.05) and decreased if the individual was in Montana (unstandardized odds ratio = 0.69, 95% CI = 0.46–1.03) when compared to Alberta. The top model performed good with a ROC score of 0.90.

For white-tailed deer, we recorded 205 individual deer deciding to cross under a fence, resulting in 60% (205/340) of the individual deer deciding to cross under as opposed to jumping over. We removed the 1 instance of an individual deer going between the wires from the decision analysis. We selected 2 top models that had $\Delta AIC_c < 2.0$ with a total cumulative model weight of 100%. The next best model had a $\Delta AIC_c = 15.31$ and was not considered as a competing model. The covariate treatment-period was retained in the final top model for white-tailed deer crossing decision and is discussed below in the Multiple Comparison Analysis section. Our top models contained the covariates bottom wire height, adult males, and group size. The odds of a white-tailed deer successfully crossing under a fence increased for every 1 cm increase in bottom wire height (unstandardized odds ratio = 1.17, 95% CI = 1.12–1.23), while the odds decreased if the individual was an adult male (unstandardized odds ratio = 0.20, 95% CI = 0.11–0.36) than if it was an adult female, and decreased for every additional member of the group the individual was in (unstandardized odds ratio = 0.83, 95% CI = 0.68–1.01). The top model performed good with a ROC score of 0.85.

Multiple Comparison Analysis Results.—Crossing success. The categorical covariate ‘treatment type-period’ was included in the top model for crossing success for all three ungulates. The beta coefficients for this categorical covariate are in comparison to the reference category (i.e., control-before); therefore, we fit our Tukey-like multiple comparisons to understand how each level of the covariate compared to the other levels. We found a trend, though not significant, of a higher probability of successful crossing by pronghorn during the after period at all camera sites compared to the corresponding camera sites during the before period (Figure 6). For mule deer we found the probability of successfully crossing changed between the before and after periods for each camera site type (Figure 7). Mule deer had a higher probability of successfully crossing at each modified camera site following installation of the modifications in respect to the same camera sites during the before period. The exception was for the control camera sites where the probability was lower during the after period than the before period (Figure 7), which may indicate that mule deer were drawn to modified fence panels (PVC pipes, SAGR markers) within the study area during the after period. For white-tailed deer, we found none of the levels (e.g., control-after) influenced the probability of successfully crossing a fence than any of the other levels (Figure 7). However, though not significant, there was a trend of increased mean probability of successfully crossing a fence at the modified camera sites during the before period compared to the same camera sites during the after period (Figure 7). The exception was at control camera sites where crossing success remained relatively the same between periods (Figure 7).

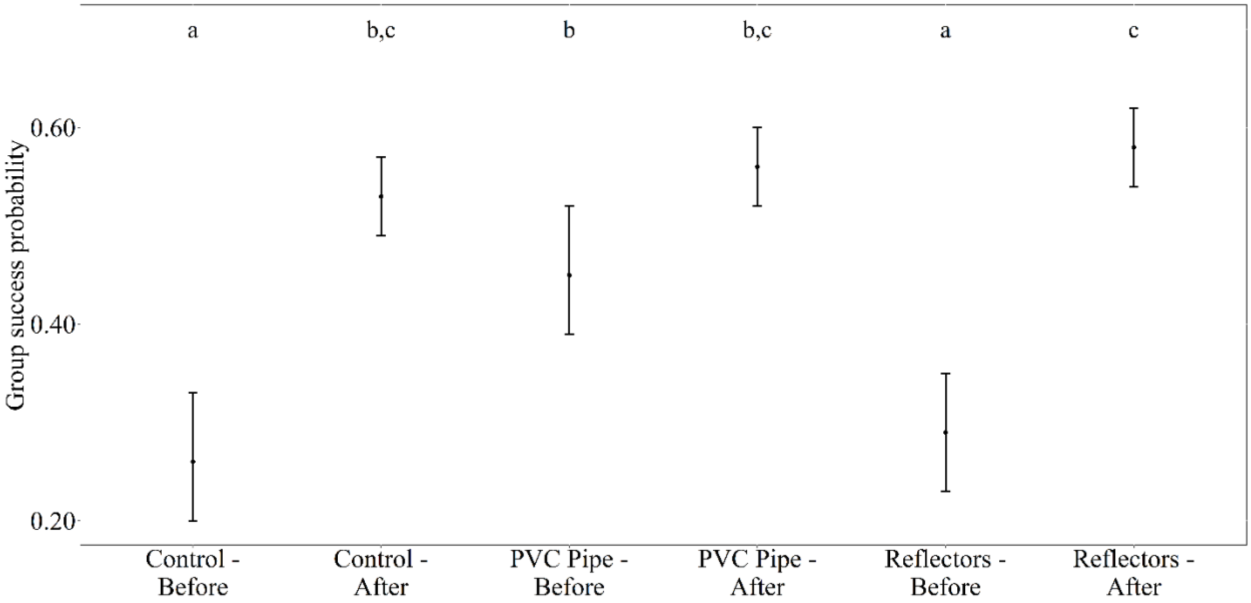


Figure 6. Pronghorn crossing success probabilities (Field Trial 2): Mean probability and 95% confidence limits for the covariate treatment-period for group crossing success by pronghorn in Alberta, Canada, and Montana, USA, 2016–2018. For pronghorn, we classified successful crossing events where > 50% of the group successfully crossed from one side of the fence to the other by any means (under, over, through). Similar letters above points indicate no difference between probabilities based on Tukey-like multiple pair-wise comparisons. We completed the multiple comparisons using a Tukey-like comparison to account for the proper alpha level when comparing proportions (and not means as used in the standard Tukey comparison) to estimate pairwise-effect sizes among levels of the categorical covariate on the probability scale using just the covariate separately and not in conjunction with the other covariates in the top model.

Multiple Comparison Analysis Results.—*Crossing decision.* The categorical covariates treatment-period was included in the top model for crossing decision by both deer species with the beta coefficients in table 2 in reference to the category (control-before). When we fit our multiple comparisons, we found mule deer had a higher probability of crossing under the bottom wire at the SAGR reflectors and PVC pipe camera sites following installation compared to the same camera sites before we installed the modifications (Figure 7). There was a lower probability of crossing under at the control camera sites during the after period compared to the before period (Figure 7). For white-tailed deer, though not statistically significant, we found a similar pattern of a higher probability of crossing under a fence at the modified camera sites once the modifications were installed (Figure 7). There was a consistent probability of crossing under at the control camera sites between the before and after periods (Figure 7).

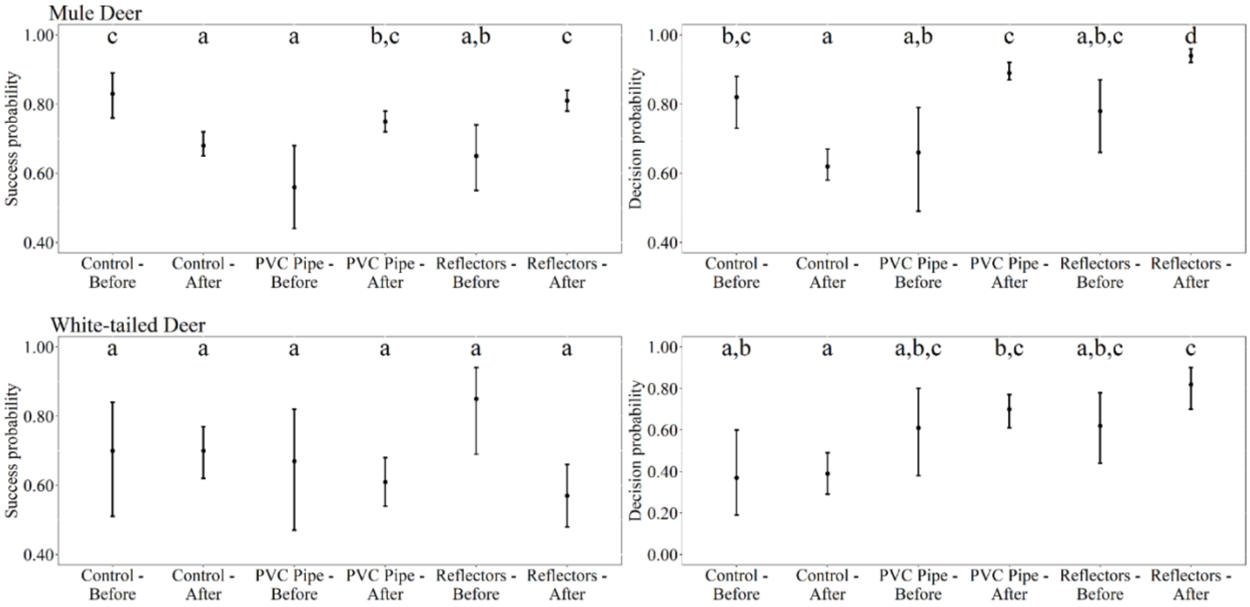


Figure 7. Deer crossing and decision success probabilities (Field Trial 2): Mean probability and 95% confidence limits for the covariate treatment-period for individual crossing success (left column) and crossing decision (right column) by mule deer (top row) and white-tailed deer (bottom row) in Alberta, Canada, and Montana, USA, 2016–2018. Crossing success was defined as crossing from one side of the fence to the other by any means (e.g., under, over, or through), while crossing decision was defined as the probability of crossing under. Similar letters above points indicate no difference between probabilities based on Tukey-like multiple pair-wise comparisons. We completed the multiple comparisons using a Tukey-like comparison to account for the proper alpha level when comparing proportions (and not means as used in the standard Tukey comparison) to estimate pairwise-effect sizes among levels of the categorical covariate on the probability scale using just the covariate separately and not in conjunction with the other covariates in the top model.

Time-to-Event Analysis Results.—Our pooled analysis for pronghorn included 4,850 camera-days during the before period and 24,548 camera-days during the after period. We detected 247 and 1,034 pronghorn daily crossing events during the before (days 0–105) and after (days 0–456) periods, respectively. Most daily pronghorn crossing events during the before period occurred at the PVC pipe camera sites, which reached a cumulative rate of 5.20 (95% CI = 3.91 – 6.48) daily crossings/fence by 105 days since camera deployment (Figure 8). By day 105 (Figure 8) during the after period all treatments had reached their respective before period cumulative crossing rate indicating no effect of the fence modifications. The cumulative rate of daily crossings per fence continued to increase at all camera sites during the after period (Figure 8), with the greatest increase observed at the SAGR reflector camera sites (after CIF = 22.18, 95% CI = 7.36–37.05) followed by the PVC pipe camera sites (after CIF = 20.48, 95% CI = 7.77–33.23).

Our pooled analysis for mule deer included 4,850 camera-days during the before period and 24,548 camera-days during the after period. We detected 76 and 779 mule deer daily crossing events during the before (days 0–105) and after (days 0–456) periods, respectively. Most daily mule deer crossing events during the before period occurred at the SAGR reflector camera sites, which reached a cumulative rate of 1.49 (95% CI = 1.34–1.65) daily crossings/fence by 105 days since camera deployment (Figure 8).

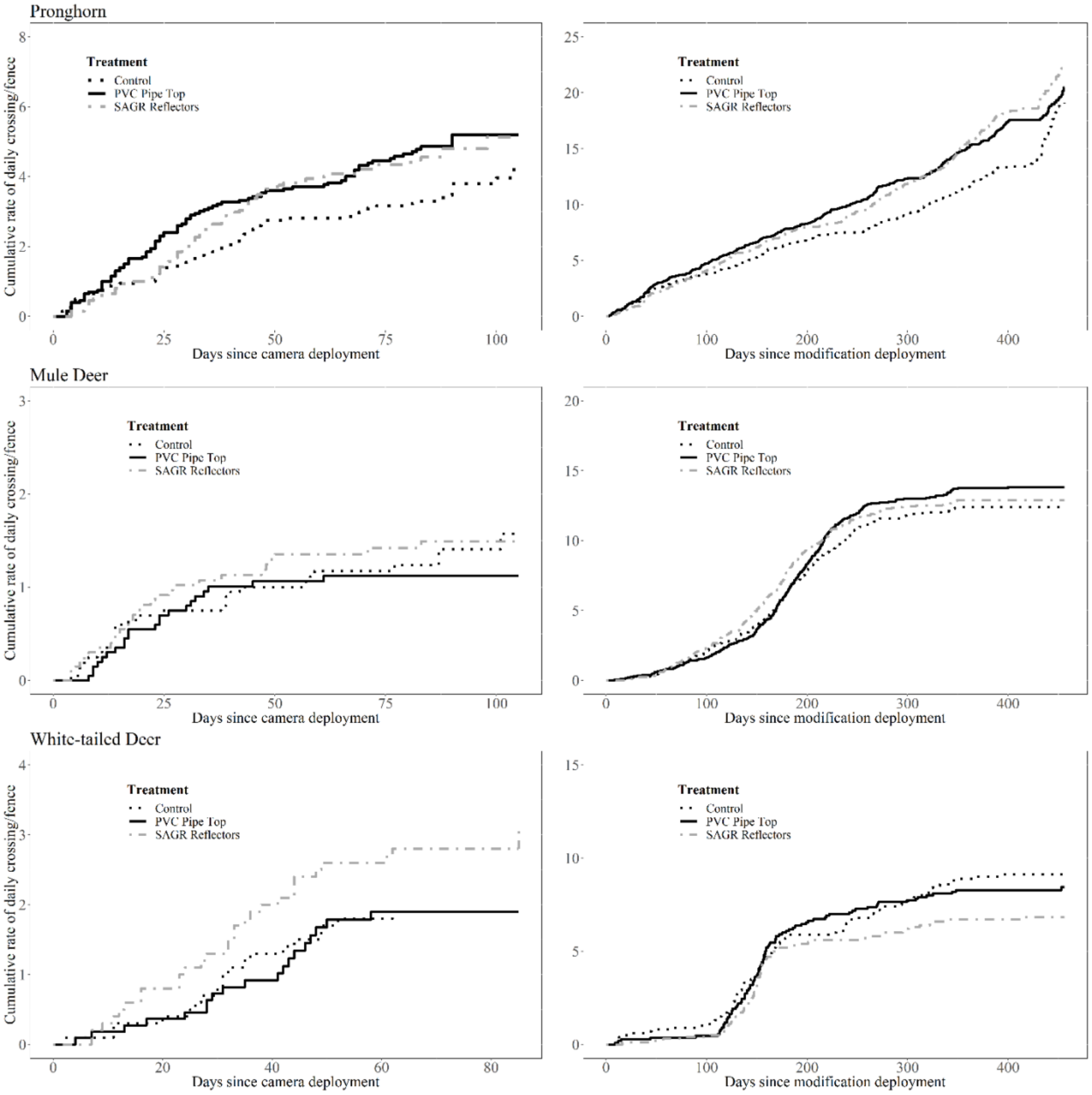


Figure 8. Ungulate time lag results to modifications (Field Trial 2): Cumulative incidence functions (CIF) for fence modification treatments during before (t = 0–105, left column) and after (t = 0–456, right column) periods for pronghorn (top), mule deer (middle), and white-tailed deer (bottom) in Alberta, Canada and Montana, USA, 2016–2018. Treatments included control, PVC pipe, and sage grouse reflectors. White-tailed deer had a before period of 85 days as data was from Alberta only. Although multiple crossing events occurred within a day at a fence, we restricted crossing rates to a maximum of 1 event/day/fence to eliminate potential bias due to multiple crossings of the same individual at a fence.

At all camera sites there was a leveling off for daily crossing rates occurring around day 30 of the before period. By day 105 (Figure 8) during the after period all treatments had reached or slightly exceed their respective before period cumulative crossing rate indicating no effect of the fence modifications. The cumulative rate of daily crossings per fence continued to increase at all camera sites during the after period until approximately day 250 where the rates leveled off (Figure 8). By day 456 all the treatment types exceeded their before crossing rates with the greatest increase observed at the PVC pipe camera sites (after CIF = 13.85, 95% CI = 6.43–21.26) followed by the SAGR reflector camera sites (after CIF = 12.89, 95% CI = 6.91–18.88).

Our pooled analysis for white-tailed deer in Alberta included 2,498 camera-days during the before period and 13,579 camera-days during the after period. We detected 67 and 251 white-tailed deer daily crossing events during the before (days 0–85) and after (days 0–456) periods, respectively. Most daily white-tailed deer crossing events during the before period occurred at the SAGR reflector camera sites, which reached a cumulative rate of 3.13 (95% CI = 2.25–4.02) daily crossings/fence by 85 days since camera deployment (Figure 4). By day 85 (Figure 4) during the after period all treatments had cumulative crossing rates slightly below their respective before period, but by day 100 cumulative crossing rate increased and by day 456 rates exceeded those observed during the before period. Overall the greatest increase in cumulative crossing rates were at control camera sites (after CIF = 9.11, 95% CI = 4.12–14.11) followed by the PVC pipe camera sites (after CIF = 8.45, 95% CI = 3.88–13.02).

3.2. Objective 2: Pronghorn movement modeling and fence density connectivity modeling.

3.2.1. Study area and pronghorn movement model

To study regional connectivity of pronghorn at their northern terminus and across the Hi-Line study area, we used the Northern Sagebrush Steppe (NSS) GIS boundary layer produced by Jakes et al 2015. This allowed us to seed connectivity paths in Canada, rather than restricting movement to only the Montana Hi-Line area. The NSS area encompasses roughly 316,000 km^2 across through the prairie/sagebrush steppe regions of Alberta, Saskatchewan and Northern Montana (Figure 9). GPS data collected from collared female pronghorn over 6 years (n = 185) from 2004-2010. Both environmental gradients (e.g., slope, landcover, forage productivity) and anthropogenic factors (e.g., gas well density, road density) were used to assess migratory pathway selection. These data were used to produce integrated step selection function (ISSF) maps for three seasons for pronghorn movement: spring, fall, and winter. See Jakes et al. 2015 for capture, data collection and modelling details. Figure 10 shows spring pronghorn movement.

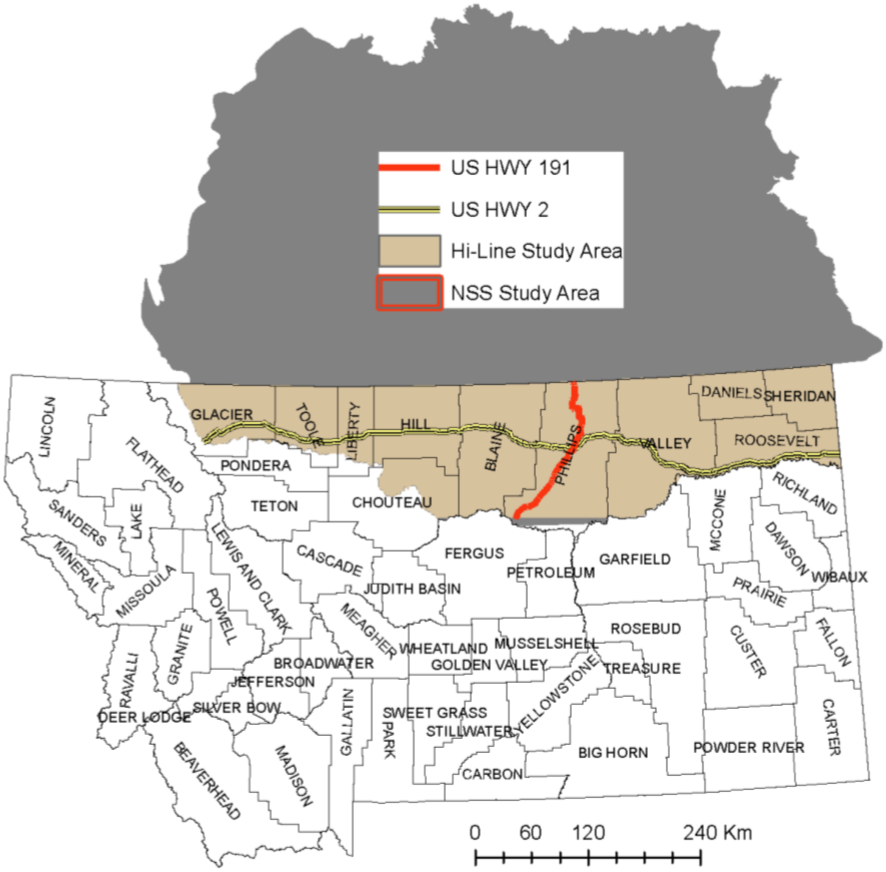


Figure 9. Study area: Northern Sagebrush Steppe study area in grey encompassing the Montana Hi-Line study area in tan.

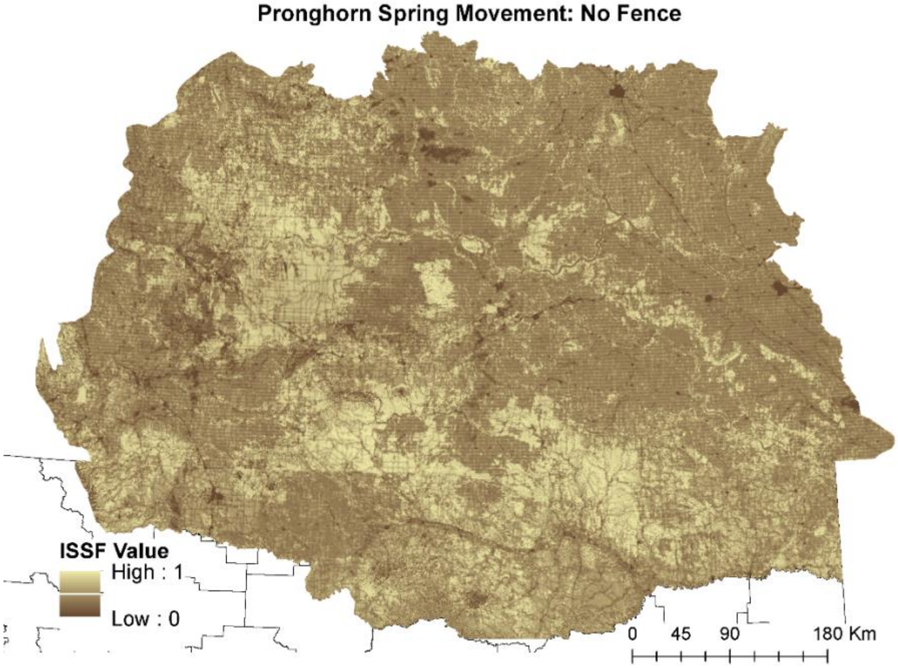


Figure 10. Pronghorn ISSF map during spring migration: Pronghorn ISSF movement model for spring for the entire NSS study area (Jakes et al. 2015). Fence density was not included in this model.

3.2.2. *Fence density mapping*

To study the effects of fence density on pronghorn movement across the Hi-Line study area, we used the publish fence density layer create by Poor et al. 2014 (Figure 11). Fence density models were modelled using barbed-wire fence field data collected across 2 km transects (n = 632). Models included assumptions for fences along roads, and fences relative to landcover type, parcel size, parcel ownership and neighboring parcel ownership. This variable was then integrated into the ISSF seasonal maps produced by Jakes et al. 2015 and 6 model scenarios were produced for the connectivity modeling: spring, fall, winter with and without fence density effects. Figure 12 shows a comparison of two scenarios for spring movement with and without fence density.

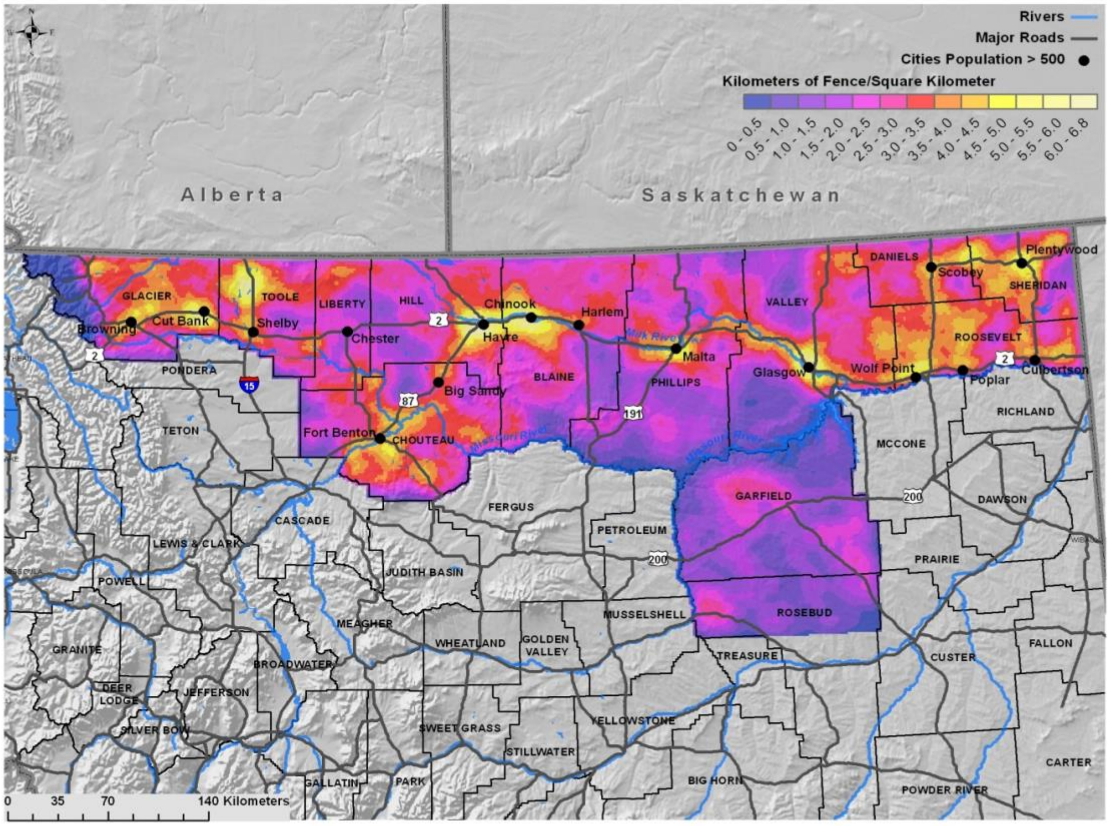


Figure 11. Fence density map across the Hi-Line: Map output of fence density across the Montana Hi-Line study area. Note that Garfield and Rosebud counties were not included in the pronghorn habitat modeling and therefore, excluded from the connectivity modeling as well.

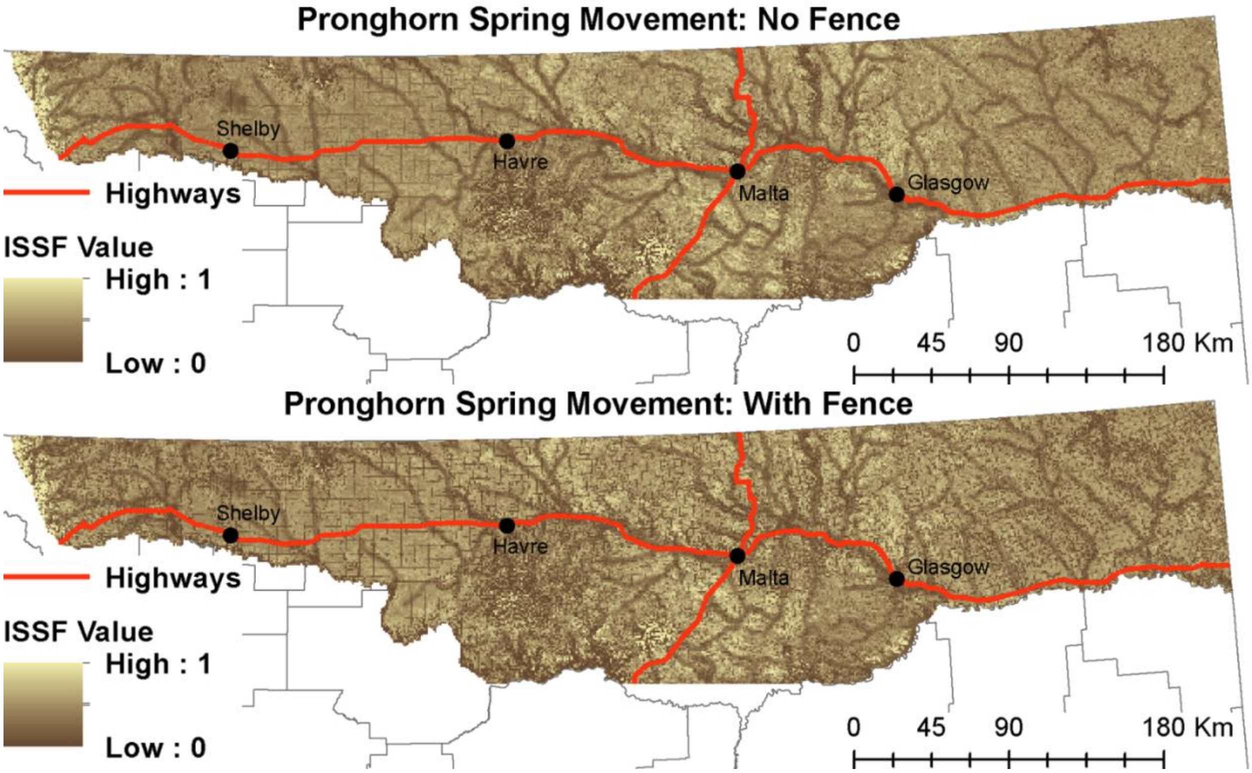


Figure 12. Comparative pronghorn ISSF maps across the Hi-Line during spring migration: Pronghorn ISSF movement model for spring for the Montana Hi-Line study area for no fence (top panel) and including fence density (bottom panel).

3.2.3. *Road mortality data*

We used maintenance road mortality data across US Hwy 2 and US Hwy 191 from 2007-2017 to evaluate predicted seasonal migratory connectivity maps. US Highway 2 data spanned from mile post 210.3 (west end) to mile post 668 (east end, which is the North Dakota state line) or 457.7 miles total. US Highway 191 data spanned mile post 0.0 (the US 2/US 191 intersection at Malta) to mile post 55 (the US-Canada border at the Port of Morgan) or 55 miles total with mile post 88.1 (the north end of the Fred Robinson Bridge) to mile post 158 (the US 191/US2 intersection at Malta) or 69.9 miles total. Figure 13 shows pronghorn mortalities split between total and their corresponding seasons. Across the 10 years of data, there were 117 total data points: 33 in the fall, 14 in the spring, 57 in the summer, and 13 in the winter.

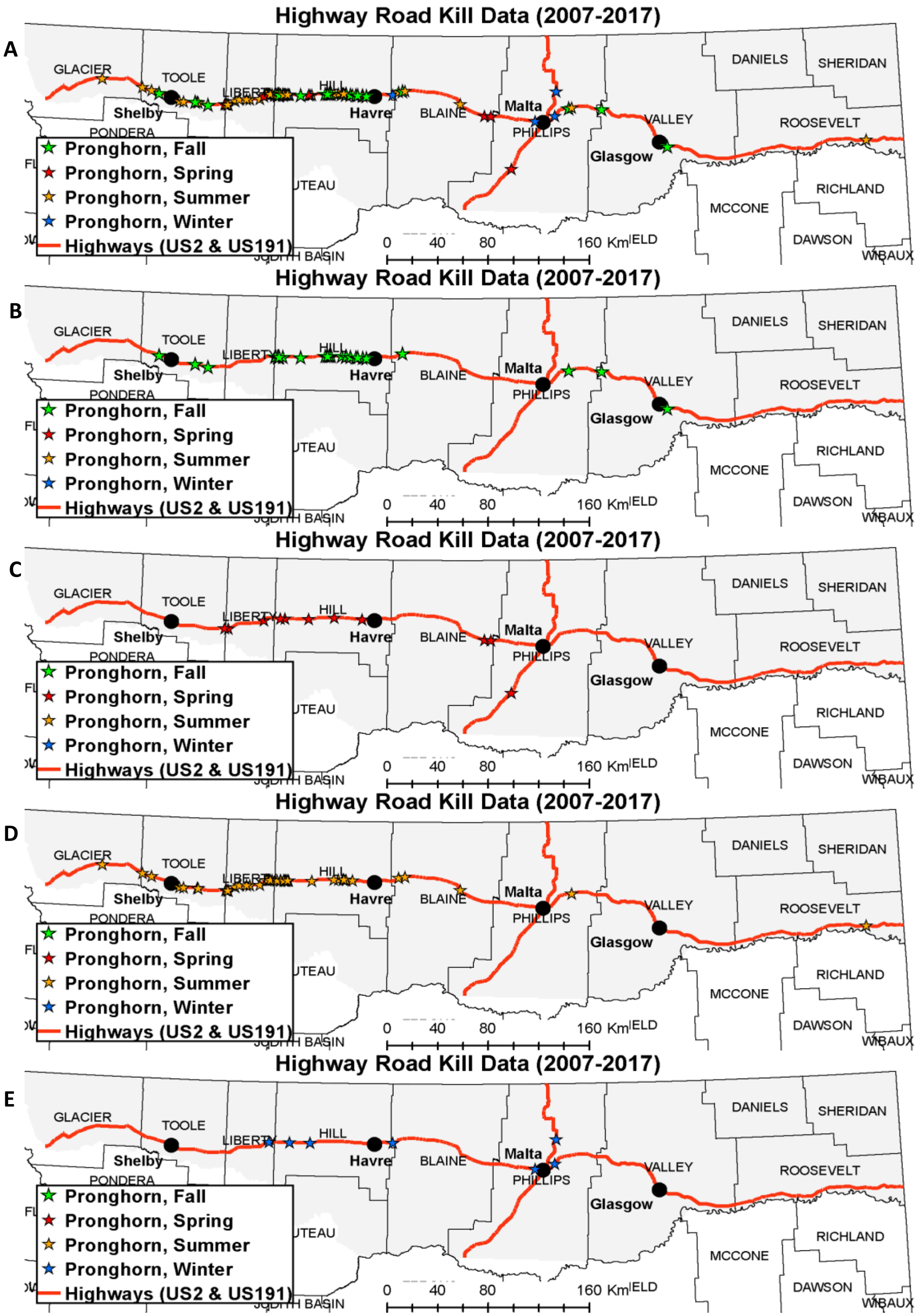


Figure 13. Pronghorn road mortality along Hi-Line: Maintenance road mortality data for pronghorn (2007-2017) for (A) total, (B) fall, (C) spring, (D) summer, and (E) winter.

We also mapped mule deer maintenance road mortality data. Across the 10 years of data, there were 832 total data points: 230 in the fall, 149 in the spring, 105 in the summer, and 348 in the winter. Figure 14 shows mule deer mortalities split between total and their corresponding seasons. Finally, Figure 15 shows the spatial location of fence densities in relation to pronghorn and mule deer maintenance road mortality.

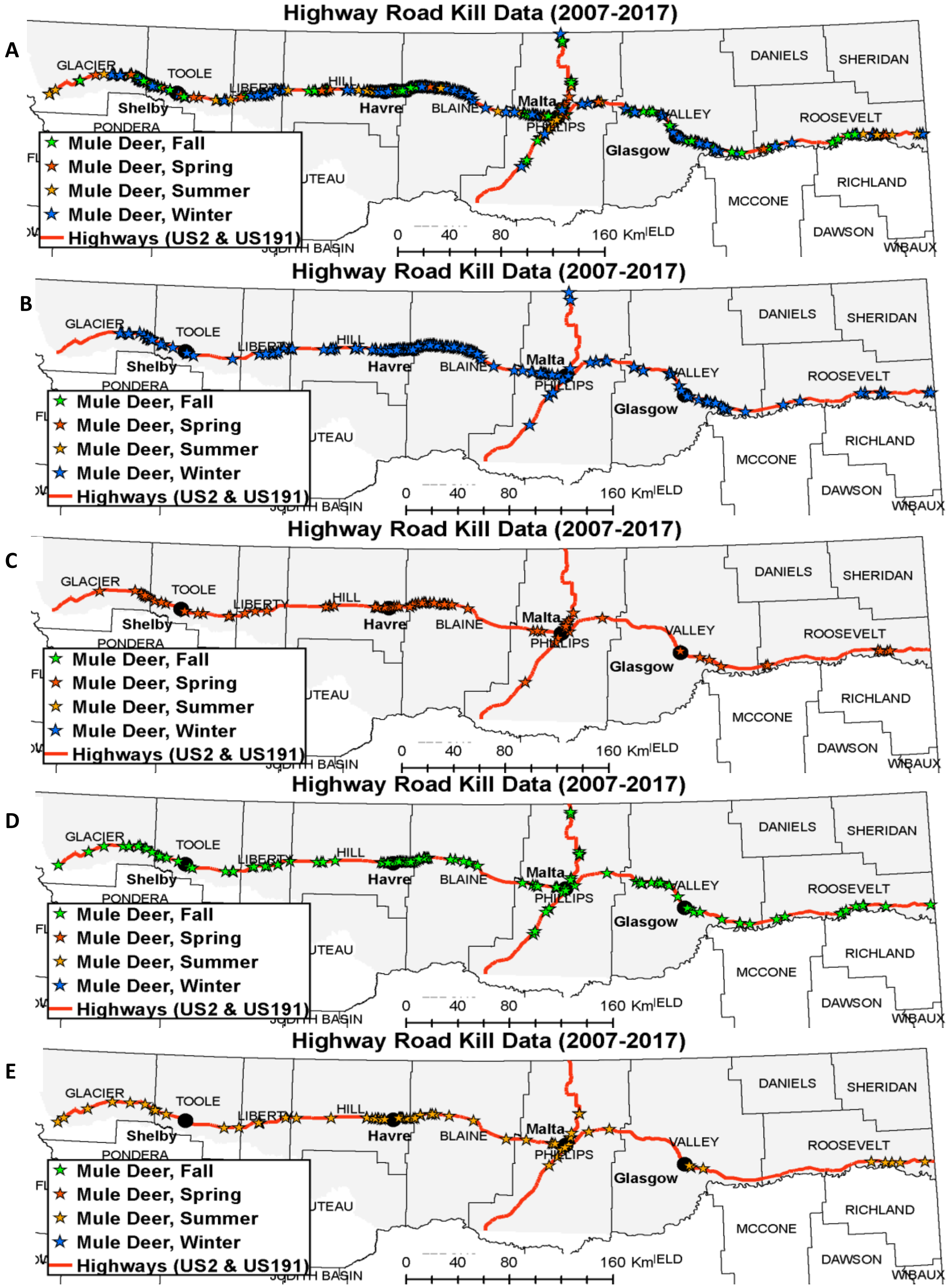
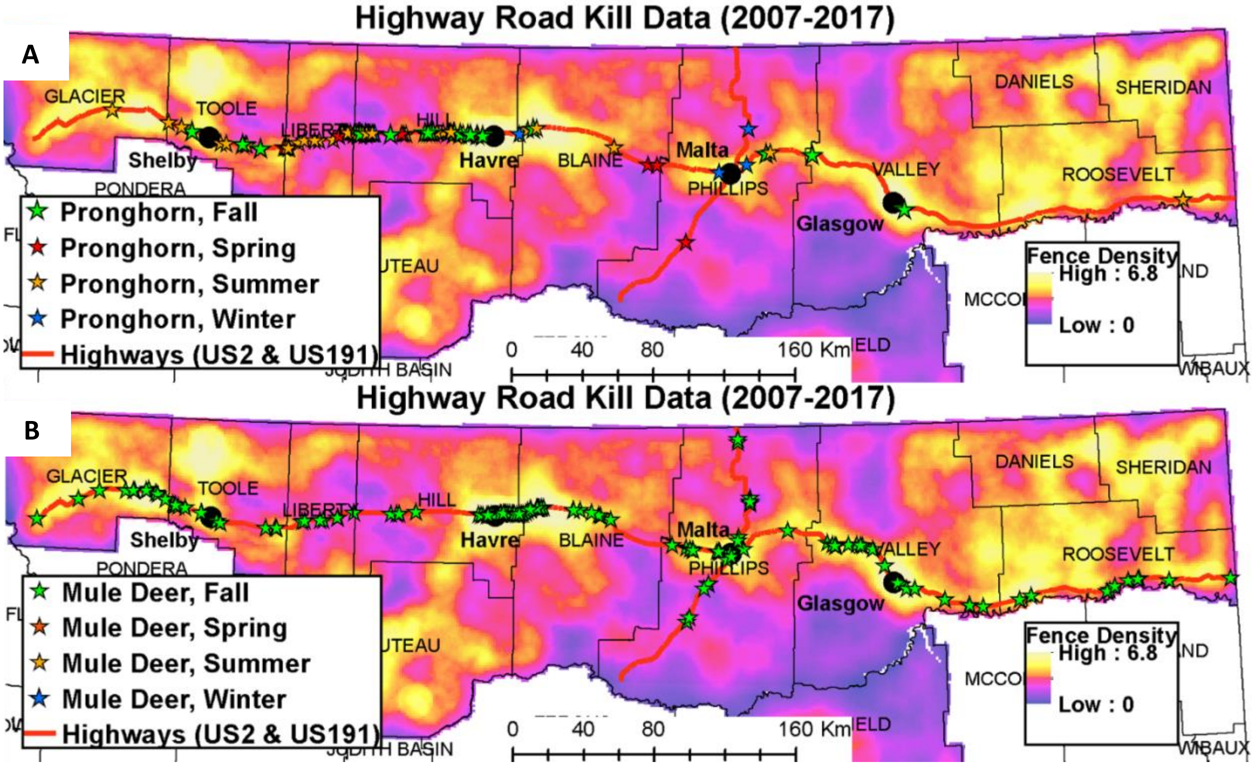


Figure 14. Mule deer road mortality along Hi-Line: Maintenance road mortality data for mule deer (2007-2017) for (A) total, (B) fall, (C) spring, (D) fall, and (E) summer.


Highway Road Kill Data (2007-2017)

Highway Road Kill Data (2007-2017)

Figure 15. Hi-Line fences densities plotted with road mortalities: Fence density location plotted with (A) All pronghorn maintenance road kill data and (B) fall mule deer maintenance road kill data.

3.2.4. Connectivity modeling

Presently, there are a number of choices available for researchers to address regional connectivity (See http://www.conservationcorridor.org/). After reviewing available options and conducting preliminary analyses with a number of the existing platforms, including the R function gdistance (van Etten 2018), Linkage Mapper and Circuitscape (e.g., McRae 2006), we selected the UNICOR program (Landguth et al. 2012). UNICOR uses Dijstkra's algorithm to integrate least-cost path theory while allowing flexibility in selecting the appropriate corridor widths to sustain network across the study area (e.g., Cushman et al. 2013). The steps involved in connectivity modeling are as follows: (1) creating resistance to movement surfaces, (2) identifying source-destination points from species distributions, and (3) running the connectivity simulations.

3.2.4.1.Resistance models

The first step in creating any wildlife connectivity regional design is to create resistance to movement surfaces. We used the 6 movement model scenarios described previously for spring, fall, and winter with and without fence density. See Jakes et al. 2015 for the methodology details in developing these maps. Next is to convert the movement model maps into resistance models. Landscape resistance models assign a value to each pixel which represents the associate movement cost. Low resistance values indicate areas easier and more likely for a species to traverse. Conversely, high resistance values indicate areas unfavorable for species movement. We transformed the predicted habitat suitability into a resistance surface for each season and scenario using a negative exponential function that has shown to have the best performance (Keeley et al. 2016). The resulting resistance surfaces for pronghorn had a value between 1 (when movement suitability = 1) and 10 (when movement suitability = 0). The 6 resistance surface scenarios are shown in Figure 16(A-C).

All GIS layers were resampled to 193 m x 193 m resolution prior to modeling. The landscape resistance models were converted to ascii files and used in a later step of the assessment as input files for our connectivity simulations.

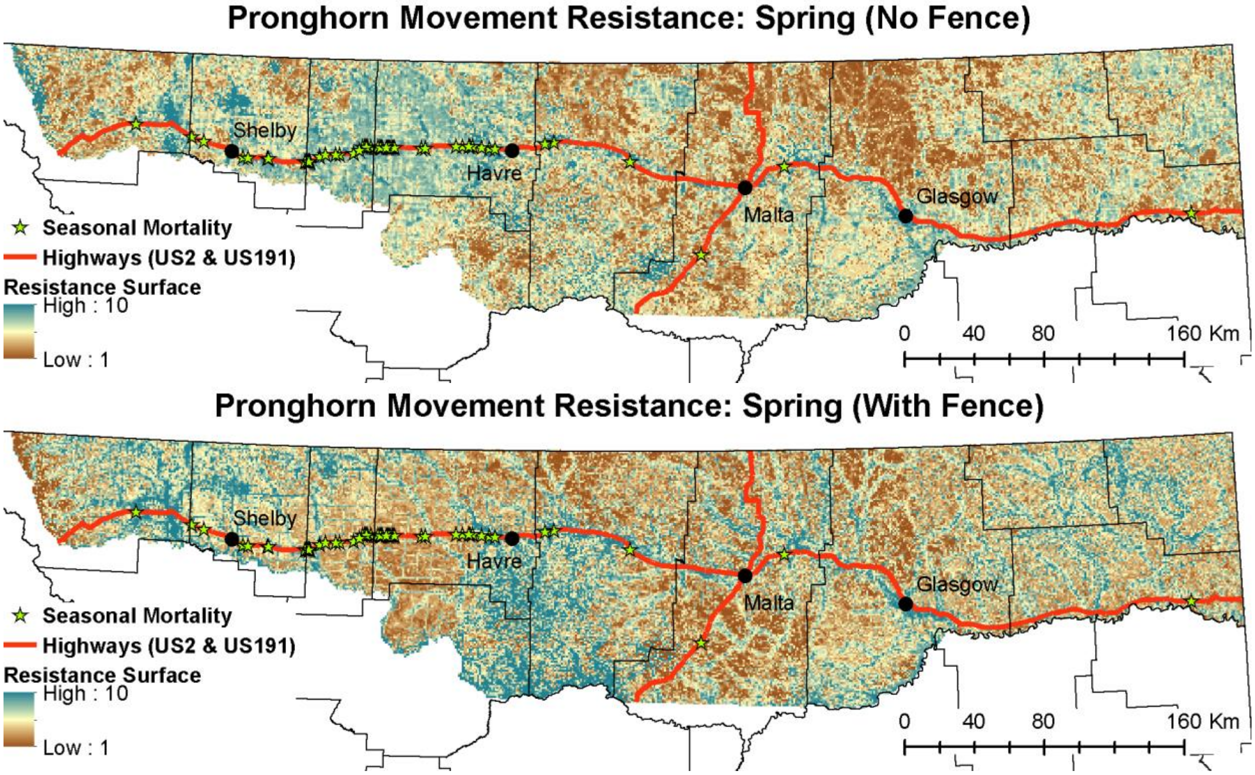


Figure 16A. **Pronghorn habitat resistance results for spring:** Pronghorn habitat resistance for spring including no fence effect (top panel) and fence effect (bottom panel).

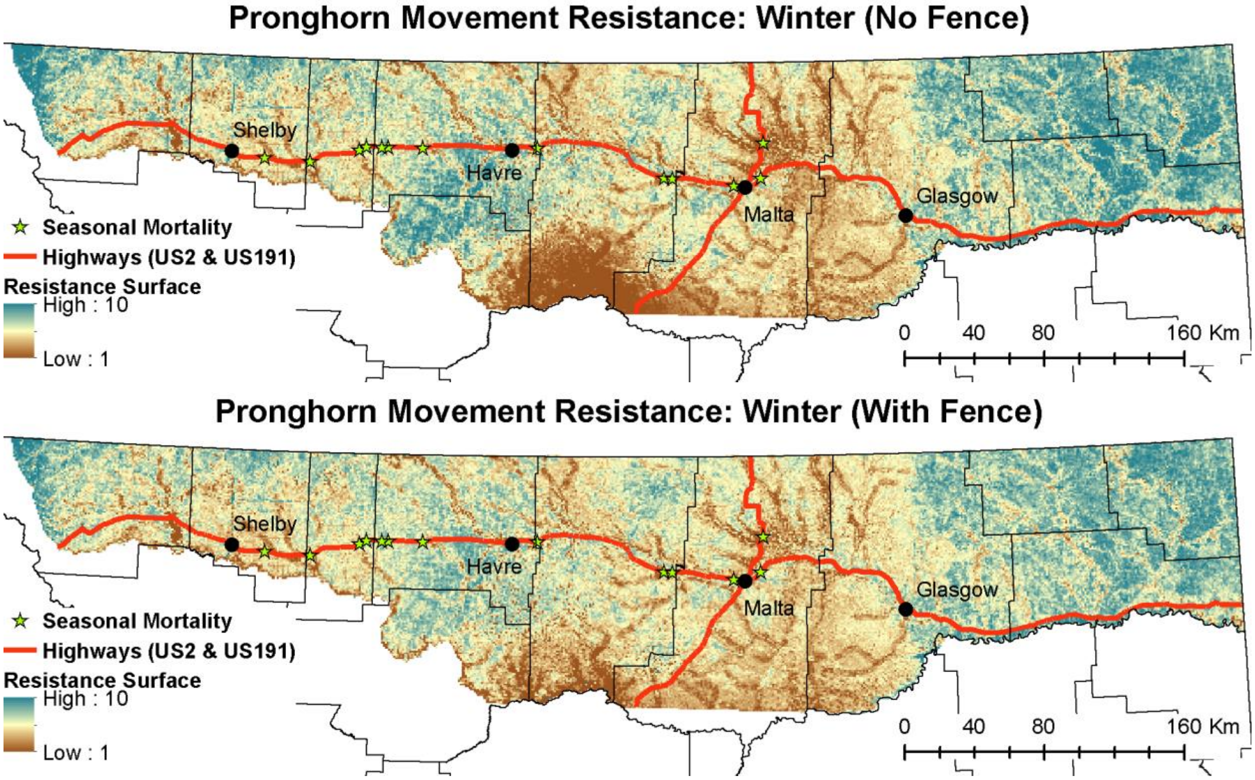
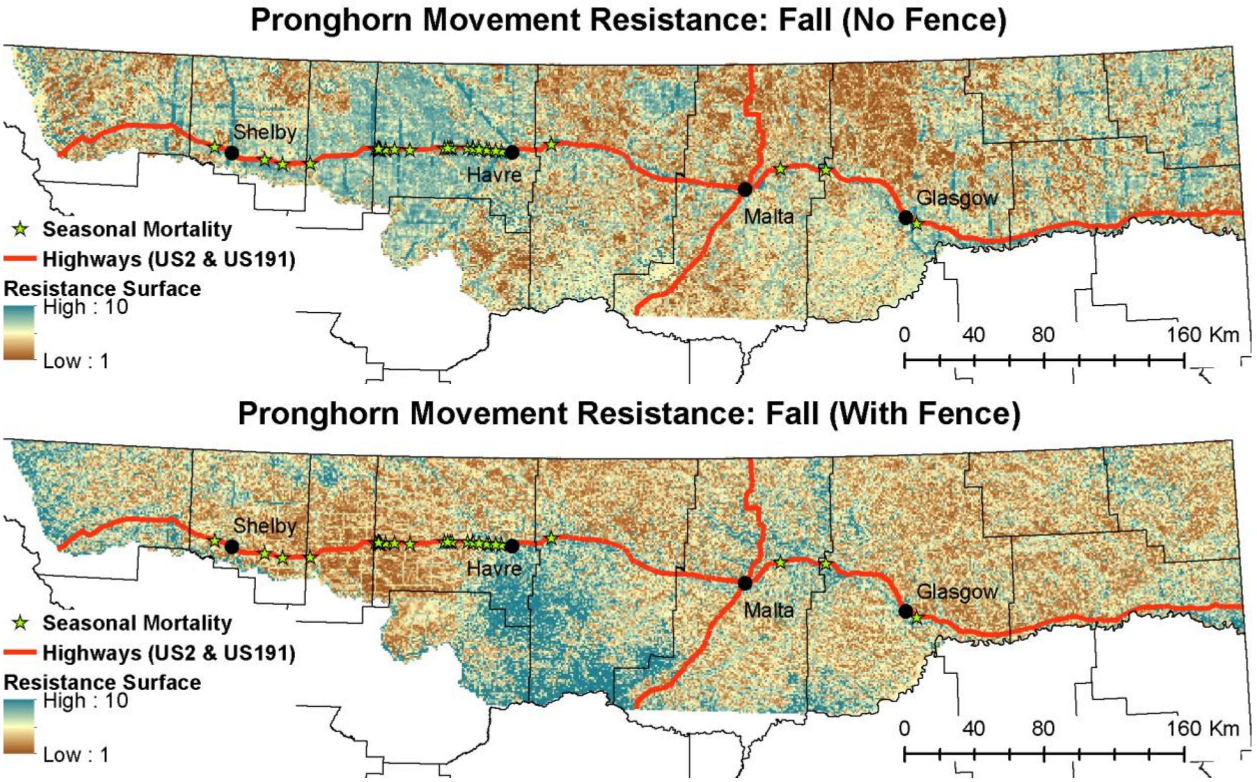


Figure 16B. Pronghorn habitat resistance results for winter: Pronghorn habitat resistance for winter season including no fence effect (top panel) and fence effect (bottom panel).


Pronghorn Movement Resistance: Fall (No Fence)

Pronghorn Movement Resistance: Fall (With Fence)

Figure 16C. Pronghorn habitat resistance results for fall: Pronghorn habitat resistance for fall season including no fence effect (top panel) and fence effect (bottom panel).

3.2.4.2. *Species distribution*

In order to conduct our connectivity simulations, we also needed information about the relative distribution of pronghorn across the study area. This information was used to help create initial individuals' locations in our connectivity simulations. For this purpose, we used defined habitat patches from Jake et al. 2015. They identified the mean annual home range size for the population per individual, which resulted in 47 habitat patches across the NSS study area. We randomly selected 100 points within these polygons, which provide source and destination points for the connectivity simulations (Figure 17).

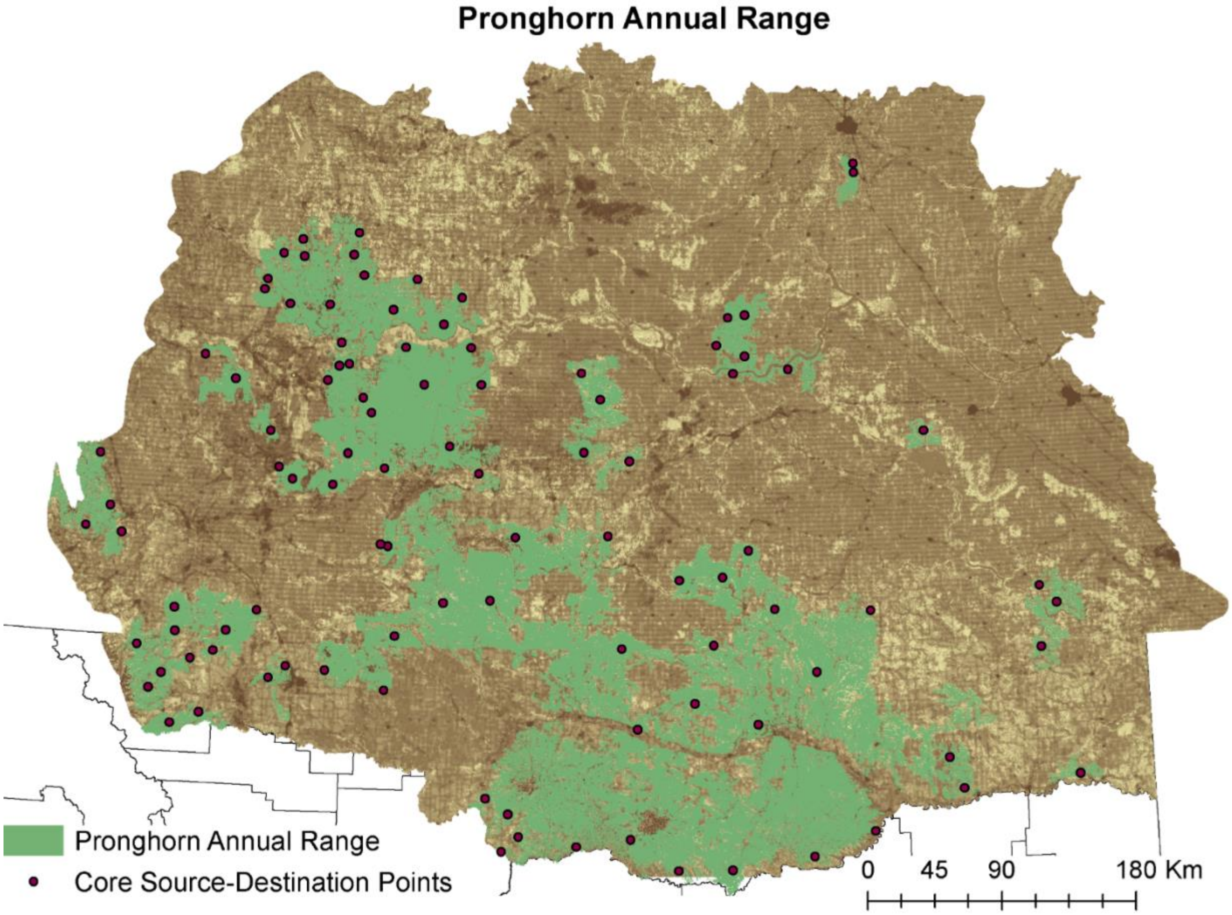


Figure 17. Connectivity modelling nodes: Source-destination points used for the connectivity modeling.

3.2.4.3.Connectivity corridor simulation

We used UNICOR (Landguth et al. 2012), an individual-based species connectivity and corridor identification simulation tool, to predict and map connectivity corridors for each studied species. UNICOR applies Dijkastra's shortest path algorithm to analyze movement cost around any number of individual's locations on a resistance surface. The resulting output is a raster surface of expected density of dispersing individuals. We used the landscape resistance models and spatial points samples described in previous steps as input resistance surfaces and individuals' locations in the UNICOR simulations, and mapped connectivity corridors for each model scenario producing kernel density estimations on least cost paths. Factorial least cost path analysis is commonly used for analyzing connectivity patterns. It quantifies pairwise optimal paths between all individuals on a landscape. However, it is unrealistic to assume that only a single path is being used between any given two individuals. To more realistically represent the behavior of organisms, we incorporated a kernel density estimation by buffering all least cost paths with a 2 km Gaussian smoothing kernels. This approach produces density surfaces that predict the most probable movement routes connecting species populations, which provides managers with visual guidance on identifying corridors for maintaining connectivity.

Figures 18 show the corridors for each seasonal model without fence (panels A), including fence density (panels B), and the difference between with and without fencing (panels C). The dark lines in panels C highlight the influence of the fence effect within each seasonal model.

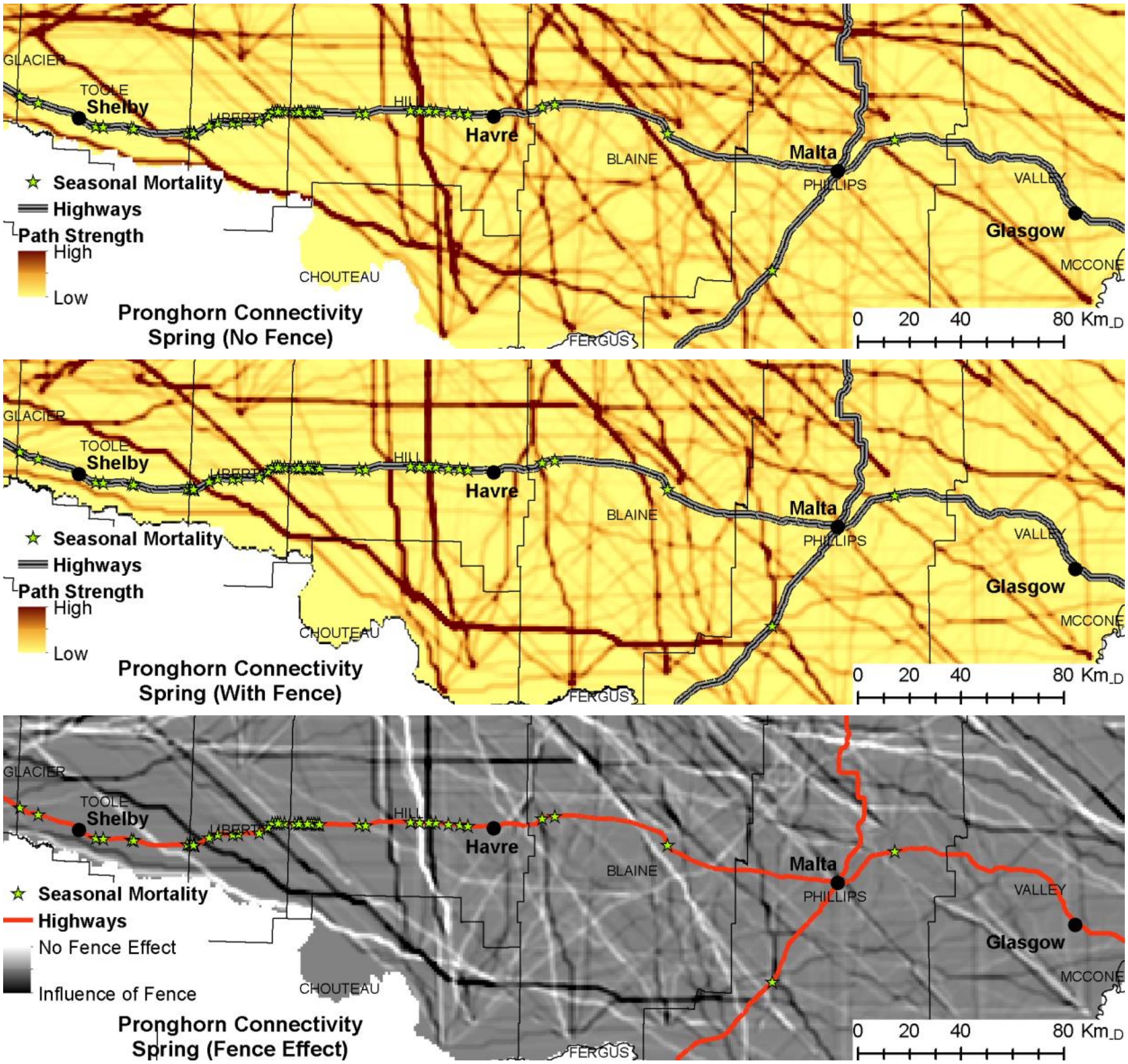


Figure 18A. Comparative pronghorn connectivity results for spring: Pronghorn connectivity for spring including no fence effect (top panel) and fence effect (middle panel). Bottom panel differences the two maps, showing the influence of the fence effect (dark corridor lines Note that due to the three seasonal models, we grouped the Seasonal Mortality data from March 15 – July 31 here.

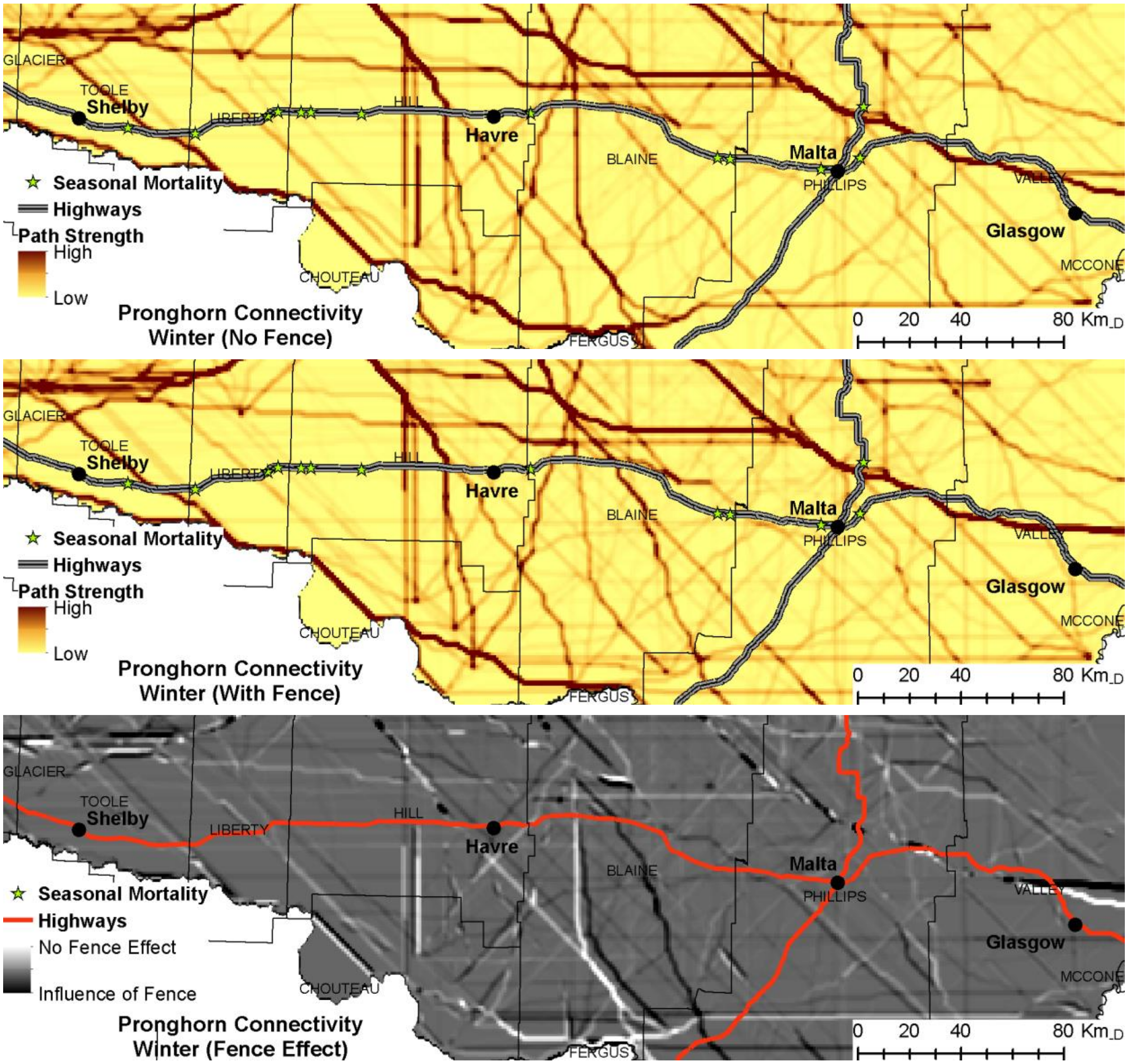


Figure 18B. Comparative pronghorn connectivity results for winter: Pronghorn connectivity for winter including no fence effect (top panel) and fence effect (bottom panel). Bottom panel differences the two maps, showing the influence of the fence effect (dark corridor lines only). Note that due to the three seasonal models, we grouped the Seasonal Mortality data from November 16 – March 14 here.

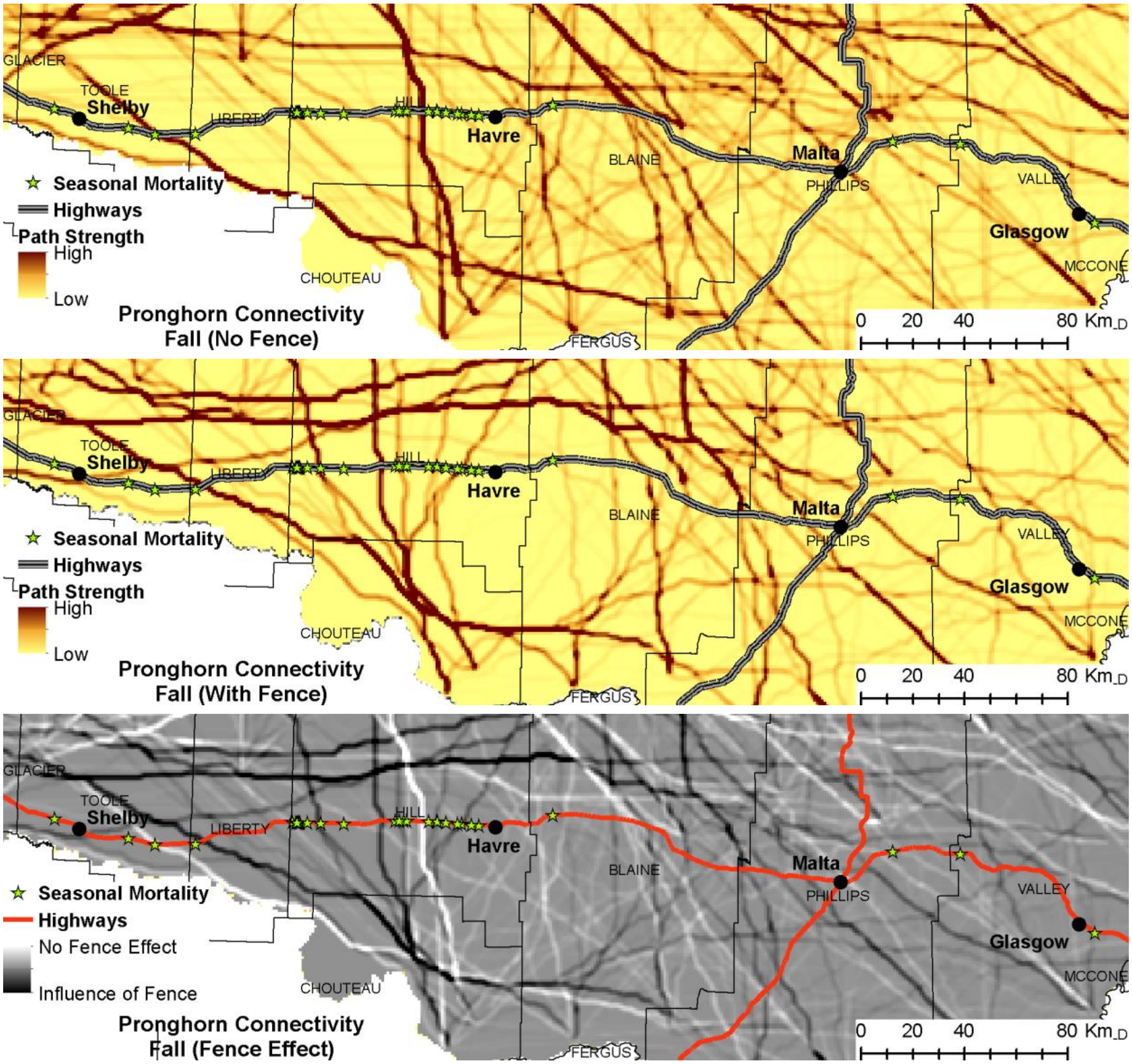


Figure 18C. Comparative pronghorn connectivity results for fall: Pronghorn connectivity for fall including no fence effect (top panel) and fence effect (bottom panel). Bottom panel differences the two maps, showing the influence of the fence effect (dark corridor lines only). Note that due to the three seasonal models, we grouped the Seasonal Mortality data from August 1 – November 15 here.

3.3. Objective 3: Effectively demonstrate and present the importance of developing fence density maps and 'wildlife friendly' areas.

Our research team first requested funding from Montana Department of Transportation to complete this work in spring 2017. Since then, our team has presented portions of this work at national, regional and local levels. In addition, we have either published or are in the process of publishing peer-reviewed articles on original work that was partially funded by this contract. Through this research, as well as other recent research published by our team, we show that fencing is a ubiquitous feature across the landscape and that it has implications for wildlife, ecosystem processes and societal needs. Once fence maps have been developed across a broad scale, agencies including MDT can begin to prioritize mitigation efforts to account for societal (i.e., safety, economic) and wildlife connectivity needs. Below is a list of presentations given by A. Jakes since spring 2017 as well as the accompanying peer-reviewed articles that are relevant to satisfying Objective 3:

Presentations

-Testing Wildlife-Friendly Modifications to Manage Wildlife and Livestock Movements, 100th Annual Montana Farm Bureau Federation Convention, Billings, Montana, November 2019.

-Pronghorn: A Focal Species for Grassland Connectivity, Webinar hosted by Prairie Conservation Forum, Missoula, Montana, October 2019.

-Testing Wildlife-Friendly Modifications to Manage Wildlife and Livestock Movements, Hi-Line Wildlife and Habitat Professionals Meeting, Malta, Montana, September 2019.

-Testing Wildlife-Friendly Modifications to Manage Wildlife and Livestock Movements, Rancher's Stewardship Alliance Conservation Committee, Malta, Montana, September 2019.

-Connectivity in Wildlife Conservation Management – Using Pronghorn and Fencing as a Case Study, WBIO 480: Wildlife Conservation Lecture – University of Montana, Missoula, Montana, April 2019.

-Connectivity in Wildlife Conservation Management – Using Pronghorn and Fencing as a Case Study, WBIO 370: Wildlife Conservation Lecture – University of Montana, Missoula, Montana, March 2019.

-Identification, challenges and opportunities in wildlife connectivity across the Northern Great Plains region. Transboundary Grasslands Conservation Conference, Glasgow, Montana, February 2018.

-Episode 011: Pronghorn, Speedgoats, Antelope, Oh My! Right To Roam Podcast, aired September 10, 2017. https://righttoroampodcast.com

-Evaluating Responses by Pronghorn to Fence Modifications across the Northern Great Plains, 7th Annual TNC Matador Ranch Science and Land Management Symposium, Zortman, Montana, June 2017.

Peer-reviewed articles

-Jakes, A.F., Landguth, E.L., Telander, A.C., Jones, P.F., Bushey, J., Sawyer, H., Hebblewhite, M. Fence effects on migratory habitat selection for pronghorn: An assessment to conserve connectivity across a transportation corridor. Journal of Applied Ecology. *In Preparation.*

-Jones, P.F., Jakes, A.F., McDonald, A., Hanlon, J., Eacker, D.R., Martin, B.H., Hebblewhite, M. 2020. Evaluating responses by sympatric ungulates to fence modifications across the Northern Great Plains. Wildlife Society Bulletin. 44(1): 130-141.

-Jones, P.F., Jakes, A. F., Eacker, D.R., Seward, B.C., Hebblewhite, M., B.H. Martin. 2018 Evaluating responses by pronghorn to fence modifications across the Northern Great Plains. Wildlife Society Bulletin. 42(2): 225-236.

4. SUMMARY, DISCUSSION, and RECOMMENDATIONS

Fences are ubiquitous across the landscape, yet there is little understanding on their effects on wildlife. Fences pose both indirect (i.e., access to habitat, energetic costs) and direct (i.e., mortality) consequences to wildlife, and so their effects are an important consideration. Wildlife and land managers must explore mitigation options to allow for wildlife connectivity, while concurrently addressing human concerns (i.e., keeping motorists safe, keeping cattle in desired pastures). With increased technological advances in collecting spatiotemporal wildlife movement data, this is an ideal time for researchers and agencies to investigate wildlife-fence interactions. Meaningful results from this work will provide scientifically-defensible recommendations that can be used to inform both agencies and the public of a more holistic multi-species 'wildlife friendly' fence design, including those that continue to keep livestock in desired pastures. These fence designs can be implemented in targeted multi-species seasonal ranges and migratory pathways and can be an effective and economic tool to both agencies and landowners by limiting both the time and money required to fix fencing. In our project, these 'wildlife friendly' fence modifications were tested over large areas, and consequently, we believe results can be implemented in many areas across Montana, not just the study area. These include the three bottom wire modifications (i.e., smooth wire, clip/carabiners of the bottom two wires together and, PVC pipe) as well as two fence modifications (sage-grouse reflectors and PVC pipe) on top wires that are commonly used as visual warnings to wildlife. Therefore, results can be used to produce a 'wildlife-friendly' assessment framework that can be used for other areas across Montana, as well as the country. Additionally, the techniques used to identify and prioritize important locations for fence modification along roadways can be used as a framework in other systems, using many species. As far as we know, implementing these research findings is not currently required for any federal or state initiative or law. However, it will fulfill the goals outlined in MDT's mission statement which include providing a transportation system that is safe, cost effective, and sensitive to the environment. Specifically, this provides a cost-effective approach (relative to time and money) for mitigating road impacts on wildlife. The Benefit Cost (B/C) and Return on Investment (ROI) potential is high. The funding provided for this research can be returned to MDT and their stakeholders through the targeted application and scientifically defensible application of this research's findings.

Table 3. **Cost comparison of fence type:** Cost of each fence type given per linear foot and mile.

FENCE TYPE	FY2019 COST/LINEAR FOOT	FY2019 COST/MILE
WILDLIFE FRIENDLY FARM FENCE, WOODEN POST	$2.31	$12,196.80
WILDLIFE FRIENDLY FARM FENCE, METAL POST	$1.82	$9,609.60
TRADITIONAL FARM FENCE, 3-STRAND, METAL POST	$2.47	$13,041.60
TRADITIONAL FARM FENCE, 4-STRAND, WOODEN POST	$2.75	$14,520.00
TRADITIONAL FARM FENCE, 4-STRAND, METAL POST	$2.26	$11,932.80
FARM FENCE - 2-STRAND TOP, 39" WOVEN-WIRE, WOODEN POST	$2.85	$15,048.00
FARM FENCE - 2-STRAND TOP, 32" WOVEN-WIRE, METAL POST	$3.26	$17,212.80
FARM FENCE - 2-STRAND TOP, 32" WOVEN-WIRE, WOODEN POST	$3.34	$17,635.20
FARM FENCE - 3-STRAND TOP, 32" WOVEN-WIRE, WOODEN POST	$4.07	$21,489.60

For every recommended wildlife friendly fence design agreed to and constructed as right of way fence, MDT could see a substantial per linear foot cost savings over other commonly used fence designs (see Table 3). The ultimate result of which would be a potential cost savings to MDT of hundreds of thousands of dollars annually, based on MDT average bid prices from fiscal year 2020. In addition, more robust wildlife populations, with decreased direct and indirect fence barrier effects will provide greater revenue to the state wildlife agency from hunting licenses, and increased recreational opportunities and revenues to local communities.

By using vigorous scientific approaches to test various fence modification effectiveness, the research developed recommended fence modifications that will allow for wildlife connectivity across the landscape. The ultimate goal is to create a multi-species wildlife friendly fence design that allows for daily and seasonal wildlife movements, while simultaneously keeping livestock in desired pastures. From field trial 1 where bottom wire modifications were evaluated, results indicate the use of either smooth wire or carabineers as a method to clip together the bottom two wires to a height of approximately 18 inches off the ground were two effective modifications at allowing passage by pronghorn, while the commonly proposed goat-bar modification was ineffective and created a negative behavioral response by pronghorn. Though smooth wire and clips were effective at allowing passage, we observed a time lag as pronghorn switched use from their strong fidelity at known-crossing sites to using modified sites. Pronghorn-group crossing success was greatest during summer, for all-male groups, and increased with larger group sizes. From field trial 2 where top wire modifications were evaluated, results indicate that both sage-grouse reflectors, spaced approximately every 24 inches, and white PVC pipe did not impede fence crossing behaviors for either pronghorn or deer, nor was there a time lag in use of camera sites observed after modifications were deployed. Both pronghorn and deer species tend to cross fences where they will have the best success rate, which we infer to be a learned process. When left undisturbed, we found that deer species (in particular females and fawns) will crawl underneath fencing at known crossing locations, similar to pronghorn. Although slower, this may be the result of less energy required to crawl under a fence as opposed to jumping over. Though we did not alter the height of the bottom wire, there was enough variability in bottom wire height between camera sites that our results indicate a greater probability of successful crossing by all three ungulates as bottom wire height increased. Across both trials, only in one instance did a cow calf cross at a modified fence panel and this was through the barbed-wire (not under) at a PVC pipe (i.e., goat bar) modified fence. We advocate not using goat-bars as modifications to fences, and instead, recommend using smooth wire and clips at a minimum bottom-wire height of 18 in. to allow movement by pronghorn. Our study provides guidance for wildlife-friendly fencing techniques to wildlife managers and private landholders as a means to improve permeability for pronghorn crossing underneath fencing. In addition, we recommend the implementation of both sage-grouse reflectors and white PVC pipe on top of barbed wire fences as our results demonstrate no substantial unintended consequences on the crossing behavior of pronghorn and deer. Personnel from the USFWS Partners for Wildlife Program, the U.S. Bureau of Land Management and The Nature Conservancy are already using information and recommendations when discussing the application of wildlife friendly fences with area ranchers, and with those who graze livestock on BLM allotments and this work will act as a force multiplier when combined with these similar efforts to benefit landowners and wildlife alike. However, careful consideration should be taken when implementing these wildlife friendly fence modifications adjacent to pastures that have been overgrazed or during late summer/fall when livestock are pressured to find higher quality grass which may be found on the other side of a fence. We continue to present our findings to local, regional and national audiences, both private landowners and wildlife and habitat managers.

Here, we present one of the first applications of connectivity modeling for the state of Montana. Fence density mapping and species movement modeling, together with highway mortality data showed areas along US 2 and US 191 of increased mortality for wildlife during different seasons and associated with fences. For example, our connectivity modeling approach suggested that fences act as barriers for pronghorn during fall and spring, which indicates that increased fence densities may act as an ecological trap to individuals forced to move through sub-optimal habitat. Additionally, we see increased mortalities for mule deer along high fence density areas during fall and winter seasons. This approach may identify prioritized locations along US 2 to mitigate future wildlife-fence interactions for multiple wildlife species. In addition, the large-scale fence density analysis that is a critical part of this research will allow MDT to target specific areas across the state for the application of these recommended fence designs, allowing for more cost-effective use of its limited funding.

5. RECOMMENDATIONS

The Hi-Line area provides an opportunity to assess the impacts of fencing on wildlife connectivity, particularly across a large transportation system (i.e., US HWY 2). We recommend that on the bottom wire, barbed wire be replaced with smooth wire or clipped to the second to bottom wire with a carabineer to the height of 18”. We do not recommend the use of a PVC-pipe ‘goat-bar’ as a mitigation tool on the bottom wire. However, on the top barbed wire strand, we recommend the continued use of sage-grouse markers or PVC-pipes as a tactic for ungulates to visualize crossing sites. These fence designs can be implemented in identified multi-species seasonal ranges and migratory pathways and can be an effective and economic tool to both agencies and landowners by limiting both the time and money required to fix fencing. In concert, analytically proven wildlife friendly fencing techniques could be used along targeted roadside sections where fencing impedes wildlife connectivity. We recommend that if fencing on one side of a highway is mitigated that indeed, the fence on the other side must be mitigated as well so that wildlife are not potentially trapped in the right-of-way. Fencing modifications have been tested only on interior pasture fencing in open native sagebrush/grassland landscapes. As a result, managers must consider placement of fence modifications along highways based on landcover types. These targeting approaches and techniques can provide a reproducible framework for other parts of the state where GPS collar information is available for wildlife and where fencing is mapped from a broad-scale. Once models are completed in other areas, MDT can identify appropriate mitigation tools using a similar targeted approach. Academic, agency and/or non-government organization researchers familiar with targeting approaches and Montana landscapes would be well situated to work with MDT personnel in prioritization efforts. Our connectivity results along the Hi-Line are from a very broad-scale assessment. Consequently, site-by-site identification and monitoring will be required while working with landowners to implement targeted mitigation opportunities. From this assessment, we have identified the following areas for targeted mitigation efforts along roadways in the study area: 1) West of Havre in Hill County from approximately Burnham headed West to Gilford; 2) The Verona to Big Sandy section of HWY 287 in Choteau County as well as areas directly East of this highway stretch; 3) On the Liberty/Hill County boarder, from approximately Iverness headed West to Chester and; 4) On the Liberty/Toole County boarder, from approximately Lothair headed West to Galeta. These four areas have 1) fence densities that have a moderate to high influence on connectivity; 2) are areas considered optimal to moderate migratory habitat where the fencing parameter was accounted for in the modeling process and; 3) are areas with documented wildlife mortalities due to vehicular collisions. A repeatable process for prioritizing road and highway sections for future mitigation is key. The following set of factors could be considered for future processes: 1) wildlife telemetry data; 2) carcass collection data; 3) difference between connectivity modeling which do and do not include fence densities; 4) the amount of spatial overlap between spring and fall priority areas; 5) vehicle collision data; 6) seasonal range predictions to assess required habitats outside of a given transportation corridor; 7) and results from any previous modelling efforts. The scoring and weight for each of these parameters will need to be discussed and agreed to by future stakeholders. Finally, we recommend that results here provide opportunities to update both the current MDT "Wildlife Friendly Fence" brochure and can provide language to the MDT Right-of-Way manual to include the importance of having MDT right of way personnel share the results of this research with private landowners while they are negotiating for new right of way and/or fences.

6. GLOSSARY

Carabineer/Clip – a wildlife friendly fence modification used to clip or connect the two bottom wires together, thus raising the bottom wire height of a barbed-wire fence using one of these two equivalent devices.

Fence Panel – A section of fence line between two posts, typically either wooden posts or T-posts.

Goat Bar – Colloquial term for PVC pipe used as a wildlife friendly fence modification, placed on the bottom wire of a barbed-wire fence.

Known-crossing site – A fence panel that has been extensively used over time by ungulates. They may be identified by a well worn-down path leading to and from the fence line with bare ground beneath the fence, ungulate hair on the fence, scat located on either side of the fence.

PVC pipe – A pipe made of polyvinyl chloride that can be installed on barbed-wire fence, typically as a wildlife friendly fence modification. PVC pipe on the bottom wire is termed a Goat Bar in this report (see above).

Smooth wire – a wildlife friendly fence modification that is installed as the bottom wire on a barbed wire fence, replacing a barbed wire as the bottom wire.

7. REFERENCES

Arnold, T. W. 2010. Uninformative parameters and model selection using Akaike's Information Criterion. Journal of Wildlife Management 74:1175-1178.

Barton, K. 2016. MuMIn: Multi-Model Inference. R package version 1.15.6. https://CRAN.R-project.org/package=MuMIn. Accessed 21 Dec 2016.

Burkholder, E., Jakes, A.F., Jones, P.F., Hebblewhite, M., Bishop, C.J. 2018. To jump or not to jump: mule deer and white-tailed deer fence crossing decisions. Wildlife Society Bulletin 42:420–429.

Burnham, K. P., and D. R. Anderson. 2002. Model selection and multimodel inference: a practical information-theoretic approach. Springer-Verlag, New York, New York, USA.

Cushman S.A., Lewis J.S., Landguth E.L. 2013. Evaluating the intersection of a regional wildlife connectivity network with highways. Movement Ecology, doi:10.1186/2051-3933-1-12

Eacker, D. R., M. Hebblewhite, K. M. Proffitt, B. S. Jimenez, M. S. Mitchell, and H. S. Robinson. 2016. Annual elk calf survival in a multiple carnivore system. Journal of Wildlife Management 80:1345–1359.

Gelman, A. 2008. Scaling regression inputs by dividing by two standard deviations. Statistics in Medicine 27:2865–2873.

Grueber, C. E., S. Nakagawa, R. J. Laws, and I. G. Jamieson. 2011. Multimodel inference in ecology and evolution: challenges and solutions. Journal of Evolutionary Biology 24:699–711.

Heisey, D. M., and B. R. Patterson. 2006. Review of methods to estimate cause-specific mortality in the presence of competing risks. Journal of Wildlife Management 70:1544–1555.

Hosmer, D. W., and S. Lemeshow, editors. 2000. Applied logistic regression. John Wiley and Sons, New York, New York, USA.

Hosmer, D. W., S. Lemeshow, and S. May. 2008. Applied survival analysis: regression modeling of time-to-event data. Second edition. John Wiley & Sons, Hoboken, New Jersey, USA.

Jakes, A. F. 2015. Factors influencing seasonal migration of pronghorn across the Northern Sagebrush Steppe. Dissertation, University of Calgary, Calgary, Alberta, Canada.

Jones, P.F., Jakes, A. F., Eacker, D.R., Seward, B.C., Hebblewhite, M., B.H. Martin. 2018. Evaluating responses by pronghorn to fence modifications across the Northern Great Plains. Wildlife Society Bulletin, 42(2): 225-236.

Keeley, A.T.H., Beier, P., Gagnon, J.W. 2016. Estimating landscape resistance from habitat suitability: effects of data source and nonlinearities. Landscape Ecology, 31(9):2151–2162.

Kleinbaum, D. G., and M. Klein. 2012. Survival analysis: a self-learning text. Third edition. Statistics for Biology and Health, Springer Science and Business Media, LLC, Atlanta, Georgia.

Landguth E.L., Hand B.K., Glassy J.M., Cushman S.A., Sawaya M . 2012. UNICOR: a species corridor and connectivity network simulator. Ecography, 12: 9-14.

Lenth, R. 2018. emmeans: estimated marginal means, aka least-squares means. R package version .3.0. https://CRAN.R-project.org/package=emmeans. Accessed 18 Mar 2019.

McRae, B.H. 2006. Isolation by resistance. Evolution, 60:1551-1561.

Poor, E., Jakes, A., Loucks, C., Suitor, M. 2014. Modeling Fence Location and Density at a Regional Scale for use in Wildlife Management. PLoS One. 9(1): e83912.

R Core Team. 2016. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org/. Accessed 21 Dec 2016.

R Core Team. 2018. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org/. Accessed 21 Sep 2018.

Rebora, P., A. Salim, and M. Reilly. 2018. bshazard: Nonparametric Smoothing of the Hazard Function. R package version 1.1. https://CRAN.R-project.org/package=bshazard/. Accessed 15 Oct 2018.

Stevens, B.S., Reese, K.P., Connelly, J.W., Musil, D.D. 2012. Greater sage-grouse and fences: does marking reduce collisions? Wildlife Society Bulletin, 36(2): 297-303.

Therneau, T. 2015. A package for survival analysis in S. R package, version 2.38. http://CRAN.R-project.org/package=survival. Accessed 18 Apr 2017

van Etten, J. 2018. gdistance: distances and Routes on geographical grids. R package v.1.2-2.

Zar, J. H. 1984. Biostatistical analysis. Second edition. Prentice-Hall, Englewood Cliffs, New Jersey, USA.

Zuur, A. F., E. N. Ieno, and C. S. Elphick. 2010. A protocol for data exploration to avoid common statistical problems. Methods in Ecology and Evolution 1:3-14.