Research Results and Mitigation Strategies

to Improve Wildlife Connectivity and Human Safety along I-40 in the Pigeon River Gorge

June 2022

A herd of elk grazes on grasses of Great Smoky Mountain National Park. Photo: Bella B Photography

Liz Hillard - Ph.D., Senior Wildlife Biologist, *Wildlands Network*

Steve Goodman - Conservation Biologist, *National Parks Conservation Association*

Ron Sutherland - Ph.D., Chief Scientist, *Wildlands Network*

Jeff Hunter - Southeast Regional Program Manager, *National Parks Conservation Association*

Abstract

Tens of millions of birds, reptiles, amphibians, and mammals are killed per year on roads in the United States. In addition to causing direct mortality, roads can hinder the movement behavior of large-bodied mammals—such as dispersal and migration—that are typically associated with key ecological processes. Additionally, vehicle collisions with these large mammals pose significant threats to driver safety. A solution for mitigating the negative effects of roads on wildlife and human safety is creating wildlife road infrastructure that provides safe passage for wildlife across roads by excluding wildlife from the roadway. Road ecology research is necessary to identify the patterns and processes of wildlife-road interactions and to guide the placement of wildlife structures along a given stretch of highway. Given the ecological diversity, importance of wildlife connectivity, and the severity of elk-, deer-, and bear-vehicle collisions in the mountainous region surrounding Great Smoky Mountains National Park, our research focused on a 28-mile stretch of Interstate 40 that winds through the steep and rocky Pigeon River Gorge, where the busy interstate impedes wildlife movement and access to adjacent National Forest lands. We conducted multifaceted research and subsequent analysis to provide a framework that identifies areas along the interstate where mitigation strategies such as road crossing structures could be best implemented to reduce wildlife-vehicle collisions and increase wildlife habitat connectivity. Based on our research findings, we provide 20 detailed mitigation recommendations for improvements to existing structures or the creation of new structures throughout the Gorge and we call for the installation of a system of strategically-placed wildlife fencing.

Table of Contents

Chapter 1

Introduction **5-8**
Methods **8-13**
Results **14-22**
Discussion **22-27**

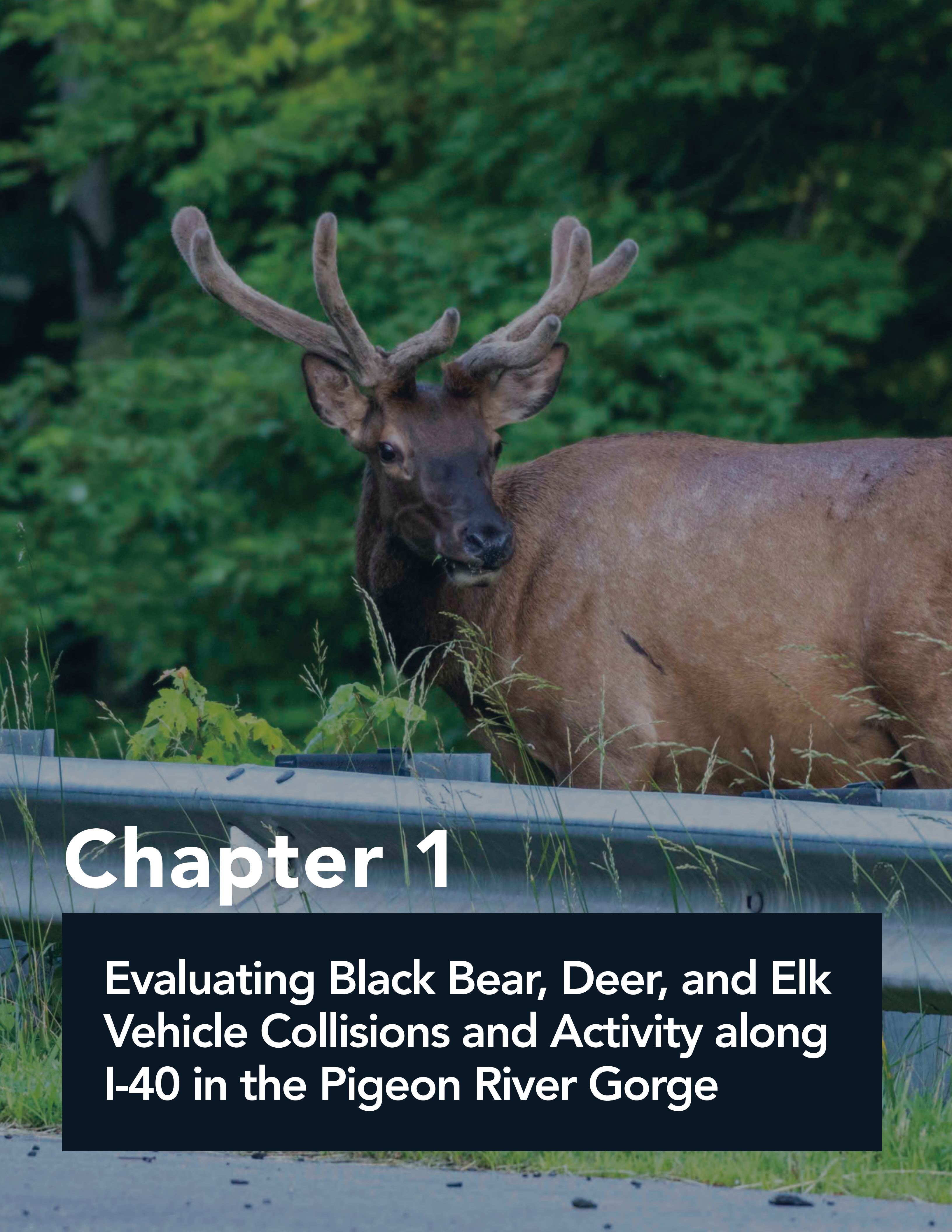
Chapter 2

Introduction **29-31**
Methods **31-35**
Results **35-40**
Discussion **41-43**

Chapter 3

Section 1: Top Priority Recommendations **45**
Section 2: Detailed Wildlife Mitigation Recommendations List **45-61**
Section 3: Fencing and Miscellaneous Improvements **62**
Section 4: Land Acquisition Recommendations List **63**

Acknowledgements **64**
Map Series A **65-67**
Appendix **68-77**
References **78-84**
Supplemental Materials **85**



Chapter 1

Evaluating Black Bear, Deer, and Elk Vehicle Collisions and Activity along I-40 in the Pigeon River Gorge

Introduction

Elk a crossing highway. Photo: Jeff Gresko

Roadways and traffic have far-reaching and pervasive negative impacts on ecosystems worldwide. It is estimated that tens of millions of birds, reptiles, amphibians, and mammals are killed per year on U.S. roadways (Forman and Alexander 1998, Loss et al. 2014, Shilling et al. 2020). In addition to contributing to direct mortality (Litvaitis and Tash 2008, Garrote et al. 2018), roads cause habitat fragmentation and degradation (Theobald et al. 1997, Epps et al. 2005), create barriers to movement (Shepard et al. 2008, Benoit et al. 2020), and limit gene flow (Proctor et al. 2005, Holderegger and Giulion 2010). These negative effects threaten biodiversity by decreasing species abundance and richness (Fahrig and Rytwinski 2009).

Connectivity of protected systems of natural habitat is necessary to facilitate large-scale ecological and evolutionary processes essential for the persistence of viable wildlife populations, especially due to climatic and environmental changes that are increasingly transforming and fragmenting landscapes (Theobald et al. 2012, Belote et al. 2016, Carroll et al. 2018). Improving or sustaining connectivity between protected areas is vital for the effective conservation and management of biodiversity (The Strategic Plan for Biodiversity 2011–2020). Connectivity of wildlife habitat allow animals to access resources and mates that maybe spatially remote due to landscape changes and seasonal availability of resources and mates, ensuring functional connectivity among populations.

For large ungulates, roads can hinder movement behavior such as dispersal and migration typically associated with key ecological processes (Benoit et al. 2020). Multiple studies have detected avoidance of high traffic roads by elk *(Cervus elaphus)* including Rowland et al. (2000) who found a significant decline in elk habitat use ≤1.8 km from high traffic roads. Long et al. (2010) found that although some white-tailed deer *(odocoileus Virginianus)* crossed major roads in Pennsylvania, they generally avoided crossing and terminated dispersal movements when they encountered a major road. These road effects divide large wildlife populations into smaller populations that are more prone to extinction due to demographic and environmental irregularities (Noss et al. 2012).

Other large-bodied mammals such as big horn sheep and bear can be especially impacted by roadways due to their large home-range requirements, extensive movements to find resources and mates, and lower reproductive rates (Rytwinski and Fahhrig 2011, 2012). Isolation of desert big horn sheep *(Ovis canadensis nelson)* populations by interstate highways, canals, and developed areas have eliminated gene flow, severely threatening the persistence of fragmented populations due to reduced genetic diversity (Epps et al. 2005). Genetic analysis of grizzly bear *(Ursus arctos)* populations near the U.S.-Canadian border found Canadian Highway 3 and subsequent human development in the area had severed demographic linkages, cutting off opportunities for three fragmented U.S. grizzly bear populations to breed with Canadian grizzly bears to the north (Proctor et al. 2005).

Black bears *(Ursus americanus)* can be especially impacted by habitat fragmentation because because they require large home ranges to adapt to seasonal changes in food availability (Clark 2004, Ryan et al. 2007). During years of acorn mast failure, black bears may respond by undertaking extensive movements to find food (Pelton 1989), increasing their interactions with roads and road mortality (Noyce and Garshelis 1997).

Additionally, vehicle collisions (VCs) with these large mammals pose significant threats to driver safety due to collision severity, which increases with animal size. While human injuries and death are relatively rare (i.e. <5% of wildlife-vehicle collisions, or WVCs), an estimated 1-2 million total crashes between motor vehicles and large animals such as deer occur every year in the United States. These crashes cause approximately 25,000 injuries, about 200 human fatalities, and more than $8 billion in property damage and medical costs (Huijser et al. 2008).

White-tailed deer inspects the Naillon Branch Culvert. Photo: Wildlands Network / NPCA

A solution for mitigating the negative effects of roads on wildlife and human safety is creating wildlife road infrastructure that provides safe passage for wildlife across roads and excludes wildlife from the roadway. Wildlife conservationists from nongovernmental, state, and federal agencies work with state transportation agencies to identify, monitor, and create safe passage opportunities for wildlife through the construction of wildlife-specific overpasses and underpasses, retrofitting existing infrastructure to promote wildlife use, and by incorporating fencing to exclude wildlife from the roadway and guide them to crossing structures (Clevenger and Huijser 2011).

Numerous examples show the positive impacts of installing wildlife crossing infrastructure across North America.

- **In Wyoming,** the construction of six wildlife underpasses and two wildlife overpasses in a critical migration area greatly increased wildlife connectivity, reducing pronghorn vehicle collisions by 100% and mule deer vehicle collisions by 78% (Sawyer et al. 2016).
- **On I-64 in Virginia,** researchers found that incorporating a mile of eight-foot fencing at two road structures (box culvert and river bridge) reduced white-tailed deer collisions by 96.5% and 88%, respectively, and increased white-tailed deer use of structures by 410% and 71% (Donaldson and Elliott 2021).
- In 2014, Sawaya et al. found increased genetic diversity of grizzly bears and black bears near wildlife crossing sites along the **Trans-Canada Highway** in the Canadian Rockies. Male bears that used crossing structures more frequently had higher reproductive success.
- Retrofitting a six-mile section of **I-17 in Arizona** with eight-foot fencing to guide elk to two large canyon bridges, and a vehicle overpass and underpass, resulted in a 97.5% reduction in elk-vehicle collisions and an 88.9% decrease in wildlife vehicle collisions (Gagnon et al. 2016).
- Exclusionary fencing linking wildlife crossing structures along the **Trans-Canada Highway in Banff National Park** reduced ungulate mortalities by 80% (Clevenger et al. 2001).

Bobcat, black bear, and elk detected in wildlife cameras adjacent to the roadway. Photos: Wildlands Network / NPCA

The recognized success of wildlife crossing structures in reducing WVCs and increasing permeability for wildlifemovement led to $350 million of dedicated funding for wildlife crossings construction in the U.S. through the Wildlife Crossings Safety Pilot Program within the 2021 Infrastructure Investment and Jobs Act.

The relative success of wildlife road crossing structures is highly dependent on the crossing structure type (i.e. size, openness, Clevenger and Huijser. 2011) and their proper placement on the landscape (Glista et al. 2009). Wildlife do not treat all sections of a roadway indiscriminately. Topography, landscape features, vegetation cover, road characteristics, and species behavior contribute to wildlife movement at the larger landscape scale (Litvaitis and Tash, 2008) and those factors specific to the roadway influence crossing behavior and thus the probability of WVCs (Dickson et al. 2005). In addition to structure placement, structure dimensions and characteristics have considerable influence on species structure use. In general, ungulates such as elk and deer need high openness ratios (opening height times opening width divided by length) to facilitate use, whereas black bears and mountain lions (*Puma concolor*) have been shown to prefer tunnels with smaller openness ratios (Gloyne and Clevenger 2001, Sawaya et al. 2014).

Road ecology research is necessary to identify the patterns and processes of wildlife-road interactions and to guide the placement of wildlife structures along a given stretch of highway. High priority crossing areas can be identified by collecting many types of data such as WVC locations, animal movement patterns, and roadside animal activity, allowing researchers to determine how the design of the existing highway interacts with wildlife habitat suitability and landscape structure to influence crossing behavior (Clevenger and Huijser 2011). Although knowledge on the impacts of roads on wildlife has improved, little information exists on the fine-scaled distribution of highway effects and mitigation opportunities across roadways in important conservation areas where alleviating roadway barrier effects, restoring connectivity, and protecting wildlife are imperative. Therefore, research at a project-level is key for understanding how the design of the existing highway interacts with wildlife habitat suitability and landscape structure to influence crossing behavior.

In the mountainous region at the border of Tennessee and North Carolina, Interstate 40 winds through the steep and rocky Pigeon River Gorge (PRG, Gorge). The busy highway divides the Pisgah and Cherokee National Forests (512,758 and 650,000 acres, respectively) and is in close proximity to the 522,42-acre Great Smoky Mountains National Park (GSMNP). These protected areas exist in an ecologically diverse and important region and are home to a growing and dispersing elk population, a large and robust black bear (hereafter, bear) population, and modest numbers of white-tailed deer (hereafter, deer). Due to the abundance of large-bodied wildlife and increased traffic in the region, WVCs are frequent.

Given the ecological diversity and importance of wildlife connectivity in the region and the severity of elk-, deer-, and bear-VCs, state, federal, and NGO partners research to identify human/wildlife conflicts in the PRG. We therefore conducted multifaceted field research focused on a 28-mile section of I-40 to meet the following objectives: (1) identify locations with high incidences of WVCs of our target species, bear, deer, and elk, and identify road and landscape attributes that influence WVCs along the roadway; (2) index target species activity rates along the roadside, compare activity to WVC occurrences, and identify road and landscape attributes that influence wildlife activity along the highway; and (3) evaluate existing levels of roadway permeability by monitoring target species use of existing roadway structures (i.e. culverts, bridges, and land bridges). Our research provides a framework that identifies areas along the interstate where mitigation strategies such as road crossing structures could be best implemented to reduce WVCs and increase wildlife habitat connectivity. This report focuses on our target species, but we also collected similar data on mesocarnivores and smaller mammals that can be analyzed (e.g. Objectives 2 and 3) at a later date.

Methods

Study Area

We conducted our study along a 28-mile stretch of Interstate 40 in the PRG, a mostly steep, rugged drainage that cuts through the southern Blue Ridge Mountains halfway between Asheville, NC and Knoxville, TN (**Figure 1.1**). This stretch of four-lane highway was constructed in the 1960s and the current average annual daily traffic is 28,500 vehicles (North Carolina Department of Transportation, NCDOT). The Pigeon River parallels the highway, with several coldwater tributaries crossing under the road through a variety of drainage structures not specifically designed for wildlife. The river is dammed in the southern section in NC, and the resulting Waterville Lake borders the highway for four miles. Elevation ranges from 400 meters at river level to 950 meters along the highest overlying ridgelines. From a wildlife movement perspective, one defining feature is the high concrete median barrier that creates an impediment to wildlife, both large and small traversing the highway. Another defining feature are the intermittent long stretches of near vertical rock cuts above the highway right-of-way that limits wildlife movement options in many areas. Broadly, vegetation in the study area consists of Southern Appalachian Oak Forest interspersed with Southern Appalachian Cove Forest (NatureServe and GAP/LANDFIRE National Terrestrial Ecosystems 2011). The swath of land descending from the highway to the river consists mostly of fast-growing, mid-successional hardwoods on moderate slopes within a matrix of cobble and boulder riprap leftover from blasting during highway construction. Thin strips of river floodplain forest occur in some areas along the river. On the non-river side for 60 percent of the study corridor, edge habitat in the narrow right-of-way transitions into regionally typic forests of the Pisgah and Cherokee National Forests, which includes the Harmon Den Black Bear Sanctuary. The remaining adjacent lands are private, ranging from undeveloped large, forested parcels to patchworks of rural residential areas and small agricultural fields, and include the unincorporated populated areas of Fines Creek, White Oak, and Hartford. The GSMNP lies a few miles west, and the Appalachian National Scenic Trail crosses under the highway near the stateline. Recreational activities include whitewater rafting, horseback riding, trout and smallmouth bass fishing in the summer, and bear and deer hunting in the fall.

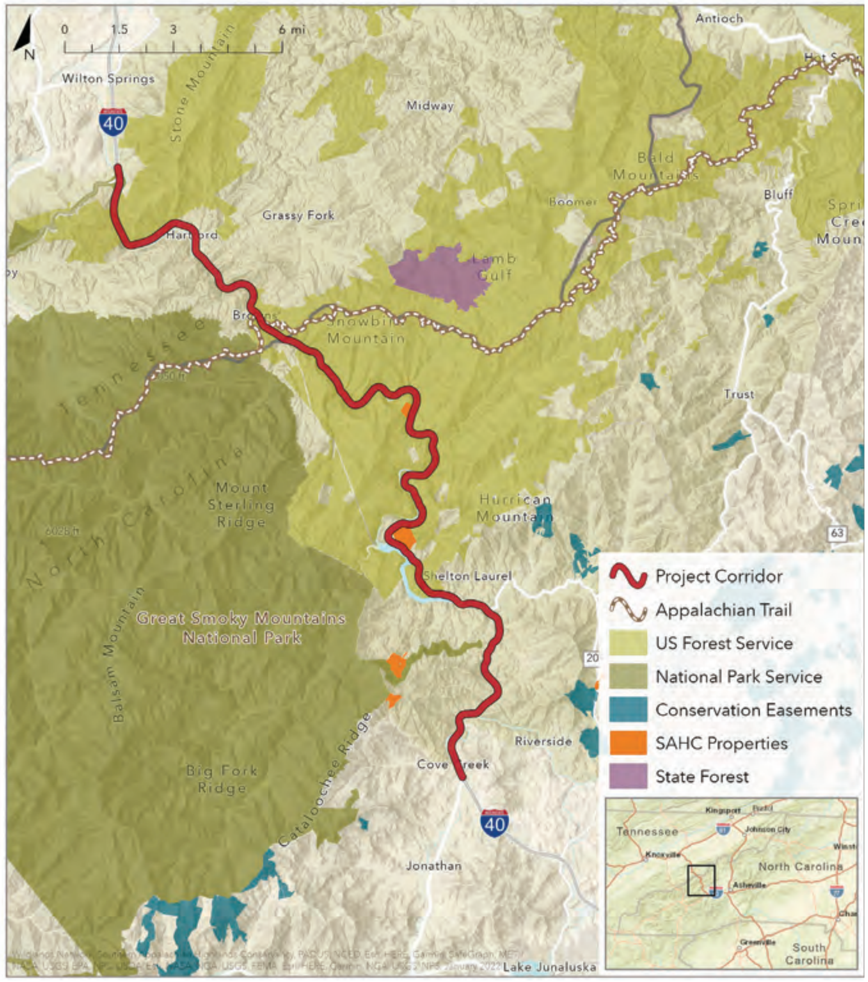


Figure 1.1 (above) - The study area, a 28-mile section of Interstate 40 that winds through the steep and rocky Pigeon River Gorge between Great Smoky Mountains National Park and Pisgah and Cherokee National Forests near the Tennessee and North Carolina border.

Bears are common throughout the study area. Nearby in GSMNP there are an estimated 1,900 individuals (Joe Clark, pers. comm.) forming one of the denser bear populations in the Southeast (Humm and Clark 2021). Deer are also common, becoming locally abundant in less densely forested areas. Elk, a state species of special concern in North Carolina (North Carolina Wildlife Resources Comission [NCWRC] 2015), are less common, occurring in a few small populations adjacent to I-40 with the primary core population further west in Cataloochee Valley in GSMNP. Recently, Pisgah National Forest published a management plan to promote ecosystem resiliency and expansion of elk and other wildlife habitat, by boosting sustainable timber production and prescribed burning along thirteen miles of I-40 over the next several decades (U.S. Forest Service [USFS] 2019). With improved wildlife habitat conditions, this project is likely to increase the population of elk living along the highway. Common mesocarnivores include coyote (*Canis latrans*), bobcat (*Lynx rufus*), red fox (*Vulpes vulpes*), raccoon (*Procyon lotor*) and striped skunk (*Mephitis mephitis*); less common species include grey fox (*Urocyon cinereoargenteus*), Northern river otter (*Lontra canadensis*), American mink (*Neogale vison*), Eastern spotted skunk (*Spilogale putorius*) and long-tailed weasel (*Neogale frenata*) —the latter two are species of growing conservation interest. Eastern box turtle (*Terrapene carolina carolina*), state species of greatest conservation need (SGCN) and the timber rattlesnake (*Crotalus horridus*), state endangered, (NCWRC 2015), also occur in the study area, along with dense and diverse populations of salamanders. In fact, the Smokies region is considered the "Salamander Capital of the World," with the national park hosting an incredible 30 species inside its borders.

Looking Glass Bald, Pisgah National Forest, North Carolina. Photo: JAD Images.

Road Mortality Data

We compiled a database of bear, deer, and elk road mortality and WVCs from state agency records NCWRC, NCDOT, Tennessee Department of Transportation) that included carcass removals and law enforcement crash reports between the years 2001 and 2020. For state agency records, location error estimates ranged from 0.16–0.80 kilometers and locations were often based on mile marker estimates. In addition to compiling records, we conducted weekly roadkill driving surveys to record locations of target species roadkill from September 24, 2018 to December 9, 2021. For 2021, only our data from our weekly roadkill driving surveys were included since updated state agency records were not available at the time of this report. To reduce the potential for inflated counts and ensure mortality locations were not counted twice, records of the same species within 400 meters and reported within 10 days of each other were counted as one occurrence unless stated otherwise in recorded notes. We eliminated entries where species identification or geospatial data was missing and where WVC locations were plotted as >50 meters from the interstate.

Road Mortality Analysis

We projected WVC occurrences in ArcMap 10.3 (Esri® software, Redlands, CA) to systematically identify "hotspots" and the spatial variability in WVC occurrences throughout the study area. We divided the roadway into 400-meter segments (n=115), snapped WVC locations to the nearest road segment, and tabulated WVC count totals per segment (Santos et al., 2015, Ascensão et al. 2017). To help identify areas along the road with high numbers of WVC occurrences we calculated the 25th and 75th percentiles of WVC total observations per segment, and categorized segments as follows: "zero"=0, "low": ≤25th percentile (not including zero), "moderate": >25th≤ 75th percentile, "high": >75th percentile (Coelhoet et al. 2012). We identified WVC hotspots as segments categorized with "high" WVC counts. We evaluated how road and landscape features predict the spatial

White-tailed deer. Photo: Balashark

patterns in WVC occurrences by establishing a use-availability framework, where environmental covariates at the WVC locations (the used locations) were compared with covariates at locations generated systematically every 50 meters along the 28-mile section of interstate (n=943), deemed "available" or where a WVC could occur. We used a conditional logistic regression with a binary predictor variable (1=WVC, 0=available location) in program R to estimate coefficients to obtain inference on the influence of landscape and road covariates on WVCs occurrence. While predicted values from these models do not reflect true probabilities of WVCs (Keating and Cherry 2004), they provide an informative and unbiased method for ranking landscape and road features influence on WVCs and comparing relative probability of WVCs along the roadway (Johnson et al. 2006, Bencin et al. 2019).

We explored a suite of landscape characteristics (e.g. land cover, human disturbance, streams, terrain ruggedness, slope position) known to influence target species movement and habitat selection in the region (Hillard 2013, Braunstein et al. 2021) and thus road crossing behavior. Landscape and topographic covariates were characterized as the proportion of area within a 100-meter radius circular buffer (31,416 m^2) area around each WVC and available location. Using a 100-meter radius buffer around points allowed us to somewhat offset potential errors in WVC location reporting and was large enough to characterize localized conditions on both sides of the roadway. Landscape and topographic data were obtained from National Land Cover Data (Dewitz 2019) and USGS National Elevation and Hydrography datasets (U.S. Geological Survey, 2019). We constrained analyses to 12 covariates that were well represented in the study area and indicative of crossing conditions specific to the roadway (**Appendix A: Table A.1**). Existing road infrastructure (bridges, culverts, land bridges) can provide safe passage for wildlife and may influence WVC occurrence along the roadway. We therefore included a "distance to structure" variable by measuring the Euclidean distance in meters from each WVC and available location to the nearest road infrastructure that have passed or have the potential to pass (e.g. opening >2.0 m2) our target wildlife species. We calculated pairwise correlations between all model covariates. For pairs of highly correlated ($|r| \geq 0.7$, $P<0.05$) variables, we retained the variable that provided the simplest biological explanation for further analysis. In this case, terrain ruggedness-level and flat slope position were highly correlated; we retained flat slope for analysis.

Black bear. Photo: Larry Knupp.

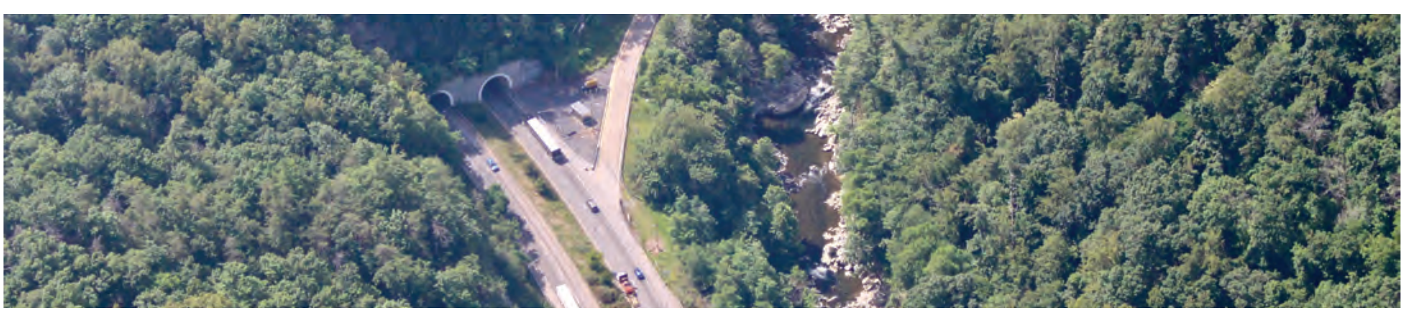
White-tailed deer in the forest adjacent to I-40.
Photo: Wildlands Network / NPCA

To explain variation in WVCs along the roadway based on landscape and topographic characteristics, we developed models using all combinations of covariates with all WVC locations as the response variable. Because many of these features influence bear, deer, and elk behavior in different ways, models using all combinations of covariates were created with species specific locations as the response variable, if species specific data was adequate (Lachin 2008). We used differences in Akaike's Information Criterion corrected for small sample size (delta AICc) values to rank candidate models; we considered models within two AICc units of the top model to be competitive (Burnham and Anderson 2002). If maximized log-likelihood estimates were similar, we considered the model with the fewest parameters as the most parsimonious. We calculated the odds ratios for the predictors selected in the most parsimonious model based on coefficients and their unconditional standard errors. To test the robustness and prediction accuracy of the top preforming models, we used a k-fold cross validation (k=5) to calculate the mean cross-validation estimate of accuracy (between 0 and 1: Koper and Manseau 2009).

Roadside Camera Trap Monitoring

We monitored target species activity along the interstate with heat and motion triggered Reconyx Hyper Fire 1 and 2 infrared wildlife cameras (RECONYX, inc. Holmen, WI) to determine if the frequency and spatial variation in WVC occurrences reflect wildlife activity along the interstate and obtain a general measure of wildlife activity in the PRG. We monitored a total of 33 400-meter road segments with 66 wildlife cameras (2 cameras per segment), out of a total of 115 potential 400-meter segments in the target stretch of I-40. To determine segments to survey with cameras, we categorized each segment into high, medium, or low based on 2001-2017 WVC locations. We first excluded segments (n=27) from monitoring that contained continuous rock cut cliff (>65-degree slope) paralleling the roadway due to these characteristics being unlikely to support wildlife crossing from one side of the road to the other. We then systematically sampled all but one of the (excluded because of safety concerns) segments with high WVC indices (n=17), and randomly selected seven and six segments with moderate and low WVC indices, respectively, to assure variation for comparison. We added three additional segments based on expected importance in the landscape. Within segments, we placed two camera traps in areas with animal sign (trails, tracks, scat) or if no sign existed, locations that appeared more conducive for target species movement (more gradual slope areas within the segment). Cameras were placed >5 meters away from the roadway and >50 meters away from each other.

We counted the number of individual detections per species for each camera. To reduce the likelihood of counting the same animal multiple times, independent detections were only counted when a species completely left the camera field of view and then was observed again >30 minutes apart from the prior detection (Tambling et al. 2015). For road segment



Double Tunnel. Photo: Paul Noah, NPCA and SouthWings inference, the photos from the two cameras monitoring the same 400-meter road segment were combined, and a longer >60-minute observation window was used for tallying independent detections to account for spatial and temporal independence and minimize counting the same animal twice within segments. We calculated average detection rates per 100 days for each segment and each camera site by dividing the number of individual detections for a given species by the total number of trap days and multiplying by 100. Trap days were computed as the number of 24-hour periods from deployment to retrieval in which cameras were functioning correctly. We used average species detection rates per 100 days at segments and cameras sites as an index of target species activity along the roadside since camera trap detection rates are strongly correlated with localized population density (Parsons et al. 2017). No attempt was made to identify or track individual animals during the camera study though we did record the number of individuals within each observation window and estimated black bear age classes (e.g. adult with cubs).

Roadside Camera Trap Analysis

We calculated species detection rates for each road segment (n=33) and each camera site (n=66) separately. We conducted preliminary data exploration using descriptive statistics, and plotted box and whisker plots to visualize the data and identify outliers. To investigate the relationship between WVC occurrences and activity rates within road segments, we directly compared species specific VC counts per segment to their respective detection rates per segment using a linear regression with a Poisson distribution and log link function for each species.

To determine how landscape and road features may influence the variation in species detection rates along the roadway, we used species detection rates from camera sites (n=66) as response variables to land cover covariates used in the WVC analysis. We derived landscape covariates for camera sites similarly to WVC locations (**Appendix A: Table A.1**). Variables were characterized as the proportion of area within a 100-meter radius circular buffer (31,416 m^2) around each camera location. This buffer size was used as a compromise between having a large enough area to characterize the site and recognizing the limitations in the distance at which cameras can detect animals. Because distance to the roadway likely influences wildlife activity, we included a "distance to roadway" variable by measuring the Euclidean distance in meters from each camera site to the road surface.

We used generalized linear model analysis to construct models to evaluate how bear and deer detection rates were influenced by landscape and road covariates. A negative binomial error distribution was used to allow for over dispersion from a standard Poisson distribution, as appropriate for rate (proportional) response variables (Zuur et al. 2007). We used difference in Akaike's Information Criterion corrected for small sample size (delta AICc) values to rank candidate models and considered models within two AICc units of the top model to be competitive (Burnham and Anderson 2002). We used these model findings to simply identify environmental drivers of detection rate of bear and deer relative to other camera sites.

A great blue heron at the Groundhog Creek Culvert.
Photos: Wildlands Network / NPCA

Monitoring Structure Use with Camera Traps

We monitored existing roadway structures (n=21), including bridges (n=8), culverts (n=11), and land bridges (n=2; where the road tunnels under or partially under the landscape (**Appendix A: Table A.2**) distributed throughout the 28-mile study area with camera traps to evaluate animal activity and determine if bear, deer, and elk use these structures to cross the interstate. To monitor structures, in most cases we placed cameras on both sides of the roadway (cameras per structure ranged from two-four) and focused cameras on openings or locations conducive for detecting wildlife entering or exiting the structure. Two concrete box culverts, Mill Creek A and Mill Creek B were monitored with only one camera each. At each structure and for each target species we calculated species detection rate per 100 days. Because both land bridges (Double Tunnel and Single Tunnel) are large open structures, we could not explicitly confirm structure use from cameras, and therefore they were excluded from further analysis. For the remaining 19 structures we also calculated the number of confirmed crossings (i.e. number of paired detections where an individual animal clearly enters one side and exits the other side of a structure in a 30-minute period) and the use-count (i.e. includes confirmed crossings [each equals two detections], plus unpaired structure entrances or exits). Use-counts include detections where targets species investigated a structure (i.e. stepped into the entrance) before turning around and retreating.

Structure Camera Analysis

We compared species detection rates to use counts to determine if wildlife detection rates at structures are related to wildlife use of structures to infer the potential value of the Double and Single Tunnel due to limitations in monitoring their use by wildlife. To evaluate how structure conditions might influence species use, we created categories to describe parameters known to influence bear, deer, and elk structure use. We categorized structures by type (bridge, culvert, land bridge), ground substrate (metal, concrete, natural), and the general size of opening (small <2 m^2, medium >2<5 m^2, large >5 m^2). All road structures monitored were constructed to move either vehicle traffic or water (hydrological), therefore we categorized each structure as water or vehicle to examine the influence of these two conditions on wildlife use. To determine if there is any significant difference between the use rates of the different structures due to structure characteristics, we used the Kruskal-Wallis test to compare factors for all species respectively using the count-of-use at each structure. If a factor was significant ($p<0.05$) we calculated effect size (eta squared) and used Wilcoxon's Test to calculate pairwise comparisons and box plots to investigate further (Zurr et al. 2017).

Millcreek A Box Culvert. Photo: NPCA

Hurricane Creek Culvert. Photo: NPCA

Results

Road Mortality

We recorded 336 incidents of WVCs in the PRG from 2001-2021, 304 of which met our criteria for further evaluation. Fifty-one (~17%) of the 304 records did not distinguish between bear and deer and 14 records did not contain month-specific information. Bear (n=167) accounted for approximately 55% of WVCs, followed by 28% deer (n=85) and <1% elk (n=1, **Figure 1.2**). WVC counts were highest in the months of October, November, and December. Not surprisingly, the highest yearly WVC counts occurred during years 2018-2020, when roadkill surveys from our research and state agencies records were included in yearly totals. The 20 years of crash report data compiled from 2001-2020 only accounted for ~39% of the total WVC data (**Figure 1.3**). In years where crash reports were paired with more intensive data collection methods from surveys and carcass removal (2018-2020), crash reports only accounted for approximately 16% of the WVC locations, while surveys and carcass removal accounted for 52% and 32% of WVCs for those years, respectively. Only a single crash report was recorded in 2020 of the 50 WVCs documented overall.

Within road segments (n=115), total WVC counts averaged 2.6±2.0 [SD]) and ranged between 0 and 9 WVCs per segment. The 25th and 75th percentiles were one and four collisions, respectively. Based on percentile ranks, 22 segments were categorized as "high": (counts 5-9, "hotspots"), twenty-eight segments as "moderate" (counts: 2-4), fifty-one as "low" (count=1), and 14 segments as "zero" (**Figure 1.4**). Hotspot segments were distributed in 10 general areas throughout the 28-mile study area (**Appendix A: Map 1-3**). Seven of these locations included single road segments (segments: 96, 79, 74, 56, 44, 39, 13) separated from other hotspot segments (>1200 meters away). The other three locations contained strings of multiple hotspots in close proximity (~800 meters) to each other: segments 67, 64, 62, 60, segments: 33, 32, 29, 26, 24, 22, 20, 19, segments: 9, 8, 7).

K-fold cross validation estimates of accuracy were 0.707±0.006 (SD), 0.747±0.002 (SD), and 0.697±0.009 (SD) for all target species-, bear-, and deer-WVC analyses, respectively. For all target species WVCs, the top model included forest area, flat area, and distance to structure (**Table 1.1**). The relative probability of a WVC increased as distance to usable road structures decreased (**Table 1.2, Figure 1.5A**). The top model for bear-VCs included forest area, flat area, and distance to structure and the relative probability of a bear-VC increased as area of forest increased and as the distance to usable road structures decreased (**Table 1.2, Figure 1.5B**). The top model from our logistic regression analysis of landscape predictors of deer-VCs included ridge area and distance to structure and the relative probability of a deer-VC increased as ridge area decreased, and as the distance to usable road structures decreased (**Table 1.2, Figure 1.5:C**).

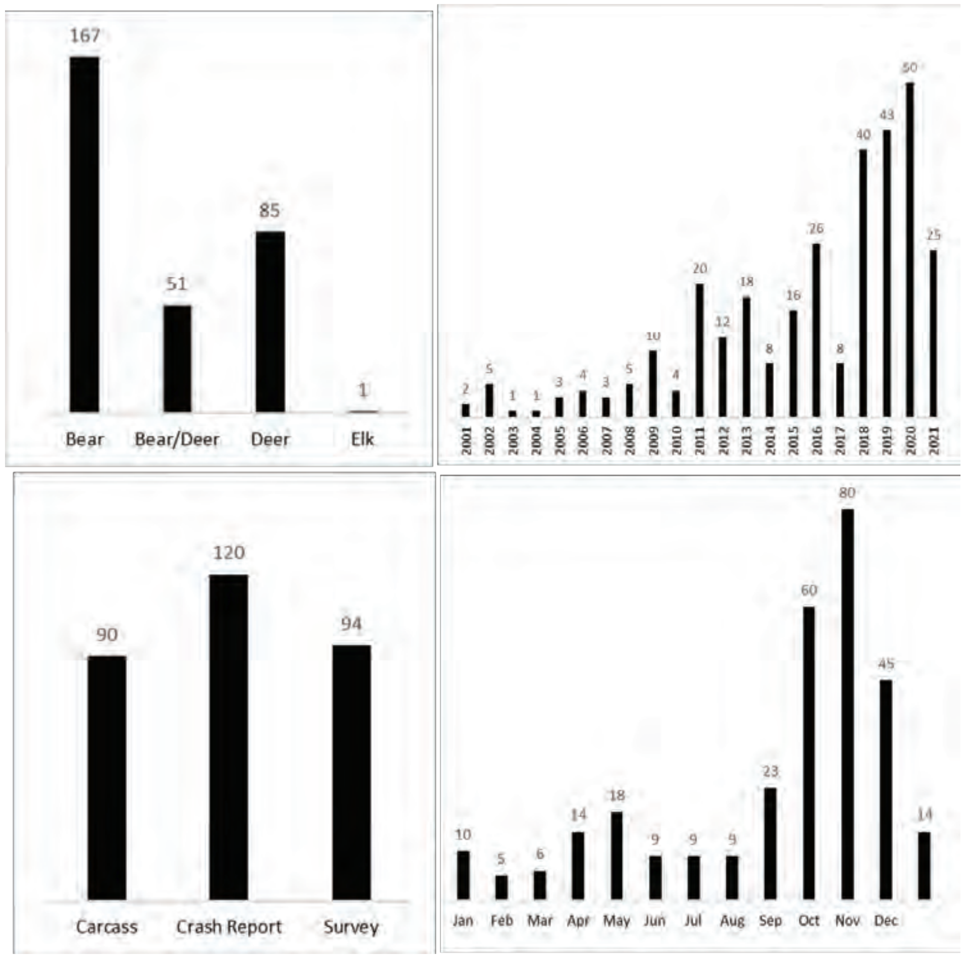
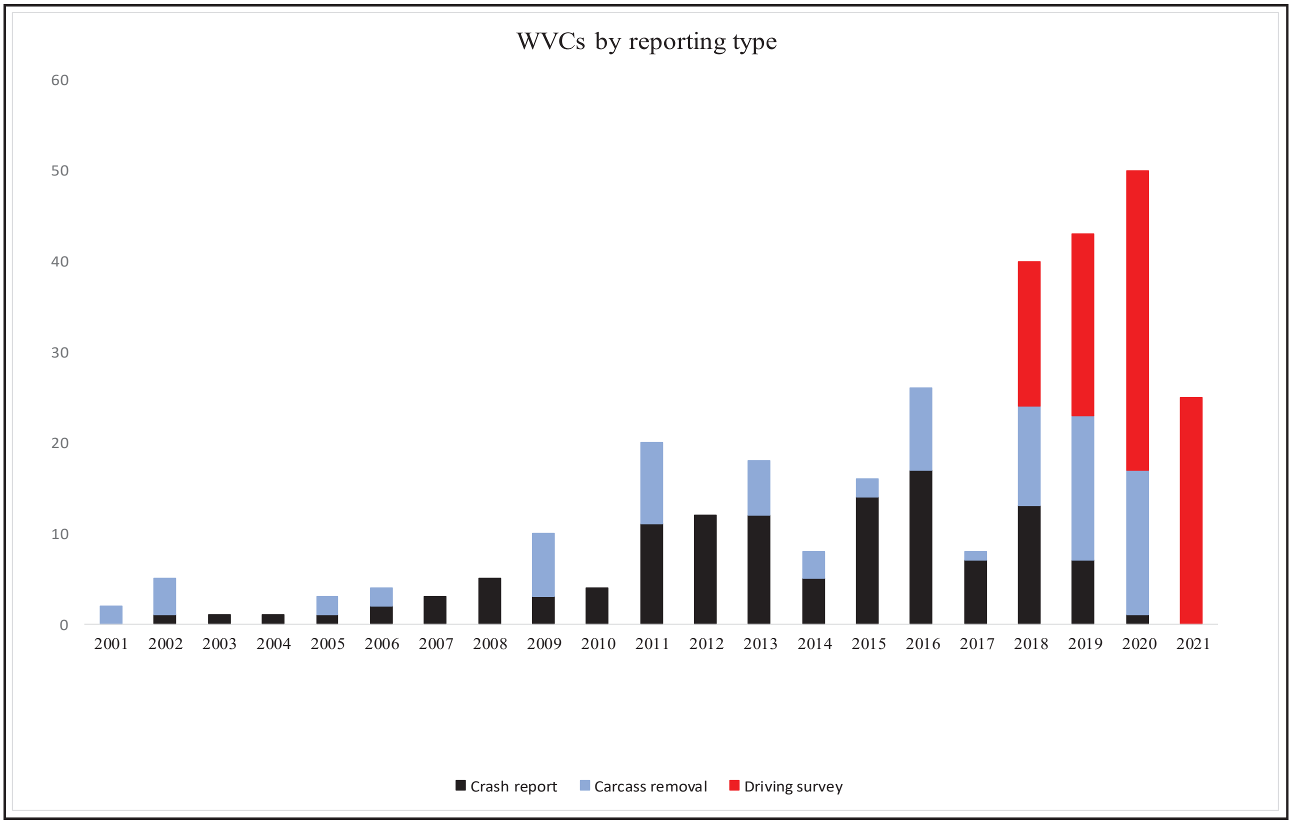


Figure 1.2. (above) - The total number of black bear, white-tailed deer, and elk road mortalities from carcass, crash reports, and research surveys collected from 2001-2021 along a 28-mile section of Interstate 40 in the Pigeon River Gorge near the Tennessee and North Carolina border.



*Carcass removal prior to 2018 were collected by NCWRC, whereas 2018–2020 data were collcted by NCWRC, NCDOT, and TDOT. Carcass removal data was not reported for 2021 at the time of this report.

Figure 1.3. (above) - The number of wildlife vehicle collisions (2001-2021) in 400-meter road segments (n=115) categorized by zero (gray), low (green), moderate (yellow), and high (red) counts along a 28-mile section of Interstate 40 in the Pigeon River Gorge near Great Smoky Mountains National Park, Tennessee and North Carolina.

Wildlife Vehicle Collision Model	K	AICc	Δi	*wi*	LL
Forest + Highly-rugged + Flat + Distance to structure	5	1374.5	0	0.43	-682.21
*Forest + Flat + Distance to Structure	4	1375	0.52	0.37	-683.48
Forest + Distance to Structure	3	1376.75	2.28	0.15	-685.37
Bear Vehicle Collision Model	**K**	**AICc**	**Δi**	***wi***	**LL**
*Forest + Flat + Distance to structure	4	930.73	0	0.33	-461.35
Forest + Protected + Flat + Distance to structure	5	930.87	0.14	0.31	-462.42
Flat + Distance to structure	3	933.17	2.44	0.10	-460.55
Deer Vehicle Collision Model	**K**	**AICc**	**Δi**	***wi***	**LL**
*Ridge + Distance to structure	3	570.76	0	0.51	-281.36
Intermediately-rugged + Ridge + Distance to structure	4	571.84	1.08	0.29	-280.89
Flat + Ridge + Distance to structure	4	572.61	1.85	0.20	-281.27

* Top model

Table 1.1. (left) - Number of estimated parameters (K), small sample Akaike's Information Criterion (AICc), difference between model AIC and that of the best model (Δi), and log-liklihood (LL) to assess best model fit for conditional logistic regression models used assess the influence of landscape and road characteristics on wildlife vehicle collisions (black bear, white-tailed deer, elk), black bear vehicle collisions, and white-tailed deer vehicle collisions along a 28-mile section of Interstate 40 in the Pigeon River Gorge,Tennessee and North Carolina, September 2018–December 2021.

Wildlife Vehicle Collision

Variable	B	SE	Z^b	P
Intercept	-1.432	0.300	-4.780	<0.001 *
Forest	0.009	0.050	1.670	0.096
Flat	0.017	0.010	1.850	0.064
Distance to structure	-0.028	0.000	-2.690	<0.01 *

Black Bear Vehicle Collision

Variable	B	SE	Z^b	P
Intercept	-2.170	0.380	-5.710	<0.001 *
Forest	0.010	0.006	2.052	<0.05 *
Flat	0.017	0.011	1.512	0.130
Distance to structure	-0.040	0.000	-3.161	<0.01 *

White-tailed Deer Vehicle Collision

Variable	B	SE	Z^b	P
Intercept	-1.339	0.280	-5.121	<0.001 *
Ridge	-0.045	0.010	-3.410	<0.001 *
Distance to structure	-0.036	0.000	-2.070	<0.05 *

Table 1.2. (above) - Variable estimates for the most parsimonious models used to assess the influence of landscape and road characteristics on wildlife vehicle collision- (black bear, white-tailed deer, elk), black bear vehicle collision-, and white-tailed deer vehicle collision-models along a 28-mile section of Interstate 40 in the Pigeon River Gorge, Tennessee and North Carolina, September 2018–December 2021.

	White-tailed deer				Black bear			
	B	SE	Zb	P	B	SE	Zb	P
Intercept	2.946	0.157	18.748	<0.001*	-0.307	0.520	-0.830	0.41
Forest	-	-	-	-	0.014	0.389	2.436	<0.05*
Human disturbance	-	-	-	-	-	-	-	-
Protected land	-	-	-	-	0.015	0.002	6.011	<0.001*
Stream	-0.094	0.030	-3.143	<0.01*	-0.074	0.033	-2.220	<0.05*
Ridge	-	-	-	-	-	-	-	-
Flat	-	-	-	-	-	-	-	-
Low slope	-	-	-	-	-	-	-	-
Valley	-	-	-	-	-	-	-	-
Highly rugged	-0.077	0.016	-4.693	<0.001*	-	-	-	-
Distance to I-40	-	-	-	-	-	-	-	-

Table 1.3. (above) - Variable estimates for the most parsimonious models used to assess the influence of landscape and road characteristics on white-tailed deer and black bear detection rates in cameras (n=66) adjacent to Interstate 40 in the Pigeon River Gorge, Tennessee and North Carolina, October 2018–December 2020.

Roadside Cameras

We obtained 6,598 independent detections of our three target species at roadside cameras from October 30, 2018 to December 31, 2020. Deer was the most recorded species (n=5,174), followed by bear (n=1,371), and elk (n=53). Trap days at camera sites (n=66) averaged 666±43.3 days and ranged between 520 and 784 days. For roadway segments (n=33, 2 cameras/segment), trap days averaged 1,332±79.9 and ranged between 1069–1450 days. Elk were detected at 17% of roadside cameras (n=11) and 21% of monitored roadway segments (n=7). Bear and deer were detected in all monitored road segments, and 95% (bear, n=63) and 98% (deer, n=65) of roadside cameras, respectively. All three target species were detected at nine camera sites (113A, 113B, 80B, 79B, 23A, 24A, 24B, 32A, 32B). Average detection rates per 100 days varied by species across road segments (bear: 2.77±3.12, range=0.07-16.2, deer: 9.2±8.6, range=0.93–47.8, elk: 0.09±0.2, range = 0-1.1, **Figure 1.6**) and across camera sites (bear: 3.1±4.1, range=0.00-29.3, deer: 11.8±12.7 range=0.00–87.6, elk: 0.12±0.43, range=0.00-2.6, **Figure 1.7**).

Since analysis of WVCs indicated species-specific factors influencing deer- and bear-VC occurrence patterns, we only compared deer and bear segment detection rates from the roadside cameras with the corresponding species-specific VC segment counts. There was insufficient data available to compare elk detection rates at segments (n=7) to WVC counts per segment. When comparing deer detection rates to the number of deer-VCs in segments we removed segment 114 due to the detection rate for that segment (61.6 per 100 trap days) being >5x the mean deer detection rate for all monitored segments (**Figure 1.7**). Segment 67 was removed from analyses comparing bear detection rates to bear-VC counts due to the bear detection rate (16.6 per 100 trap days) being >5x the mean bear detection rate for all monitored segments. We found no significant linear relationship (p>0.05) between deer detection rates and the number of deer-VCs within road segments or bear detection rates and the number of bear-VCs within segments.

For models evaluating the influence of landscape covariates on deer and bear detection, we removed camera site 114B (87.6 deer/100 trap day) and 67A respectively due to those camera sites having detection rates >4x and >5x the mean rate.

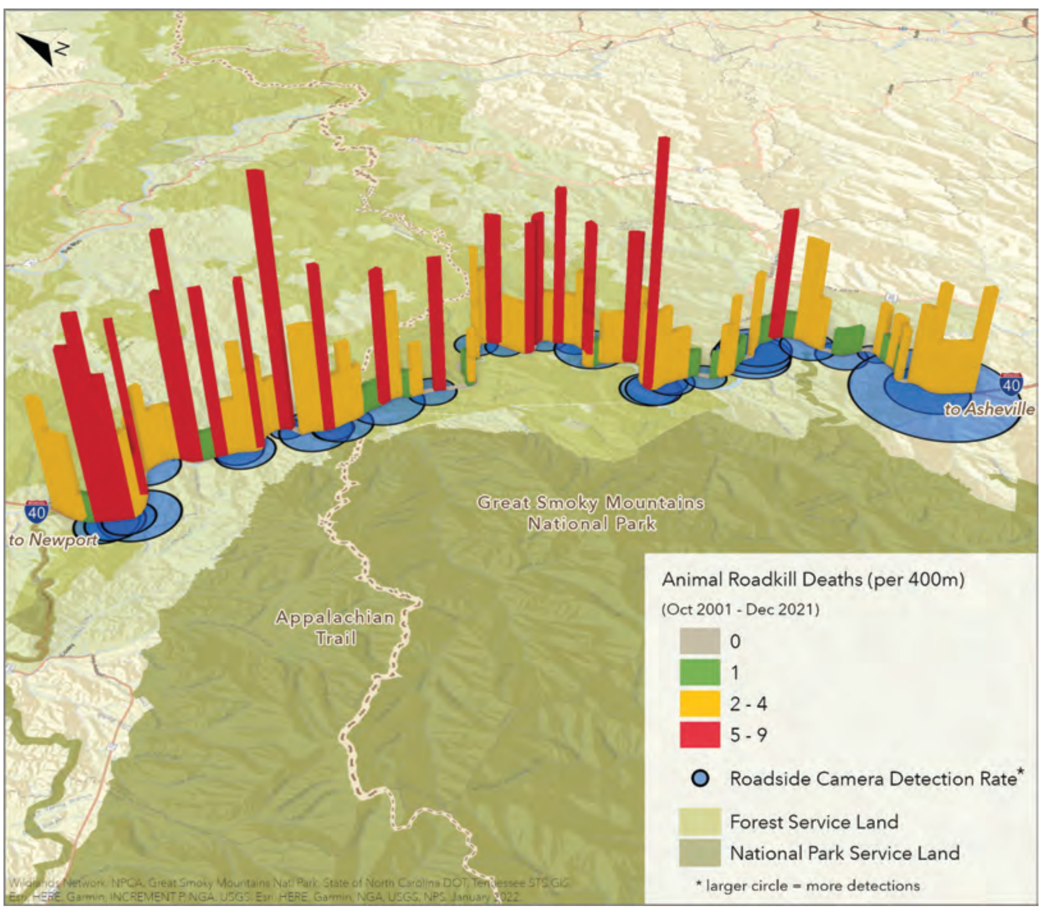


Figure 1.4. (left) - The number of wildlife vehicle collisions (2001-2021) in 400-meter road segments (n=115) categorized by zero (gray), low (green), moderate (yellow), and high (red) counts along a 28-mile section of Interstate 40 in the Pigeon River near Great Smoky Mountains National Park, Tennessee and North Carolina.

There were insufficient data available for modeling landscape predictors of elk detection rate at cameras (n=11). For bear detection rate, the top model included proportion of forest area, protected area, and stream area and bear detection rates were relatively higher at camera sites that contained more forest area, more protected area, and less stream area (**Table 1.3**). The top deer detection rate model included the proportion of highly rugged area and stream area, and deer detection rates were relatively higher at camera sites that contained less highly rugged area and less stream area (**Table 1.3**).

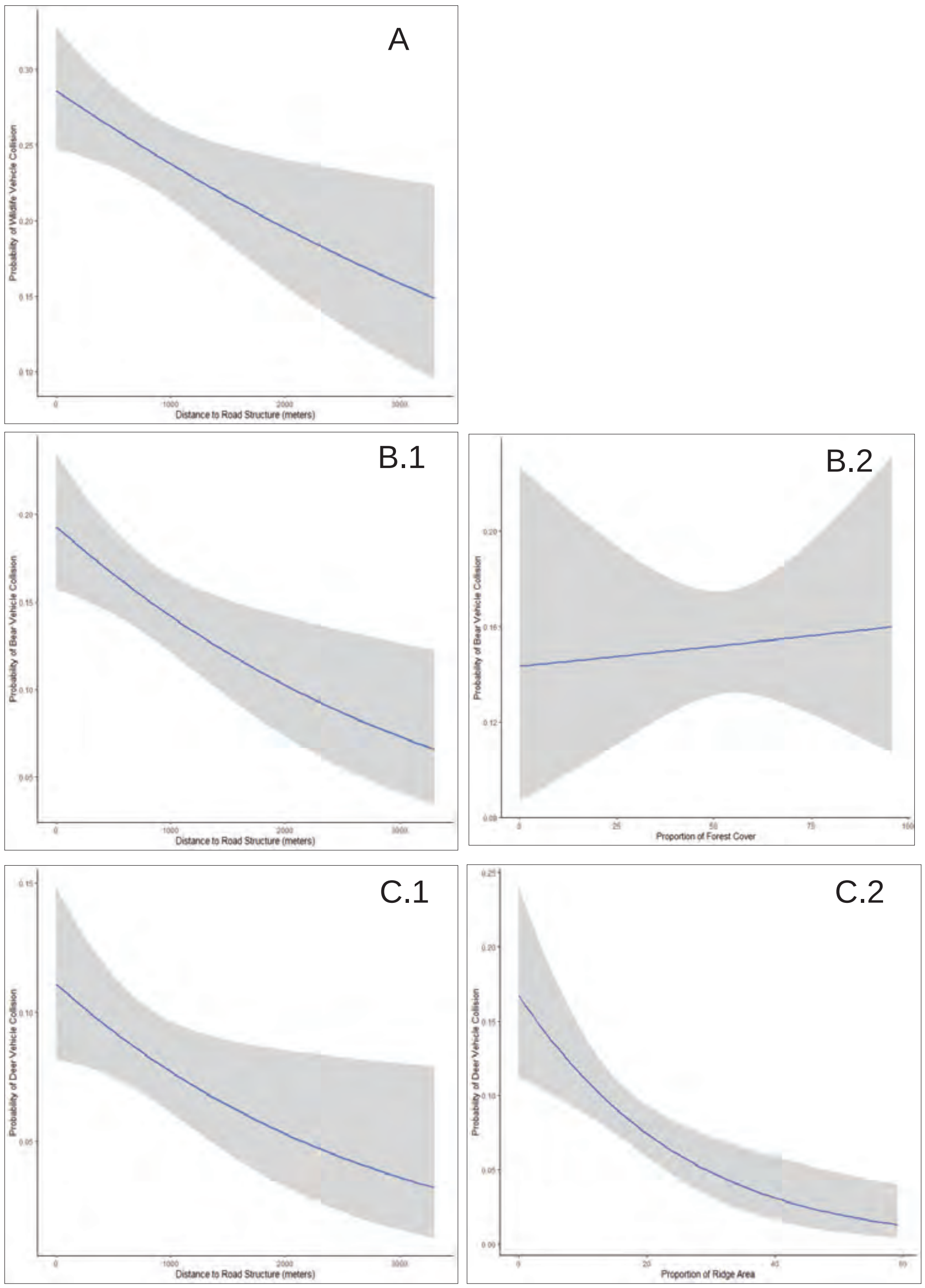


Figure 1.5. (above) - Probabilities and 95% confidence intervals for predictors of target species vehicle collisions (i.e.., black bear, white-tailed deer, elk, A.1), black bear vehicle collisions (B.1, B.2), and white-tailed deer vehicle collisions (C.1, C.2) along a 28-mile section of Interstate 40 in the Pigeon River Gorge, Tennessee and North Carolina, September 2018—December 2021.

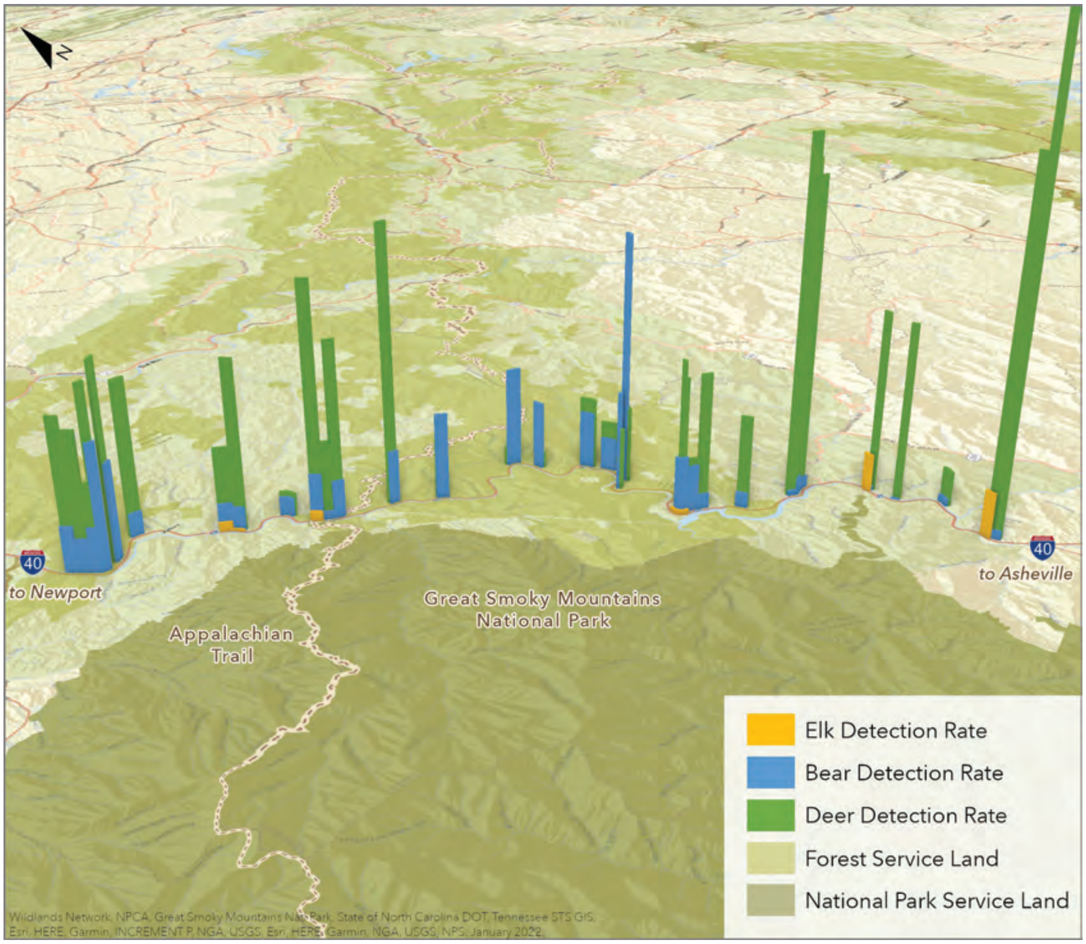


Figure 1.6. (left) - Black bear, white-tailed deer, and elk detection rate/100 days in 400-meter road segments (n=33) monitored with cameras traps (n=66) adjacent to Interstate 40 in the Pigeon River Gorge, Tennessee and North Carolina, October 2018–December 2020.

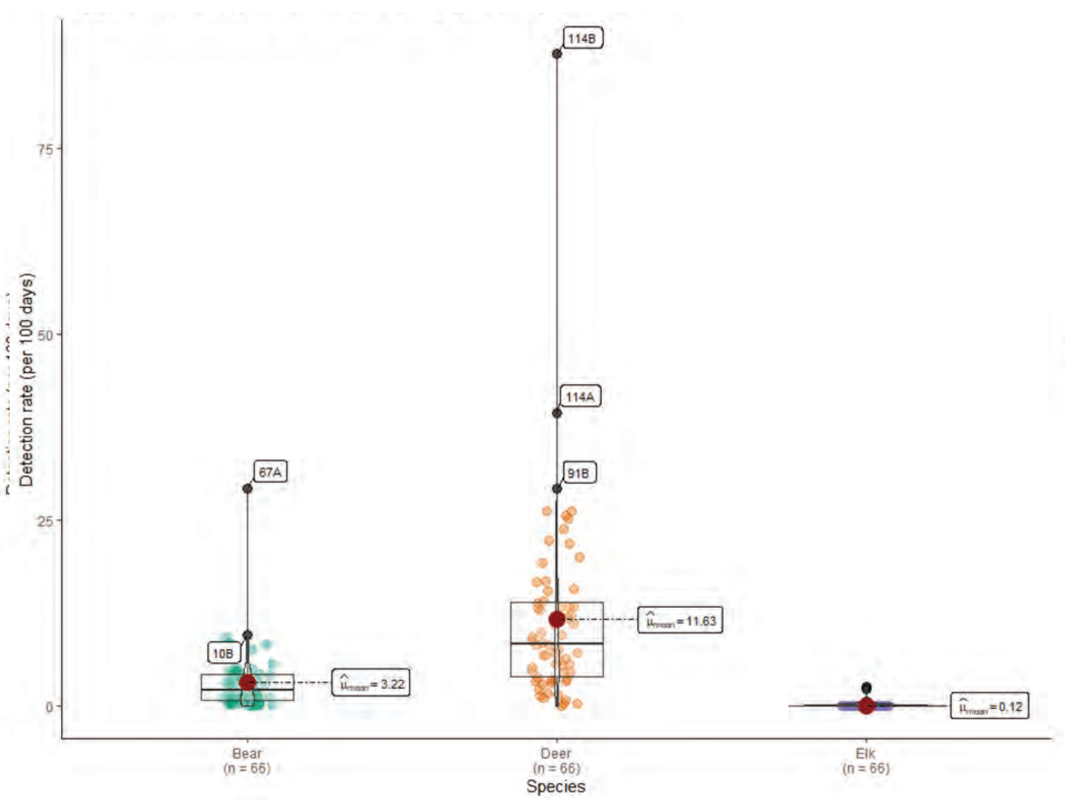
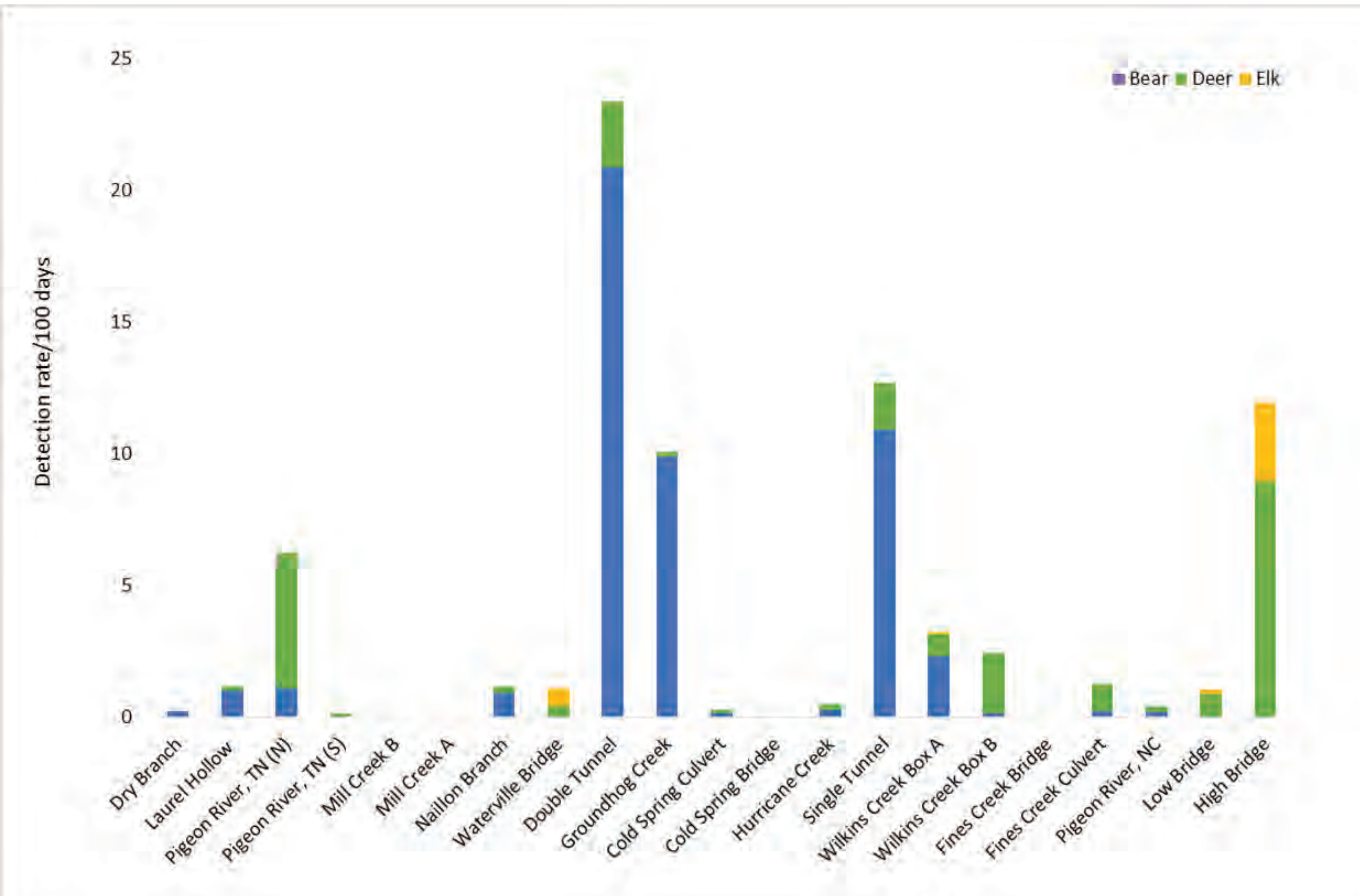


Figure 1.7. (left) - Black bear, white-tailed deer, and elk detection rate/100 days from cameras traps (n = 66) monitoring wildlife activity adjacent to Interstate 40 in the Pigeon River Gorge, Tennessee and North Carolina, October 2018–December 2020.

Structure Cameras

Target species detection rates varied between the 21 road structures monitored (**Figure 1.8**). One or more target species was detected in camera traps at 86% of the structures, with 67% of structures detecting bear, 76% detecting deer, and 19% detecting elk. Bear detections rates at structure cameras (x=3.74±6.0) were highest at the Double Tunnel (23.4/100 trap days), Single Tunnel (12.7/100 trap days), and Groundhog Creek (10.1/100 trap days), while detection rates for deer (x=1.20±2.2) and elk (x=0.19±0.66) were highest at the High Bridge, 9.0 and 3.0 respectively.

A was the only structure to have confirmed crossings or use by all three target species. Bear were detected crossing 16% of the monitored structures and using 37% of them, with the highest number of crossing and use detections at Groundhog Creek and Wilkins Creek Box Culvert A. Thirty-seven percent of structures were crossed by deer and 58% were used. The highest detections of crossing and use for deer were at the High Bridge and the northern span of the Pigeon River Bridge in Tennessee. Elk crossings were detected at 21% of structures, with the High Bridge and the Waterville Bridge having the highest number of use detections (19 and 6, respectively).



Of the 19 road structures monitored for confirmed crossings and use, overall target species detection rates significantly predicted the number of confirmed crossings by target species at structures ($\beta 1=0.54$, $p<0.001$, $R2=0.77$) and the number of detections indicating use by target species at structures ($\beta 1=0.12$, $p<0.001$, $R2=0.90$). Forty-two percent of structures had confirmed crossings by one or more target species (**Figure 1.9**) and 68% had indicated use by one or more target species (**Figure 1.10**). Wilkins Creek Box Culvert

Figure 1.8. (above) - Black bear, white-tailed deer, and elk detection rates/100 days at 21 road structures (i.e. bridges, culverts,land-bridges) monitored with camera traps in the Pigeon River Gorge, Tennessee and North Carolina, October 2018–December 2020.

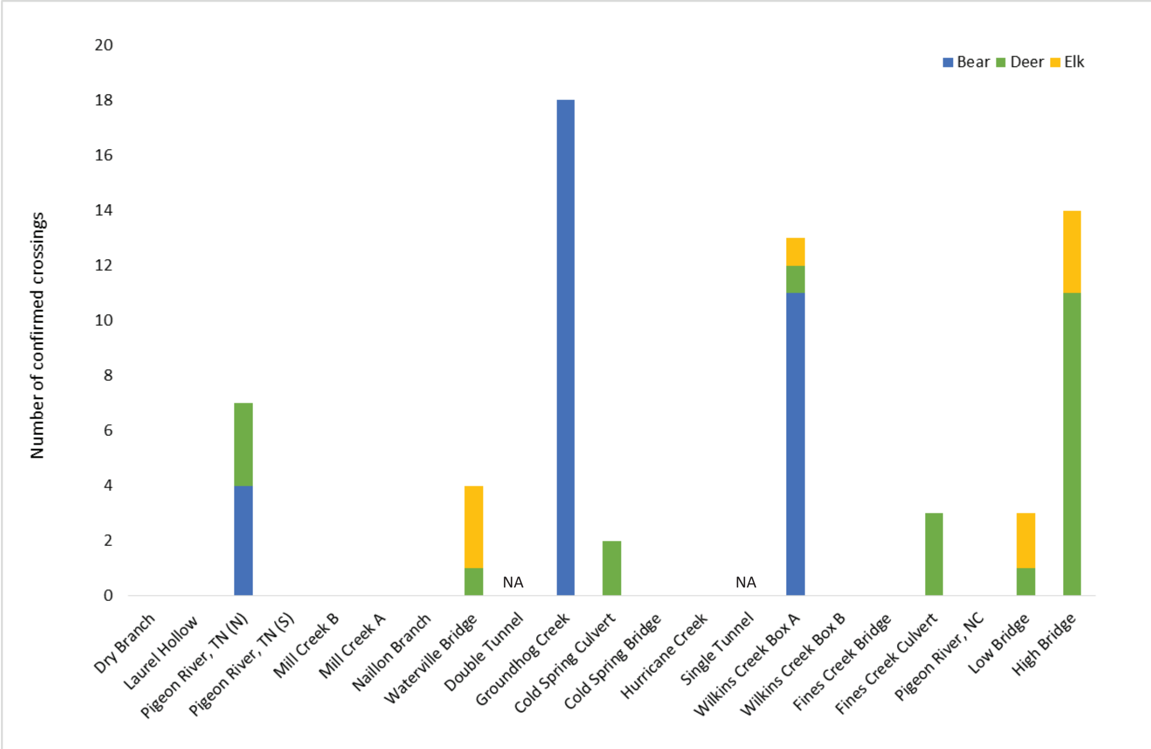


Figure 1.9. (above) -The number of black bear, white-tailed deer, and elk confirmed crossings (enters and exits structures in <30 minutes) at 21 road structures (i.e. bridges, culverts, land-bridges) monitored with camera traps in the Pigeon River Gorge, Tennessee and North Carolina, October 2018–December 2020.

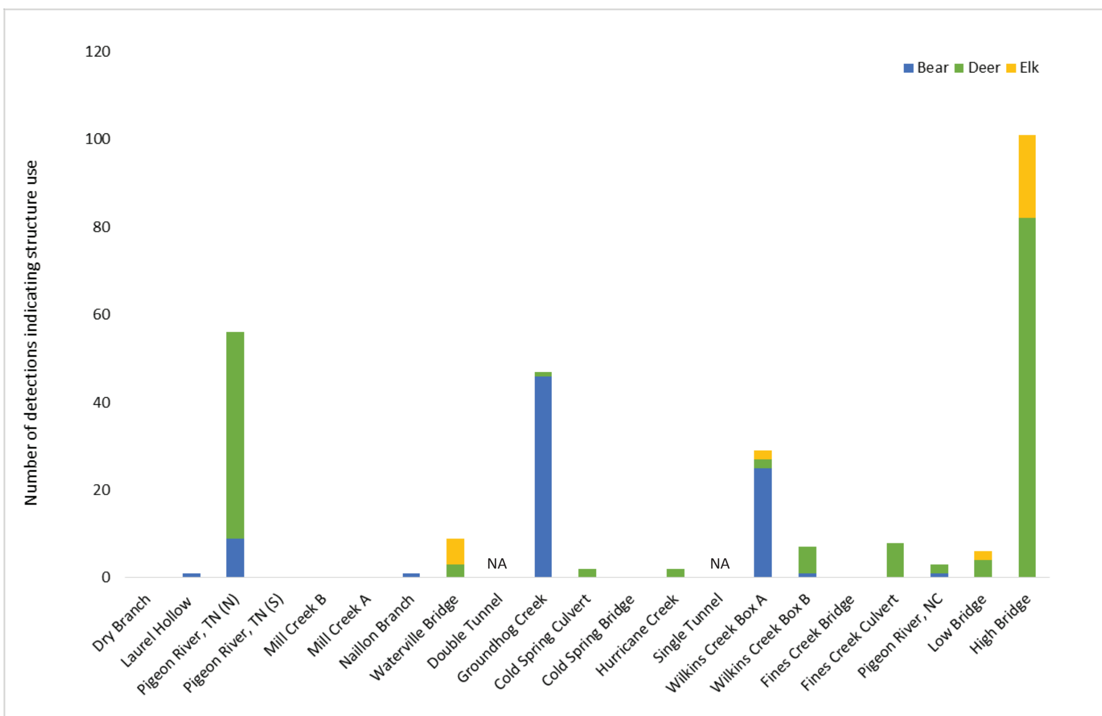


Figure 1.10. (above) - The number of black bear, white-tailed deer, and elk detections of use (number of detections where individual enters or exits structure) at 21 road structures (i.e. bridges, culverts, land-bridges) monitoredwith camera traps in the Pigeon River Gorge, Tennessee and North Carolina, October 2018–December 2020.

We found no significant influence ($p>0.05$) of structure characteristics on bear use, however structure characteristics did significantly influence deer and elk use. Size of structure openings significantly influenced deer use ($p=0.03$, $eta^2=0.33$). Small openings (<2 m^2) were not used by deer. Elk use was positively influenced by structures that moved motor vehicles ($p=0.03$, $eta^2=0.42$) and elk used structures that moved vehicle traffic exclusively and not water.

Discussion

Characterizing bear, deer, and elk activity and vehicle collision locations along I-40 in the PRG provides information on the patterns and processes of wildlife road interactions and can be used to help prioritize locations for mitigation of impacts to wildlife and motorists. In the PRG, WVCs varied spatially along the interstate and consisted mostly of bear- and deer-VCs (only one elk-VC). High counts of WVCs were identified at 22 road segments in roughly 10 "hotspot" areas along the 28-mile section of roadway. Camera monitoring of wildlife activity adjacent to the roadway revealed the omnipresence of deer and bear throughout the PRG, and the lack of relationship between WVC counts and activity rates suggest WVC hotspots occur at specific areas on the landscape regardless of animal activity. Cross-validation ensured that inferences regarding WVC predictive models were robust and revealed higher probabilities of WVCs in areas along the roadway where more bear and deer preferred habitat exists and in areas closer to current bridges/culverts. We found the majority (76%) of bridges/culverts occurred in close proximity (within 400 meters) to WVC hotspots. While total crossing events were low overall, camera monitoring revealed varying degrees of interest by wildlife (i.e. use). Even structures with less than ideal openness conditions were sometimes used by one or more target species to cross under the interstate. But even with structures available along the roadway, wildlife sometimes chose to cross at highway grade, as evidenced by nearby mortality hotspots. This suggests good location, suboptimal structure for wildlife use for safe passage across the interstate. In general, different structures were used by ungulates and bear separately and structure characteristics influencing their use generally reflected species-specific high openness requirements (Huijser et al. 2008, Clevenger and Huijser 2011).

The higher number of WVCs in 22 road segments (i.e. hotspots) revealed the non-random distribution of WVC hotspots in the PRG (Ramp et al. 2005, Neumann et al. 2012). The concentration of these "hotspots" into ten

A black bear near the Bluffton Bridge accessing the interstate below.
Photo: Wildlands Network / NPCA

areas requires prioritization of these areas for mitigation measures such as fencing and crossing structures (Clevenger et al. 2001, Olsson and Widen 2008, Polak et al. 2014). Wildlife crossings placed in areas where clusters of WVCs occur can promote wildlife connectivity and reduce collisions (Gagnon et al. 2011, van der Grift and Pouwels 2006). In Wyoming, the construction of six wildlife underpasses and two wildlife overpasses in a critical migration area greatly increased wildlife connectivity, reducing pronghorn-VCs by 100% and mule deer-VCs by 78% (Sawyer et al. 2016). Exclusionary fencing (used to exclude wildlife from accessing road rights-of-way) is often required in areas with high traffic volumes and high numbers of WVCs (Clevenger at al. 2001). In Virginia on I-64, within an area of high deer-VCs, a bridge and culvert were retrofitted with exclusion and guide fencing, leading to >95% and >85% reduction in deer-VCs at the two sites (Donaldson and Elliot 2021).

In addition to identifying hotspots, another key for prioritizing locations for mitigation lies in identifying how these hotspots vary depending on habitat types and landscape characteristics surrounding the road (Červinka et al. 2015; Russo et al. 2020).

A view of the Blue Ridge Mountains surrounding the Pigeon River Gorge. Photo: Digidream Grafix

The main drivers of WVCs specific to the roadway included road characteristics and landscape features indicative of species-specific habitat preferences. Species-specific differences in habitat preference and movement behavior influence WVC rates (Litvaitis and Tash 2009). Areas in the PRG with more forest cover had a higher probability of bear-VCs. Bears are closely tied to forest cover for both habitat resources and movement. Braunstein et al. (2020) found forest cover was the most important factor influencing bear movements in GSMNP and surrounding areas. Forest cover provides habitat conducive to bear movement and food resources, leading to increased road interactions and road mortality where forest cover intersects with the highway. The top bear-VC model and all species-VC model had the same top covariates. These similarities are likely due to the higher influence of the number of bear-VCs (n=167, 55%). The lack of significant landscape predictors for all species-VCs yet significant influence of forest cover on bear-VCs, points toward patterns of WVCs in the PRG being species-specific. Deer-VCs probability increased along the roadway in areas with less ridge area, an index of slope position calculated from elevation data to delineate ridgetops. Deer are a highly adaptable species, but known for selecting habitat in open fields, river bottoms, croplands, young forests, and rural and exurban areas, in general preferring areas considered lower-lying areas (Campbell et al. 2004). In Pennsylvania, white-tailed deer were found more in low-lying areas than ridgetop and hilly areas adjacent to interstates (Peek and Bellis 1969). In our study, the higher probability of deer-VCs in areas along the roadway that intersect with less ridge topography is likely an effect of overall deer habitat preferences and movement behavior.

While landscape features that predicted species-specific WVCs followed biological explanations, the finding that the probability of VC for bear, deer, and all WVCs combined was higher in areas closer to road structures was surprising. We incorporated the influence of road structures on WVCs to account for the fact that road infrastructure such as bridges and culverts are known to safely move wildlife, and thus we hypothesized that WVCs would be reduced near road structures due to potential safe passage opportunities for wildlife, even though none of the structures were built with wildlife consideration. We selected structures for monitoring and analysis based on them being large enough to pass at least potentially one of our target species, bear. The fact that higher WVCs occurred in areas closer to road structures indicates that bear and deer are likely funneled to these locations on the landscape where the interstate intersects with drainage or other human movement corridors (i.e. other roadways), and instead of using the structure to cross under the interstate, wildlife often cross at road grade leading to a higher probability of WVCs near these structures.

Coyote pups play and howl in the PRG. Photo: Wildlands Network / NPCA

A literature review by Gunson et al. 2011 describing predictors of WVCs from multiple studies found that in general WVCs are more common in areas where roads bisect preferred habitat and when roads cut through hydrological passageways.

Our more intensive WVC data collection indicates that WVCs are highly underreported by typical reporting efforts that only use sheriff-generated wildlife crash reports. Further, Huijser et al. (2007) reported that thoroughness and reliability of reported crash data varied widely across jurisdictions. Even with our higher intensity monitoring efforts, many WVCs likely went undetected due to injured animals moving off the road and out of view. Lee et al. (2021) reported a correction factor of 2.8 that can be applied to road survey data to account for injured animals that have moved out of view from typical survey methods.

Camera monitoring adjacent to the roadway revealed that bear and deer were nearly omnipresent throughout the PRG but activity rates in segments were not related to WVC counts. In some areas where wildlife activity is relatively high and WVCs are low it appears wildlife is safely crossing the road. One of the best examples is in the eastern-most section of the study area near the High Bridge (e.g. segments 113 and 114) where we recorded our highest deer and elk detection rates. However, WVCs in the area were moderate to low. This can be explained by high use and multiple safe crossings under the large spanning High Bridge. Another example is the Double Tunnel, where the interstate tunnels under the mountain slope creating a land bridge over the interstate. The Double Tunnel had the highest bear detection rates out of all structure and roadside cameras, but WVC counts in the area were low. The Double Tunnel is providing safe passage over the interstate for bear, and to a lesser degree, deer, and thus likely is resulting in reduced WVCs. Similarly, the Single Tunnel (where the eastbound lane tunnels under the mountain slope leaving wildlife to only have to cross the westbound lane) had the second highest structure detection rates for bear and zero to low WVCs in the surrounding area, suggesting an improvement in safe passage compared to crossing two lanes of interstate traffic.

In contrast, the majority (76%) of bridges/culverts occurred in close proximity (within 400 meters) of WVC hotspots. Overall confirmed crossing events were few, but our camera monitoring revealed some structures successfully moving one or more target species under the interstate at low levels. However, such use was uncommon across structures due to current structure characteristics and conditions not being ideal for wildlife. For example, the Hurricane Creek Culvert located in close proximity to our camera with the highest bear detection rate of all roadside cameras was in a study segment (67) that contained a high number of WVCs (n=5), yet we confirmed no target species crossings through the structure. In fact, this structure appears highly unlikely to provide safe passage to most wildlife given its length, darkness, high volume of water moving through the culvert, and the stream velocity deflectors placed in the bottom. Another example where both wildlife activity and WVC counts are relatively high, and where structure use is minimal is in the western-most section of the study area in Tennessee where three structures are within multiple hotspot segments (7, 8, and 9). Except for the Pigeon River Bridge that had four and three confirmed crossings of bear and deer respectively, the other two structures (Laurel Hollow and Dry Branch), both small metal drainage culverts, passed no target species due to their small sizes, water flows, and current physical conditions. There is a threshold effect in terms of structure usability

Opossum carries her young on her back through the PRG.
Photo: Wildlands Network / NPCA

for wildlife (Huijser et al. 2009, Clevenger and Huijser 2011), and certain highly favorable structures such as the massive High Bridge, Double Tunnel, and Single Tunnel must be appropriately attractive to wildlife as evidenced by the reduced or nearly eliminated WVCs nearby. Other structures that are potentially suitable for wildlife movement may not (especially in the absence of fencing) sufficiently entice animals away from attempting to cross directly over the highway, even if the structures do get some level of use. We documented only one structure, a concrete vehicle box culvert, Wilkins Creek Box A, safely passing all three target species, and even so, nearby WVC counts (primarily bears) were still among the highest in our study corridor. While both bear and deer successfully crossed under the north side of the Pigeon River Bridge in Tennessee, structure use by ungulates and bear varied throughout the PRG and generally followed documented structure use differences based on species trait characteristics (Clevenger and Huijser 2011). Black bears have been documented to be adaptive when it comes to structure use, using diverse structures with a range of conditions from moderate to high openness ratios (height times width divided by length). In the PRG, structure characteristics did not significantly influence bear structure use (keeping in mind that we only monitored structures that to us appeared large enough for bears to use). Three structures with different sizes and conditions: a triple metal hydrological culvert (Groundhog Creek), a concrete single box culvert (Wilkins Creek Box A), and a large bridge over the Pigeon River (TN) were all used multiple times by bear to cross under the interstate. Except for Wilkins Creek Box A, all structures with confirmed elk crossings (High Bridge, Low Bridge, and Waterville) were structures with relatively large openings. Further, elk exclusively used structures that passed vehicles, likely an influence of structure size. Deer followed similar structure use patterns, but in addition to using structures with large openings, deer infrequently used an additional mix of culverts and bridges that had moderate to large openings (e.g. Fines Creek Culvert, Cold Springs Culvert, Pigeon River Bridge, TN) but did not use structures with openings less than <2 m^2.

It is important to note that our predictive analysis of WVCs in the PRG is specific to the roadway (≤ approximately 100 meters from the road surface) and larger landscape characteristics such as topography and terrain ruggedness that were not significant predictors of WVCs at the road-scale are likely influencing wildlife movement on a larger spatial scale. For example, terrain ruggedness was not a significant predictor of WVCs specific to the roadway, but the presence of rock cuts created during I-40 road construction are likely influencing wildlife movement through the landscape and shaping where they show up along the roadside. Topographic GIS feature layers (e.g. terrain ruggedness and slope) may lack the resolution to fully capture these sometimes narrow features, therefore we visually estimated and ground mapped all rock cuts >45 degrees along with the intervening open areas (which included gentler-sloped rock cuts) on the non-Pigeon River side of our study area, where all our roadside cameras were deployed. We estimated 55% of our study corridor contained rock cuts >45 degrees with an average length of 319 meters (longest=2.0 mi, Double Tunnel area) and 45% open areas with average length of 272 meters (longest=2.2 mi, Hartford area). Of the 304 WVCs, 79% were within 100 m of an opening, with an

Black bear cub inspects the culvert at Laurel Hollow.
Photo: Wildlands Network / NPCA

average of 23.9 meters. This high percentage held true for bear (75%) and deer (85%). This suggests that rock cuts are influencing wildlife movement and subsequent WVC patterns, and also that wildlife may be selecting to cross the interstate back and forth between the gentler-sloped Pigeon River side to roughly directly across the interstate to locations where landscape breaks occur; this rather than travelling long distances in the open right-of-way below rock cuts in search of an opening. If true, these movement patterns and pathways are potentially well-established after five decades since highway completion.

on both bear and deer activity rates. This could be an artifact of camera site placement and not animal activity. For example, segments 82 and 83 had the highest proportions of stream area (and low target species detection rates) and were located very close to the steep bank of Waterville Lake which could limit species use. The proportion of stream area was incorporated into analyses to account for how riparian corridors might influence WVCs and wildlife activity rates. Riparian corridors are known to facilitate animal activity and movement, and while extracting the proportion of stream area identified smaller streams with potential to facilitate movement, Waterville Lake and Pigeon River areas were also included which may have been confounding factors. Deer detection rates were higher at camera sites with less highly rugged terrain. Deer often prefer paths of least resistance and movement through the landscape in areas with flat to intermediate terrain ruggedness. As stated above, terrain ruggedness, topography, and other landscape characteristics are likely predictors of animal movement in the PRG at a larger spatial scale, and while our top model indicated they didn't influence WVCs at the road-scale, protected areas and terrain ruggedness influenced animal activity adjacent to the roadway.

White-tailed deer in the PRG. Photo: Wildlands Network / NPCA

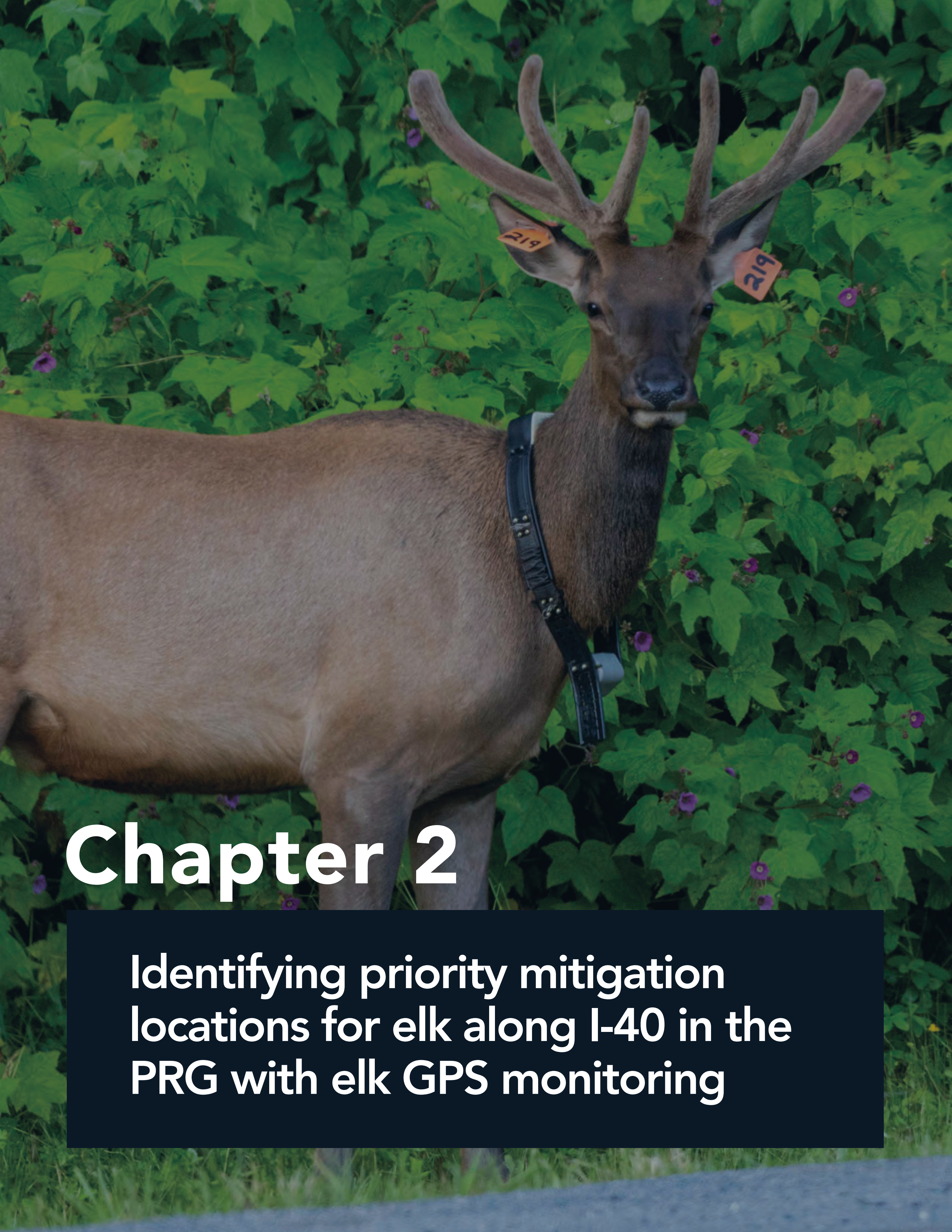
We gained more insight on the influence of landscape characteristics on animal activity in the PRG by looking at how those factors influence bear and deer detection rates in the area adjacent to the roadway. Bear detection rates were higher at camera sites with more forest cover, more protected area, and less stream area. With protected land, it is not surprising that we documented higher detection rates of bears. The protected lands adjacent to the interstate are comprised primarily of large mid-successional to mature USFS forest lands that generally contain good quality uninterrupted mixed-oak habitats, denning opportunities, and considerably less human disturbance when compared to mixed-use and often fragmented private parcels in other parts of our study area. We see synergy in the importance of forest cover on bear-VCs and bear detection rates in the PRG. The protected lands adjacent to the interstate are comprised primarily of large mid-successional to mature USFS forest lands that generally contain good quality uninterrupted mixed-oak habitats, denning opportunities, and considerably less human disturbance when compared to mixed-use and often fragmented private parcels in other parts of our study area. We see synergy in the importance of forest cover on bear-VCs and bear detection rates in the PRG. No biological explanation comes to mind for the negative influence of stream area

Our camera and mortality research lacked adequate data on elk, primarily due to the localized incidence of elk occurrence in the PRG. Given their large home range and movement requirements, population status, and the severity of elk-VCs, they are an important focus for wildlife/road mitigation efforts in the PRG. In Chapter 2, we focus on identifying elk road conflict areas along the roadway using GPS collar technology.

For this report, the target species were bear, deer, and elk. They were selected because they were relatively easy to monitor and the ones of highest concern from a driver safety-perspective, but we also intentionally collected data for many other smaller species. While improving safe passage for larger mammals should, in general, benefit smaller animals too, several may have specific requirements that need to be considered about when planning for new highway structures or improvements to existing ones. Plans are underway to partner with NCWRC and Clemson University to analyze the mesocarnivore data to gain an understanding of those species' relationships to I-40 and their crossing needs. Some general guidance is provided in Chapter 3.

Our research identified WVC hotspots and revealed that WVCs are driven by where bridge/culvert structures are along the roadway and where species-specific habitat intersects the road. Due to higher probabilities of WVCs near structures and the limited use of structures by wildlife, priorities for mitigation efforts should focus on retrofitting existing structures, creating new dedicated crossing structures for wildlife, and incorporate fencing to provide multiple and adequate safe crossing opportunities throughout 28-mile section of I-40 (**see Chapter 3**). Future research efforts should focus on understanding how the landscape on a larger spatial scale influences wildlife movement and crossing behavior in the PRG.

A cow elk monitored with a GPS collar and her calf use the Waterville Bridge to cross under the interstate. Photo: Caara Hunter



Chapter 2

Identifying priority mitigation locations for elk along I-40 in the PRG with elk GPS monitoring

Introduction

A cow elk and her calf move parallel to the interstate near Naillon Branch. Photo: Wildlands Network / NPCA

Roads impede ecological flows through landscapes in three main ways: by acting as barriers to animal movement, by reducing habitat connectivity, and by increasing animal mortality due to vehicle collisions. Elk are especially prone to be impacted by roadways due to their large home-range requirements, extensive movements to find resources and mates, and lower reproductive rates compared to more common ungulates such as deer (Rytwinski and Fahhrig 2012). Additionally, vehicle collisions with elk pose significant threats to driver safety. A female elk weighs between 375 and 660 pounds, and a male elk weighs between 550-1300 pounds (Hudson and Haigh 2002). Due to their large size, elk collision severity is high, costly, and twice as likely to result in human injury than with smaller bodied animals (Huijser et al. 2008). Research that identifies elk-road conflict areas can lead to mitigation strategies such as wildlife infrastructure, providing a solution for increasing human safety and reducing the negative effects of roads on elk populations.

Where and why wildlife end up near roadways, as well as whether they decide to cross the road, is a product of animal behavior and decisions made by animals while moving through the environment (Fortin et al. 2005). Research focused on understanding animal movement and resource selection can be used to answer fundamental questions related to species distributions (Johnson and Gillingham 2008, Matthiopoulos et al. 2011), key habitat components (Squires et al. 2013), and movement corridors (Chetkiewicz et al. 2006). Animal movement and habitat-use patterns are tightly linked, with habitat selection and availability affecting the animal's movement patterns and the animal's movement capability affecting its habitat-use patterns (Avgar et al. 2013, Avgar et al. 2015). Specific habitat resources selected by large ungulates such as elk vary depending on geographic area (Skovlin et al., 2002; Sawyer et al., 2007), vegetation type (Beck and Peek 2005), and season (Ager et al., 2003; Beck and Peek 2005). Topographic features such as slope, elevation, and aspect affect resource availability and movement costs, thus influencing habitat selection (Frair et al., 2005; Fryxell et al., 2008). Elk typically use open areas such as meadows and fields for grazing while forested areas are used for browsing, cover for calving and escape from predators (Bender and Haufler 1999; Mysterud and Ostbye 1999). Graminoids (i.e. grasses) are the main component of elk diets throughout their North America range (Christianson and Creel 2007).

In 2001-2002, an experimental herd of 52 elk was reintroduced in the Cataloochee Valley located in the southeastern portion of the Great Smoky Mountains National Park. In contrast to the majority of elk habitat in the western United States, GSMNP is more than 99% forested. The park consists of a mosaic of temperate and boreal forest types that support some of the most species-rich vegetation and community types in North America (Whittaker 1956; Herrman and Bratton 1977; Jenkins 2007). Elk are opportunistic and intermediate feeders who move between the spectrum of grazing and browsing to take advantage of locally abundant resources (Augustine and McNaughton 1998; Skovlin et al., 2002; Palmer et al., 2003). Given the widespread availability of resources in areas where elk have been reintroduced in the eastern U.S., elk populations have not displayed migratory tendencies in the eastern ranges, whereas seasonal migration is typical for elk in the western U.S. (Boyce, 1991). Currently, elk in the region exist in sub herds distributed throughout both public (GSMNP, Pisgah National Forest) and private lands surrounding the PRG/Interstate 40 study area. The epicenter of elk activity, the Cataloochee Valley within GSMNP is approximately six kilometers from the interstate. Habitat research in GSMNP indicated elk preferred open grazing land with interspersed cover, and diet analysis concluded the primary diet component of the elk herd in all seasons was grasses. In addition, evaluation of movements during the early phase of reintroduction suggested elk were not migrating and were using relatively small annual home ranges (female 10.4 km^2, males 22.4 km^2) (Murrow et al., 2009).

The now larger, slow-growing elk population (n>225 individuals, NCWRC) is showing greater movement outside of GSMNP, and the majority of the population is in close proximity to I-40. Therefore, research focused on elk is necessary to identify the patterns and processes of elk-road interactions to help site locations for mitigation opportunities along I-40 to allow elk safe passage to and from GSMNP and adjacent Pisgah and Cherokee National Forests.

Priority crossing areas can be identified by monitoring wildlife with GPS collars to understand where animals cross and interact with the interstate. GPS locations and lines between successive locations have been used to determine the number of highway approaches and crossings road segments to guide elk road mitigation efforts in Arizona (Gagnon et al. 2007, Gagnon and Dodd 2011). Further understanding of how landscape features influence wildlife movement can be used to help guide mitigation by identifying areas with higher probabilities of animal movement/road crossing. For example, Zeller et al. 2020 found that bears preferred to cross smaller, less trafficked roads in areas with lower speed limits, less human development and more forest in Massachusetts, U.S.

The large size of elk, the absence of predicable migration periods, and the abundance of high-quality habitat along and surrounding GSMNP and the PRG present challenges with regard to driver safety. Given the severity of elk-vehicle collisions and the population's habitat connectivity needs, we monitored elk with GPS collars and applied subsequent analysis to the PRG study area to meet the following objectives: (1) identify locations where elk cross the interstate (2) identify locations where elk approach or interact with

A cow elk and her calf move through the PRG. Photo: Wildlands Network / NPCA

A white-tailed deer on a ridge top. Photo: Tom Reichner

the interstate but do not cross (3) create predictive models of elk movement and use the information to identify locations along the interstate where elk movement probability is more likely (4) use connectivity models to determine important movement paths across the interstate. This chapter will focus on identifying areas along the interstate where mitigation strategies such as road crossing structures and fencing could be best implemented to reduce elk-vehicle collisions and increase elk habitat connectivity.

Methods

Elk Data

Thirteen elk were captured during 2018 and 2019 and fitted with GPS PLUS Iridium global positioning system-collars (i.e. GPS-collars, Vectronics Aerospace, GPS PLUS Iridium) programmed to acquire a location fix every 60 minutes. Elk were captured by Great Smoky Mountains National Park (GSMNP) and North Carolina Wildlife Resources Commission biologists via free range darting with chemical immobilization to anesthetize animals. Elk were captured near the Cataloochee Valley, GSMNP and public and private land just south of the Park due to the close proximity of I-40 (<6 kilometers). Capture efforts attempted to focus on any elk known to use the I-40 Pigeon River Gorge area, as well as young male bulls due to their potential for long exploratory movements. Animals were monitored until the collar was programmed to drop off (~500-700 days), the collar fell off prematurely, or the animal was deceased.

Elk locations were acquired from GPS iridium satellite communications uploaded to the Vectronics GPS-PlusX Software. We screened GPS fixes prior to analysis to remove inaccurate or erroneous data. We first removed obvious location errors from pre- and post-deployment fixes. GPS device location errors are related to location type, two-dimensional vs three-dimensional fix, and the positional dilution of precision (PDOP, a measure of satellite geometry). To increase the accuracy of the GPS location data used in our analyses, we removed all 2-D fixes, and retained all 3-D fixes with PDOP values <7 (Lewis et al. 2007, Braunstein et al. 2020). This minimization of locational error resulted in a loss of 14.8% of the data points.

A total of 123,606 elk locations met our above criteria for further analysis (**Appendix A: Table A.3**). Elk (n=13) averaged 9,508 locations±5,216 [SD]) per individual and locations among individuals ranged between 400-16,923 locations (**Figure 2.1**). The number of locations acquired were associated with the duration of collar deployment days. Elk were monitored a total of 15.6 elk years (5,706 days), with monitoring averaging 439 days±229 [SD] and ranged between 18-763 days per individual.

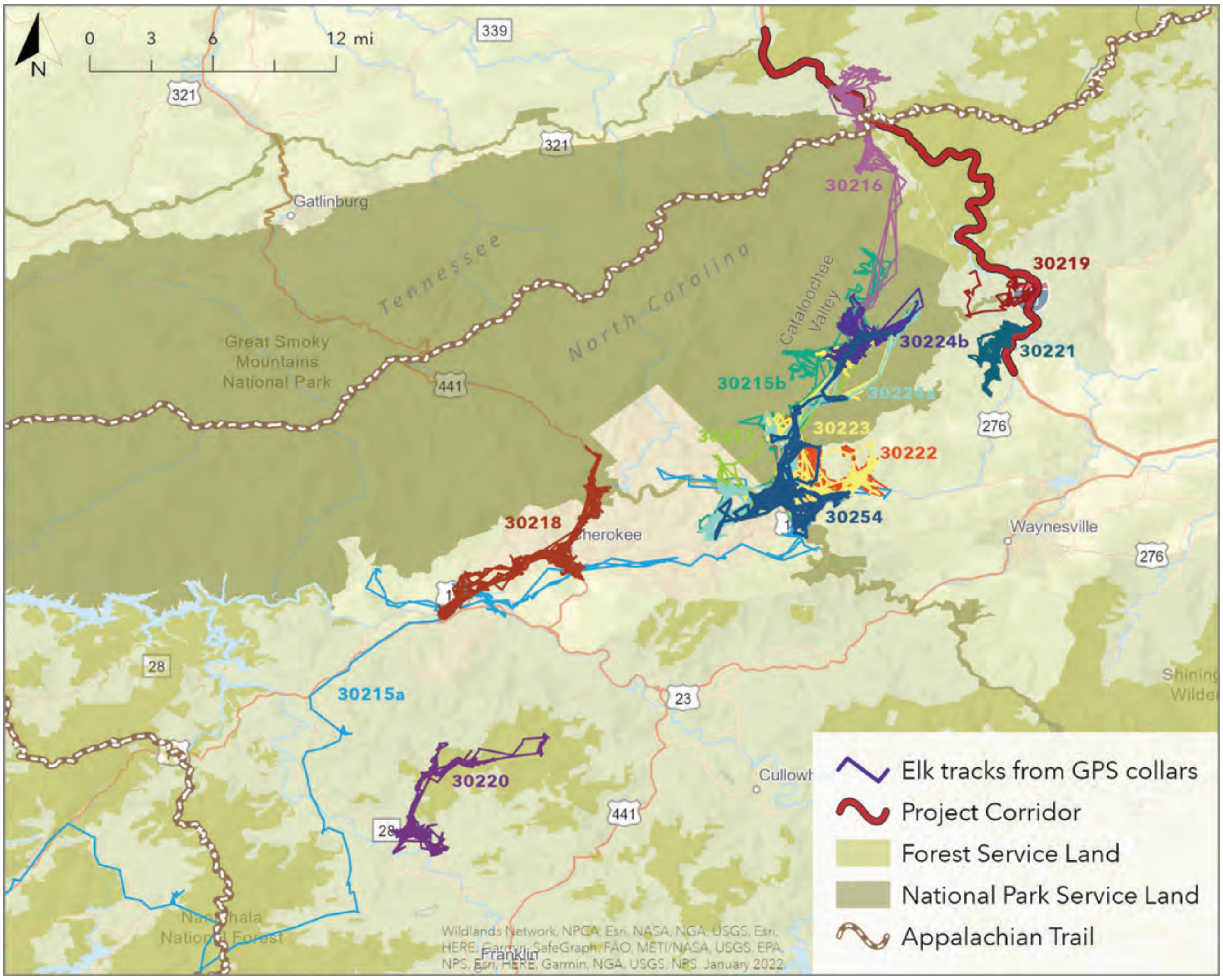


Figure 2.1. (above) - GPS tracks from 13 elk collared in and around Great Smoky Mountains National Park and Interstate 40 and the Pigeon River Gorge, North Carolina and Tennessee from 2018–2020.

I-40 Crossings and Approaches

We used the elk GPS data and ArcMap version 10.8 geographic information system (GIS) software to examine elk road crossings and approaches. The road segments delineated for corresponding road ecology research, where the 28 miles of Interstate 40 within our study area were divided into 115 sequential 400-meter segments (**see Chapter 1**), was used to quantify elk crossings and highway approaches. To identify interstate crossings, we created elk "steps" represented by line segments between consecutive GPS fixes. We inferred crossings where steps crossed the interstate through a given segment and calculated the total number of crossings within each segment (Dodd et al. 2007). To assess elk road approaches (i.e. where elk approached the road but did not cross) within I-40, we established a buffer zone around each segment that extended 200 meters to either side of the road centerline. We calculated the number of elk approaches as the number of elk steps within each road segment buffer.

Elk Movement Steps

Because our interest was investigating how landscape features influence elk movement through the landscape and thus lead to elk interactions with the roadway, we first had to identify when elk were in a moving behavioral state. Hidden Maklov models have become a popular tool for the analysis of movement data to an underlying latent process, generally interpreted as the animal's unobserved behavior (Karelus et al. 2019, Zeller et al. 2020, Dániel-Ferreira et al. 2022). Analyzing the behavioral states of individuals can lead to insights regarding resource and space use (Forester et al. 2007, Fryxell et al. 2008) and can be scaled up to examine population processes. Step length and turning angles are taken into account to divide GPS data into states representative of resting and transiting (two-state model), or resting, foraging, and transiting (three-state model). Examples of recent research that has categorized movement paths into states that link to underlying individual animal motivations and behaviors include "encamped" and "exploratory" states in elk (Morales et al. 2004) and "bedding", "feeding", and "relocating" states in woodland caribou (Rangifer tarandus) (Franke et al. 2004). We used a three-state Hidden Maklov model to identify elk movement behavioral states in R using the moveHMM package (Michelot et al. 2016). We categorized the behavior of each elk step as resting (very short steps with ambiguous turn angles), foraging (short steps with small turn angles), or moving (i.e. transiting, long step lengths and directed movement) based on model parameters of step length and turn angles (i.e. radians) (Morales et al. 2010). Only steps identified as "movement steps" were used for the subsequent analyses. Animals with <50 movement steps were removed from further analysis.

Step Selection Functions

We used step-selection functions (SSF; Avgar et al. 2016, Signer et al. 2019) to estimate resource selection by elk moving through the landscape. Animal movement and habitat-use patterns are tightly linked, with habitat selection and availability affecting the animal's movement patterns and the animal's movement capability affecting its habitat-use patterns (Avgar et al. 2013, Avgar et al. 2015). Integrated step selection functions account for the influence of movement constraints on resource selection by incorporating movement parameters (e.g. step length and turning angle) into the resource selection process. Using R package "amt" (Signer et al. 2019), we broke down movement locations into steps (i.e. straight line segments linking consecutive elk locations at 60-minute time intervals). We paired each step at time *t* with nine random steps with the same starting point and randomly fitted step length and turn angles based on gamma and von Mises distributions, respectively (Avgar et al. 2016, Singer et al. 2019).

At the end of each step, we extracted explanatory variables from geographic information system (GIS) raster data that were indicative of landscape conditions that may influence elk movement and well-represented in the study area (**Appendix A: Table A.4**).
Topographic rasters were created from 10 meter-Digital Elevation Models (USGS 2019) at a 10x10 meters cell resolution, with each raster cell containing measures of elevation (meters), slope (degrees), and aspect (degrees). We derived habitat resource (forest cover, herbaceous cover, hay/pasture cover, shrub cover, open water cover) and human development (human development, open-human development) variables from National Land Cover Database 2019 data. Road variables (primary road, secondary road) were derived from the National Transportation Dataset (USGS 2020).
We created Euclidean distance rasters with at at 10 x 10-meter resolution with each respective raster cell containing the distance in meters to the nearest occurrence of that specific feature. "Distance to" measures were used to better characterize elk movement in consideration of linear features and habitat edge effects (Gillies and St. Clair 2010).
We calculated pairwise correlations between all 12 variables.

Elk forage and move under the interstate via the High Bridge.
Photo: Wildlands Network / NPCA

An elk uses Wilkins Creek Box Culvert A to cross under the interstate. Photo: Wildlands Network / NPCA

For pairs of highly correlated (|r|≥0.7, P<0.01) variables we retained the variable that provided the simplest biological explanation for further analysis. The variable distance to human development was dropped from model analysis due to high correlation with distance to major road (|r|=0.92, P<0.01), distance to herbaceous cover (|r|≥0.95, P<0.01), and distance to open water (|r|≥ 0.91, P<0.01). Open human development and distance to minor road were highly correlated (|r|≥0.96, P<0.01), therefore open human development was dropped from model analysis. Distance to hay/pasture was highly correlated with elevation (|r|≥0.98, P<0.01), so distance to hay/pasture was dropped from model analysis. Nine explanatory variables were used to estimate elk resource selection while moving through the landscape: elevation, slope, aspect, distance to forest cover, distance to herbaceous cover, distance to shrub cover, distance to open water, distance to major road, and distance to minor road.

We then created models that contrasted the explanatory variable composition of the availability domain ("random steps") with the used domain ("true steps") with a conditional logistic regression to infer resource selection and the influence of explanatory variables on used and available steps (Fortin et al. 2005, Thurfjell et al. 2014, Signer et al. 2019). To explain variation in elk movement, we developed models using all combinations of covariates and included each individual elk (Id) as a random intercept in the models to address issues associated with non-independence and unbalanced sample sizes (Gillies et al. 2006). We used difference in Akaike's Information Criterion corrected for small sample size (ΔAICc) values to rank candidate models; we considered models within two AICc units of the top model to be competitive (Burnham and Anderson 2002). If maximized log-likelihood estimates were similar, we considered the model with the fewest parameters as the most parsimonious (Burnham and Anderson 2002) and evaluated that model further.

To assess the robustness and prediction accuracy of the top performing model, we used a k-fold cross validation (k=10) to calculate the mean cross-validation estimate of accuracy (between zero and one; Boyce et al. 2002, Koper and Manseau 2009). We also evaluated the predictive performance of SSF models by randomly dividing the GPS locations into two groups before model development: 80% of the data comprised a 'model-training' group and the remaining 20% comprised a 'model-testing' group for validation. We compared the observed (withheld model-testing sample) and expected numbers of GPS locations with chi-squared, Spearman rank and linear regression (Johnson et al. 2006).

Elk Movement Probability Surface

We spatially predicted the relative probability of an elk moving through the landscape using the following formula: $w(x)=\exp(\beta 1x1+\beta 2x2+\beta 3x3+\ldots+\beta pxp)$ (Johnson et al., 2006) to create a predictive raster surface based on SSF covariates from the best elk movement model (Zeller et al. 2020). We examined the relative probability of elk movement across the interstate by calculating the average elk movement probability value for each roadway segment within segment buffers. We identified road segments with higher average movement probability values and considered those segments as likely elk/road conflict areas due to their higher probability of elk movement and thus potential locations for road mitigation (Loro et al. 2015, Cushman et al. 2013, McRae et al. 2012).

Connectivity Models

We inversed the predictive movement surface to create a resistance surface. With the elk resistance surface, areas with high elk movement probability are inferred to have low resistance to elk movement and used to identify what pathways through the landscape elk are most likely to take across I-40 study area. The elk resistance surface was used as the input to Omniscape, a connectivity model that uses circuit theory to simulate the predicted movement of wildlife across a landscape with varying resistance (Landau et al. 2021). Omniscape uses a circular moving window (which we set to a 500-meter radius) to calculate the likelihood of every possible path an elk might take to the raster cell in the center, repeats this process for every cell in the landscape, and then sums the results to create a cumulative current map where higher current means that elk are more likely to travel along that path. Unlike traditional Circuitscape or least cost path modeling, Omniscape examines every possible path an elk might take in any direction, including the entirety of the 28 miles of I-40 in our study area. We used the cumulative current map from Omniscape to examine the relative predicted movement connectivity of elk near I-40 by calculating the average cumulative current (i.e. connectivity value) within 200 meters of each roadway segment. We identified road segments with higher-than-average connectivity values and considered those segments as potentially important for elk functional connectivity and thus potential locations for road mitigation (Loro et al. 2015, Cushman et al. 2013, McRae et al. 2012).

Results

I-40 Crossing and Approaches

Three of the 13 elk monitored with GPS collars interacted with I-40 in the Pigeon River Gorge. One female elk (Id: 30216) crossed the interstate near the North Carolina/Tennessee border 107 times within 11 different road segments in three separate years

Elk crossing a roadway. Photo: Jeff Gresko

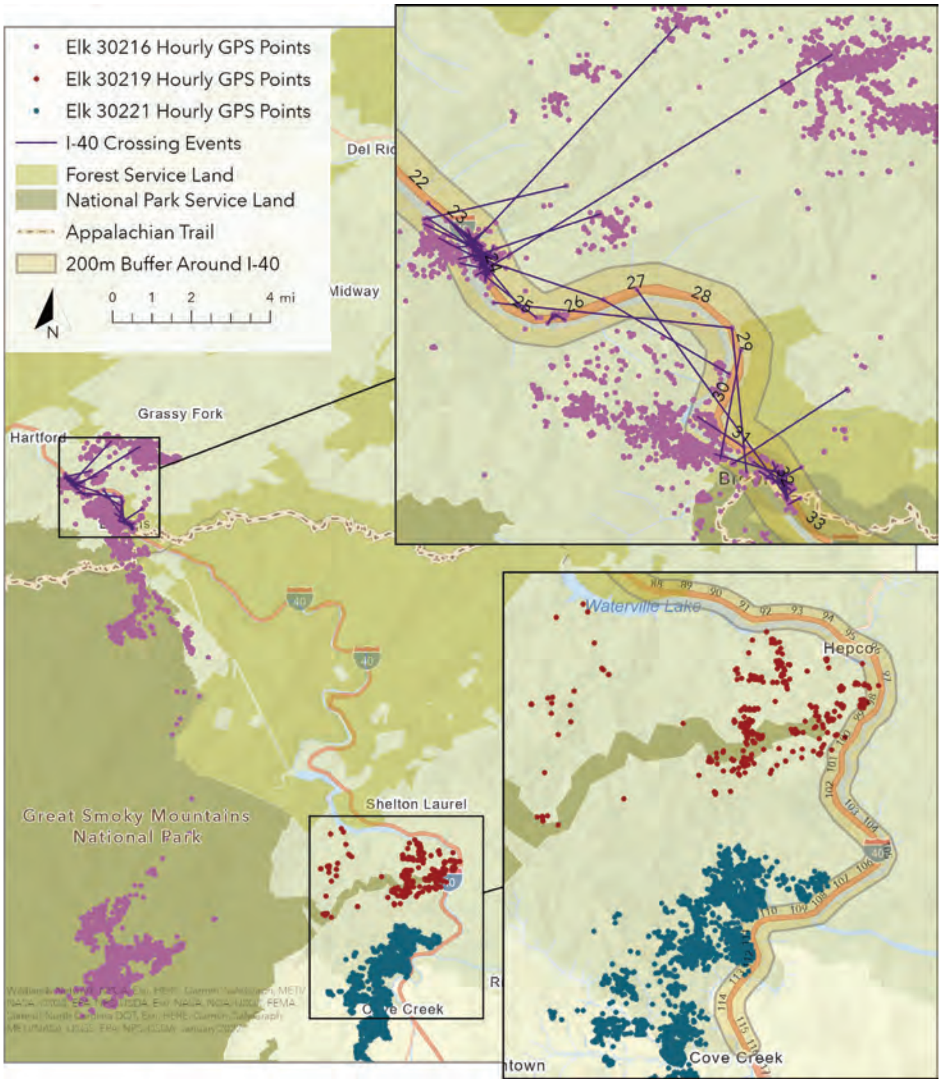


Figure 2.2. (above) - Elk road crossing and road approaches along Interstate-40 outside of Great Smoky Mountains National Park in the Pigeon River Gorge, North Carolina and Tennessee from 2018–2020.

(**Figure 2.2**). Crossing locations for elk 30216 were concentrated in two areas. One area was focused on an interstate bridge (Waterville Bridge) that moves interstate traffic over Green Corner Road (segments 31-32, n=22 crossings). This area is located at the TN/NC border and is where the Appalachian Trail also crosses under the interstate. She also crossed multiple times at road grade near the Naillon Branch Creek Drainage (segments 24-23, n=60). The remaining two elk approached but did not cross the interstate. The number of elk approaches (steps where elk did not cross but were <200 meters from the roadway) for all three elk totaled 2,341 steps and were distributed within 23 road segment areas. The three animals did not overlap in their use of areas near the roadway. The three elk approached the road at different road segments (elk-30216: segments 22-33, elk-30219: 96-100, elk-30221: 108-113).

Movement Steps

We identified the following three general elk behavioral states (**Figure 2.3**): (1) "resting," a state with short step-lengths (0.014±0.011 [SD]), and turning angles near pi radians (x=3.11, i.e. indistinct turn angles). (2) "movement" a state with long step-lengths (0.358±0.345 [SD]) and turning angles around 0 radians (x=-0.002, i.e. direct movement). (3) "foraging" a state with moderate step-lengths (0.079±0.067 [SD]) and turning angles near pi radians (x=-3.093, i.e. sharp turn angles). Each step was categorized as one of the three identified behavioral states based on Viterbi algorithm probabilities. Only the traveling/movement state was used in subsequent analyses of habitat selection/connectivity.

Step Selection Function

The top elk movement model included eight of the nine explanatory variables: elevation, slope, aspect, distance to forest cover, distance to herbaceous cover, distance to shrub cover, distance to major road, and distance to minor road. The relative probability of elk movement increased at areas with lower slopes, higher elevations, northeasterly aspects, in areas closer to herbaceous cover and minor roads, and in areas farther from forest cover, shrub cover, and major roads (**Table 2.1**) than available steps. Slope had the largest influence on the model. For a one-degree decrease in slope, we saw an approximately 25% increase in the odds of elk movement probability (**Figure 2.4**). The next most influential covariate estimates on elk movement were distance to herbaceous cover and elevation, a decrease in one meter from herbaceous cover resulted in an

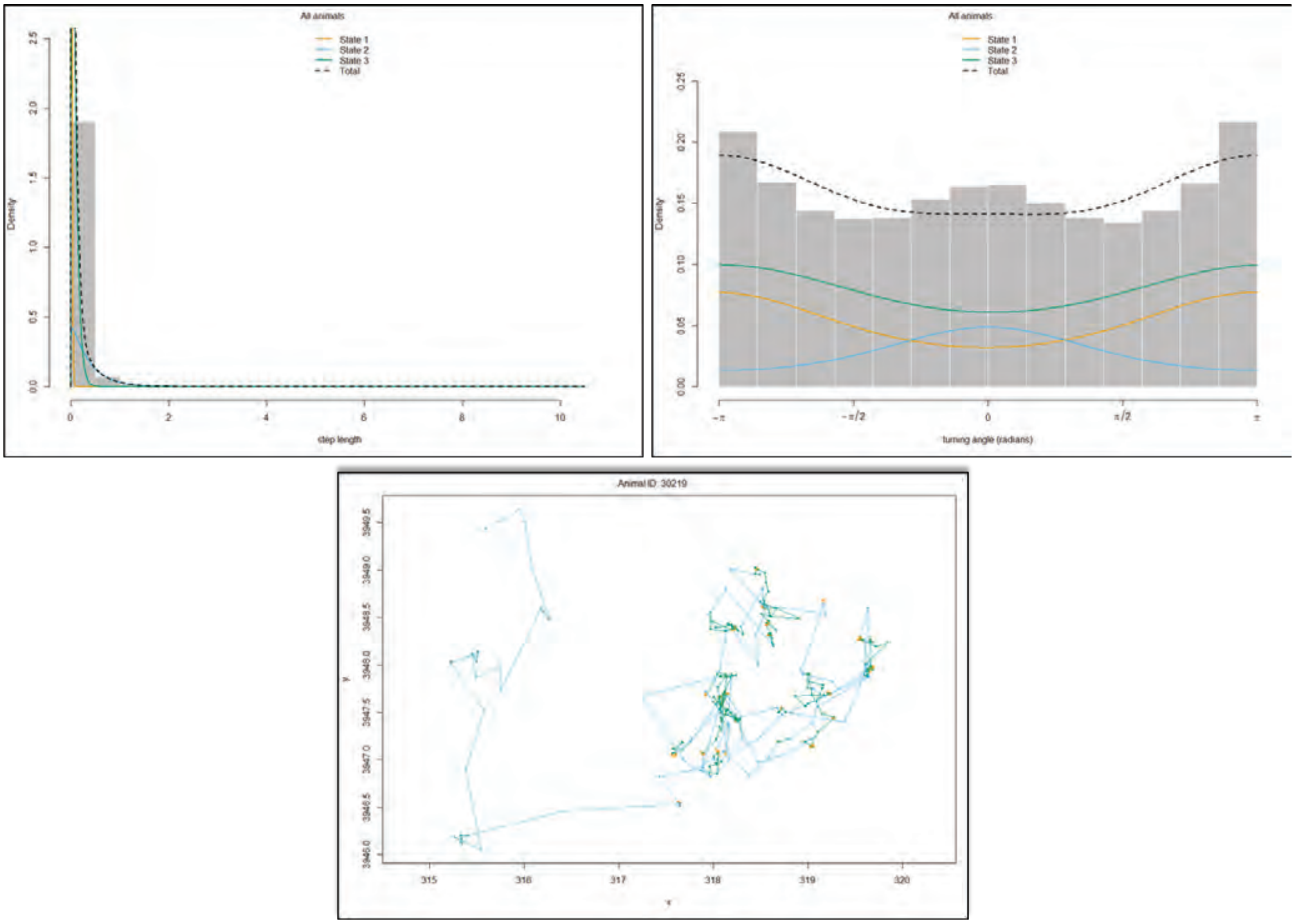


Figure 2.3. (above) - Figure 2.3. Elk behavior states (state 1 = resting [yellow], state 2 = moving [blue], state 3 = foraging [green]) identified from Hidden Markov models derived from step length and turn angles parameters of 13 elk monitored with GPS collars programmed for 1-hour location fixes. The bottom figure shows an example of the behavior states applied to one individual elk-30219's steps.

Variable	B	SE	Z^b	*P*
Intercept	-2.43	0.05	-48.66	<0.001 *
Elevation	0.24	0.02	14.88	<0.001 *
Slope	-0.78	0.01	-60.12	<0.001 *
Aspect	-0.09	0.01	-8.82	<0.001 *
Forest	0.06	0.01	6.45	<0.001 *
Herbaceous	-0.26	0.03	-7.73	<0.001 *
Shrub	0.09	0.01	6.44	<0.001 *
Major Road	0.15	0.03	4.36	<0.001 *
Minor Road	-0.06	0.01	-4.18	<0.001 *

Table 2.1. (above) - Variable estimates for the most parsimonious models used to assess the influence of topographic habitat resources, and road characteristics on elk movement in and around Great Smoky Mountains National Park, Tennessee and North Carolina, September 2018–December 2021.

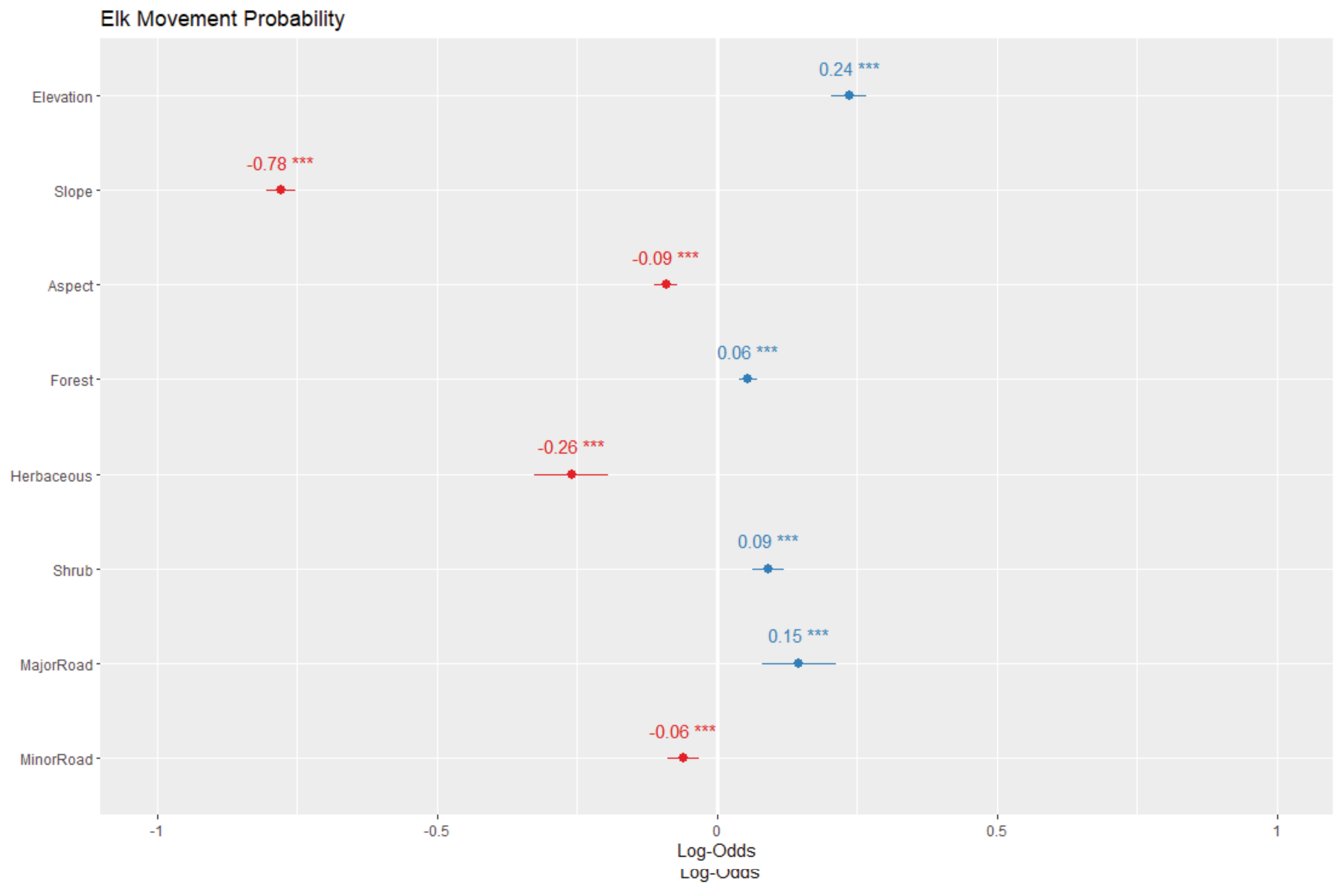


Figure 2.4. (above) - Figure 2.4. Log-odds and variable estimates for the most parsimonious model used to assess the influence of topographic, habitat resources, and road characteristics on elk movement in and around Great Smoky Mountains National Park, Tennessee and North Carolina, September 2018–December 2020.

8% increase elk movement probability and an increase in one-meter of elevation resulted in a 6% increase in elk movement probability. All other model estimates resulted in <1% standard deviation increase in elk movement probability. See **Appendix A: Figure A.1** for additional information.

Elk Movement Probability and Connectivity

Average elk movement probability scores for each buffered roadway segment averaged 0.07±0.02 [SD], and ranged between 0.11 and 0.14. Eight segments had relatively high elk movement probability values based on standard deviation from the mean: 13-14, 16-19, 78, 92, and 117 (**Figure 2.5**). Average elk connectivity values from Omniscape for each buffered roadway segment ranged between 33.4 and 69.8 and averaged between 45.8±5.15 [SD]. Seven segments had relatively high elk connectivity scores: 10, 13, 17-18, 78, 92 (**Figure 2.6**).

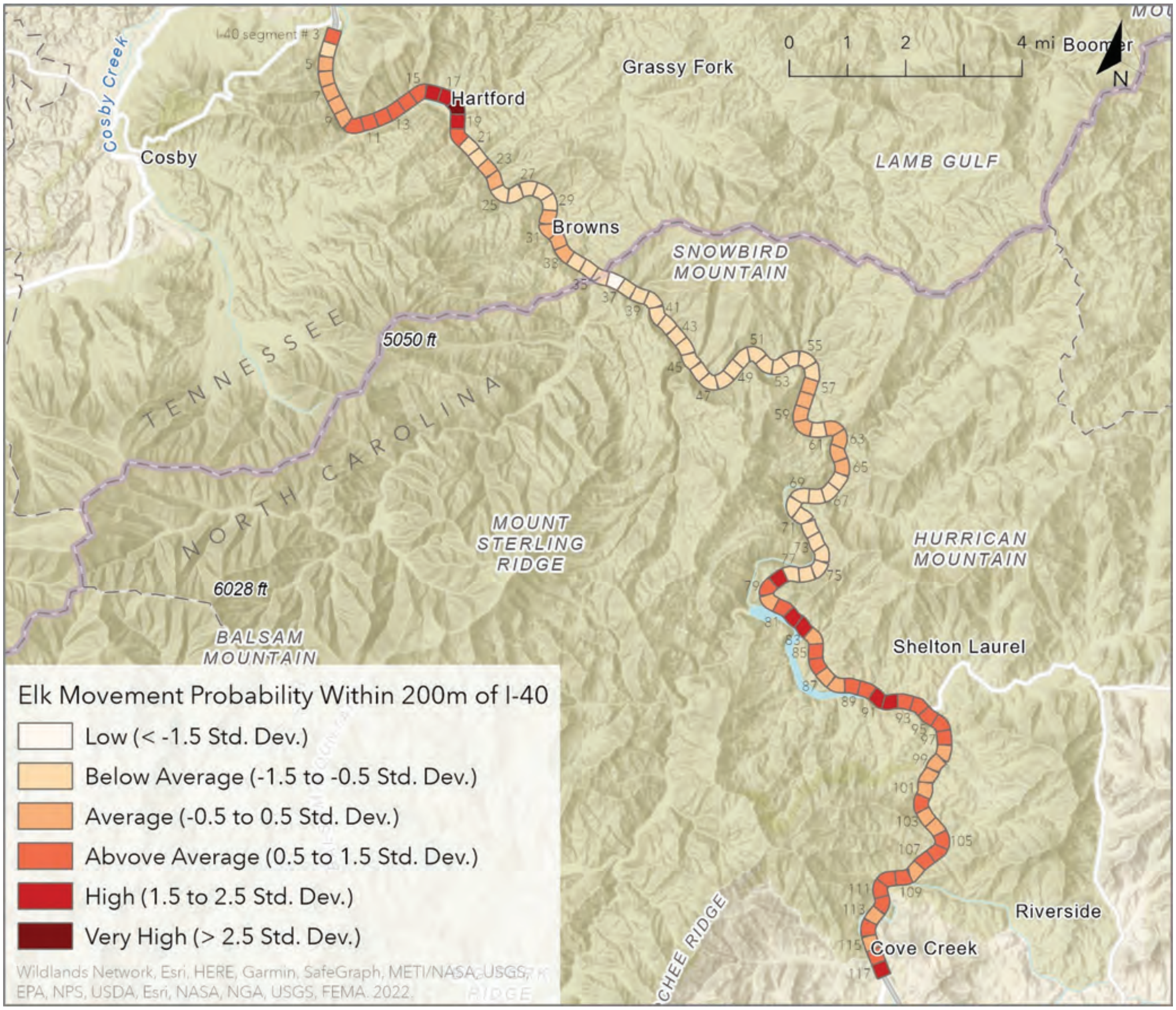


Figure 2.5. (above) - Elk movement probability within 200 meters of Interstate 40 in the Pigeon River Gorge, North Carolina and Tennessee, based on GPS locations and analyses conducted 2018–2020.

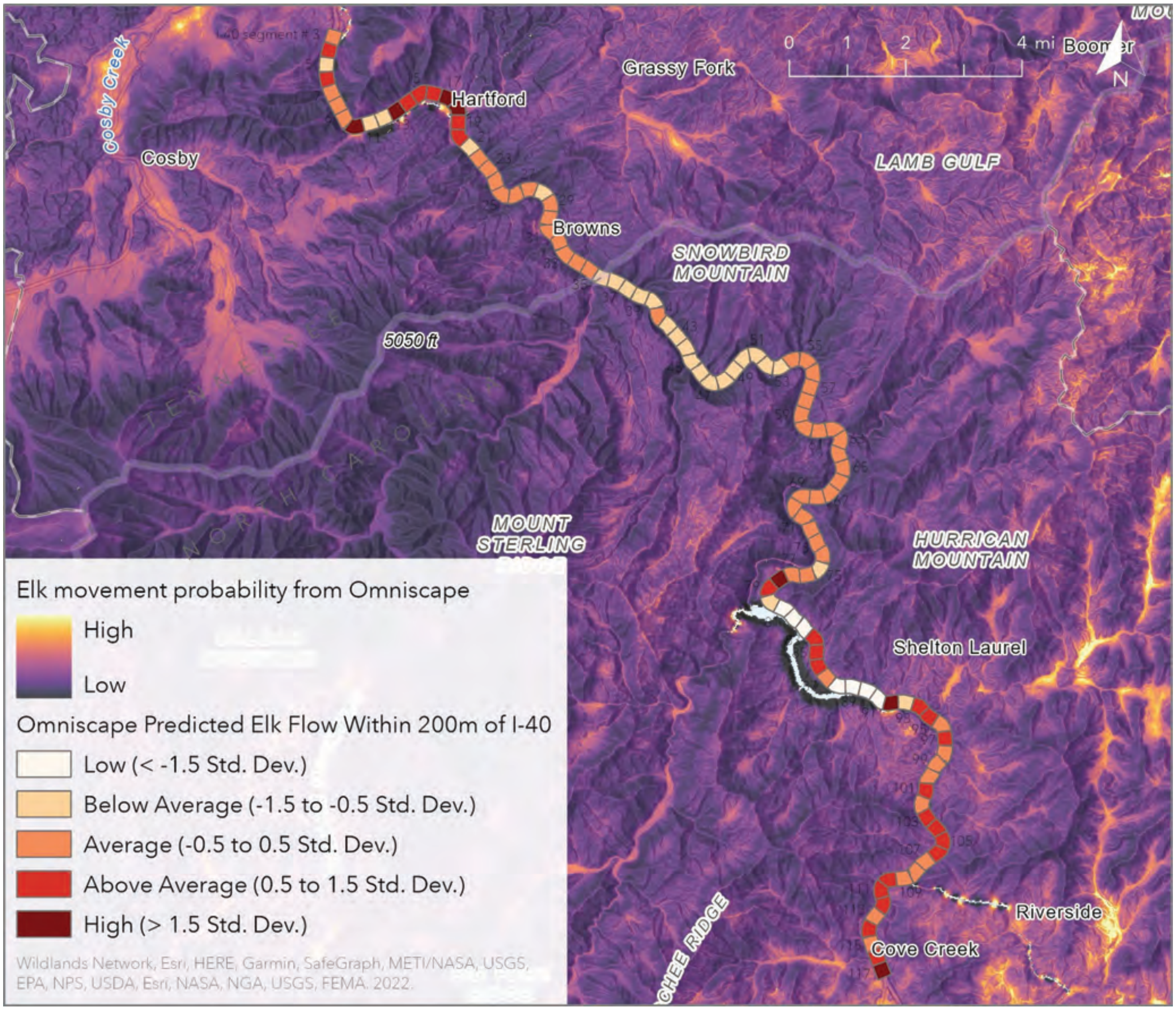


Figure 2.6. (above) - Figure 2.6. Omniscape predictive connectivity surface showing elk flow through the landscape and movement connectivity scores within 200 meters of Interstate 40 in the Pigeon River Gorge, North Carolina and Tennessee, 2018–2020.

Discussion

Large bull elk in the fall. Photo: Kerry Hargrove

Our research identified elk crossings locations and interactions along I-40, pinpointing areas along the roadway where elk are mostly likely to cross based on how they move through the landscape. The fact that elk selected areas that are lower sloped, that are closer to herbaceous vegetation, and that are farther from forest cover, shrub cover, and major roads is consistent with elk habitat selection and movement throughout their North American ranges. Elk tend to choose habitat that contains preferred grass forage (Christianson and Creel 2007; Lashley et al., 2011), and avoid steep slopes and dense vegetation, due to high energetic movement costs, (Frair et al., 2005; Fryxell et al., 2008) and regular vehicle traffic, due to psychological stress (Millspaugh et al. 2001). The elk road crossings and approaches we documented combined with elk movement probability and connectivity scores along I-40 provides the information needed to guide mitigation not only for current elk road conflicts, but also for future conflicts as the elk population continues to grow. Information from this research can be used to site locations for crossing structures, fencing, and retrofits to existing structures to mitigate potential elk vehicle mortality, increase elk habitat connectivity, and improve driver safety in the PRG.

While only three of the 13 monitored elk interacted with the roadway, all three elk approached the roadway in different areas with no overlap. The spatial distribution of these three animals along the interstate indicates that despite the current relatively small population, in the future we may see a more pervasive effect on driver safety in the Gorge when the elk population grows larger and continues to expand its range.Twenty-two percent of the elk we monitored for our research interacted with the roadway. If this subsample is at all representative of the larger elk population (n=225), more elk are likely crossing the roadway but going undetected. One indication of this were detections of non-GPS monitored elk in structure cameras using the High Bridge and Wilkins Creek Culvert (**Chapter 1**).

The one elk that did cross the interstate did so both at road grade and at the Waterville Bridge, using the structure to cross safely under the interstate. One animal can seem like a minimal issue. However, this one elk crossed the interstate 107 times, crossing and approaching the same segments that makes up a continuous ~2.7-mile stretch of I-40 near the TN/NC boarder in all three years she was monitored. Due to detections in our wildlife cameras (**Chapter 1**) and observations from a GSMNP biologist, we know that she crossed the interstate to calve on the other side. In all three years she left the Cataloochee Valley in the spring, crossed the interstate, and stayed northeast of the roadway during the summer, crossing the interstate again in late fall to return back to Cataloochee with calf in tow. This one individual elk's behavior isn't necessarily indicative of the populations movement behavior and dispersal, but it does highlight—along with other elk structure use detections in Chapter 1—that elk are current using road structures in the PRG to safely pass under the interstate and that incorporating retrofitted existing structures into mitigation plans will increase safe passage opportunities for elk.

While the identified approaches and crossings by our monitored elk are qualitative in nature due to small sample size, our population level model evaluating how landscape features influence the movement of monitored elk gives us a better understanding of how and where elk are likely to end up near the roadway. Slope was the main landscape feature driving elk movement through the landscape. Elk selected for more shallow slopes which is consist with elk behavior throughout North America and in GSMNP (Christianson and Creel 2007; Murrow et al. 2019, Lashley et al., 2011). Shallow slopes are more conducive to elk's "paths of least resistance" movement behavior. In GSMNP and the PRG, terrain is rugged and slopes are steep. It is not surprising that elk in our study tended to avoid high energy costs associated with steep slopes, instead choosing more shallow slopes to move through the landscape.

It is important to note that our finding that elevation contributes to elk movement and resource selection and that elk select for higher elevations while moving through the landscape, is only true in the limited scope of this analysis. All 13 elk monitored existed in areas at relatively low elevations (range 335-1697, mean = 1092 meters) and elevation data extracted from both true steps and the random steps (representing availability and limited by step length) remained within this narrow elevation range (387-1797 meters, mean = 1100 meters). Meaning that elk select for higher elevations while moving through the landscape where elevation in general, was relatively low (i.e. between 400-1200 meters).

The influence we detected of other landscape features on elk movement follow general elk ecology behavior throughout their North American range. While forest cover is often used for escape cover, temperature amelioration, and browsing, and shrub cover provides forage opportunities, we found elk selected for areas farther from forest and shrub cover when moving through the landscape. While this could seem confusing, our analysis specifically evaluated elk selection during movement or transient behavior where these habitat features can become costly to elk movement. For example, in the Canadian Rocky Mountains, elk selected areas with less dense understory where movement costs were lower (Frair et al., 2005). Similarly, newborn calves in north-central Idaho had difficulty negotiating dense shrub fields causing them to be more vulnerable to predation (White et al., 2010).

Both low movement costs and preferred forage availability in the form of grasses are the most obvious reasons for elk selection of herbaceous vegetation cover while moving. Elk typically use open areas such as meadows, fields, and roadways for grazing due to grass availability, the main component of elk diets throughout their North America range (Christianson and Creel 2007). Habitat research during the experimental phase of elk reintroduction in GSMNP indicated elk preferred open grazing land with interspersed cover, and diet analysis concluded the primary diet component of the elk in all seasons was grasses (Murrow et al. 2019). Elk selection for lower aspect slopes (i.e. more southeasterly slopes, ~150 degrees) while moving through the landscape could be due to those conditions creating preferred forage. It is known that aspect affects the diversity and density of plant communities in this region. Southeasterly slope-aspects (110-160 degrees) have sunnier conditions that are more conducive for grass production as opposed to many shade loving forbs (Whittaker 1956).

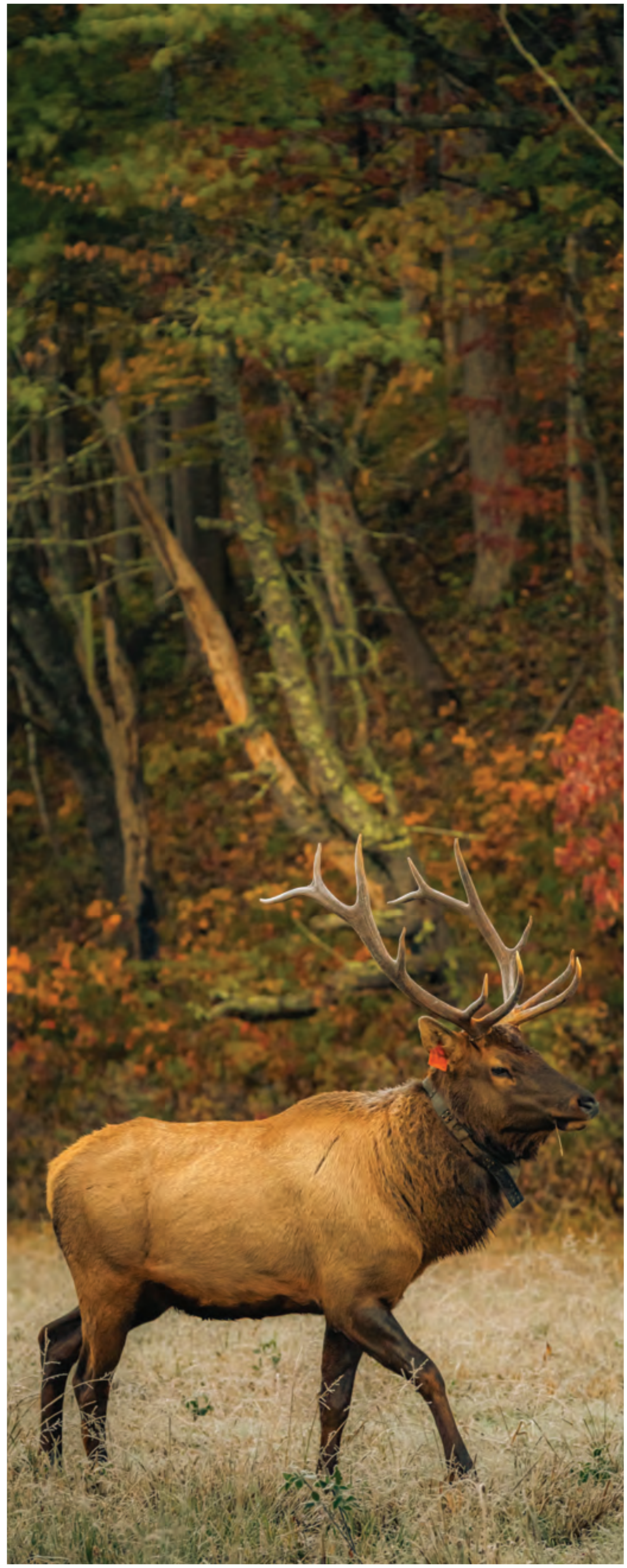
It is most likely that elk are selecting for minor roadways while they move through the landscape due to the open conditions that create grass habitat. Not only are grasses available along roadways, but in our region these roadways are often paths of least resistance. Roads in the topographically diverse southern Appalachians are often established in lower slope areas that would be more conducive for both human and elk movement. In contrast, elk selected habitat father from major roads while moving through the landscape. While the conditions near minor roads that influence elk selection (easy paths for movement, open conditions with available grasses) are also prevalent at major road areas, the increased vehicle traffic and noise likely cause elk to select habitat and move in areas farther from roads. For example, elk in Alberta, Canada reduced the time they devoted to feeding when they were closer to roads and traffic volumes of ≥1 vehicle every two hours. The elk also switched to a more vigilant mode of behavior (Ciuti et al. 2012). Millspaugh et al. (2001) quantified stress hormones produced in elk fecal samples at Custer State Park, South Dakota,

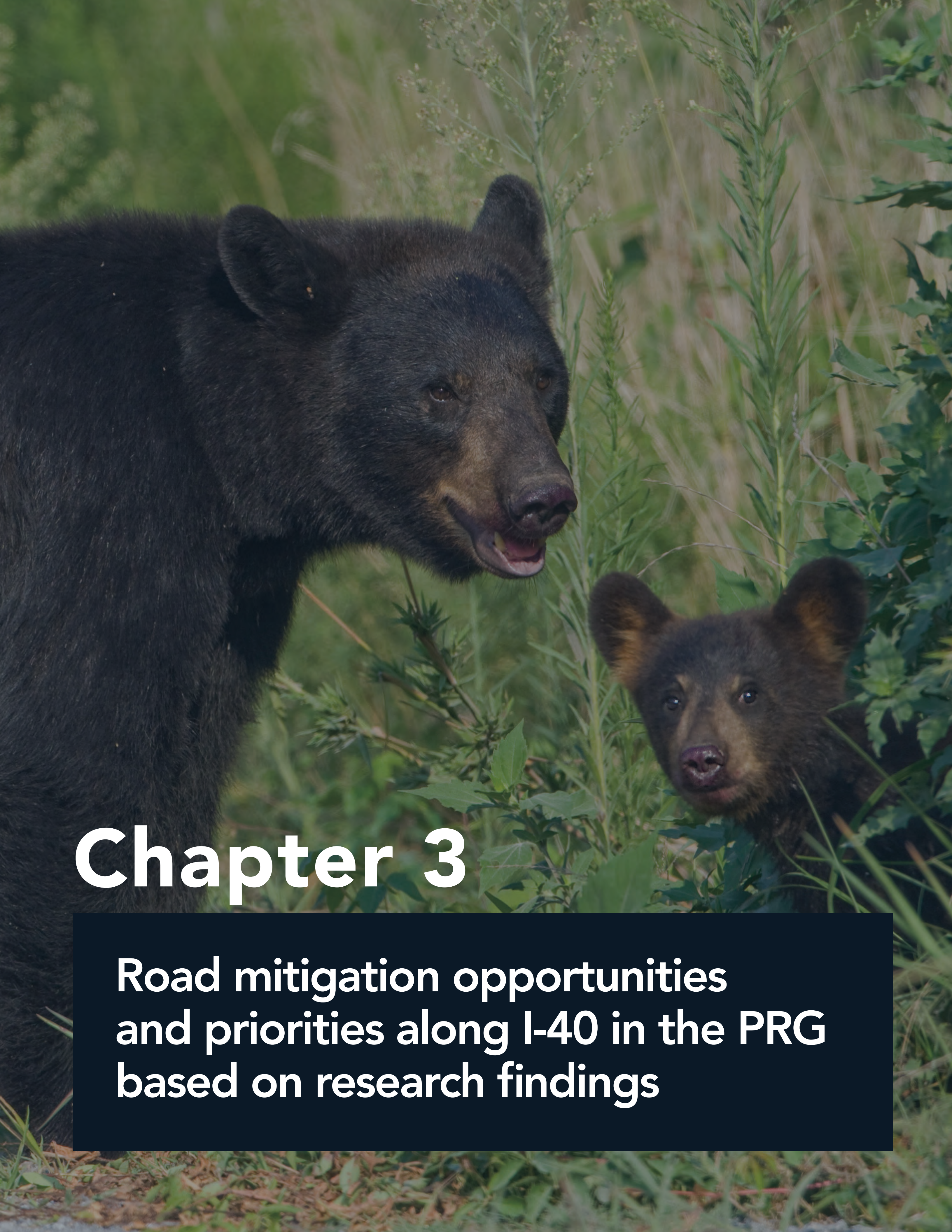
An elk uses the Waterville Bridge to pass under I-40.
Photo: Wildlands Network / NPCA

finding that the density and use of primary roads were two of the three best predictors of fecal glucocorticoid levels, indicating elk perceived regular vehicle activity as a psychological stressor.

Given the fact that regular vehicle activity is a psychological stressor for elk and that I-40 in the PRG has consistent heavy traffic, it is likely that the current noise and movement from vehicles on the interstate dissuade many elk from moving in its direction let alone deciding to cross it. But elk are crossing the interstate likely to take advantage of resources on the other side. Ample forage, grazing opportunities, and protected space exist just beyond the Park's boundary and on the other side of the interstate in the form of Pisgah and Cherokee National Forests. In addition, Pisgah National Forest plans to create young forest conditions that promote grasses forelk in Forest Service land on both sides of the interstate (**Twelve Mile Project**). Elk will be drawn to these areas due to the availability of grasses meaning that in the future elk movement and crossing will increase in this area of the interstate. Using the elk predictive probability scores for roadway segments allow for identification of where elk are most likely to move and end up at the roadway. For example, the 12-mile project will span both sides of the interstate along segments 89 to 63, approximately. High movement probability scores in segments 78 and above average movement probability scores for 77, 79, 80, 82-89 make these areas priorities for mitigation solutions. And further still, we can look at connectivity scores for the target 400-meter segments of I-40 in the Gorge. While movement probability scores identify where elk are likely to end up near the roadway based on movement behavior, connectivity scores identify where elk are more likely to actually cross the interstate due to conditions on both sides of the roadway. Segment 78 with a high connectivity score and segments 79, 84-86 with above average scores can be further prioritized for mitigation sites.

The information gained from elk GPS monitoring can be used not only to guide mitigation for current elk road conflicts but also for future conflicts as the elk population continues to grow. Our research identified elk crossing locations and approaches, identified elk movement behavior and how landscape features influence elk movement, and used those landscape features to identify where elk are most likely to end up near the interstate as well as important function connectivity areas. Priorities for elk mitigation efforts should focus on retrofitting existing structures, creating new dedicated crossing structures for wildlife, and incorporating fencing to provide multiple and adequate safe crossing opportunities throughout the 28-mile section of I-40.


Bull elk in Great Smoky Mountains National Park. Photo: Johnnie



Chapter 3

Road mitigation opportunities and priorities along I-40 in the PRG based on research findings

Section 1:
Top Priority Recommendations

*Please see **Supplemental Materials A** and **B** for recommendations for five North Carolina bridge replacements that were previously given to the North Carolina Department of Transportation by this research group and Terry McGuire. The following seven projects represent our highest priority recommendations for construction along I-40 in the Pigeon River Gorge (PRG) to improve wildlife habitat connectivity and human safety. Please refer to Section 2 below for further details and justifications on these seven sites and our full suite of 20 recommendations across the Gorge. See **Appendix A: Table A5** for all road segment data for reference.*

North Carolina

1. Wilkins Creek Overpass: Construct an overpass over I-40 between Wilkins Creek Box Culvert A (i.e. north) and the NCDOT Rest Area. Pursue land acquisition or conservation easements to stabilize the area for wildlife.

2. Single Tunnel Overpass: Construct an overpass extending the existing Single Tunnel land bridge across the rest of I-40.

3. Cold Springs Creek Exit Culverts: Replace the existing culverts on both the entrance and exit ramps with larger structures to facilitate better terrestrial and aquatic wildlife passage.

4. Groundhog Creek: Replace the three small existing culverts with a larger structure suitable for all of our target species.

Tennessee

1. Waterville Bridge: Add a wildlife-friendly shoulder along the underpass road when the bridge is replaced, and consider a future wildlife and pedestrian overpass in this area.

2. Naillon Branch: Replace the existing culvert with a larger structure suitable for all our target species or construct an elk-friendly overpass. Pursue land acquisition or conservation easements to stabilize the area for wildlife.

3. Laurel Hollow: Replace the existing culvert with a larger structure (culvert or small bridge) suitable for all our target species.

Section 2:
Detailed Wildlife Mitigation Recommendations List

*Our recommendations focus on our target species of black bear (bear), white-tailed deer (deer), and elk. These species were selected because they were relatively easy to monitor and were the wildlife of highest concern from a driver safety perspective. While improving safe passage for these larger mammals may, in some cases, benefit smaller animals (mesocarnivores, reptiles, amphibians, etc.), these other wildlife groups have specific requirements that need to be considered with any new structures or improvements to existing ones. To optimize wildlife connectivity and WVC reduction, deflection fencing (also known as directional fencing) and associated mitigations (jumpouts, cattle guards, etc.) should be considered for most projects, with specifics (type, length, etc.) determined by individual site needs and landscape or topography characteristics. Please refer to **Section 3** below for more detailed information on fencing needs and specifications (also see Hillard and Sutherland 2019).*

*For some projects, we recommend pursuing land acquisition or conservation easements to stabilize the area for wildlife. Please refer to **Section 4** below for general information. More specific information (i.e. individual parcels) will be provided to the DOTs and land conservancy and other partners at a later date, or as needed.*

North Carolina

Site 1. High Bridge

Core Recommendations:

1. During upcoming bridge replacement, fully maintain the extensive riparian pathways for terrestrial wildlife to travel under the south end of the bridge.

2. On the north end of the bridge, create a level path (~2-3 meters wide) traversing the embankment under the bridge to facilitate easy movement of elk and other species under the interstate. This may involve removing riprap or at least filling in riprap with a well-secured layer of soil (using additional rocks to stabilize the soil path).

3. Remove existing right-of-way fencing in vicinity of bridge that may be precluding or impairing wildlife movement and replace with new properly aligned deflection fencing to direct animals toward the improved structure.

Justification:

This large bridge already appears to provide substantial existing amounts of wildlife connectivity along and above Jonathan Creek under I-40. The embankment under the north end of the High Bridge is steeply sloped, but we have records of elk using the slope to cross under I-40. The elk appear to forage just east of the bridge but return and exit the bridge (where they entered) on the western side (both GPS locations data and cameras confirm this). High deer use of the bridge was also recorded. Surprisingly, we did not record bear passing under the bridge, even though bear were detected at our nearby roadside cameras and as roadkill on the relevant road segments.

Relevant Segments: 112-114

Data:

Segment 112 had three WVC (unspecified), 113 had four bear collisions, and 114 had two bear. Roadside cameras at 113 detected all three target species, and at 114 detected bear and deer. The structure cameras indicated high use by deer, moderate use by elk, and no bear detected. Elk GPS data revealed 409 approaches to the highway for segment 112, and four approaches for segment 113, but no crossings were detected in our GPS data.

Site 2. Low Bridge

Core Recommendations:

1. Either extend the length of the bridge to provide at minimum a 7-10-meter wide by four-meter tall space for wildlife and pedestrians on one side of White Oak Road, or, if the bridge is to be replaced with a culvert, provide a second culvert space of that size (7-10 meters W x 4 meters H) for wildlife.

2. Alternatively, if moving the bridge support piers on one side of the bridge ~7-10 meters closer to the end of the bridge would be an option, that would create a sufficient space for wildlife movement along the side of this relatively low-traffic road. The corresponding embankment would have to be trimmed back (and stabilized) to provide sufficient level ground along the side of White Oak Road for elk and other species to traverse under the bridge.

3. Remove existing right-of-way fencing in vicinity of bridge that may be precluding or impairing wildlife movement and replace with new properly aligned deflection fencing to direct animals toward the improved or new structure(s).

Justification:

The current bridge design with narrow, steep embankments does not provide much room for wildlife, and the bridge likely experiences elk and deer use only due to the low amounts of vehicle traffic on White Oak Road. The bridge is in an area of high activity by elk and deer, and modest improvements to the structure would increase its use by these species, and hopefully encourage bears to use the bridge as well.

Relevant Segments: 110-112

Data:

Segment 110 had two bear collisions recorded, 111 (site of bridge) had zero WVC, and 112 had three unspecified WVC. No roadside cameras were deployed. Structure cameras recorded use by both

High Bridge. Photo: Wildlands Network

deer and elk, no bear were detected. Elk GPS collars revealed 29 approaches to segment 110, 348 approaches to 111, and 409 approaches to 112, but no crossings of our collared elk were detected.

Site 3. Pigeon River Bridge

Core Recommendations:

1. After the bridge replacement construction has finished, maintain the flat, level access road on the south side of the bridge as a passageway (at least 2-3 meters wide) for terrestrial wildlife. Ideally this passageway would be closed to motorized vehicles but maintained in a semi-open state for wildlife.

2. In the upper corner of the north end of the bridge, excavate the existing narrow gap in such a way as to create a four meters-tall passageway for wildlife to enter underneath the bridge. It would also be necessary to smooth and contour the soil/rock surface from the excavation at that side of the highway down to the other side of highway, in order to create an easier pathway for target species to navigate under the bridge. We suggest a 7-10-meter wide by four-meter tall pathway under the north end of the bridge would be adequate.

3. Install deflection fencing to direct animals toward the new structure.

4. Pursue land acquisition or conservation easements to stabilize the area for wildlife.

Justification:

The Pigeon River Bridge is a large, well-elevated span that nevertheless has limited current opportunities for terrestrial wildlife to pass underneath. On the north end of the bridge, there is a major constriction where the land surface under the bridge is steeply slanted up to the bottom edge of the highway, and only a narrow and quite steep gap exists between the bridge and the ground underneath. This passageway is inadequate for passage of our target species and seems marginal for most other species—indeed it was difficult for humans to climb through that gap and down the slope under the highway. The same side of the bridge is further constrained by the steep rock cut or rock face where the land surface slopes into the river.

On the south end of the Pigeon River Bridge, there is not much existing room for wildlife passage either. However, NCDOT staff indicated an access road would be constructed under this end of the bridge to facilitate the bridge replacement, and leaving this road in place for wildlife use would be an easy way to greatly enhance connectivity under the interstate at this location.

Relevant Segments: 96-97

Data:

Segment 96 had five total WVC's recorded, including two bear and one deer. Segment 97 had one deer collision. No roadside cameras were deployed. Structure cameras recorded bear and deer using the bridge, no elk were detected. Elk GPS collar data indicated a small number of approaches at these segments (two at 96 and five at 97) but no crossings.

Pigeon River Bridge. Photo: Wildlands Network

Site 4. Fines Creek Large Culvert

Core Recommendations:

1. Add 1–2 meter dry passage shelves on one or both sides of the culvert (depending on hydrological limitations) to benefit target species movement as well as mesocarnivore species such as bobcats and raccoons.

2. Install deflection fencing to direct animals toward the improved structure.

Fines Creek Culvert. Photo: Wildlands Network

Fines Creek Bridge. Photo: Ron Sutherland

Justification:

The large culvert where Fines Creek passes under I-40 is already in good shape for aquatic connectivity (i.e. wide natural bottom), and we recorded crossing use by deer and approaches by bear. Dry shelves mounted or built up on the side of the culvert would likely be used by bobcat, raccoons, and other mesocarnivores, and bears if the shelves were large enough. Currently the site of the culvert is a hotspot of road mortality, so wildlife may be following the creek to the highway and then attempting to cross the highway at grade.

Relevant Segments: 95-97

Data:

Segment 95 had one bear collision recorded, segment 96 (at the culvert) had five WVC including two bear, one deer, and two unspecified animals, and segment 97 had one deer collision. No roadside cameras were deployed, and structure cameras indicated use of the culvert by deer, with bear detected as well. No approaches or crossings by elk were recorded by our elk GPS collars.

Site 5. Fines Creek Bridge

Core Recommendations:

1. If possible, the best solution for wildlife connectivity would be to extend the length of the Fines Creek Road Bridge (while it is being replaced) to provide at minimum a 7-10-meter wide by four-meter tall extension space for animals to cross under the interstate, on one side or the other of Fines Creek Road. The space would ideally be level and easy for elk and deer to traverse and have a mix of native grasses and forbs and bare dirt/fine gravel, depending on the level of sunlight reaching the ground to support the growth of plants. No riprap or large boulders should be used along the floor of the wildlife passageway. Thus, there would be one space under the bridge for cars and an adjacent space under the bridge (separated from the road by a row of support columns or guardrails) for wildlife. The side of Fines Creek Road chosen for wildlife passageway should be the one that provides the easiest access to the most gently sloped natural habitats on either side of I-40.

2. Guardrails, curbs, and other impediments to animal movement should be removed or at least partly gapped or lowered in such a way as to promote wildlife movement from one side of the relevant exit ramp on one side of I-40, to the far side of the other exit ramp on the other side. Even though elk, deer, and bear are capable of jumping over a typical metal guardrail, their use of the bridge extension would likely be enhanced if they did not have to make such exertions to cross under the highway. At the same time, care should be taken not to block the movement pathways for smaller species such as box turtles, snakes, and salamanders. High curbs or low solid walls should be avoided except as a means to funnel smaller species towards appropriate pathways under the bridge.

3. If NCDOT instead chooses to replace the Fines Creek Bridge with a culvert structure,

then we request that a second culvert (ideal minimum dimensions 7-10-meter wide by four-meter tall) be provided for wildlife, sharing one wall with the road culvert. Again, the side for the wildlife culvert placement should be chosen as described above, and appropriate vegetation provided to guide animals to use the correct culvert.

4. Install deflection fencing to direct animals toward the new structure.

Justification:

The bridge where I-40 passes over Fines Creek Road does not currently provide much room on either side of Fines Creek Road for terrestrial wildlife to move underneath, which we confirmed with our data showing zero current use by wildlife. The embankments under both ends of the bridge slope down steeply to the support columns/piers.

While the Fines Creek Road Bridge is not located in an area surrounded by substantial protected forests, it needs to be acknowledged that the fields, pastures, lawns, and even the revegetated portions of the White Oak landfill all provide excellent foraging habitat for elk and deer in this region. Indeed, ongoing elk GPS collar studies (including our own project) reveal significant use of this area by elk. This portion of the I-40 corridor also interferes with wildlife movement from the National Park to the significant acreage of protected conservation easement lands in the "Sandy Mush" area north of Canton, NC. Therefore, from the standpoint of preventing collisions between ungulates and motorists on I-40 it is important to maintain as many safe routes under the highway as possible in this area.

Relevant Segments: 94-96

Data:

Segment 94 had one deer collision recorded, segment 95 had one bear collision, and segment 96 had five WVC, including two bear, one deer, and two unspecified animals. No roadside cameras were deployed, and the structure cameras at this bridge did not detect any of our target species. Elk GPS collar data revealed two approaches by elk at segment 96, and no crossings.

A bull elk in Cataloochee Valley, Great Smoky Mountain National Park. Photo: Ron Sutherland

Wilkin's Creek Box Culvert A. Photo: NPCA

Site 6. Wilkins Creek Box Culvert B

Core Recommendations:

1. Maintain existing box culvert.

2. Add deflection fencing to direct animals to the existing structure.

Justification:

The Wilkins Creek Box Culvert B site would otherwise provide a decent opportunity for wildlife to cross under the interstate. However, the area experiences high human use, and the lake on one side of the highway likely serves to constrain terrestrial habitat connectivity. We therefore think this culvert can be left alone, with fencing provided as part of the overall fencing network needed for the PRG.

Relevant Segments: 85-87

Data:

Segment 85 had zero WVC, segment 86 had one unspecified animal collision, and segment 87 had one bear and one deer collision. Roadside cameras at segment 85 detected deer and bear. The structure cameras at the culvert did record some use by bear and deer. No elk GPS collar approaches or crossings were recorded.

Site 7. Wilkin's Creek Box Culvert A

Core Recommendations:

1. Maintain existing box culvert.

2. Construct a wildlife overpass (ideal minimum width 30 meters) to the north of the existing culvert. This overpass should be large enough to promote use by elk, bear, and deer, along with the full range of terrestrial wildlife.

3. Pursue land acquisition or conservation easements to stabilize the area for wildlife. Land conservation efforts should be pursued at the location of any new wildlife structure to ensure that the parcels on either side of the mitigation effort remain undeveloped and suitable for wildlife usage.

4. Install deflection fencing to direct animals toward the existing and/or new structures.

Justification:

The Wilkins Creek Box Culvert A is already performing relatively well for wildlife, allowing the passage of elk, bear, and deer under the highway. However, given the high WVC numbers experienced along this road segment (nine, tied for highest across our study area), and the highly suitable terrain at this site, we think it should be considered for the addition of a wildlife overpass as well. There is a short ridge on the west side of I-40 that an overpass could easily tie into, compared to much of the PRG where the river on one side or the other of I-40 frequently gets in the way of overpass feasibility. Once on the saddle ridge, wildlife could disperse across the Pigeon River in multiple directions. Given the lake that interferes with wildlife connectivity upstream from this site, it is important to provide a substantial crossing opportunity at this strategic location. Also, we note that the NCDOT rest area facility just to the north of the location would provide an excellent staging area during overpass construction. Post construction, the rest area would also provide an advantageous location for public education and outreach efforts related to explaining the benefits of providing safe passage for wildlife across the highway.

Duke Energy owns some of the land that might be involved in the construction of the overpass, but we do not think the wildlife infrastructure would interfere with their hydroelectric operations at the site.

Relevant Segments: 78-80

Data:

Segment 78 had three WVC, including two bear. Segment 79 had nine WVC, including seven bear, one deer, and one unspecified animal, making it tied for first place for the most WVC in our study area. Segment 80 had three WVC, including one bear and two unspecified. The structure cameras at site recorded all three target species using the culvert. Roadside cameras at segment 79 and 80 recorded all three target species. Our own elk GPS collar data revealed no approaches or crossings, but we did record a bull elk collared by NC Wildlife Resources Commission crossing through the culvert on our structure cameras.

Single Tunnel. Photo: Paul Noah, NPCA and SouthWings

Site 8. Single Tunnel

Core Recommendations:

1. Construct an overpass (ideal minimum width 30 meters) over the two lanes of exposed highway, extending the natural bridge that is formed by the other two lanes of the interstate passing through a tunnel.

2. Establish a clear 1-2-meter wide wildlife path/trail(s) from the overpass leading down to the river to help animals navigate the steep slope that is currently partially covered in riprap.

3. Install deflection fencing to direct animals toward the existing and new structures and trails.

Justification:

The Single Tunnel at this location provides the easiest and likely least expensive option for a wildlife overpass in the PRG, as half of the highway is already tunneled under the mountain. Conveniently, there is also raised terrain on the other side of the exposed lanes of traffic, facilitating overpass construction. Our cameras on top of the existing partial land bridge and just east on the other side of the interstate have revealed very high wildlife use, including 15 species of mammals. There is substantial national forest lands on both sides of I-40 at this location, and a major spur ridge from Hurricane Mountain descends and releases down to the highway, with the ridge serving as an important wildlife funneling natural landscape feature. This represents an outstanding opportunity to provide multi-species connectivity across the interstate and would help mitigate the fact that it may be infeasible to replace the nearby Hurricane Creek Culvert. Also, two potential staging areas exist for overpass construction, one is located between the eastbound and westbound lanes. and the other just west of the eastbound lane, both immediately south of the existing tunnel.

Relevant Segments: 69-70

Data:

Segments 69 and 70 each had two WVC, including one bear each and one unspecified animal. The “structure” cameras on top of the single tunnel land bridge recorded high bear activity and deer as well. Our elk GPS collar data did not indicate any approaches or crossings by elk in this location.

Site 9. Hurricane Creek

Core Recommendations:

1. Add a 1-2 meter dry shelf for mesocarnivores (and possibly bear, if large enough) along one side of the culvert.

2. Consider adding lighting (solar-powered) in the middle of the culvert, which is quite long and dark.

Prior to implementation a bat inventory should be conducted, and proper precautionary measures implemented to avoid negative impacts to existing or future bat use for roosting or breeding.

Justification:

The Hurricane Creek Culvert sits at an important location for wildlife, including a wildlife-vehicle collision (WVC) hotspot. Due to the way the interstate was constructed at this site, the culvert ended up being exceptionally long and dark. Given its size and buried depth, the culvert may be too expensive to replace. So, we suggest focusing on improving Hurricane Creek for terrestrial wildlife by adding a dry shelf for mesocarnivore species such as bobcat, and raccoon, and possibly bear. Many wildlife species may be deterred by the darkness of the culvert, so it would likely help to add some kind of dim solar-powered lighting in the middle of the structure.

Relevant Segments: 67-68

Data:

Segment 67 had five bear collisions reported, and segment 68 had three bear collisions as well. The structure cameras at the culvert recorded deer using the culvert, and also detected bear adjacent to the entrance. Roadside cameras at segment 67 recorded high bear activity and some deer. Our elk GPS collar data did not indicate any approaches or crossings at this location.

Hurricane Creek Culvert. Photo: NPCA

Site 10. Cold Springs Bridge and Culverts

Cold Springs Culvert. Photo: Wildlands Network / NPCA

Core Recommendations:

1. Construct the new bridge in accordance with the plans already released by NCDOT, which depicted a wide shoulder for wildlife at grade along Cold Springs Road, and benches/level trails for wildlife above Cold Springs Creek as it passes under the interstate.

2. Replace the on/off ramp culverts on both sides of the bridge (once the bridge replacement process is complete and the exit ramps are no longer being used to reroute interstate traffic) with larger structures (ideal minimum dimensions 7-10 meters wide by four meters tall) with natural substrate bottoms. If the replacement is a double box culvert, at least one of the culverts on each side of the highway should be elevated above the creek to provide dry passage for wildlife, while still maintaining flood capacity. If the replacements are single structures, each should be wide enough to include substantial amounts of dry land on both sides of the creek (4+ meters on each side ideally) and should be as tall as possible (four meters ideally, but as high as possible given any constraints posed by the height of the ramp road surfaces). The underpass structures should have a natural surface along the bottom (for both the creek and the dry riparian zone) to promote natural erosion patterns in the creek and to avoid the creek undercutting the downstream side of an enclosed culvert and thus creating a barrier to fish and salamander migration. Such enhanced structures would provide a robust route for many species of wildlife large and small to

Cold Springs Creek Culvert. Photo: NPCA

migrate/disperse along Cold Springs Creek from Harmon Den to the Pigeon River and other locations beyond. The larger structures would also serve to significantly reduce the risk of Cold Springs Creek exceeding structure capacity (via existing smaller culverts) and causing damage to I-40 during major flood events.

3. Install deflection fencing to direct animals toward the existing and new structures.

Justification:

Of the five structures along I-40 in the PRG that are being replaced in the near term by NCDOT, this bridge and culvert complex has the potential to be the most important for wildlife habitat connectivity, not just for our large target mammal species but for the full range of southern Appalachian biodiversity. Further, it provides a potential opportunity for wildlife to cross under the interstate in a location where extensive and significant protected public natural lands exist on both sides of the highway (e.g. the Harmon Den Wildlife Management Area and Max Patch on the east and north side of I-40, and Great Smoky Mountains National Park (GSMNP) on the west and south). According to our data, there are WVC hotspots to the north and south of the bridge location.

The situation for wildlife movement under the existing bridge is complicated (but also potentially enhanced) by the presence of Cold Springs Creek, which passes under the respective interstate exit and entrance ramps via a pair of double box culverts. The culverts are large enough to allow some wildlife to pass underneath, but they do not have the dryland space that most terrestrial species require for passage. The relatively dark box culverts also do not appear to be tall or wide enough for elk use. These factors likely contribute to the low use of the culverts by wildlife and in turn likely deter most wildlife from crossing under the highway bridge itself along the creek. Instead, given the observed WVC hotspots, it appears animals are being funneled to this general location by topography, and then attempting to cross the interstate at grade.

Relevant Segments: 62-64

Data:

Segment 62 had five WVC including four bear and one unspecified animal. Segment 63 had two bear WVC, and segment 64 had six WVC including two bear, one deer, and three unspecified animals. The structure cameras under the highway bridge recorded no wildlife, whereas the cameras on the exit ramp culverts recorded deer using the culverts and bear nearby. Roadside cameras at segment 63 recorded bear and deer activity.

Groundhog Creek. Photo: Wildlands Network

Site 11. Groundhog Creek

Core Recommendations:

1. Replace the three pipe culverts at this location with a much larger culvert structure (ideal minimum dimensions 7-10 meters wide by four meters tall) or structures that would pass all our target species, with natural creek bottoms for fish and aquatic life passage. Add dry passage as well by elevating one or more culverts above the normal level of the stream.

2. Alternatively, look at the possibility of constructing an overpass (ideal minimum width 30 meters) at this location if culvert replacement is not feasible.

3. Install deflection fencing to direct animals toward the improved or new structures.

Justification:

The Groundhog Creek area is strategically important for bear connectivity, which like Cold Springs Creek, is dominated by national forest land on both sides of the highway. We recorded bear frequently using the culverts despite their small size, and a few deer approached but did not cross through. This particular bend in the Pigeon River (and interstate) is also notable for having a total of five creeks flowing under the highway in a short span. There is a WVC hotspot along the bend, perhaps caused by animals being funneled to the area but then inhibited from crossing through the small structures at Groundhog Creek (and the even smaller structures at the other creeks). Most or all the other creeks pass through substantially "perched" culverts, where the downstream end of the culvert ends up elevated above the eroding creek below, thus cutting the upstream area above the culvert off in terms of aquatic connectivity.

Relevant Segments: 54-56

Data:

Segment 54 had four WVC, including two bear. Segment 55 had three bear collisions, and segment 56 had five WVC including four bear and one unspecified animal. Roadside cameras at segment 55 recorded bear and deer activity. Structure cameras at the culverts recorded high bear use and low deer use. Our elk GPS collar data indicated no approaches or crossings at this location.

Double Tunnel. Photo: Paul Noah, NPCA and SouthWings

Site 12. Double Tunnel

Core Recommendations:

1. Consult with Pisgah National Forest to investigate special designation status for the natural bridge at this location and protect the forest on and adjacent to the land bridge.

I-40 traffic moves through the Double Tunnel. Photo: Ron Sutherland

2. Construct a 1–2-meter wide, easily traversable trail(s) for wildlife leading from the land bridge down through the riprap (below the access road) to and along the Pigeon River. Add corresponding short breaks in the jersey barrier along the access road.

3. Install deflection fencing to direct animals toward the existing structure and trails.

Justification:

The Double Tunnel where I-40 passes fully under the mountains provides some of the best existing connectivity for wildlife across the interstate, both in our 28-mile study area in the PRG and well beyond. Our cameras indicated high use by wildlife, including bear, deer, and many regional mesocarnivore and small terrestrial mammal species. High use of the natural bridge helps explains the low level of WVCs near the Double Tunnel, coupled with the funneling effect from roadside topographic constraints leading to and from the tunnel. The main obstacle to ungulate passage at this location seems to be the steep terrain on the river side of the land bridge, compounded by heavy application of riprap to stabilize the bank. Elk, deer, and other animals such as box turtles are likely significantly deterred by the steep riprap, and we therefore recommend the creation of a smooth-surfaced (dirt) path leading from the land bridge, across the access road, and down to the edge of the river.

Relevant Segments: 52-53

Data:

Segment 52 had one bear collision, and segment 53 had two bear collisions. There were no roadside cameras at this location, but "structure" cameras on top of the natural land bridge detected high levels of bear activity and some use by deer as well. None of our GPS-collared elk approached or crossed the highway at this location.

Site 13. Snowbird Creek

Core Recommendations:

1. Replace the existing culvert with a larger culvert structure suitable for bear and deer (ideal minimum dimensions 7-10 meters wide by four meters tall), including dry passage options for terrestrial wildlife and a natural substrate bottom for aquatic connectivity.

2. Install deflection fencing to direct animals toward the improved structure(s).

Justification:

Although we did not monitor the existing culverts at Snowbird Creek due due to their location on the river side of the highway, the site showed up as a clear WVC hotspot in our mortality data, and we recorded high deer and above average bear use in our roadside cameras. Snowbird Creek has a long, impressive valley to the northeast and likely funnels wildlife to the interstate at this location, and currently there is no suitable structure for bear or deer to cross in the greater vicinity. Adding a larger culvert structure (or pair of structures, one wet and one dry) at Snowbird Creek would address the wildlife mortality and help to fill in what would otherwise be a long gap in crossing structures between the Double Tunnel in North Carolina and the Waterville Bridge in Tennessee.

Relevant Segments: 39

Data:

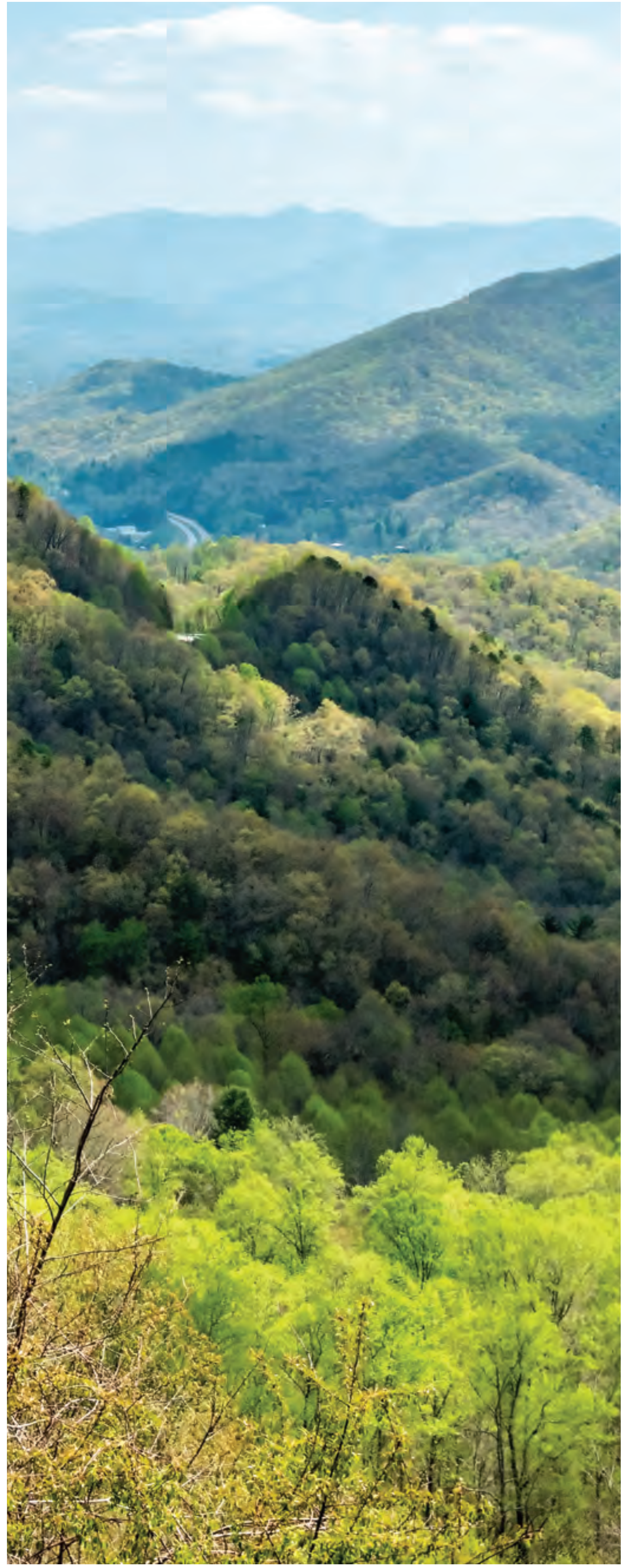
Segment 39 had five WVC, including two bear, two deer, and one unspecified animal. Our roadside cameras at this location recorded bear activity and high deer activity. No structure cameras were deployed at the existing small culvert. Our elk GPS collar data indicated no approaches or crossings at this location.

Tennessee

Site 14. Waterville/Green Corner Road Bridge

Core Recommendations:

1. The best solution for improving wildlife connectivity under the Green Corner Road Bridge would be to extend the length of the bridge to provide a 7-10 meter-wide extension space for animals and people to cross under the interstate. Preferably, there would be one space under the bridge for cars and an adjacent space under the bridge for cars and an adjacent space under the bridge for wildlife and Appalachian Trail (AT) hikers. The pathway for wildlife and AT hikers could be separated from the road by a structure such as support columns or guardrails. The space would ideally be level and easy for elk and deer to traverse and have a mix of grass and forb native vegetation and bare dirt/fine gravel. No riprap



Blue Ridge Mountains surround the PRG. Photo: Ron Sutherland or large boulders should be used along the floor of the wildlife passageway. Grassland vegetation appropriate for attracting elk and deer should be used to demarcate the likely pathway that those species would use to access the extended bridge pathway.

2. This site should also be considered for a potential overpass location (ideal minimum width 30 meters), with the overpass serving to allow wildlife and AT hikers to safely cross the interstate.

3. Install deflection fencing to direct animals toward the any new structures and pathways.

Justification:

At this location, the AT intersects with Interstate 40. As part of the trail, hikers currently cross under the interstate using the Green Corner Road Bridge. The bridge is surrounded by substantial protected forests with GSMNP to the southwest and Cherokee National Forest (CNF) to the northeast. This portion of I-40 interferes with wildlife movement to and from the National Park and national forest lands, making the future replacement of this bridge (as planned by Tennessee Department of Transportation) an important opportunity to provide wildlife habitat connectivity. Our WVC data indicate that both of the closest segments to the bridge are hotspots of mortality. Elk GPS collar research from our project show multiple years of a female elk using the Green Corner Road Bridge to cross under the interstate, and research cameras monitoring the underpass detected use by deer and elk (including our GPS-collared elk with her calf). In September 2019, an elk was killed due to a vehicle collision one kilometer north of the underpass. Therefore, from the standpoint of preventing collisions between our target species and motorists on I-40, it is important to create a safe route under the highway at this location.

As an alternative (or as an addition) to substantially widening the Green Corner Road Bridge, it may be equally desirable to consider installing a combined wildlife and pedestrian overpass at or near this critical location. Elk are thought to prefer overpasses versus underpasses (Huijser et al. 2009), and the throng of AT hikers would likely appreciate a more elegant pathway across the highway, and one that doesn't require as much of a drop in elevation as the current arrangement. NCDOT is currently in the active planning stages for a combined wildlife/hiker crossing further south in the mountains of North Carolina, where the AT crosses NC-143. Some of the same design considerations from that project could likely inform an overpass at this location.

Relevant Segments: 32-34

Data:

Segment 32 had five WVC including two bear and three deer. Segment 33 had six bear collisions, and segment 34 had one bear and one deer. Roadside cameras at segment 32 recorded bear and deer, and the structure cameras at the bridge recorded substantial use by elk and deer. Our elk GPS collar data indicated that segment 32 had 17 elk crossings and 98 approaches, and segment 33 had 12 approaches. We also note that segment 31 immediately to the north had six elk crossings and 437 approaches.

Waterville Bridge. Photo: Wildlands Network

Site 15. Pigeon River Bend

Core Recommendations:

1. Consider an overpass (ideal minimum width 30 meters) or underpass/large culvert at this location.

2. Install deflection fencing to direct animals toward the new structure.

Justification:

The Pigeon River Bend between segments 29-31 is an area of concentrated elk activity, as shown by our GPS collar data. The heavy elk use is likely influenced by the overall gently sloped topography and availability of grasses provided by the open conditions of the adjacent rock quarry. The elbow at the bend of the river

Naillon Branch. Photo: Wildlands Network / NPCA

appears to provide a shallow slope out of the river for access to the interstate right-of-way. We recorded a hotspot of WVC at Segment 29 (nine road-killed animals, tied for highest across the PRG), including the only elk that was killed on the highway during our study.

Relevant Segments: 29-31

Data:

Segment 29 had nine WVC, including four bear, four deer, and one elk. Segment 30 had no WVC, and segment 31 had four bears killed. Roadside cameras at segment 29 and 31 detected low bear and deer activity, whereas the cameras at segment 30 recorded high deer activity plus bear and elk. No structure cameras were deployed due to lack of existing structures. Our elk GPS collars tracked high activity, including four crossings and 55 approaches at segment 29, four crossings and 72 approaches at segment 30, and six crossings and 437 approaches at segment 31.

Site 16. Tinker Branch

Core Recommendations:

1. Consider a wildlife overpass (ideal minimum width 30 meters) or underpass/large culvert at this location as an alternative to the Site 15 recommendation.

2. Install deflection fencing to direct animals toward the new structure.

Justification:

The area where Tinker Branch Creek flows into the Pigeon River seems to be another important site for elk activity. Our GPS collar data indicate frequent road crossings occurred in segments 25 and 26, and segment 26 was a WVC hotspot for bear and deer. Given the topography, a wildlife overpass that connects Tinker Branch to the ridgeline north of the interstate could be a feasible way of increasing connectivity within the "S-Curve" of the Pigeon River/I-40. An underpass or large culvert might also be feasible, though Tinker Branch doesn't actually flow under I-40, so there is not an existing culvert at this location to work with.

Relevant Segments: 25-26

Data:

Segment 25 had three WVCs including two bear and one deer. Segment 26 had six WVC including two bear and four deer. There were no structure or roadside cameras at this location. Our elk GPS collar data indicated high use, with segment 25 having three crossings and 16 approaches, and segment 26 having seven crossings and 26 approaches.

Site 17. Naillon Branch

Core Recommendations:

1. Replace the existing damaged culvert with a larger diameter structure to provide a passage opportunity for bear and deer, ideally at least 7-10 meters wide by 4 meters high.

2. To target elk, consider a wildlife overpass (ideal minimum width 30 meters) or large underpass (ideal minimum dimensions 7-10 meters wide by four meters tall) in this location as an alternative to the overpass recommendations for Site 15 and 16.

A large bull elk rubs on a tree under the High Bridge. Photo: Wildlands Network / NPCA

3. Pursue land acquisition or conservation easements to stabilize the area for wildlife and to connect with the CNF and GSMNP to the south. Land conservation efforts should be pursued at the location of any new wildlife structure to ensure that the parcels on either side of the mitigation effort remain undeveloped and suitable for wildlife usage.

4. Install deflection fencing to direct animals toward the new structure.

Justification:

Elk GPS collar locations show multiple years of an elk crossing the interstate at road surface and heavy use along both sides of the interstate near Naillon Branch. We recorded high incidences of bear and deer vehicle mortality near Naillon Branch, with segment 24 qualifying as a WVC hotspot. Cameras monitoring the culvert that crosses under the interstate detected moderate use by small to medium sized wildlife species including raccoons and otter, and interest by bobcat, fox, deer, and bear (i.e. approaching but not entering the culvert). This is most likely due to the size, condition, and placement of the structure. We only detected elk along the roadway and not at either culvert entrance.

Relevant Segments: 23-25

Data:

Segment 23 had two deer WVC. Segment 24 had six WVC, including four bear and two deer, and segment 25 had two bear and one deer. Roadside cameras at 23 and 24 each detected all three of our target species. Structure cameras at the culvert detected bear use, and deer were also observed. Our elk GPS collars recorded very high activity, including 42 crossings (highest in the PRG) and 510 approaches (highest in the PRG). Segment 23 had 18 crossings and 264 approaches, and segment 25 had three crossings and 16 approaches.

Site 18. Deer Mortality South of Hartford

Core Recommendations:

1. Explore the possibility of wildlife detection systems for this busy, somewhat commercialized area.

Justification:

Just south of the small town of Hartford, TN, our data indicated two adjacent segments with high levels of wildlife vehicle mortality. Both segments tied for first place in terms of recorded deer collisions, and we also found several dead bears as well. The deer population is likely higher given the mix of open habitats associated with the town.

Relevant Segments: 19-20

Data:

Segment 19 had six WVC including one bear and five deer. Segment 20 had eight WVC (second highest overall) and five deer (tied with segment 19 for most deer). No roadside or structure cameras were deployed, and no elk approached or crossed the highway according to our GPS collar data.

Pigeon River Bridge in Tennessee. Photo: Wildlands Network

Deer near Bluffton Bridge. Photo: Wildlands Network / NPCA

Site 19. Bluffton Bridge over Pigeon River

Core Recommendations:

1. On the north end of the bridge, carve out a bench 2-3 meters wide into the upper third of the abutment slope, traversing the embankment under the bridge to facilitate easy movement of bear, deer, and other species under the interstate. Excavated material could be used to fill the downhill slope. Retaining structures would likely be required to support the bench and downhill fill.

2. Install deflection fencing to direct animals toward the improved structure.

Justification:

The Pigeon River Bridge is a large, well-elevated span surrounded by CNF that has the potential to provide significant wildlife connectivity under the interstate along the river corridor. However, the bridge currently has suboptimal conditions for terrestrial wildlife to pass underneath. In particular, the south side of the bridge has a paved road that takes up most of the space that would be used by wildlife. The north end is much more favorable, but the abutment slope has problematic (for wildlife passage) riprap and loose substrate, and thus could greatly benefit from a defined "bench" for wildlife. Based on WVC records from our research, this

A bear enters the Groundhog Creek Culvert. Photo: Wildlands Network / NPCA

area has high incidences of bear and deer vehicle mortality, including a large WVC hotspot from segments 7-9.

Relevant Segments: 9-10

Data:

Segment 9 had five WVC including three bear and two deer. Segment 10 had two bear and one deer. Roadside cameras at nine and ten each detected bear and deer activity, and the structure cameras at the bridge detected use by bear and deer as well. Our elk GPS collar data did not indicate any approaches or crossings in this area.

Site 20. Laurel Hollow

Core Recommendations:

1. Replace the Laurel Hollow Creek Culvert with a structure (underpass, bridge, large creek culvert) that has a larger diameter (ideal minimum dimensions 7-10 meters wide by four meters tall) to provide a dry crossing location for bear, bobcat, coyotes, deer, and elk in addition to passage for aquatic organisms along the creek. Design the culvert entrances such that smaller wildlife, including aquatic organisms, will easily be able to access the culvert.

2. Install deflection fencing to direct animals toward the new structure.

Justification:

From a landscape perspective, Laurel Hollow is an important mitigation opportunity as it marks an area where CNF covers both sides of the interstate, and the orientation of local topography appears conducive for funneling wildlife along Laurel Hollow Creek to under the highway to the Pigeon River and beyond. We recorded high incidences of bear and deer vehicle mortality at Laurel Hollow, including an extensive WVC hotspot from segments 7-9. This indicates the need for enhanced infrastructure at this site, and a larger culvert or small bridge/underpass would be more attractive to bear, deer, bobcat, and other large species. The new culvert or underpass should have a natural substrate bottom in order to facilitate aquatic connectivity between the Pigeon River and Laurel Hollow Creek.

Camera monitoring at the existing culvert at Laurel Hollow detected high animal activity and a multitude of bear, bobcat and coyote inspecting the culvert but not entering. Only raccoons were using the culvert to pass back and forth under the interstate. The bears in this region are especially impacted by I-40 due to their large population and their expansive home range requirements to accommodate large movements due to seasonal changes in food availability.

Relevant Segments: 7-9

Data:

Segment 7 had six WVC including four bear and two deer. Segment 8 had seven WVC including three bear and Four deer, and segment nine had five WVC including three bear and two deer. Roadside cameras at 7, 8, and 9 all detected bear and deer activity. Structure cameras at the culvert detected use by bears and detected deer adjacent to the culvert. No elk were detected in the area according to our elk GPS collar data.

Section 3:
Fencing and Miscellaneous Improvements

A bull elk in North Carolina. Photo: Jo

Numerous studies have demonstrated that it is the combination of fencing with wildlife crossing structures that yields the incredible reductions in WVC rates that are commonly associated with overpasses and underpasses. Crossing structures alone are not enough to deter animals from attempting unsafe transits across roadways. Fencing alone (without crossing opportunities) is the antithesis of connectivity and can have serious impacts on wildlife populations by magnifying the barrier effects associated with busy highways.

Rather than address fencing needs repetitively at each site listed above, we decided to focus on more general fencing recommendations here. Ultimately, the best solution for promoting driver safety and reducing WVCs in the PRG is to add appropriate 10-foot tall wildlife fencing along the entire PRG, on both sides of I-40. The extensive exceptions to this rule occur where steep cliffs/rock cuts preclude fencing or make it impossible to install.

The fencing needs to be 10-foot tall to block high-jumping deer (and possibly elk) and to discourage bear, coyote, bobcats, and smaller animals from climbing. Where possible given the rocky substrate in the PRG, the fencing should be buried underground sufficiently far to block bear, coyotes, groundhogs, skunks, etc. from attempting to burrow underneath.

One additional challenge with installing fencing along I-40 in the PRG is the presence of accessory roads entering and exiting the interstate at various locations. These additional roads obviously cannot be fenced, and so wildlife would tend to try to exploit the gaps in fencing to cross the highway in unsafe locations. This problem cannot be fully mitigated using currently available technology, only closing the side roads would block all relevant species. But deer and elk can be effectively deterred from accessing highways using "wildlife guards" installed where the side roads meet the larger roadway.

Wildlife guards (essentially larger versions of the cattleguards used in ranch country) consist of a grate of rounded metal bars installed at road grade (and tied into fencing on either side), strong enough to support passing vehicles, but difficult for hoofed animals to safely navigate. Unfortunately, carnivore species with paws instead of hooves are not deterred by these structures. Luckily, there is some evidence that bears and other carnivores may be more adept at learning to safely use wildlife crossing structures.

Even with fences and wildlife guards in place, there is always the chance that some wildlife may end up along the highway. Road ecologists have therefore devised structures known as jumpouts, which are essentially one-way exit ramps that allow animals to easily jump down and away from the road, but which are difficult to navigate in the opposite direction due to the abrupt wall formed by the jumpout design. The North Carolina and Tennessee Departments of Transportation should follow guidelines established in western states for installing jumpouts at regular intervals through the PRG. Jumpouts should also be targeted to specific locations where some leakage of wildlife onto the highway is expected given the terrain, exit ramps, or other features such as fence ends. Jumpouts and wildlife guards also require regular maintenance, as with fencing.

Section 4:
Land Acquisition

Given the high (but justifiable, in terms of public benefits) cost of wildlife road infrastructure, state DOTs are often reluctant to invest what can be millions of dollars into new wildlife underpasses or overpasses unless there is a reasonable guarantee that the usefulness of the structure will not be ruined by commercial or residential development in the future. Therefore, it is critical to set the stage for wildlife crossing installation by first securing the land on either side of the highway from development. Land conservation could mean adding to existing local, state, or federal protected lands, or it could involve securing development rights via conservation easements (either paid or voluntary) with private landowners.
In the case of the PRG, at the macro-scale there is already a substantial connected swath of protected land on both sides of the highway connecting GSMNP to the national forests to the north. Zooming in, however, it is clear there are still substantial opportunities for land trusts and government conservation agencies to get involved in firming up the protected land base along this critical stretch of interstate.

There have already been some key steps in this direction since we started the PRG research effort in 2018. For example, the Southern Appalachian Highlands Conservancy was able to protect the 200-acre Wilkins Creek property adjacent to the location of the functional Wilkins Creek A box culvert (and near the location of our proposed overpass at this site as well).

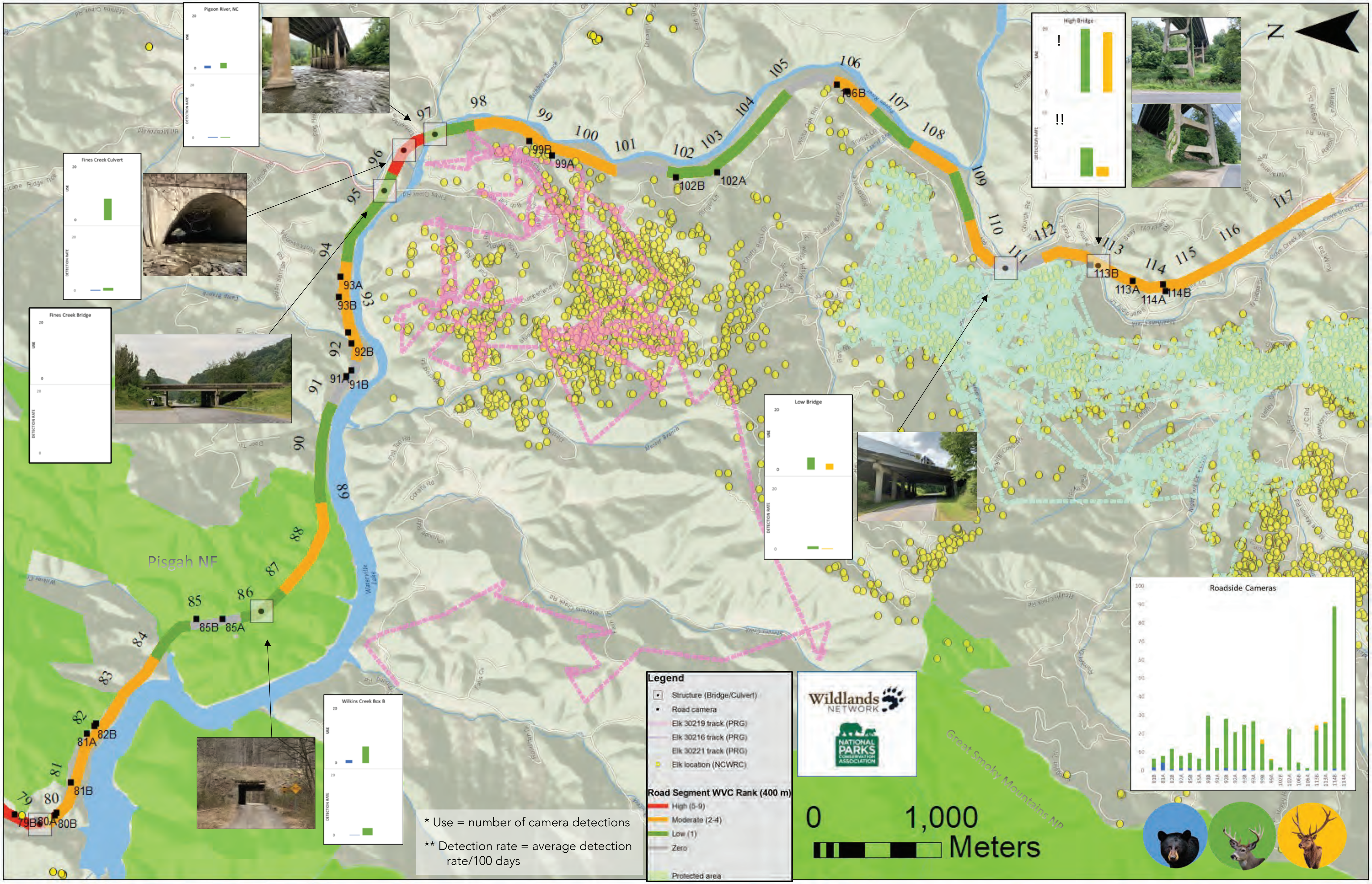
We encourage close examination of the protected area status at each of the priority wildlife mitigation sites listed bove. If key gaps are discovered, robust efforts to protect those gaps using voluntary land conservation need to quickly commence. For example, the Naillon Branch site in Tennessee is noted for potentially benefiting from land conservation actions.

Fall foliage in the Pigeon River Gorge. Photo: Danita Delimont

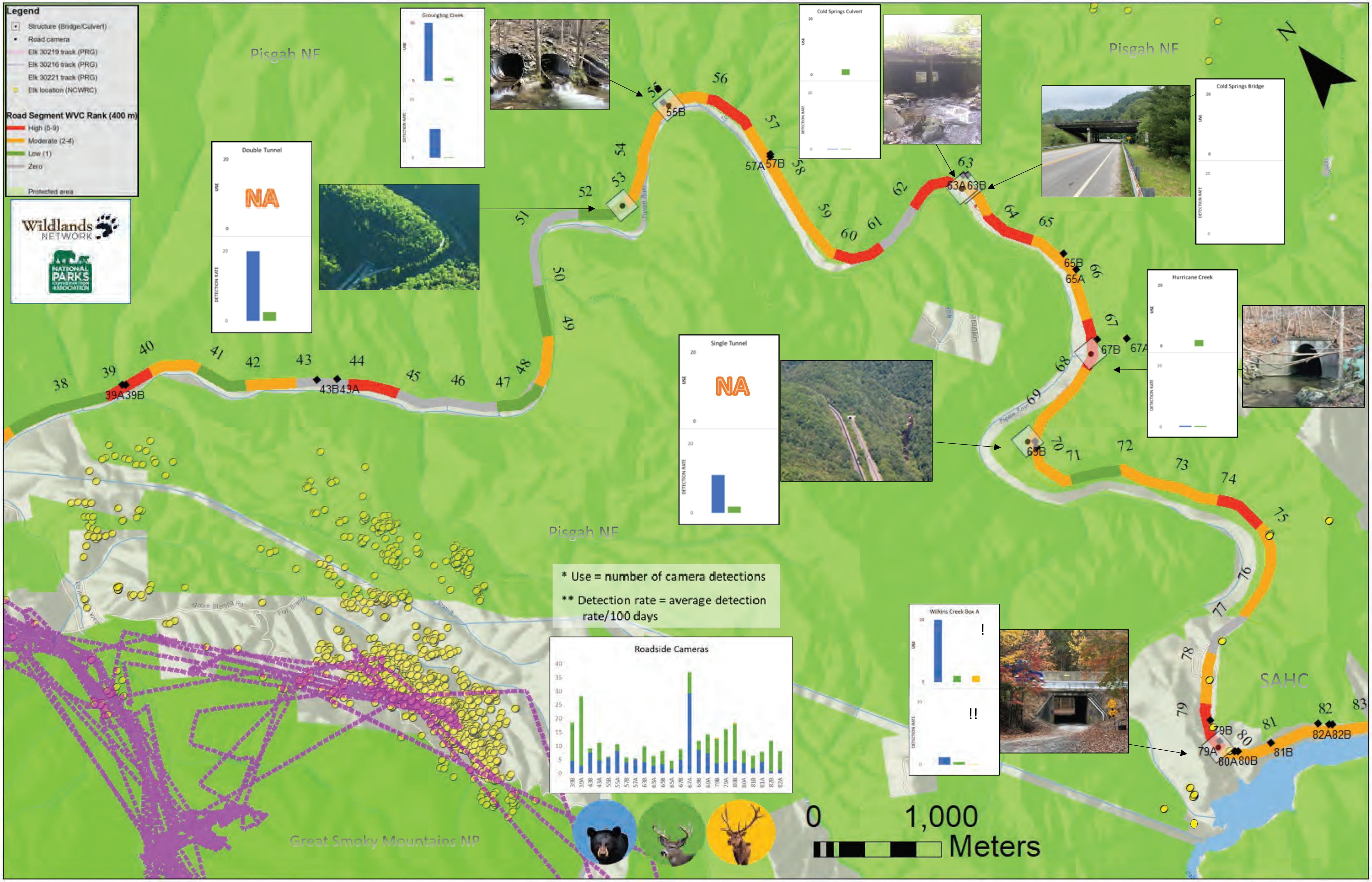
Acknowledgements

We thank the Stanback Family and the Foundation for the Carolinas and The Volgenau Foundation for their generous funding; North Carolina Wildlife Resources Commission for loaning wildlife cameras, GPS-collaring elk, and sharing roadkill data; Great Smoky Mountains National Park for deploying and monitoring elk GPS collars; Rocky Mountain Elk Foundation for wildlife camera funding; and North Carolina and Tennessee Departments of Transportation for issuing permits and sharing their wildlife vehicle collision data. We much appreciate Tara Anderson, Anne Burroughs, Joe Clark, Kim Delozier, Hugh Irwin, Terry McGuire, Bill Stiver, and Travis Wilson for sharing their expertise and/or reviewing draft documents. We are especially indebted to Michelle Hunt, Dave McHenry, Justin McVey, Colleen Olfenbuttel, Zane Pannell, Nick Melton, Alex Vanko, and Joe Yarkovich for generously sharing their time, equipment, data, expertise, and/or reviewing documents. Finally, we thank all our partners in the Safe Passage and Pigeon River Gorge Wildlife Connectivity coalition for their tremendous support of this research.

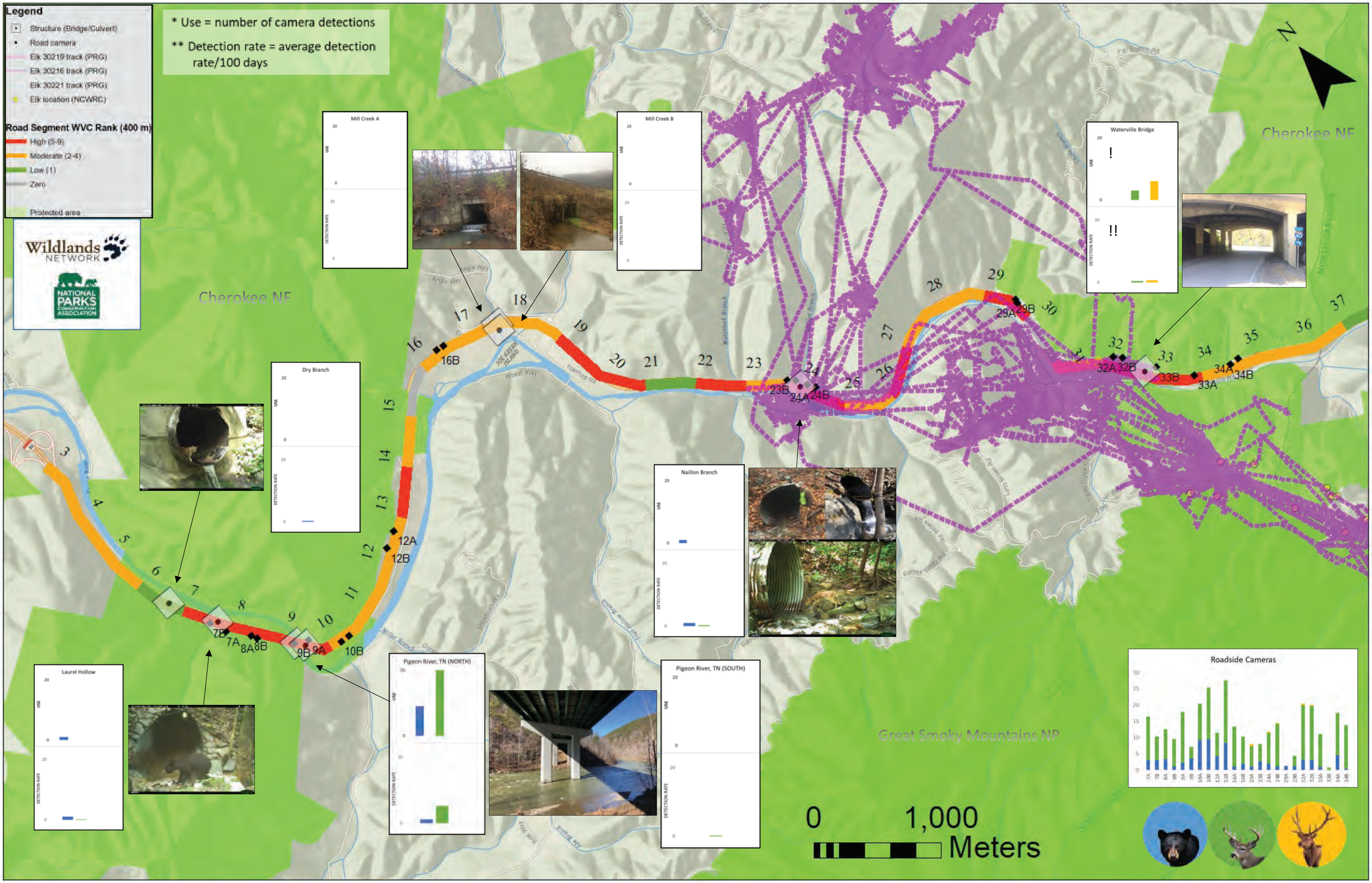
Map Series A: *Map A1 South*



Map Series A: *Map A2 Central*



Map Series A: *Map A3 North*



Appendix: *Table A.1.*

Variable	Description	Source
Terrain Ruggedness Index (TRI):	The mean of the absolute differences between the elevation value of a cell and the value of its 8 surrounding cells from digital elevation model data.	USGS National Elevation Dataset
High	Elevation difference = 959-4367	
Intermediate	Elevation difference = 162-239	
Low	Elevation difference = 0-80	
Topographic Position Index (TPI)	The difference between the value of a cell and the mean value of its 8 surrounding cells from digital elevation model data.	USGS National Elevation Dataset
Valley	TPI < -1 STDV	
Lower slope	TPI > -1 STDV, < 0.5 STDV	
Flat	TPI > -0.5 STDV, < 0.5 STDV	
Ridge	TPI > 1 STDV	
Forest Cover	Areas dominated by decidious and evergreen treees generally greater than 5 meters tall, and greater than 20% of total vegetation cover	NLCD 2019
Human Development	Areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20% to 100% of the total land cover.	NLCD 2019
Stream	Areas of open water, streams, drainages, and creeks	USGS National Hydrography Dataset
Protect land	Areas that includue National Park, National Forest, and conservation easment lands	Protected Area Database of the United States and Land Conservation Agency data
Distance to road structure *	Distance in meters to 19 road structures that have adequete sizes (>2m2) to pass target wildlife	Polygon shape file defining stuctures
Distance to Interstate 40**	Distance to the I-40 road surface	USGS National Transportation Dataset

* only used for WVC models
** only used for road camera models

Table A.1. Landscape and road variables extracted and used to assess their influence on wildlife vehicle collisions (black bear, white-tailed deer, and elk) and wildlife detection rates in cameras along a 28-mile section of Interstate 40 in the Pigeon River Gorge, Tennessee and North Carolina, September 2018—December 2021.

Appendix: *Table A.2.*

Structure name	Type	Height (meters)	Width (meters)	Length (meters)	Openness Ratio	Wet or Dry	Human Activity	Notes
Cold Springs Bridge*	bridge underpass	6.5	76.0	20.0	24.7	dry	high	used same height as Fines Creek Bridge
Cold Springs Culvert 1	double box culvert	2.6	3.0	23.9	0.3	wet	low-moderate	measurements for 1 of 2 culverts
Cold Springs Culvert 2	double box culvert	2.1	3.0	30.3	0.2	wet	low-moderate	measurements for 1 of 2 culverts
Double Tunnel	land bridge	n/a	n/a	n/a	n/a	dry	low	
Dry Branch	metal drainage pipe	1.4	1.4	30.0	0.1	wet	low	hanging culvert
Fines Creek Bridge*	bridge underpass	6.5	51.0	24.0	13.8	dry	high	
Fines Creek Culvert	arched concrete culvert	5.5	100.0	11.0	50.0	wet	low	
Groundhog Creek^	metal drainage pipe	1.8	2.2	65.0	0.1	wet	low	mmt for 1 of 3 side-by-side culverts
High Bridge*	bridge underpass	20.0	186.0	18.0	206.7	dry	low-moderate	height is conservative estimate
Hurricane Creek^	arched concrete culvert	6.0	4.4	150.0	0.2	wet	low	
Laurel Hollow	metal drainage pipe	1.7	1.7	25.0	0.1	wet	low	hanging culvert
Low Bridge*	bridge underpass	6.1	51.0	27.0	11.5	dry	moderate-high	
Mill Creek 1	box culvert	1.8	2.4	40.0	0.1	wet	low	
Mill Creek 2	box culvert	1.8	2.5	29.2	0.2	wet	low	
Naillon Branch^	metal drainage pipe	1.5	1.7	100.0	0.0	wet	low	length may be much > than 100m, hanging culvert
Pigeon River NC*	river bridge	20.0	114.0	20.0	114.0	dry	low-moderate	height is conservative estimate
Pigeon River TN*	river bridge	20.0	173.0	25.0	138.4	dry	low	height is conservative estimate
Single Tunnel	land bridge	n/a	n/a	n/a	n/a	dry	low	partial land bridge
Waterville Bridge*	bridge underpass	6.7	33.0	28.0	7.9	dry	high	
Wilkins Ck Box Culvert N	box culvert	3.6	4.3	29.5	0.5	dry	moderate-low	
Wilkins Ck Box Culvert S	box culvert	3.7	4.3	31.0	0.5	dry	moderate	

1.0 meter = 3.3 feet

*width and length measured in ArcGIS. Height field measured at Low Bridge, Fines Creek Bridge, and Waterville Bridge, and estimated for other bridges

^length measured in ArcGIS

Table A.2. Current road structures monitored to assess wildlife use of structure to cross the interstate along a 28-mile section of Interstate 40 in the Pigeon River Gorge, Tennessee and North Carolina, September 2018—December 2021.

Appendix: *Table A.3.*

Elk ID	Sex	Capture date	End date	# GPS locations	Days Monitored
30215A	m	3/8/2018	9/25/2018	4465	201
30215B	m	11/16/2018	6/26/2020	12878	588
30216	f	3/8/2018	2/26/2020	16320	720
30217	f	4/5/2018	4/14/2020	16592	740
30218	m	9/25/2018	11/9/2019	6109	410
30219	m	4/11/2019	4/29/2019	400	18
30220	f	1/11/2019	7/14/2020	12441	550
30221	f	3/19/2019	2/11/2020	7476	329
30222	f	4/11/2019	8/2/2020	9731	479
30223	f	3/8/2018	4/9/2020	16923	763
30224A	m	11/16/2018	9/21/2019	6957	309
30224B	m	10/24/2019	11/22/2020	8668	395
30254	m	3/5/2019	9/25/2019	4646	204

Table A.3. Information from 13 elk collared to assess elk crossings, approaches, and movement in the Pigeon River Gorge, Tennessee and North Carolina, October 2018—December 2020.

Appendix: *Table A.4.*

Variable	Description	Source
Slope	Percent slope calculated from digital elevation model	USGS National Elevation Dataset
Aspect	Degree aspect calculated from digital elevation model	USGS National Elevation Dataset
Elevation	Meters in elevation calculated from digital elevation model	USGS National Elevation Dataset
Forest Cover	Distance to areas dominated by deciduous and evergreen trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover.	NLCD 2019
Herbaceous	Distance to areas dominated by gramanoid or herbaceous vegetation, generally greater than 80% of total vegetation.	NLCD 2019
Hay/Pasture	Distance to areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops, typically on a perennial cycle. Pasture/hay vegetation accounts for greater than 20% of total vegetation.	NLCD 2019
Shrub	Distance to areas dominated by shrubs; less than 5 meters tall with shrub canopy typically greater than 20% of total vegetation.	NLCD 2019
Open Water	Distance to areas of open water, generally with less than 25% cover of vegetation or soil.	NLCD 2019
Primary Roads	Distance to major road; controlled-access highway, secondary highway or major connecting road, ramp, and tunnel.	USGS National Transportation Dataset
Secondary Roads	Distance to minor road; local road and local connecting road.	USGS National Transportation Dataset
Human Development	Distance to areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20% to 100% of the total cover.	NLCD 2019
Human Development-Open	Distance to areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account Impervious surfaces account for less than 20% of total cover. These areas most commonly include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes.	NLCD 2019

Table A.4. Topographic, habitat resource, and road variables extracted and used to assess their influence on elk movement in and around Great Smoky Mountains National Park, Tennessee and North Carolina, 2018—December 2020.

Appendix: *Table A.5.*

Road Segment	WVCs	Target Species DR	Elk Crossing	Elk movement probability rank	Elk connectivity rank
3	4	NA	0	Above_average	Average
4	3	NA	0	Average	Above_average
5	3	NA	0	Above_average	Below_average
6	1	NA	0	Average	Above_average
7	6	12.59600614	0	Average	Average
8	7	10.98310292	0	Above_average	Average
9	5	8.481110254	0	Average	Average
10	3	19.73581974	0	Above_average	High
11	2	NA	0	Above_average	Below_average
12	3	18.88544892	0	Above_average	Below_average
13	6	NA	0	High	High
14	3	NA	0	High	Above_average
15	0	NA	0	Above_average	Above_average
16	3	11.7151608	0	High	Above_average
17	2	NA	0	High	High
18	2	NA	0	High	High
19	6	NA	0	High	Above_average
20	8	NA	0	Above_average	Above_average
21	1	NA	0	Below_average	Below_average
22	6	NA	0	Below_average	Average
23	2	7.503828484	8	Above_average	Average
24	4	12.76923077	58	Above_average	Average
25	3	NA	1	Below_average	Average
26	6	NA	7	Below_average	Average
27	3	NA	1	Below_average	Average
28	2	NA	0	Below_average	Below_average
29	9	2.786377709	3	Below_average	Average
30	0	NA	3	Average	Average
31	4	NA	5	Above_average	Average
32	4	18.91025641	15	Above_average	Average
33	6	5.733944954	0	Above_average	Average
34	2	14.20765027	0	Below_average	Average
35	3	NA	0	Average	Average
36	2	NA	0	Average	Below_average
37	1	NA	0	Low	Below_average
38	1	NA	0	Below_average	Below_average
39	5	21.88405797	0	Below_average	Below_average
40	4	NA	0	Below_average	Below_average
41	1	NA	0	Below_average	Average
42	2	NA	0	Below_average	Below_average
43	0	9.728183119	0	Below_average	Below_average
44	5	NA	0	Below_average	Below_average
45	0	NA	0	Below_average	Below_average
46	0	NA	0	Below_average	Below_average
47	1	NA	0	Below_average	Below_average
48	2	NA	0	Below_average	Below_average
49	1	NA	0	Below_average	Below_average
50	0	NA	0	Below_average	Below_average
51	0	NA	0	Below_average	Below_average
52	1	NA	0	Below_average	Below_average
53	2	NA	0	Below_average	Below_average
54	4	NA	0	Average	Average
55	3	8.138447147	0	Average	Average
56	5	NA	0	Above_average	Average
57	2	5.722460658	0	Above_average	Average
58	2	NA	0	Above_average	Average
59	2	NA	0	Above_average	Average
60	5	NA	0	Above_average	Average

Table A.5. Information for all 115 400-meter road segments from research sited in Chapter 1 and 2, including: total target species WVC, target species detection rates in cameras (where applicable), number of elk crossings, elk movement probability rank, and elk movement connectivity rank.

Appendix: *Table A.5. cont.*

60	5	NA	0	Above_average	Average
61	0	NA	0	Average	Average
62	5	NA	0	Above_average	Average
63	2	8.718330849	0	Above_average	Average
64	6	NA	0	Above_average	Average
65	2	5.595930233	0	Above_average	Average
66	3	NA	0	Average	Average
67	5	21.67266187	0	Average	Average
68	3	NA	0	Average	Average
69	2	10.75862069	0	Below_average	Average
70	2	NA	0	Average	Average
71	1	NA	0	Below_average	Average
72	2	NA	0	Below_average	Average
73	2	NA	0	Average	Average
74	5	NA	0	Below_average	Average
75	3	NA	0	Below_average	Below_average
76	2	NA	0	Below_average	Average
77	0	NA	0	Above_average	Average
78	3	NA	0	High	High
79	9	14	0	Above_average	Above_average
80	3	12.91012839	0	Above_average	Below_average
81	3	6.499261448	0	Average	Low
82	2	10.02277904	0	Above_average	Low
83	2	NA	0	Above_average	Low
84	1	NA	0	Above_average	Above_average
85	0	7.142857143	0	Above_average	Above_average
86	1	NA	0	Above_average	Above_average
87	2	NA	0	Above_average	Average
88	3	NA	0	Above_average	Low
89	1	NA	0	Above_average	Low
90	1	NA	0	Above_average	Low
91	0	23.75178317	0	Above_average	Low
92	3	22.82453638	0	Above_average	High
93	3	21.36431784	0	Above_average	Below_average
94	1	NA	0	Above_average	Above_average
95	1	NA	0	Above_average	Above_average
96	5	NA	0	Above_average	Average
97	1	NA	0	Above_average	Above_average
98	4	NA	0	Above_average	Average
99	4	13.69760479	0	Above_average	Average
100	2	NA	0	Above_average	Average
101	0	NA	0	Above_average	Above_average
102	1	11.91860465	0	Above_average	Average
103	1	NA	0	Above_average	Above_average
104	1	NA	0	Above_average	Above_average
105	0	NA	0	Above_average	Above_average
106	2	2.844950213	0	Above_average	Above_average
107	1	NA	0	Above_average	Average
108	2	NA	0	Above_average	Average
109	1	NA	0	Above_average	Average
110	2	NA	0	Above_average	Above_average
111	0	NA	0	Above_average	Above_average
112	3	NA	0	Above_average	Above_average
113	4	25.03566334	0	Above_average	Average
114	2	62.2013034	0	Above_average	Above_average
115	2	NA	0	Above_average	Average
116	2	NA	0	Above_average	Above_average
117	4	NA	0	High	High

Appendix: *Figure A.1.*

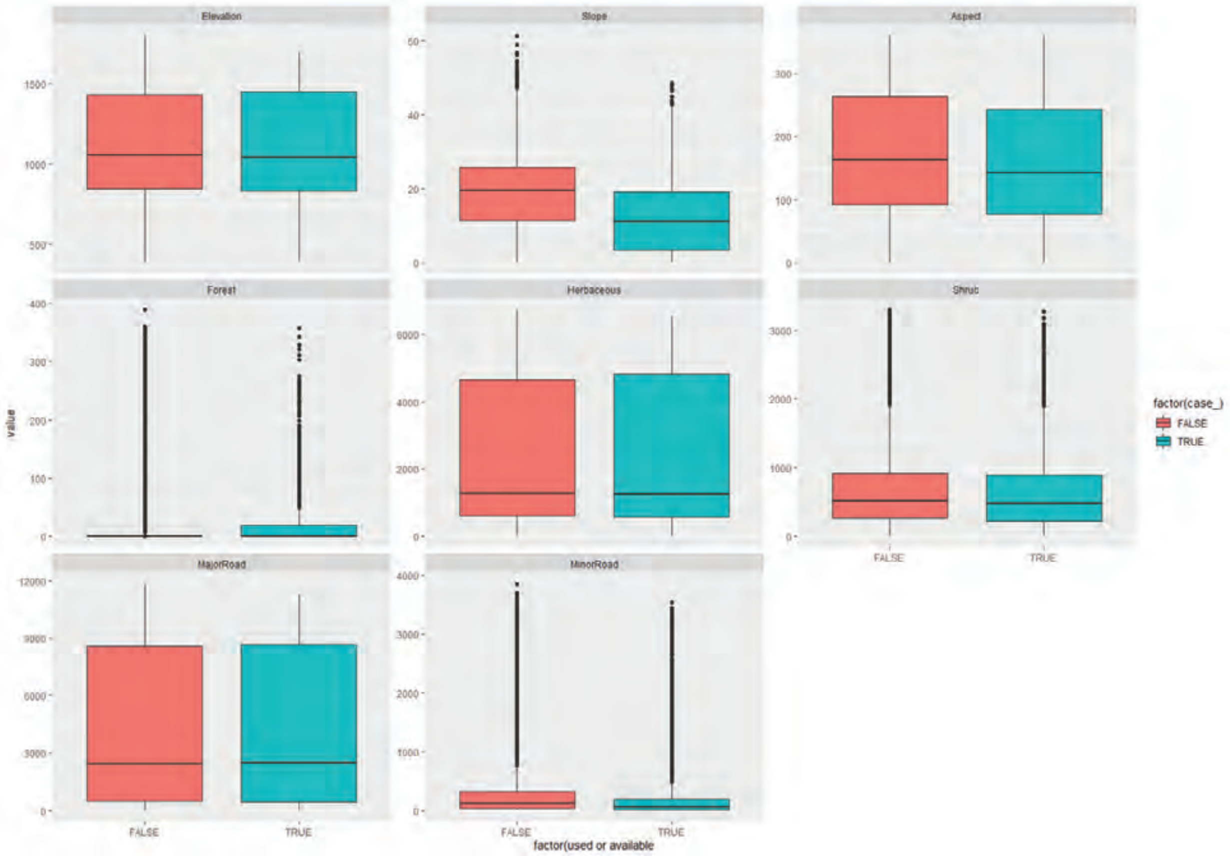
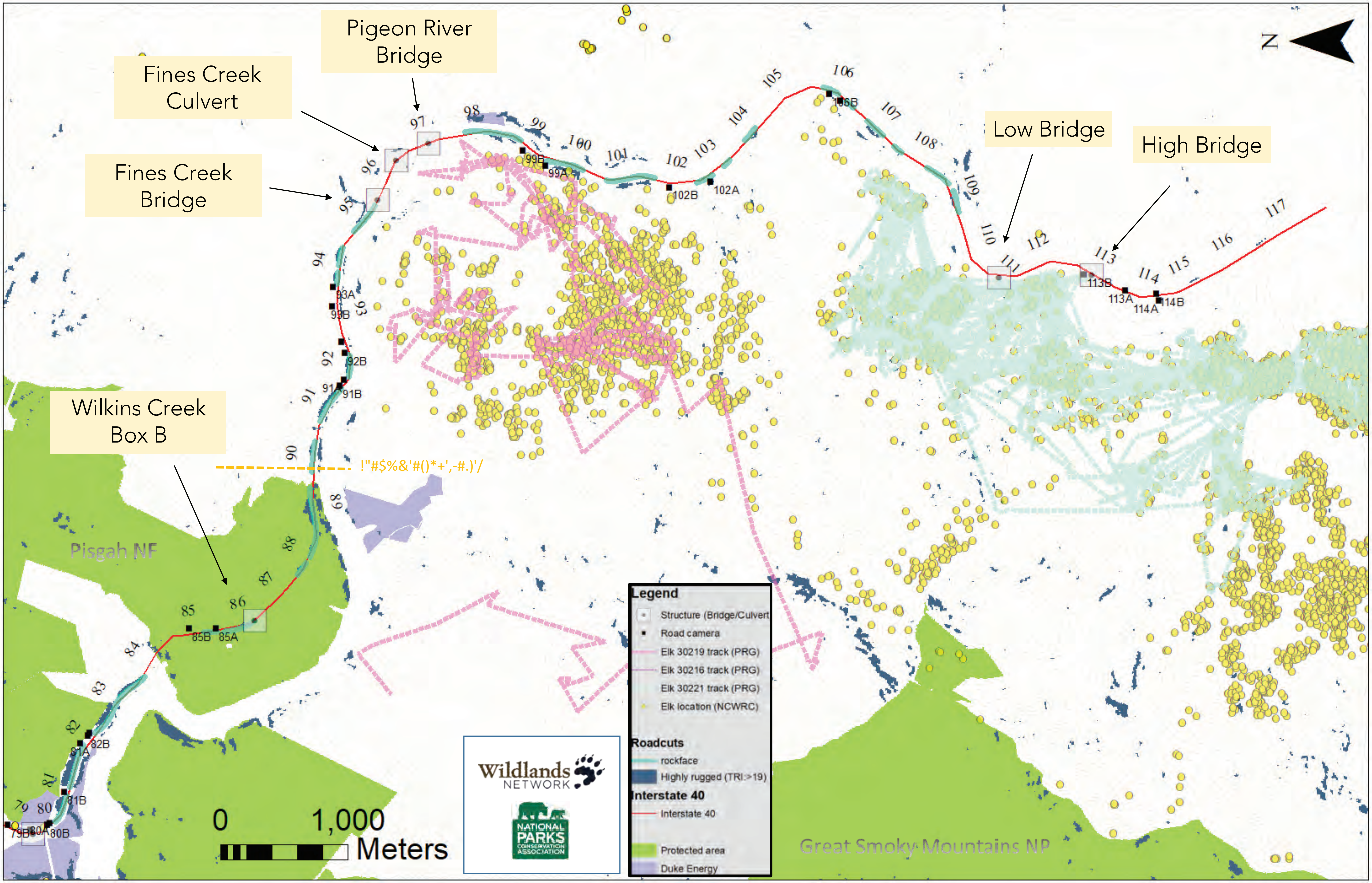
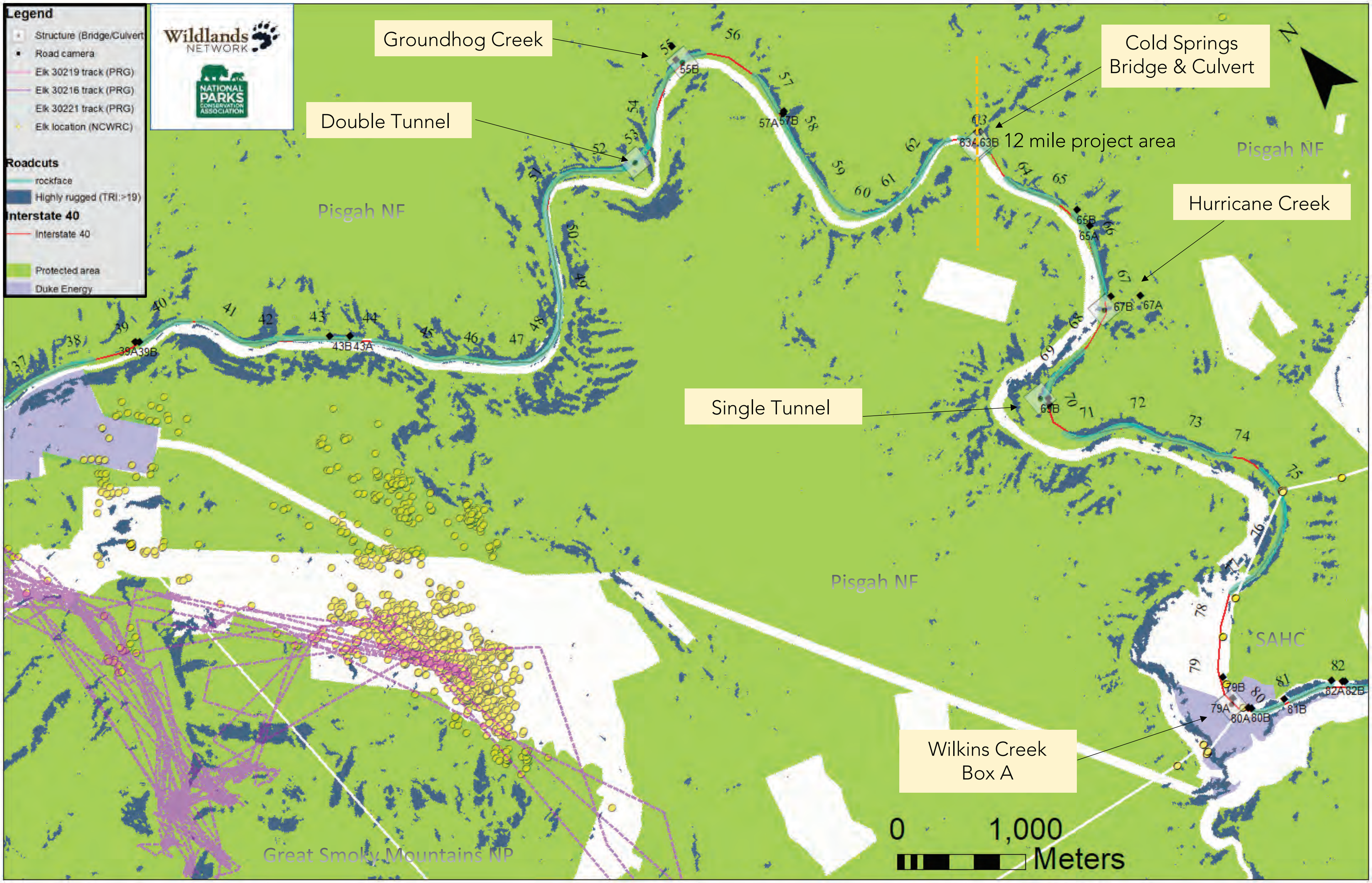


Figure A.1. Box plots showing mean and standard deviations measures for covariates in the top elk movement model. Covariates include elevation (meters), slope (degrees), aspect (degrees), distance to forest cover (meters), distance to herbaceous cover (meters), distance to shrub cover (meters), distance to major road (meters), distance to minor road (meters) extracted at the end of each “used” (True) and “available” (False) elk step to assess how elk select resources as they move through the landscape.

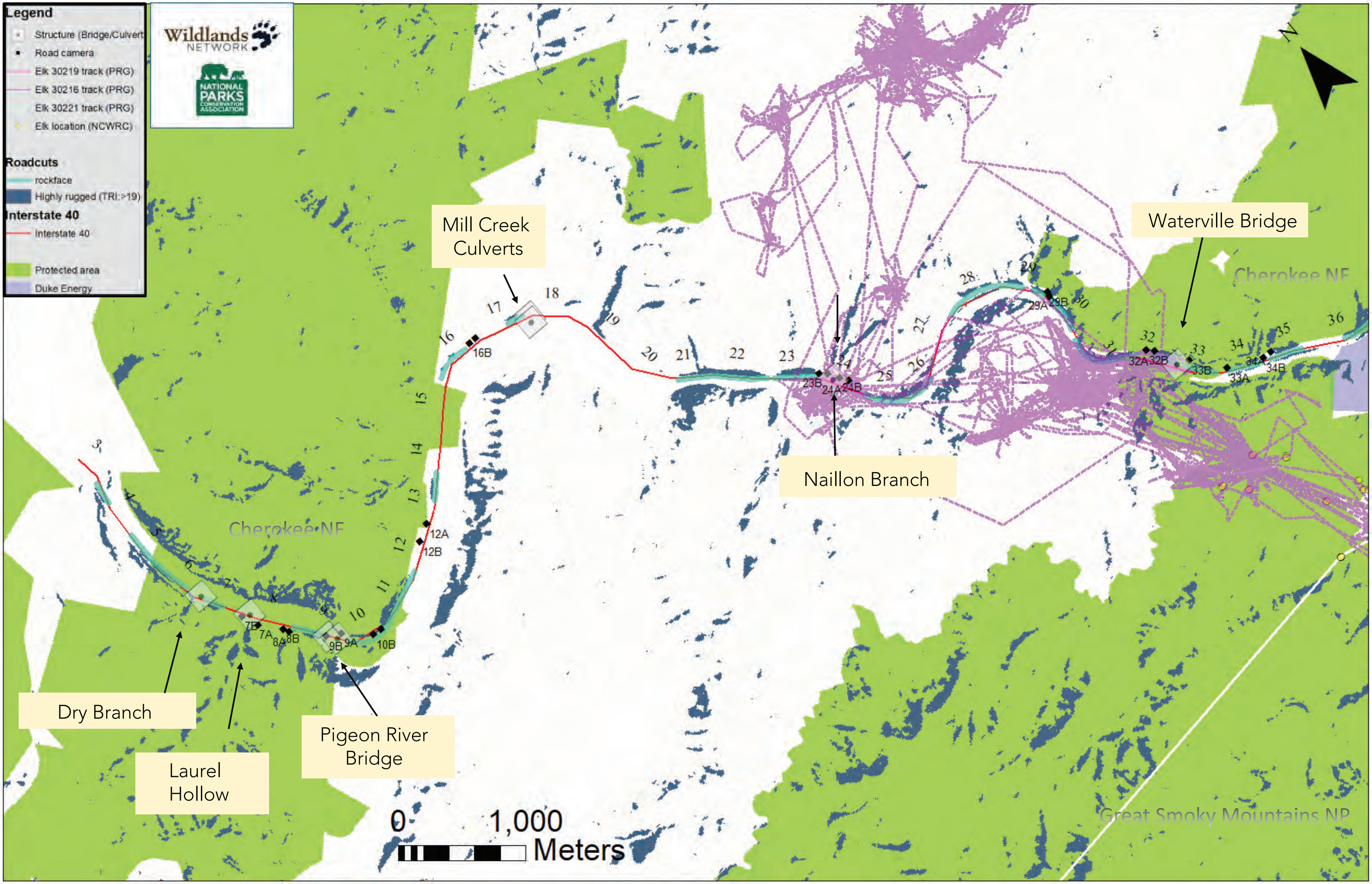
Appendix - Map Series B: *Map B1 South*



Appendix - Map Series B: *Map B2 Central*



Appendix - Map Series B: *Map B3 North*



References

Ascensão, F., P.S. Lucas, A. Costa, and A. Bager. 2017. The effect of roads on edge permeability and movement patterns for small mammals: a case study with Montane Akodont Landscape Ecology 32: 781-790.

Avgar, T., J. A. Baker, G. S. Brown, J. S. Hagens, A. M. Kittle, E. E. Mallon, M. T. McGreer, A. Mosser, S. G. Newmaster, B. R. Patterson, D. E. Reid, A. R. Rodgers, J. Shuter, G. M. Street, I. Thompson, M. J. Turetsky, P. A. Wiebe, and J. M. Fryxell. 2015. Space-use behaviour of woodland caribou based on a cognitive movement model. Journal of Animal Ecology 84:1059–1070.

Avgar, T., J. R. Potts, M. A. Lewis, and M. S. Boyce. 2016. Integrated step selection analysis: bridging the gap between resource selection and animal movement. Methods in Ecology and Evolution 7:619–630.

Avgar, T., R. Deardon, and J. M. Fryxell. 2013. An empirically parameterized individual based model of animal movement, perception, and memory. Ecological Modelling 251:158–172.

Belote R.T., M.S. Dietz, B.H. McRae, D.M. Theobald, M.L. McClure, G.H. Irwin, P.S. McKinley, J.A. Gage, and G.H. Aplet. 2016. Identifying corridors among large protected areas in the United States. PLOS One: https://doi.org/10.1371/journal.pone.0154223.

Bencin, H., S. Prange, C. Rose, and V. Popescu. 2019. Roadkill and space use data predict vehicle-strike hotspots and mortality rates in a recovering bobcat (Lynx rufus) population. Scientific Reports. 9:10.

Benoit, L., M. Hewison, A. Coulon, L. Debeffe, D. Gremillet, D. Ducros, B. Cargnelutti, Y. Chaval, and N. Morellet. 2019. Accelerating across the landscape: The energetic cost of natal dispersal in large herbivore. Journal of Animal Ecology 89:173-185.

Boyce, M. S., P. R. Vernier, S. E. Nielsen, and F. K. A. Schmiegelow. 2002. Evaluating resource selection functions. Ecological Modelling 157:281–300.

Braunstein, J. L., J. D. Clark, R. H. Williamson, and W. H. Stiver. 2020. Black Bear Movement and Food Conditioning in an Exurban Landscape. Journal of Wildlife Management 84: 1038-1050.

Burnham, K.P. and D.R. Anderson. 2002. Model Selection and Inference: A Practical Information-Theoretic Approach. 2nd Edition, Springer-Verlag, New York.

Campbell, T. A., B.R. Laseter, W.M. Ford, and K.V. Miller. 2004. Topographic home ranges of white-tailed deer in the central Appalachians. Southeastern Naturalist 3:645-652.

Carroll C., S.A. Parks, S.Z. Dobrowski, and D.R. Roberts. 2018. Climatic, topographic, and anthropogenic factors determine connectivity between current and future climate analogs in North America. Global Change Biology 24: 5318–5331.

Červinka, J., J. Riegert, S. Grill, and M. Salek. 2014. Large-scale evaluation of carnivore road mortality: the effect of landscape and local scale characteristics. Mammal Research 60:3.

Christianson, D. A., and S. Creel. 2007. A review of environmental factors affecting elk winter diets. Journal of Wildlife Management 71:164–176.

Ciuti, S., T. B. Muhly, D. G. Paton, A. D. McDevitt, M. Musiani, and M. S. Boyce. 2012. Human selection of elk behavioural traits in a landscape of fear. Proceedings of the Royal Society B: Biological Sciences 279:4407–4416.

References

Clark, J. D. 2004. Oak-black bear relationships in southeastern uplands. Pages 116-119 in Spetich, M. A. editor. Proceedings of the Upland Oak Ecology Symposium: history, current conditions, and sustainability. USDA Forest Service General Technical Report SRS-73. Southern Forest Research Station, Asheville, NC, USA.

Clevenger, A. P., and M P. Huijser. 2011. Wildlife Crossing Structure Handbook: Design and Evaluation in North America. Federal Highway Administration Report: FHWA-CFL/TD-11-003

Clevenger, A. P., B. Chruszcz, and K. E. Gunson. 2001. Highway Mitigation Fencing Reduces Wildlife Vehicle Collisions. Wildlife Society Bulletin 29: 646-653

Coelhoet, I. P., F.Z. Teixeira, P. Colombo, et al. 2012. Anuran road-kills neighboring a peri-urban reserve in the Atlantic Forest, Brazil. Journal of Environmental Management 112:17-26.

Cushman, S. A., E. L. Landguth, and C. H. Flather. 2013. Evaluating population connectivity for species of conservation concern in the American Great Plains. Biodiversity and Conservation 22:2583–2605.

Dániel-Ferreira, J., Å. Berggren, J. Wissman, and E. Öckinger. 2021. Road verges are corridors and roads barriers for the movement of flower-visiting insects. Ecography 2022.

Dewitz, J. 2019. National Land Cover Database (NLCD). 2016. Products: U.S. Geological Survey.

Dickson, B., J. Jenness, and P. Beier. 2005. Influence of vegetation, topography, and roads on cougar movement in Southern California. Journal of Wildlife Management, 69: 264-276.

Dodd, N. L., J. W. Gagnon, A. L. Manzo, and R. E. Schweinsburg. 2007. Video surveillance to assess highway underpass use by elk in Arizona. Journal of Wildlife Management 71:637–645.

Donaldson, B.M., and K.M. Elliott. 2021. Enhancing existing isolated underpasses with fencing reduces wildlife crashes and connects habitat. Human-Wildlife Interactions 15: https://digitalcommons.usu.edu/hwi/vol15/iss1/20.

Dormann, C.F., J.M. McPherson, M.B. Araújo, R. Bivand, J. Bolliger, G. Carl, R. G. Davies, R. A. Hirzel et al. 2007. Methods to account for spatial autocorrelation in the analysis of species distributional data: a review. Ecography 30: 609–628.

Epps, C.W., P. J Palsbøll, J.D. Wehausen, G. K. Roderick, R.R. Ramey, and D.R. McCullough. 2005. Highways block gene flow and cause a rapid decline in genetic diversity of desert bighorn sheep.

Fahrig L. and T. Rytwinski. 2009. Effects of roads on animal abundance: an empirical review and synthesis. Ecology and Society 14: 2.

Forester, J. D., A. R. Ives, M. G. Turner, D. P. Anderson, D. Fortin, H. L. Beyer, D. W. Smith, and M. S. Boyce. 2007. State–space models link elk movement patterns to landscape characteristics in Yellowstone National Park. Ecological Monographs 77:285–299.

Forman, R.T. and L.E. Alexander. 1998. Roads and their major ecological effects. Annual Review of Ecology and Systematics 29:207-231.

Frair, J. L., E. H. Merrill, D. R. Visscher, D. Fortin, H. L. Beyer, and J. M. Morales. 2005. Scales of movement by Elk (Cervus elaphus) in response to heterogeneity in forage resources and predation risk. Landscape Ecology 20:273–287.

References

Franke, A., T. Caelli, and R. J. Hudson. 2004. Analysis of movements and behavior of caribou (Rangifer tarandus) using hidden Markov models. Ecological Modelling 173:259–270.

Fryxell, J. M., M. Hazell, L. Börger, B. D. Dalziel, D. T. Haydon, J. M. Morales, T. McIntosh, and R. C. Rosatte. 2008. Multiple movement modes by large herbivores at multiple spatiotemporal scales. Proceedings of the National Academy of Sciences 105:19114–19119.

Gagnon, J.W., N.L. Dodd, K.S. Ogren, and R.E. Schweinsburg. 2011. Factors associated with use of wildlife underpasses and importance of long-term monitoring. Journal of Wildlife Management 75: 1477-1487.

Gagnon, J.W., C.D. Loberger, S. C. Sprague, S. R. Boe, K. S. Ogren, and R. E. Schweinsburg. 2016. Creating Multi-Use Highway Structures with Retrofitted Fencing to Reduce Collisions with Elk on Interstate 17. Report: FHWA-AZ-16-689. Phoenix: Arizona Department of Transportation.

Garrote G., J. Fernández-López, G. López, G. Ruiz, and M.A. Simón 2018. Prediction of Iberian lynx road–mortality in southern Spain: a new approach using the MaxEnt algorithm. Animal Biodiversity Conservation 2:217-226.

Gillies, C. S., and C. C. St. Clair. 2010. Functional responses in habitat selection by tropical birds moving through fragmented forest. Journal of Applied Ecology 47:182–190.

Gillies, C. S., M. Hebblewhite, S. E. Nielsen, M. A. Krawchuk , C. L. Aldridge, J. L. Frair, D. J. Saher, C. E. Stevens, and C. L. Jerde. 2006. Application of random effects to the study of resource selection by animals. Journal of Animal Ecology 75:887–898.

Glista, D.J., T.L. DeVault, and J.A. DeWoody. 2009. A review of mitigation measures for reducing wildlife mortality on roadways. Landscape and Urban Planning 91: 1-7.

Gunson, K., G. Mountrakis, and L.J. Quackenbush 2011. Spatial wildlife-vehicle collision models: a review of current work and its application to transportation mitigation projects. Journal of Environmental Management 92:1074-1082.

Haddad, N., A.B. Lars, J. Colbert, K.F. Davies, A. Gonzalez, R.D. Holt, R.E. Lovejoy, J.O. Sexton, M.P Austin et al. 2015. Habitat fragmentation and its lasting impact on Earth's ecosystems. Science Advances DOI: 10.1126/sciadv.1500052.

Hillard, E. M. 2013. Elk (Cervus elaphus) habitat selection in Great Smoky Mountains National Park. Thesis, Western Carolina University, Cullowhee, USA.

Holderegger, R. and M. Di Giulio. 2010. The genetic effects of roads: A review of empirical evidence. Basic and Applied Ecology 11:522–531.

Huijser, M.P., J. Fuller, M.E. Wagner, A. Hardy, and A.P. Clevenger. 2007. Animal-vehicle collision data collection: a synthesis of highway practice. National Cooperative Highway Research Program Synthesis 370. Transportation Research Board, Washington, DC, USA.

Huijser, M. P., P. T. McGowen, J. Fuller, A. Hardy, and A. Kociolek. 2008. Wildlife-vehicle collision reduction study: report to Congress. U.S. Department of Transportation, Federal Highway Administration, McLean, Virginia, USA.

Huijser, M.P., J.W. Duffield, A.P. Clevenger, R.J. Ament, and P.T. McGowen. Cost-benefit analysis of mitigation measures aimed at reducing collisions with large ungulates in the United States and Canada: A decision support tool. Ecology and Society 14:15 (http://www. ecologyandsociety.org/vol14/iss2/art15/)

References

Johnson, C.J., S.E. Nielsen, E.H. Merrill, T.L. McDonald, and M. S. Boyce. 2006. Resource selection functions based on use–availability data: theoretical motivation and evaluation methods. Journal of Wildlife Management 70:347-357.

Karelus D. L., J. W. McCown, B. K. Scheick, V. van de Kerk, B. M. Bolker, M. K. 2019. Incorporating movement patterns to discern habitat selection: black bears as a case study. Wildlife Research 46:76–88.

Keating, K.A. and S. Cherry. 2004. Use and interpretation of logistic regression in habitat-selection studies. Journal of Wildlife Management 68:774-789.

Koper N., and M. Manseau. 2009. Generalized estimating equations and generalized linear mixed-effects models for modelling resource selection. Journal of Applied Ecology 46:590–599.

Lachin, J.M. 2008. Sample size evaluation for a multiply matched case-control study using the score test from a conditional logistic (Discrete Cox PH) regression model. Statistics in Medicine: 2509-2523.

Landau, V., V. Shah, R. Anantharaman, and K. Hall. 2021. Omniscape.jl: Software to compute omnidirectional landscape connectivity. Journal of Open Source Software 6:2829.

Lashley, M. A., C. A. Harper, G. E. Bates, and P. D. Keyser. 2011. Forage availability for white-tailed deer following silvicultural treatments in hardwood forests. The Journal of Wildlife Management 75:1467–1476.

Litvaitis, J. and J. Tash. 2008. An approach toward understanding wildlife-vehicle collisions. Environmental Management 42: 688-697.

Lee, T.S., K. Rondeau, R. Schaufele, A.P. Clevenger, and D. Duke. 2021. Developing a correction factor to apply to animal–vehicle collision data for improved road mitigation measures. Wildlife Research 48:501–510.

Lewis, J. S., J. L. Rachlow, E. O. Garton, and L. A. Vierling. 2007. Effects of habitat on GPS collar performance: using data screening to reduce location error. Journal of Applied Ecology 44:663–671.

Long, E. S., D.R. Diefenbach, B.D. Wallingford, and C.S. Rosenberry. 2010. Influence of roads, rivers, and mountains on natal dispersal of white-tailed deer. Journal of Wildlife Management 74:1242–1249.

Loro, M., E. Ortega, R. M. Arce, and D. Geneletti. 2015. Ecological connectivity analysis to reduce the barrier effect of roads. an innovative graph-theory approach to define wildlife corridors with multiple paths and without bottlenecks. Landscape and Urban Planning 139:149–162.

Loss, S.R., T. Will, and P.P. Marra. 2014. Estimation of bird-vehicle collision mortality on U.S. roads. Journal of Wildlife Management 78:763–771.

McRae, B. H., S. A. Hall, P. Beier, and D. M. Theobald. 2012. Where to restore ecological connectivity? detecting barriers and quantifying restoration benefits. PLoS ONE 7.

Michelot, T., R. Langrock, and T. A. Patterson. 2016. MoveHMM: An R package for the statistical modelling of animal movement data using hidden Markov models. Methods in Ecology and Evolution 7:1308–1315.

Millspaugh, J. J., R. J. Woods, K. E. Hunt, K. J. Raedeke, G. C. Brundige, B. E. Washburn, and S. K. Wasser. 2001. Fecal glucocorticoid assays and the physiological stress response in elk. Wildlife Society Bulletin 899-907.

References

Morales, J. M., D. T. Haydon, J. Frair, K. E. Holsinger, and J. M. Fryxell. 2004. Extracting more out of relocation data: building movement models as mixtures of random walks. Ecology 85:2436–2445.

Morales, J. M., P. R. Moorcroft, J. Matthiopoulos, J. L. Frair, J. G. Kie, R. A. Powell, E. H. Merrill, and D. T. Haydon. 2010. Building the bridge between animal movement and population dynamics. Philosophical Transactions of the Royal Society B: Biological Sciences 365:2289–2301.

Murrow, J. L., J. D. Clark, and E. K. Delozier. 2009. Demographics of an experimentally released population of elk in Great Smoky Mountains National Park. Journal of Wildlife Management 73:1261–1268.

Neumann, W., G. Ericsson, H. Dettki, N. Bunnefeld, N.S. Keuler, D.P. Helmers, and V.C. Radeloff. 2012. Difference in spatiotemporal patterns of wildlife road-crossings and wildlife–vehicle collisions. Biological Conservation 145:70-78.

Ng, S. J., J.W. Dole, R.M. Sauvajot, S.D. Riley, and T.J. Valone. 2004. Use of highway undercrossings by wildlife in southern California. Biological Conservation 115:499-507.

North Carolina Wildlife Resources Commission (NCWRC). 2015. North Carolina Wildlife Action Plan. Raleigh, NC.

Noss, R., A. Dobson, R. Baldwin, P. Beier, C. Davis, D. Dellasala, J. Francis, H. Locke et al. 2012. Bolder Thinking for Conservation. The Journal of the Society for Conservation Biology. 26:1-4.

Noyce, K.V., and D.L. Garshelis. 1997. Influence of natural food abundance on black bear harvests in Minnesota. Journal of Wildlife Management 61:1067-107.

Olsson, M.O. and P. Widen. 2008. Effects of highway fencing and wildlife crossing on moose Alces alces movements and space use in southwestern Sweden. Wildlife Biology 14:111-117.

Parsons, A. E., W. McShea, T.D. Forrester, and R.Kays. 2017. Do occupancy or detection rates from camera traps reflect deer density? Journal of Mammalogy 5: 1-11.

Peek, F.W. and E.D. Bellis. 1969. Deer movements and behavior along an interstate highway. Highway Research News 36:36-42.

Pelton, M. R. 1989. The impacts of oak mast on black bears in the southern Appalachians. Pages 7-11 in C. E. McGee, editor. Proceedings of the workshop: Southern Appalachian mast management. University of Tennessee, Knoxville, USA.

Polak, T., Rhodes, R., Jones, D., Possingham, H.P. 2014. Optimal planning for mitigating the impacts of roads on wildlife. Journal of Applied Ecology 51:726-734.

Proctor, M. F., B.N. McLellan, G.B. Stenhouse, G. Mowat, C.T. Lamb, and M.S. Boyce. 2020. Effects of roads and motorized human access on grizzly bear populations in British Columbia and Alberta, Canada. Ursus 30:16-39.

R Core Team. 2019. R: a language and environment for statistical computing. https://cran.r-project.org/.

Ramp, D., J. Caldwell, K.A. Edwards, D. Warton, and D.B. Croft. 2005. Modelling of wildlife fatality hotspots along the Snowy Mountain Highway in New South Wales, Australia. Biological Conservation 126: 474-490.

References

Rowland, M.M., M.J. Wisdom, and B.K. Johnson. 2000. Elk distribution and modeling in relation to roads. Journal of Wildlife Management 64: 672-684.

Ryan, C. W., J. C. Pack, W. K. Igo, and A. Billings. 2007. Influence of mast production on black bear non-hunting mortalities in West Virginia. Ursus 18:46-53.

Russo L.F., R. Barrientos, M. Fabrizio, M. Di Febbraro, and A. Loy. 2020. Prioritizing road- kill mitigation areas: a spatially explicit national-scale model for an elusive carnivore. Divers of Distribution 26:1093-1103.

Rytwinski, T. and L. Fahrig. 2011. Reproductive rate and body size predict road impacts on mammal abundance. Ecological Applications 21:589–600.

Rytwinski T. and L. Fahrig. 2012. Do species life history traits explain population responses to roads? A meta-analysis. Biol. Conserv. 147, 87–98. (doi:10. 1016/j.biocon.2011.11.023)

Rytwinski T. and L. Fahrig. 2015. The impacts of roads and traffic on terrestrial animal populations. In Handbook of road ecology: editors, R. van der Ree, D.J. Smith, C. Grilo, pp. 237–246, 1st edition. Chechester, UK: JohnWiley & Sons, Ltd.

S.M. Santos, T. Marques, A. Lourenço, et al. 2015. Sampling effects on the identification of roadkill hotspots: implications for survey design. Journal of Environmental Management 162:87-95.

Sawyer, H., C. Lebeau, and T. Hart. 2013. Mitigating roadway impacts to migratory mule deer - a case study with underpasses and continuous fencing. Wildlife Society Bulletin 36: 492- 498.

Sawyer, H., P. A. Rodgers, and T. Hart. 2016. Pronghorn and mule deer use of underpasses and overpasses along U.S. Highway 191. Wildlife Society Bulletin 40:211-216.

Shepard, D.B., A.R. Kuhns, M.J. Dreslik, and C.A. Phillips. 2008. Roads as barriers to animal movement in fragmented landscapes. Animal Conservation 11:288-296.

Shilling, F., W. Collinson, M. Bil, D. Vercayie, F. Heigl, S.E. Perkins, and S. MacDougall. 2020. Designing wildlife-vehicle conflict observation systems to inform ecology and transportation studies. Biological Conservation 251.

Signer, J., J. Fieberg, and T. Avgar. 2019. Animal movement tools (amt): R package for managing tracking data and conducting habitat selection analyses. Ecology and Evolution 9:880–890.

Tambling, C. J., L. Minnie, J. Meyer, E. W. Freeman, R. M. Santymire, J. Adendorff, and G. H. Kerley. 2015. Temporal shifts in activity of prey following large predator reintroductions. Behavior Ecology and Sociobiology 69:1153-1161.

Teixeira F.Z., A. Kindel, S.M. Hartz, S. Mitchell, and L. Fahrig. 2017 When road-kill hotspots do not indicate the best sites for road-kill mitigation. Journal of Applied Ecology 54:1544-1551.

Theobald D.M., S.E. Reed, K. Fields, and M. Soulé. 2012. Connecting natural landscapes using a landscape permeability model to prioritize conservation activities in the United States. Conservation Letters 5:123-133.

Theobald, D. M., J. R. Miller, and N. T. Hobbs. 1997. Estimating the cumulative effects of development on wildlife habitat. Landscape and Urban Planning 39:25-36.

References

Thurfjell, H., S. Ciuti, and M. S. Boyce. 2014. Applications of step-selection functions in ecology and conservation. Movement Ecology 2:1-12

U.S. Geological Survey. 2019. 3D Elevation Program 1-Meter Resolution Digital Elevation Model, accessed October 23, 2020 at URL: https://www.usgs.gov/core-science-systems/ngp/3dep/data-tools

U.S. Forest Service (USFS) 2019. Twelve Mile Project Environmental Assessment. Pisgah National Forest, Appalachian District, Mars Hill, NC.

van der Grift, E. A., and R. Pouwels. 2006. Restoring habitat connectivity across transport corridors: identifying high-priority locations for de-fragmentation with the use of an expert based model. In: Davenport J, Davenport JL (eds) The ecology of transportation: managing mobility for the environment. Springer, Dordrecht, pp 205-231.

Whittaker, R. H. 1956. Vegetation of the Great Smoky Mountains. Ecological Monographs 26:1-80.

White, C. G., P. Zager, and M. W. Gratson. 2010. Influence of predator harvest, biological factors, and landscape on Elk Calf Survival in Idaho. Journal of Wildlife Management 74:355–369.

Zeller, K. A., D. W. Wattles, and S. Destefano. 2020. Evaluating methods for identifying large mammal road crossing locations: black bears as a case study. Landscape Ecology 35:1799–1808.

Zuur, A. F. et al. 2017. Beginner's guide to spatial, temporal and spatial-temporal ecological data analysis with R-INLA. – Highland Statistics, Newburgh, UK.

Supplemental Materials

Additional materials can be found at the following links:

Supplemental Materials A: This report includes recommendations for significantly enhancing wildlife connectivity under five Interstate 40 bridges proposed for replacement along the Pigeon River Gorge, North Carolina.

Supplemental Materials B: This report comprises the observations and engineering considerations associated with the potential to improve wildlife connectivity arising from the field review of five existing bridges on the I-40 within Pigeon Gorge area slated for rehabilitation by North Carolina Department of Highways.


Wildlands
NETWORK
NATIONAL
PARKS
CONSERVATION
ASSOCIATION