Appendix I

Annotated Bibliography

Summary

This annotated bibliography reviews literature focused on improving wildlife habitat and movement connectivity in areas affected by major roadways. It also summarizes methods employed by transportation departments to facilitate wildlife movement across roads while maintaining traffic safety. Sources include peer-reviewed journal articles, agency documents, and monitoring report summaries. The information is organized into focal themes for easy navigation and quick reference. Not all citations included in this annotated bibliography appear in the main body of the ODECPP report.

Highway-based Habitat Fragmentation

Richard T. T. Forman & Lauren E. Alexander, *Roads and Their Major Ecological Effects*, 29 Ann. Rev. Ecosystem Syst. 207 (1998).

Road effects are prominent across landscapes where roadways exist. In this review, the authors describe worldwide impacts of roads on the natural environment and emerging research in the field of road ecology. Specific focus was given to work that occurred in the Netherlands, Australia, and the United States. Five primary topics were selected as pertinent to roads and ecology: 1. roadsides and adjacent strips, 2. road and vehicle effects on wildlife populations, 3. water, sediment, chemicals, and streams, 4. the road network, and 5. transportation policy and planning with subtopics pertaining to most of the main topics. The review of work presented here highlights the many impacts of roads, including habitat fragmentation and road-based barrier effects. The authors indicate that all roads either filter or act as complete barriers to wildlife movement. Further, increasing traffic density and road width are identified as limiting factors to wildlife movement. Roads may also generate subpopulations due to habitat bisection by roadways, which can lead to genetic-level effects. This work finalizes with a discussion of road-effect zones which describes the surrounding area ecologically altered by a given road. Often the ecological effects of roads travel much further than the road itself; however, varies based on environmental and road-based factors.

Rodney van der Ree, Daniel J. Smith & Clara Grilo, *The Ecological Effects of Linear Infrastructure and Traffic: Challenges and Opportunities of Rapid Global Growth*, in *Handbook of Road Ecology* 1 (Rodney van der Ree, Daniel J. Smith & Clara Grilo eds., 2015).

Modern transportation infrastructure, like roads, generate multiple impacts on ecosystems and their inhabitants. Road-based influences on natural systems are anticipated to persist with the continued expansion of roads, vehicles, and vehicular travel. In this review road ecology review, the authors specify that impacts of roads are generally not constrained to the road itself and often alter the surrounding habitat through chemical, noise, and light pollution; habitat modification and fragmentation; spread of invasive species; and direct mortality to animals. The size *road-effect* zone is driven multiple factors such as road characteristics, surrounding landscape, wind speed and direction, traffic, and species traits. Road effects can travel well-beyond a roadway; however, impacts are generally more concentrated adjacent to the road. For wildlife, roads can impact individuals and populations as well as the landscapes they inhabit; however, the authors identified and discussed the primary ways roads impact wildlife which include habitat loss, habitat degradation, filter or barrier to movement, and direct mortality. Roads can also act as attractants or cause avoidance, and in some cases act as corridors for wildlife and invasive species movement. The authors discuss that wildlife-vehicle collisions are an added cost to society because of vehicle damage repairs, human injury, and death. While some road impacts can be mitigated, the authors emphasize that not all issues can be resolved especially when considering both direct and indirect effects of roads on wildlife. The field of road ecology aims to determine road-based impacts on ecosystems; however more work and collaboration are necessary to describe the full-suit of road impacts, as well as incorporate research-based findings into road design and planning.

Ungulate-Vehicle Collisions – Human and Wildlife Safety

Anthony P. Clevenger et al., *Context-Dependent Effects on Spatial Variation in Deer-Vehicle Collisions*, 6 Ecosphere 1 (2015).

The authors tested factors that influence wildlife-vehicle collisions (WVCs) in five contiguous study areas in the Canadian Rocky Mountains. Objectives of the study included evaluating broad scale versus localized impacts on WVC frequency as well as determining whether WVC patterns in areas with similar biophysical characteristics were comparable. The study focused on WVCs involving two species of deer, mule deer (*Odocoileus hemionus*) and white-tailed deer (*Odocoileus virginianus*). The best fitting model for large scale factors influencing WVCs included road width, distance to barrier, cover, topography, distance to water (drainage) and distance to human disturbance. Local scale factors driving WVCs varies between locations, with distance to water predicting WVCs in three of the five locations. The authors concluded that factors influencing WVCs are context specific (e.g., idiosyncrasies of place), and that predicting WVC probability requires data from specific locations. Drainages may increase localized WVCs by concentrating animals in specific locations.

Priscilla K. Coe et al., *Identifying Migration Corridors of Mule Deer Threatened by Highway Development*, 39 Wildl. Soc'y Bull. 256 (2015).

Many sources of information can inform the placement of wildlife crossing structures, including deer-vehicle collisions (DVCs). The objectives of this study were to predict locations for wildlife passage projects on U.S. South Highway 97 (US-97) and State Highway 31 (OR 31) in south central-Oregon by identifying the relationship between migratory corridors and deer-vehicle collisions measured as carcass counts. The study also investigated factors that influence DVCs on the two highways investigated. Utilization distributions (UDs) produced from Brownian Bridge Movement Models for south-central Oregon mule deer (*Odocoileus hemionus*) herds were used to inform migratory corridor presence. Landscape models were generated to determine the influence of spatial covariates on carcass presence. The authors determined that there was strong correlation between migratory pathways and DVCs on both highways, but the effect was stronger for US-97 (r=0.97). Covariates varied in their strength and effect to predict DVCs on the individual highways. However, a quadratic term for annual average daily traffic was found to have a negative effect on DVCs, indicating a threshold wherein DVCs decrease due to increasing traffic volume. Highest ranked models for both highways included UDs independently, and UDs in addition to AADT. This work indicates that migratory corridors and other factors like AADT are useful predictors of DVCs on US-97 and OR 31 and can be used to identify locations for wildlife passage projects on central Oregon highways.

Kari E. Gunson, Giorgos Mountrakis & Lindi J. Quackenbush, *Spatial Wildlife-Vehicle Collision Models: A Review of Current Work and Its Application to Transportation Mitigation Projects*, 92 J. Envtl. Mgmt. 1074 (2011).

The authors reviewed 24 published studies that examined predictors of WVCs to identify common and novel factors among studies. Comparison across studies was problematic due to variation in methodological approaches, including pre-and post-model tests as well as experimental design. Covariates that measured habitat attributes were significant predictors of ungulate vehicle collisions, although several different measures of habitat were utilized. Roadside vegetation also impacted collision risk for ungulates, although variability in the direction of the response between studies makes generalization of the relationship to WVC collision risk difficult. In essence, the authors found that factors influencing WVC risk are context dependent and interact in ways that can be difficult to predict at broader landscape scales. The authors recommend that localized analyses should include predictors that match the spatial and temporal scale of species movement and biological characteristics.

Marcel P. Huijser et al., *Wildlife-Vehicle Collision Reduction Study: Report to Congress* (Western Transp. Inst. 2008).

Highways bisect wildlife habitat, often generating wildlife-vehicle collisions, which are a concern for human safety and animal persistence. It is estimated that there are between 1-2 million collisions with large animals in the U.S., with nearly 90% involving deer species. The purpose of this report was to highlight WVCs as a growing national issue in the United States and discuss the various economic and wildlife related impacts, potential methods to mitigate WVCs, design and planning considerations, and knowledge gaps. One of the primary challenges to mitigating WVCs highlighted by the authors was data precision. As such, they called for more precise data to highlight areas requiring mitigation action. The report concludes that the most effective forms of mitigation for WVCs were wildlife exclusion fencing (with and without wildlife crossings), long tunnels and bridges, and animal detection systems. However, the author indicate that site-specificity and local factors are important to consider when designing and implementing a wildlife passage project.

Land-Use Change

Heather E. Johnson et al., *Increases in Residential and Energy Development Are Associated with Reductions in Recruitment for a Large Ungulate*, 23 Global Change Biology 578 (2017).

In this study, the authors performed a 20-year analysis (1980-2010) of anthropogenic land-use change and annual weather condition variation in western Colorado. Land-use change included residential and energy resource extraction which was determined to reduce yearly mule deer (*Odocoileus hemionus*) fawn recruitment rates by 0.5 fawns per 100 adult does when present in mule deer habitat. Over one million acres were impacted by residential development during this time, 96% of which were exurban or rural. Predicted fawn recruitment was highest when winter precipitation and energy development were low. Residential development overlapped mule deer winter range more than summer range, and it had the largest negative impact on fawn recruitment, followed by energy development and weather-based variables.

Jean L. Polfus & Paul R. Krausman, *Impacts of Residential Development on Ungulates in the Rocky Mountain West*, 36 Wildl. Soc'y Bull. 647 (2012).

A literature review of residential development effects on ungulates revealed that the biological impacts of exurban development are driven by multiple variables, which can be cumulative. The magnitude of impacts depends on the size of the developed area and the timespan of disturbance. Declines in ungulate recruitment are not immediate and may be better detected using long-term data and large spatial scales. Development outside urban areas have multi-scale impacts on ungulate demographics, behavior, physiology, and interspecific relationships, which alter ecological communities. Development within mule deer (*Odocoileus hemionus*) winter range increases stress on lactating females, reducing reproductive success. The authors call for multi-jurisdictional studies involving stakeholder partnerships, long-term population studies, adaptive management, and collaboration between scientists, managers, and planners to create development policies that address ungulate requirements.

Carrie A. Schloss et al., *"No Regrets" Pathways for Navigating Climate Change: Planning for Connectivity with Land Use, Topography, and Climate*, 32 Ecological Applications e02468 (2022).

Scientists and land-use planners can identify and protect lands that provide connectivity between present-day natural lands and predicted similar areas under future climate scenarios to facilitate wildlife movement and adaptation in a changing climate. This study uses Circuitscape to model linkages and microclimates, wildlife range shifts, and topographic diversity. These "no regrets" pathways tend to follow an east-west pattern in California, and some pathways are expected to follow riparian valleys under future climate scenarios. Topographic diversity was higher in models that supported future movement; however, channelized areas such as river valleys or flat lowlands were important links (sometimes the only link) between natural areas. This study did not model riparian corridors, but some climate links followed the river valleys, nonetheless. Models showed a high overlap between present-day channelized areas and climate linkages (47% overlap in one model). Differences in spatial resolution between fine-scale topographic diversity and coarse-scale climate projections may miss important microclimates, as soil and terrain are constant over time. Current land use, topography, and future climate scenarios can inform proactive planning decisions to enhance connectivity between present and future ecosystems, facilitate adaptation and movement of species, maintain biodiversity, and support ecosystem resilience.

Justin P. Suraci et al., *Disturbance Type and Species Life History Predict Mammal Responses to Humans*, 27 Global Change Biology 3718 (2021).

This analysis of a wide range of mammal species and ecosystems emphasized consideration of species-specific responses to human activities when developing conservation strategies. Mammal response to human disturbance varied with the type and scale of disturbance and individual species traits, behavior, and ecological preferences. It is important to distinguish between human presence on the land (e.g., camping) and human footprint (e.g., development, resource extraction). Human presence negatively impacted 17% of species, including elk (*Cervus elaphus*); however, human presence increased mule deer use of areas. Human footprint negatively impacted 25% of mammal species studies. Mule deer (*Odocoileus hemionus*) intensity of use increased with human footprint until a specific threshold, wherein intensity of use decreased. Higher human footprint favors small-bodied, fast-reproducing mammals with small ranges.

David M. Theobald, *A General Model to Quantify Ecological Integrity for Landscape Assessments and US Application*, 28 Landscape Ecology 1959 (2013).

The author developed a quantitative model of ecological integrity for landscape-level assessments. The model building exercise involved three steps: 1. distinguishing between the magnitude and spatial extent of a given impact at a given location, 2. use of an existing framework that catalogues stressors into a comprehensive list, and 3. combining multiple stressor layers into a single measure of human modification from low to high. Urban and residential density and agricultural activities were dominant drivers of human impacts, as was distance from major roads (in over half of the country).

Impacts to and Conservation of Ungulate Movement (Climate Change & Land Use Change)

Gregory J. M. Rickbeil et al., *Plasticity in Elk Migration Timing Is a Response to Changing Environmental Conditions*, 25 Global Change Biology 2368 (2019).

The timing of elk (*Cervus canadensis*) migration across various habitats of the Greater Yellowstone Ecosystem (GYE) was primarily influenced by changes in snowpack levels, temperature, and forage availability. Elk departed winter range later if more forage biomass was available. In summer range, elk arrived later when snowmelt was delayed, left later if snow arrived later in the fall, and left summer range earlier with increased hunting pressure. Migration timing varied across the GYE; however, there was a pattern of later summer range arrival dates. Winter range arrival dates increased by almost 50 days. The study illustrated behavioral plasticity in elk to shifting environmental conditions.

Hall Sawyer, Fred Lindzey & Doug McWhirter, *Mule Deer and Pronghorn Migration in Western Wyoming*, 33 Wildlife Soc'y Bull. 1266 (2005).

This study mapped the timing and distribution of mule deer (*Odocoileus hemionus*) and pronghorn (*Antilocapra americana*) in their winter and summer ranges, as well as their migration routes, in the Green River Basin of Wyoming. Radiotelemetry and field observations of 171 mule deer and 24 pronghorn identified migration corridors and summer, winter, transition, and parturition ranges. Mule deer migrated 20-158 km and pronghorn 116-258 km -- the longest recorded distances at the time this study was published. Local topography created a narrow and enduring ungulate migration bottleneck at Trapper's Point: archaeologists identified a 6,000-year-old pronghorn harvest site at that location. Recent human development at Trapper's Point further constricted this important route. Seasonal changes in forage, weather, landscape features, human activities, and development impact the timing and use of migration corridors and ranges. This study can inform long-term management and planning decisions to ensure the viability of mule deer and pronghorn populations in the Green River Basin.

Hall Sawyer et al., *Identifying and Prioritizing Ungulate Migration Routes for Landscape-Level Conservation*, 19 Ecological Applications 2016 (2009).

Ungulate migrations are impacted by human development worldwide. Losses to migratory corridors from land-use change are a pertinent issue in the intermountain west. However, identifying locations of migratory corridors using fine scale movement data is essential to protecting them. The goals of this study were to determine the network of migratory routes within a corridor, locate and identify migratory pathways opposed to stopover site locations, and prioritize distinct migratory routes for conservation purposes. The authors employed utilization distributions (UDs) generated from Brownian Bridge Movement Models (BBMMs) to determine migratory routes and stopover sites within routes. Areas of high use were classified as stopover sites with connected areas of moderate use (high and low) designated as movement areas. The authors determined that migratory route segments varied in proportional use across all populations studied; however, identified that routes used by > 10% of the population were of greatest conservation priority. This work identified that applying a population-level migration route can be useful in identifying areas for protection of migratory behavior and that BBMMs and subsequent UDs can help designate areas of high and low use (e.g., stopover sites) for conservation prioritization.

Effectiveness and siting of Wildlife Crossing Structures and Associated Mitigation Infrastructure

John A. Bissonette & William Adair, *Restoring Habitat Permeability to Roaded Landscapes with Isometrically-Scaled Wildlife Crossings*, 141 Biological Conservation 482 (2008).

This study examined the use of allometric scaling and ecologically informed movement metrics for optimal placement of wildlife crossing structures. The authors used home-range data to identify clustered patterns of home range size for multiple species. They then used a linear home-range measure and median dispersal distances to approximate ecological neighborhoods for species and plotted frequency distributions for different species against highway mileposts. When linear home-range distances for the 72 species examined were plotted against mile markers spaced at distances up to 10 miles the majority of species (71%) were included at spacing less than one mile. When median dispersal distance was plotted against mile markers less than 40% of species were included. The authors summarized this finding as evidence that use of dispersal distances would result in crossing structures spaced too far apart to effectively influence landscape permeability. With specific reference to mule deer (*Odocoileus hemionus*), the authors used a derived linear home range size of 1.1 miles for the low range estimate and 7.4 miles for the high range estimate. Further, the authors concluded that crossing structure planning to increase permeability for large mammals should place structures one mile apart in hotspot locations.

Hall Sawyer, Chad LeBeau & Thomas Hart, *Mitigating Roadway Impacts to Migratory Mule Deer - A Case Study with Underpasses and Continuous Fencing*, 36 Wildlife Soc'y Bull. 492 (2012).

This study measured the number of mule deer (*Odocoileus hemionus*) using seven wildlife underpasses, connected with exclusion fencing, on Highway 30, Nugget Canyon, in southwest Wyoming. Passage rates increased annually, with a first-year average of 54% growing to 92% after year three, the last year of the study. These results suggest that mule deer may take up to three years to habituate to a new crossing structure. There were 81% fewer direct vehicle collisions (DVCs) with deer in the study area, and DVCs did not increase at the fence ends. The seven crossing structures in the 21 km (13-mile) Nugget Canyon study area increased permeability. Wildlife crossing structures could reduce DVCs; however, fencing and placement of structures are critical components of success.

Marcel P. Huijser et al., *Effectiveness of Short Sections of Wildlife Fencing and Crossing Structures Along Highways in Reducing Wildlife-Vehicle Collisions and Providing Safe Crossing Opportunities for Large Mammals*, 197 Biological Conservation 61 (2016).

Wildlife passage projects typically include wildlife crossing structures with paired mitigation infrastructure like wildlife exclusion fencing. Exclusion fencing in concert with WCSs are often noted as the most effective strategy in mitigating wildlife-vehicle collisions where present. However, challenges exist concerning the length and placement of fencing. Additionally, empirically based recommendations for exclusion fencing are limited. The objectives of this study were to identify whether longer fences are more effective than shorter fence lengths in reducing WCSs and positively influencing WCS use. The authors conducted a literature review to determine the relationship between fence length and effectiveness in reducing WVCs as well as field studies to determine large-mammal use of crossing structures with no or short directional fencing. Fences ≥ 5 km were found to be more effective and less variable than fences ≤ 5 km on average. Wildlife crossing structure use by large mammals was not found to be related to fence length; however, most crossings occurred at undercrossings opposed to fence-ends. The literature review revealed that shorter fence lengths increase fence-end effects, which limits project effectiveness. The authors concluded that if highway safety for humans is the primary success metric, employing fence lengths greater than 5 km with appropriately placed WCS should be employed to meet project objectives.

Prediction and Validation of Wildlife Corridors

Shelley M. Alexander, *Snow-Tracking and GIS: Using Multiple Species-Environmental Models to Determine Optimal Wildlife Crossing Sites and Evaluate Highway Mitigation Plans on the Trans-Canada Highway*, 52 Can. Geographer 169 (2008).

Snow-tracking data and predictive surfaces in GIS were utilized to develop regional-scale habitat models for four carnivores (cougars (*Puma concolor*), Canada lynx (*Lynx canadensis*), martens (*Martes sp.*), and wolves (*Canis lupus*)) in Banff National Park and Kananaskis County, Alberta, Canada. These models represented the probability of detecting these carnivores within 1 km of roads. The study generated probability surfaces for potential crossings using exponentiated values from the presence/absence logistic regression model -- an interesting avenue for exploring wildlife crossing and abundance validation. While all four carnivores exhibited different relationships with environmental variables, some species had overlapping ranges. Interestingly, many potential wildlife crossing sites previously identified on the Trans-Canada Highway did not align with the multi-species crossing locations identified in this study.

Paul Beier & Reed F. Noss, *Do Habitat Corridors Provide Connectivity?,* 12 Conservation Biology 1241 (1998).

Landscape connectivity was once pervasive for many species; however, anthropogenic land-use change has altered or eliminated connectivity for many taxa. Theoretical models indicate that corridors may provide opportunity to generate, maintain, or enhance connectivity, but have received criticism. The purposes of this study were to review empirical papers related to corridors to assess their capacity to generate connectivity for species and develop suggestions for researchers studying movement corridors. The authors collected articles written between1980-1997 containing "corridor" as a keyword in wildlife-centric academic journals. Additional citations were gathered from searched articles. The definition of corridor in this work implies that the linear habitat connects to larger habitat patches that allow for population persistence. Findings indicate that confounding effects can conceal the importance of corridors when researching the relationship between demographic parameters and movement corridors. The authors also indicate that research on species demographics generated from Before-After-Control-Impact studies may be adequate in discerning the influence of corridors on population vitality within the boundaries of the study area. However, demographic information may not be required if the benefit of connected landscapes isn't a question, but whether species use corridors. Observational studies of corridor use, while necessitating improvement, indicate that travel between habitat patches for many wildlife species is facilitated through corridors. Studies should center on animals sensitive to fragmentation or area-dependent opposed to more generalist species. The authors conclude that the answer to whether corridors facilitate connectivity is species and landscape specific; however, many studies has identified their benefit for conservation.

Samuel A. Cushman, Jesse S. Lewis & Erin L. Landguth, *Evaluating the Intersection of a Regional Wildlife Connectivity Network with Highways*, 1 Movement Ecology 1 (2013).

This study analyzed a previously validated resistance map and American black bear (*Ursus americanus*) genetic information to predict the location and strength of movement corridors and where they intersected highways. Researchers used factorial least-cost path modeling and resistant kernel analysis (UNICORE PRO). Of the 30 million hectares in the northern Rocky Mountains of Montana and Idaho studied, 30% were predicted to be a least-cost path corridor network. Intensity varied, and less than 0.01% were covered by high-intensity corridors (score > 500). Narrow corridors indicate areas of high landscape resistance. Over 75% of corridor networks are on federal lands, and 90% of high-intensity corridors were on public lands, especially in the western part of the study area. Many newly constructed wildlife crossing structures on Hwy 93 in Montana were adjacent to predicted corridors. The authors state that reliable predictions of wildlife corridors require knowledge of 1. wildlife distribution and abundance, 2. wildlife dispersal and movement ability, and 3. the pattern of differential movement costs (i.e., resistance) across the landscape.

Autumn R. Iverson, David Waetjen & Fraser Shilling, *Functional Landscape Connectivity for a Select Few: Linkages Do Not Consistently Predict Wildlife Movement or Occupancy*, 243 Landscape & Urb. Plan. 104953 (2024).

This study tested the ability of five linkage models to predict California amphibian, reptile, and mammal species. Twenty years of wildlife detections were used to vet the models; wildlife-vehicle collision (WVC) data and occupancy models were tested against the predicted linkages. The models indicated that linkage presence was a significant predictor of WVCs for cougar (*Puma concolor*) and American black bear (*Ursus americanus*) in four models. Linkages positively predicted mule deer (*Odocoileus hemionus*) WVCs in three out of four models. Linkages did not consistently predict species presence for any of the target species, and in some cases, animal presence was negatively associated with model predictions. The relationship between the level of human development and wildlife use of the landscape is nuanced: corridors in urban areas may be the only option left for wildlife movement, while mixed-use human density may create a gradient of movement opportunities. The authors suggest that hypothetical linkages should be validated with empirical data, such as direct observation and GPS-collar data. The authors advocate for a nuanced planning approach that considers species-specific needs and empirical data in conservation planning.

A.T.H. Keeley et al., *Comment on Functional Landscape Connectivity For a Select Few: Linkages Do Not Consistently Predict Wildlife Movement or Occupancy. Autumn R. Iverson, David Waetjen, Fraser Shilling,* 253 Landscape & Urb. Plan. 105217 (2025).

In their response to Iverson et al. (2024), Keeley et al. (2025) commend the effort to evaluate connectivity model predictions across California but challenge the conclusion that promoting general landscape permeability is a superior conservation strategy to protecting habitat linkages. They argue that conservation planning should be tailored to the specific landscape context, objectives, and focal species. Keeley et al. emphasize that connectivity models, particularly linkage models, can be effective tools when properly validated, and they offer methodological guidance for aligning model assumptions with validation data.

Julia Kintsch et al., *Western Slope Wildlife Prioritization Study*. (Colo. Dep't of Transp. Research Report No. CDOT-2019-01, 2019).

The Colorado Department of Transportation and Colorado Parks and Wildlife collaborated to develop a prioritization matrix, decision-support tool, and cost-benefit analysis for identifying optimal locations for wildlife crossing structures in the western portion of the state. The authors used Wildlife Vehicle Collision (WVC) risk models that included road and road-adjacent attributes (distance to tree cover, traffic volume and speed, winter range herd density as predictors of recorded carcass and WVC collision data. Species-specific seasonal risk models were combined with magnitude of ungulate spring and fall migration data, WVC mortality as a proportion of the population, connectivity values for other species and CDOT's wild animal accident pattern recognition (hotspot) data into a decision matrix where each criterion was scored and weighted based on focus group evaluations. Summed scores were used to generate locations with the highest scores, and the top 5% of locations were considered for field review and further analysis.

Julia Kintsch et al. *Eastern Slope and Plains Wildlife Prioritization Study.* (Colo. Dep't of Transp. Research Report No. CDOT-2022-03, 2022).

Similar to the Western Slope Wildlife Prioritization Study, CDOT and CPW developed a prioritization matrix, decision-support tool and cost-benefit analysis to identify optimal locations for wildlife crossing structures in the eastern portion of the state, including the Eastern Slopes and Plains regions (treated separately). WVC risk models estimated the probability of wildlife vehicle collisions based on the influence of current and future land use patterns and traffic volume scenarios on carcass count and WVC collision data for the eastern portion of the state. Risk model output was combined with species-specific factors identified as important for migration triggers, including magnitude of spring and fall migration, WVC mortality as a proportion of the population, proximity to drainages for mule deer, habitat quality and movement index, and CDOT's animal crash pattern recognition system (hotspots). Areas within a 0.25-mile buffer of high-density development were excluded from the analysis. Values for each criterion were scaled (0-1) and weighted based on focus group evaluations, and the top 5% of locations were selected for field review and consideration.

Or. Dep't of Fish & Wildlife, *Oregon Connectivity Assessment and Mapping Project* (2023).

The Oregon Connectivity Assessment and Mapping Project was a multi-entity effort to identify and map the status of wildlife habitat connectivity statewide. The process involved multiple layers of data acquisition, expert testimony and engagement, application of various decision-support tools, and advanced modeling. The process began by identification of surrogate species for use in the modeling approach to capture habitat and connectivity requirements for the maximum number of species. Surrogate species were grouped by ecoregion and then fed into several selection processes to ensure broader selection goals were met. After six species consideration steps the team selected 54 species for analysis. Landscape permeability values were calculated as a function of how easily a species could move across a 30 m cell. Areas with high permeability values were then translated into 40-acre Priority Wildlife Connectivity Area (PWCA) hexagons, of which the top 1% for each species were selected for further analysis. Resulting PWCAs were assigned a recommended conservation action, including protection, restoration, transportation mitigation, and enhancement/maintenance. The authors acknowledge the availability of current land-use/cover change data as a limitation of the PWCA approach and recommend regular updating. Another data limitation focused on the resolution of the available datasets, essentially acknowledging that 30 m resolution may not capture all potentially important influences on animal movement at a site-specific scale. Finally, the authors acknowledge that the OCAMP process represents a snapshot but may not adequately predict changes that will influence future species movement patterns.

Meredith McClure & David M. Theobald, *Western Slope Wildlife Prioritization Study: Modeling Risk of Wildlife-Vehicle Collisions* (Colo. Dep't of Transp. 2018).

This study generated wildlife-vehicle collision (WVC) risk models to inform priority locations for future traffic mitigation infrastructure. Three approaches with four risk model variations were tested and reviewed. Generalizable trends across models included distance to tree cover, traffic volume and speed, and ungulate herd density. Other risk factors varied based on season and species. Mule deer (*Odocoileus hemionus*) collision risk decreased with increasing aspen and conifer cover; however, this pattern was not identified in elk-based models. Road width, highway curve class, highway grade, and adjacent slope were not informative in any of the models. Species-specific WVC risk models are useful inclusions in a prioritization matrix. Simple models that did not include GPS data were more predictive, as they limited effects of variability between systems.

Brad H. McRae et al., *Using Circuit Theory to Model Connectivity in Ecology, Evolution, and Conservation*, 89 Ecology 2712 (2008).

In this theoretical paper, the authors describe the application of circuit theory (a concept in electrical engineering) to wildlife connectivity between habitat patches. Habitat fragmentation impedes species movement, gene flow, and ecosystem function. In circuit theory, a landscape is modeled as a conductive surface, and animal movement across the surface is presumed to respond to ease of travel or barriers to movement (i.e., resistance). Resistance values are defined by the user (e.g., topography, roads, habitat patches, urban areas), and the model highlights the paths of least resistance. The authors recommend using circuit theory to highlight priority conservation areas as it can be adapted to different spatial scales and species needs.

Climate Change

John B. Bradford et al., *Climate-Driven Shifts in Soil Temperature and Moisture Suggest Opportunities to Enhance Assessments of Dryland Resilience and Resistance*, 7 Frontiers in Ecology & Evolution (2019).

The authors combined long-term climate datasets and modeling techniques to predict how climate change may influence soil temperature and moisture regimes across arid and semi-arid ecosystems, which are particularly sensitive to climate change. Values for landscape resistance and resilience — an ecosystem's ability to resist change or recover from disturbance — were calculated and mapped on a 10 km resolution grid (i.e., high, medium, low). Current conditions were based on 1980-2010 datasets, extracted from daily maximum and minimum temperatures 2 meters above ground and precipitation records. Results were derived from sagebrush ecosystems only. Future climate predictions were created for 2020-2050 and 2069-2099, generated from Climate Model Intercomparison Project products. Changes in soil temperature and moisture regimes affect plant growth, nutrient cycling, species distribution, and ecosystem function. Mapping and planning for future changes in ecosystem resilience and resistance can inform conservation planning decisions and mitigation efforts.

Caitlin E. Littlefield et al., *Connecting Today's Climates to Future Climate Analogs to Facilitate Movement of Species Under Climate Change*, 6 Conservation Biology 1397 (2017).

This study utilized Circuitscape to examine potential species movement (i.e., current flow) between historical ranges and analogous habitats predicted under future climate scenarios. Three key elements were utilized to predict future connectivity: 1. climate analogs, 2. accessibility constrained by landscape permeability, and 3. a given animal's dispersal capabilities. Historical climate conditions were defined by the years 1961-1990. Predicted climate conditions for 2041-2070 and 2071-2100 were used to define future habitat analogs in western North America. High current flow was consistent in mountainous regions and within narrow physiographic features (such as canyons and riparian areas). Furthermore, their importance increased with greater climate change. Under mild climate change scenarios, flow was present throughout the western U.S., including flat ecoregions like the Great Basin and northern forests in areas minimally impacted by humans. However, increasing climate change constrained animal movement. Taiga, tundra, and interior northern forests were predicted to have minimal current flow even under moderate climate scenarios. Additionally, flow was limited in high-use agricultural regions. Maps incorporating climate analogs highlighted important future linkages that differed from linkages under current climate. Coarse filter approaches may overlook areas of connectivity for some species; however, coarse filter approaches identify areas of connectivity for a broader array of species. The authors maintain that fine- and coarse-scale approaches are necessary to model climate connectivity but stress that building multiple models that capture movement for all species is improbable. Including climate change at multiple scales in connectivity models can assist planners in identifying crucial areas for maintaining connectivity under various climate regimes.

Jenny L. McGuire et al., *Achieving Climate Connectivity in a Fragmented Landscape*, 113 PNAS 7195 (2016).

At present, many natural areas remain in the U.S., but they are broken up by human activities, restricting wildlife and plants' ability to move to adapt to climate change. This study looked at present and future habitat connectivity within the contiguous U.S., buffered by 100 km, to determine how much adding corridors between natural patches increased connectivity under future climate scenarios. The authors used existing models of how much humans have changed the landscape and analyzed present and predicted future landscape temperatures. They then compared connectivity values before and after adding natural corridors between habitat patches on the landscape. Only 41% of natural areas were connected enough to allow plants and animals to move to suitable habitat as the climate warms. The western U.S. had higher climate connectivity than the east, as only 2% of the eastern U.S. had adequate connectivity for movement. Adding connection pathways through developed areas could raise the overall climate connectivity value to 65%, with most improvements at low elevations and in the southeast. Facilitating movement will reduce biodiversity losses as the climate warms and habitats shift on the landscape. This research informs scientists and planners where to focus efforts to help species adapt to a changing climate and access suitable habitats.

Brad H. McRae et al., *Conserving Nature's Stage: Mapping Omnidirectional Connectivity for Resilient Terrestrial Landscapes in the Pacific Northwest* (The Nature Conservancy 2016).

The work presented in this report applied a course-filter approach to mapping broad-scale connectivity corridors to bring forward areas that may provide habitat connectivity for multiple species under increasing land-use and climate change scenarios. Connectivity corridors are hypothesized to be an essential conservation tool allowing wildlife to move into area of more suitable climate and habitat conditions. To generate corridors, the authors employed Circuitscape with a moving window analysis, a software program that uses circuit theory to model spatial connectivity relative to resistance values of individual pixels across landscapes. For example, areas of low resistance are typically associated with higher quality habitat (natural areas) and areas of high resistance have lower habitat value (developed areas). The model output quantified areas of potential movement between natural and semi-natural areas up to 50 km apart. The authors employed a wall-to-wall methodology that reduced the need to delineate distinct core habitat areas from the surrounding matrix. However, distinction of land type was still present in the model, which allowed the authors to define areas to be connected. This generated continuous connectivity across the landscape without explicit core areas, but rather, explicitly defined connected areas. The authors conclude by informing use of the three map products (current flow, normalized flow, and potential flow) as connectivity value guides to assist in the development of conservation strategies; however, state that these products should be combined with additional data sources and products for informed connectivity-related decision-making.

Tristan A. Nuñez et al., Connectivity Planning to Address Climate Change, 27 Conservation Biology 407 (2012).

This study generated a model that uses temperature and human land use to predict animal movement and identify landscape linkages in the Pacific Northwest (PNW). Warm patches in the center of the study area contained links to cooler patches in the Cascades, Rockies, and Blue Mountain ranges. Corridors between cooler and warmer patches allowed for movement in many directions. High levels of human land use in the western and central part of the PNW had fewer suitable patches and corridors. The climate corridor model used average annual temperatures from 1971 to 2000 and a landscape-integrity index (i.e., how natural an area is considering urban areas, roads, agriculture, etc.). The model identified large-scale connectivity corridors between areas with little human impact, and it compared present-day temperatures and future climate predictions. This study focused on natural areas that crossed temperature changes and mapped where species could move as the climate changes. The authors state that their model could be adapted to different habitat scales and the movement abilities of target species.

Elizabeth M. Schuyler et al., *Effects of Anthropogenic and Climate-Induced Habitat Changes on Adult Female Mule Deer Survival*, 91 Rangeland Ecology & Mgmt. 73 (2023).

Sagebrush habitats have undergone significant changes due to climate change, juniper expansion, invasive plants, and changes in wildfire size and frequency, impacting the quantity and quality of mule deer (*Odocoileus hemionus*) forage. This study tracked the movements of 111 female resident and migratory mule deer using GPS in various habitats, including wildfire and juniper cover, to assess survival rates. During the study, adult mule deer survival was 78%, which was lower than reported in other populations. Wyoming big sagebrush (*Artemisia tridentata ssp. wyomingensis*) and western juniper (*Juniperus occidentalis*) were the predominant vegetation cover types for winter ranges (35% and 25%, respectively), while mixed conifer forests dominated summer ranges (67%). Year and the percentage of winter range burned were the strongest indicators of mule deer survival. Monthly survival rates increased with the percentage of burned area. Small patches of fire in winter ranges increased the probability of survival, likely due to the generation of understory growth from reduced canopy cover. Mule deer preferred areas burned within 1-10 years compared to unburned areas, although burn severity was not accounted for. Improving forage in mule deer habitats is necessary to improve reproduction and survival rates.

Elizabeth M. Schuyler, Katie M. Dugger & DeWaine H. Jackson, *Effects of Distribution, Behavior, and Climate on Mule Deer Survival*, 83 J. Wildlife Mgmt. 89 (2018).

The authors estimated monthly survival rates and factors influencing survival for adult female mule deer (*Odocoileus hemionus*) in south-central Oregon. The study was conducted over a period of seven years using known-fate data for 408 adult female radio-collared mule deer. Known-fate data were used to estimate survival based on seasonal distribution, temporal effects, movement behavior, weather, and climate covariates. Migration behavior and the additive effects of fall migration period and winter precipitation provided the best-fit model for adult mule deer survival. Migratory behavior was more positively associated with survival than resident behavior (non-migratory). Fall migration decreased survival rates for all groups. Predation was described as the highest single source of mortality for known-fate deer (18%), though anthropogenic mortality and illegal harvest were considered separate causes of mortality in this study. When combined, human causes of mortality accounted for the greatest proportion of known mule deer deaths.

Impacts of Various Disturbances Mule Deer and Elk Habitat Selection and Behavior

Tanya M. Roerick, James W. Cain III & J. V. Gedir, *Forest Restoration, Wildfire, and Habitat Selection by Female Mule Deer*, 447 Forest Ecology & Mgmt. 169 (2019).

The authors examined the effects of forest restoration treatments and recent wildfires on female mule deer habitat selection in the Jemez Mountains in north-central New Mexico. The primary objective of this work was to determine how mule deer (*Odocoileus hemionus*) select habitat in relation to various disturbances (positive and negative) as well as landscape characteristics (topography, water sources, forage biomass, and vegetation). The authors also evaluated potential relationships between mule deer habitat selection and mountain lion (*Puma concolor*) predation risk. Mule deer habitat selection was calculated as resource selection functions based on data obtained for 24 GPS radio-collared individuals. Mountain lion predation risk was derived from resource selection functions based on radio-collared animals in the same study area. Mule deer responses to habitat alteration were strongly influenced by disturbance type and temporal dimensions of vegetation recovery, regardless of the source of habitat impact. Mule deer selected areas burned by prescribed fire and avoided areas burned by wildfire less than five years removed from the study period. Mule deer also selected areas that had been thinned five years or more prior to the onset of data collection. Predation risk was not consistently included in the highest-ranking models.

Hall Sawyer et al., *Mule Deer and Energy Development—Long-Term Trends of Habituation and Abundance*, 23 Global Change Biology 4521 (2017).

This study examined the hypothesis that mule deer (*Odocoileus hemionus*) habituate to disturbance through time by reducing or ceasing avoidance behavior. The authors used location data from 187 GPS-collared mule deer before, during, and after natural gas development to determine the impacts of distance from infrastructure and winter severity on habitat selection in western Wyoming. Data were collected over a 17-year period, two of which were prior to development and 15 of which were after/during development. Species abundance data at study locations and region-wide were compared to evaluate development impacts on populations. Radio-collar data indicated that mule deer consistently avoided areas with energy development, maintaining an average of 913 m distance from well-pad infrastructure relative to pre-development patterns. Mule deer abundance also declined 36% during the period of energy development, suggesting a population level impact of development activities. The authors concluded that their study provides evidence that mule deer do not habituate to energy development as had been indicated in anecdotal information contained in NEPA documents used by federal agencies for project permitting.

Kaela M. Hamilton, Thomas Bommarito & Jesse S. Lewis, *Human Activities Influence Mule Deer Use of Overpasses Across Multiple Scales*, 88 J. Wildlife Mgmt. e22560 (2024).

This study evaluated the influence of human recreation and canal management activities on mule deer (*Odocoileus hemionus*) use of overpass crossing structures along a major canal in the Sonoran Desert. The authors deployed camera traps at 43 crossing structures to detect and classify mule deer and human activity over the period of one year. Mule deer detections were classified as crossings if an individual/group was detected by the camera moving in one direction and did not return in the opposite direction. Only detections were included in the analysis. Human activity was either classified as recreation or canal work. Mule deer avoided overpasses when recreationists were present during the warm season and exhibited reduced activity during both seasons when canal personnel were present. The findings indicate that mule deer may be more sensitive to human activities of a longer duration, as canal maintenance typically requires longer presence at a given location than recreation.

Joseph M. Northrup et al., *Behavioral and Demographic Responses of Mule Deer to Energy Development on Winter Range*, 208 Wildlife Monographs 1 (2021).

To assess demographic and behavioral responses of a mule deer (*Odocoileus hemionus*) levels of human activity associated with natural gas development the authors examined behavioral responses of 400 female mule deer at a natural gas well-site in Colorado. The study took place from 2008 to 2015, which spanned a transition in activity levels at the well-sites from high activity (drilling) to low activity (production). The authors measured mule deer behavioral responses as a function of habitat selection patterns, in addition to monitoring annual adult female and fawn vital rate and physiological characteristics. Deer exhibited avoidance of areas during the drilling phase while apparently tolerating levels of activity during the production phase. There was no evidence to suggest physiological or vital rate impacts of either phase on this population of deer. The authors concluded that mule deer were sensitive to periods of high human activity (human presence, vehicle activity, noise, artificial light) but adjusted to lower levels by increasing habitat use in the immediate vicinity of the wells. They also indicated that vegetation cover patterns within the developed footprint is an important condition of use by deer.

Tim S. Doherty, Graeme C. Hays & Don A. Driscoll, *Human Disturbance Causes Widespread Disruption of Animal Movement*, 5 Nature Ecology & Evolution 513 (2021).

Human-based disturbance is expected to alter animal movement and behavior worldwide; however, the magnitude of impact to movement across taxa is unknown. This study aimed to quantify changes in animal movement and home range size worldwide in response to various forms of human-based disturbance. In this meta-analysis, the authors compiled information from 208 studies, representing 167 terrestrial and aquatic species which provided 719 effect sizes. Bayesian mixed-effects analysis methods were employed to determine the effects of taxonomic group, trophic level, disturbance type, and body size on movement response. The authors found that most animals increased movement distance as a result of human-based disturbance. When considering movement types, the mean positive movement effect was a 70% increase, and a mean negative movement effect decrease of 37%. A majority of effect sizes (67%) indicated increases or decrease of ≥ 20%, with 37% of cases ≥ 50%. Movement distances were generally positive in response to disturbance (16%), whereas home range size remained neutral across taxa. However, both movement distance and home range effects varied by taxonomic group. Similar patterns were observed for movement across trophic levels as all were expected to increase mean movement distance, with herbivores generating the greatest mean estimated movement distance. Certain disturbance types had greater mean estimated effects on animal movement distances. For example, recreation, hunting, and aircraft had greater effects than logging, habitat fragmentation, and agriculture. Importantly, mean movement distances were expected to increase by 68% in response to roads. Urbanization and agriculture were expected to decrease mean mammal home range size by 49% and 27% on average, respectively. The authors conclude that their results indicate global changes to animal movement in response to disturbance and protecting against human-driven change is critical to support global biodiversity.