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Identifying Road Segments that Bisect Predicted Movement Corridors for Small Priority Species in Virginia

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16. Abstract:

The Virginia General Assembly passed legislation in 2020 requiring the preparation of the Virginia Wildlife Corridor Action Plan. It directed the Virginia Department of Wildlife Resources in collaboration with the Virginia Department of Transportation, the Virginia Department of Conservation and Recreation, and the Virginia Department of Forestry to identify wildlife corridors, identify areas with a high risk of wildlife-vehicle collisions, and recommend wildlife crossing projects intended to promote driver safety and wildlife connectivity. The first version of the Wildlife Corridor Action Plan was released in 2023 and listed several "recommendations for future actions" for its next iteration. Four of these future actions include (1) identifying at-risk terrestrial species, aquatic species, and other species of interest whose corridor needs are not sufficiently addressed by the Wildlife Biodiversity Resilience Corridors; (2) identifying important habitat corridors for these species; (3) identifying Wildlife Crossing Concern Areas (e.g., high-risk road segments) for these at-risk species; and (4) identifying and analyzing non-road human barriers (e.g., land uses) affecting corridor connectivity for the Wildlife Biodiversity Resilience Corridors.

The purpose of this study was to advance the objectives of the legislated Wildlife Corridor Action Plan by developing species-specific road risk models and identifying road segments that pose a high risk to small priority species. To identify high-risk road segments, the authors collaborated with 29 species experts to develop maps of "landscape resistance" for 12 state species on the Species of Greatest Conservation Need list. These maps represent how different landscape features are expected to affect species movement—by increasing mortality risk, influencing movement speed, acting as physical barriers, or causing behavioral avoidance. Species-specific connectivity analyses were used to generate maps of predicted movement intensity for each species and to identify areas where roads were expected to cause the greatest reductions in movement.

The 12 priority species considered in this analysis varied widely in distribution, resulting in large differences in the spatial extent and configuration of predicted movement corridors. The Mabee's salamander was unique in having compact movement zones predicted around a small number of extant source populations. For this species, a focused set of priority road segments was identified that may be suitable for site-level assessment and mitigation—such as improving existing culvert passability or adding targeted small-animal passages. Several species, including the bog turtle, wood turtle, diamondback terrapin, mud snake, rainbow snake, and fisher, had much broader but regionally concentrated movement corridors that intersected a modest number of important roads. The prioritization of road segments for these species reflects both proximity to key source habitats and road characteristics associated with high resistance to movement (e.g., high traffic volume and greater road width). For several wide-ranging species (spotted skunk, Alleghany woodrat, spotted turtle, and box turtle), predicted corridors were diffuse and covered large portions of the state. Mitigation efforts for such species should likely focus on roadway design standards (e.g., use of fencing or curbing to funnel animals to existing structures and ensuring underpasses are compatible with small-animal use) rather than prioritizing individual crossing sites. This project provides connectivity map outputs for all 12 priority species as geographic information system raster data. It develops a consistent, repeatable workflow for assessing road impacts and connectivity across multiple taxa in Virginia.

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FINAL REPORT

IDENTIFYING ROAD SEGMENTS THAT BISECT PREDICTED MOVEMENT CORRIDORS FOR SMALL PRIORITY SPECIES IN VIRGINIA

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INTRODUCTION

In 2020, the Virginia General Assembly enacted the Virginia Wildlife Corridor Action Plan (WCAP, or the "Plan") (*Code of Virginia* § 29.1-579), which directed the Virginia Department of Wildlife Resources (VDWR), in collaboration with the Virginia Department of Transportation (VDOT), the Virginia Department of Conservation and Recreation (VDCR), and the Virginia Department of Forestry, to "[i]dentify wildlife corridors, existing or planned barriers to movement along such corridors, and areas with a high risk of wildlife-vehicle collisions" and to "[p]rioritize and recommend wildlife crossing projects intended to promote driver safety and wildlife connectivity." The WCAP is required to be updated every 4 years.

The final Plan was released in May 2023 and included three primary themes: promoting driver safety, improving wildlife corridor connectivity, and advancing mutual benefits (VDWR et al., 2023). In addition to the Plan document, mapping included a map of road segments experiencing high occurrences of deer and bear conflicts, a map of Wildlife Biodiversity Resilience Corridors (WBRCs), and locations of 26 Nexus Areas where WBRCs and conflict hotspots coincide (25 square miles in size), which represent opportunities to advance mutual benefits where wildlife crossings could provide both driver safety and wildlife corridor conservation benefits. The Nexus Areas indicate broad locations that would require further scoping to determine the suitability and feasibility for wildlife crossing. Specific wildlife crossing projects, including precise locations and target species, were not identified in the Plan as a result of data gaps that were encountered, as the following details.

WBRCs adopted by the Plan were based on a modified version of the ConserveVirginia Resilience Corridors developed by VDCR (2021). The purpose of WBRCs is to maintain wildlife habitat connectivity between biodiverse and natural lands, allowing species distribution shifts as the climate changes and the landscape becomes more developed. However, the Plan acknowledges that WBRCs are coarse-scale corridors that do not fully represent habitat connections that are important at finer spatial scales, nor do they represent species with habitat requirements not captured by the broad WBRC analyses (VDWR et al., 2023). The Plan also acknowledges that species-specific wildlife corridors will need to be identified for priority species (VDWR et al., 2023).

With regard to the Plan’s evaluation of road segments at high risk for wildlife-vehicle conflict, the Plan notes that conflicts with small species are rarely reported and could therefore not be used in the identification of road risk hotspots (VDWR et al., 2023). Largely because of this scarcity of small species road mortality data, the effect of roads on small terrestrial and semiaquatic species was not evaluated in the Plan’s first iteration. Similarly, the legislative requirement to consider rare or at-risk species was not addressed in the Plan’s initial iteration and remains a need for Plan updates.

To address these and other limitations listed in the Plan, the Plan provides several “recommendations for future actions” for its next iteration. These actions include research and other efforts needed to satisfy a main intent of the legislation of identifying wildlife crossing projects in Virginia (VDWR et al., 2023). To fund these efforts and thereby advance the work of the next WCAP, VDOT’s Environmental Division applied for a federal grant through the Federal Highway Administration’s Wildlife Crossings Pilot Program (WCPP). Established under the Bipartisan Infrastructure Law (H.R. 3684, 2021), WCPP is a competitive grant program with the goal of reducing wildlife-vehicle collisions while improving habitat connectivity for terrestrial and aquatic species. Virginia was one of 17 states awarded WCPP funding for fiscal years 2022 and 2023. VDOT’s WCPP grant application identified three deliverables for the small wildlife task: (1) a small wildlife species road risk model; (2) a small wildlife species road risk and priority ranking geographic information system (GIS) layer; and (3) a list of low- and high-priority terrestrial connectivity road segment areas.

Two of the future actions described in the Plan and the WCPP funding application are of particular relevance to the study described herein: (1) the identification of habitat corridors for at-risk small terrestrial species and other species of interest not sufficiently addressed by WBRCs and (2) the identification of wildlife crossing concern areas (i.e., high-risk road segments) for these species.

PURPOSE AND SCOPE

The purpose of this study was to advance the objectives of the legislated WCAP by developing species-specific road risk models and identifying road segments that pose a high risk to small priority species. This study represents one of several efforts that fulfill the intent of VDOT’s WCPP grant award to inform the development of the WCAP by providing data to support the prioritization of wildlife crossing projects that enhance driver safety and wildlife connectivity.

The scope of this study included highlighting potential approaches to improving road-crossing connectivity based on species-specific movement corridors and road risk areas. These mitigation strategies can help inform future prioritization efforts and decision-making.

METHODS

Three primary tasks were completed to achieve the goals of this research project. The resulting framework evaluates road impacts at a fine spatial scale, incorporating both mortality risk and impeded movement, and identifies high-risk road segments for select priority species.

Task 1: Develop a List of Priority Species with a Small Species Technical Advisory Committee

The Plan notes that for its next iteration, a list of “priority species” should be identified that includes small species, particularly those considered at risk—that is, federally and state-protected species and those on the Species of Greatest Conservation Need (SGCN) list. The list of priority species was created in consultation with the Small Species Technical Advisory Committee (TAC), which was formed to support this study and to serve as a source of technical expertise to develop the next WCAP. TAC members included representatives from VDWR and VDCR who had expertise on small terrestrial and semi-terrestrial wildlife in Virginia.

To develop the list of priority species, the research team scheduled a series of meetings with the TAC in the first several weeks of the study. Information discussed included TAC expert opinion regarding small species in Virginia that may be particularly susceptible to road impacts, species that were a priority for environmental review and species for which sufficient data are available to identify likely habitats and movement patterns.

Task 2: Literature Review, Review of Species Occurrence, Habitat, and Connectivity Data Sources, and Elicit Expert Opinion

Levels of animal movement at a given location depend on the spatial configuration, size, quality, and interconnectedness of habitat patches across the landscape. The workflow designed for identifying wildlife crossing concern areas reflects this reality by incorporating available information about the spatial distribution of the selected priority species and the effects of mapped landscape features on both habitat permeability and road-related effects on movement (e.g., mortality or avoidance behavior). Data gathering efforts for this project also focused on finding the following data for the selected priority species:

- Raw occurrence and locality data.
- Existing habitat suitability maps and a list of the environmental predictors used to develop them, along with any reported effect sizes or variable importance measures.
- Existing connectivity maps, published resistance values, or reported resource selection model predictors and associated effect sizes indicating the influence of landscape features on movement.
- Expert-elicited resistance values for landscape variables identified from the connectivity and resource selection literature, with additional variables proposed by experts as relevant to species movement.
- Movement metrics such as mean and maximum dispersal distance and home range size.

Literature Review

Researchers conducted all literature searches in Web of Science using the focal species' scientific name, any taxonomic synonyms, and a standardized set of predetermined search terms designed to identify sources with relevant distribution, connectivity, or movement information (Table 1). Every search result was checked and downloaded if it was deemed relevant to the research effort. For each of the selected primary sources, researchers checked all cited literature (backward citation searching) and all publications that cite them (forward citation searching) (Briscoe et al., 2020). Relevant secondary sources identified in this way were also included for review.

Table 1. Example Full Search String for Spotted Skunk (*Spilogale putorius*)

("*Spilogale putorius*" OR "*Spilogale interrupta*") AND (distribution OR "SDM" OR ("spatial" AND (model OR ecology)) OR ("habitat" AND (range OR suitability OR fragmentation)) OR "habitat use" OR "habitat preference" OR "habitat quality" OR "ecological niche model" OR selection OR movement OR connectivity OR corridor OR "gene flow" OR "home range" OR "metapopulation dynamics" OR dispersal)

SDM = species distribution model.

A database was compiled for each selected priority species that contained relevant information extracted from the identified primary and secondary sources. The information was organized into categories of habitat suitability, resource selection, connectivity, and movement. Each predictor variable reported in spatial modeling studies (e.g., habitat suitability or distribution analyses) included a separate entry in the database that linked the variable to its source study and included the model type and any reported effect sizes, variable importance, and significance test statistics. Publicly available outputs from modeling efforts that included the species' full range in Virginia, such as a species distribution model or connectivity maps, were also downloaded. Raw movement information, such as species' home range sizes and dispersal event distances, was similarly recorded in the database for later modeling efforts.

Review of Species Occurrence, Habitat, and Connectivity Data Sources

Data sharing agreements were established between the members of the research team and both the VDCR Natural Heritage Program and VDWR. The VDCR Natural Heritage Program maintains an inventory of species occurrence data and has created predicted suitable habitat maps for a variety of rare species, including all federal and state threatened and endangered species listed prior to spring 2018. Data sharing agreements were also established with the North Carolina Natural Heritage Program, and researchers received supplemental occurrence data from the state of North Carolina (North Carolina Natural Heritage Program, 2025). Open access and citizen science occurrence data sources, such as the Global Biodiversity Information Facility (GBIF), iNaturalist, or peer-reviewed literature, were reviewed for their potential value as an additional data source but were not included in the study because most relevant data had obscured Global Positioning System (GPS) coordinates. Several experts who collaborated on this project were also able to provide additional occurrence data that were accessible to them.

Expert Elicitation

Expert judgment was used to develop a consistent and easily updated set of connectivity maps for the priority species in Virginia. Each expert assigned resistance values to mapped landscape features that they believed would influence species movement. These expert-derived resistance values were subsequently used to construct the resistance surfaces that formed the basis for connectivity modeling.

In selecting species experts for the elicitation process, researchers who had conducted movement studies of priority species were prioritized, particularly in and adjacent to Virginia or within similar biogeographical areas. Species experts were identified from two sources: authors of literature reviewed for this project (described previously) and researchers known to TAC members. Primary experts identified by these two routes were contacted and invited to participate and were asked to identify any other relevant species experts not previously identified. Four to five experts were contacted for each species, with the goal of ensuring a minimum of three specialists would participate in workshops for each species.

Participating experts were first invited to a virtual meeting that provided an overview of the project and an explanation of the resistance values being elicited for modeling purposes. The research team also provided a walkthrough of assigning resistance values to guide experts through the intended thought process. Questions were addressed during the meeting, and recordings of these initial meetings were made available for the few experts who were unable to attend.

Following the initial meetings, participating experts were provided with worksheets for their focal species that were divided into three sections (see the Appendix). The first worksheet section included a list of species-specific variables identified from the literature review as potentially important drivers of species occurrence or habitat suitability. Experts were asked to rank the importance of these predictor variables or provide additional variables of importance that were not on the list (Appendix Figures A1 and A2). The second worksheet section consisted of a set of species-independent variables (e.g., land cover types, roads of varying widths and surfaces, traffic volume, elevation, and slope) identified by the literature review as having potential effects on species movement. Experts were asked to assign resistance estimates only to variables they considered important and to indicate their confidence in those scores for each landscape feature (captured as a best estimate and 95% confidence intervals) (Appendix Figure A3). They could skip any variables they considered relatively unimportant for connectivity modeling, add additional variables not included in the worksheet, or adjust the bin thresholds used to divide certain continuous variables into categories with different resistance values (e.g., levels of traffic volume, slope, or elevation). Experts were also instructed to assign a value of “0” to any features that they believed did not add additional resistance (e.g., an expert could then allow high slopes to impede movement, whereas flat areas do not). The final worksheet section was an open space for experts to provide feedback or commentary on species ecology and the thought process behind their inputs.

Once all experts for a given species completed their worksheets, they were invited to participate in a follow-up group discussion session. These sessions provided an opportunity to review the completed worksheets, clarify definitions and assumptions for each variable, and allow experts to share their reasoning and insights. These discussions helped facilitate a common understanding of variable meanings, scales, and important thresholds while allowing experts an opportunity to reconsider or refine their initial estimates. Importantly, researchers were careful in this process to not “herd” experts into a set of consensus resistance values because the goal of having multiple experts per species was to have the final connectivity maps reflect the uncertainty in expert judgment.

Task 3: Develop Species Models

Connectivity modeling is widely used to understand how landscape features influence patterns of animal movement and to identify opportunities to avoid or mitigate human impacts (Bolliger and Silbernagel, 2020). Many connectivity assessments are based on resistance surface modeling, in which a GIS raster layer, or “resistance surface,” represents the likelihood of successful movement across different parts of the landscape. Ideally, movement data should inform the assigned resistance values for particular landscape features, but expert elicitation is frequently relied on when empirical data are lacking (Baguette and Van Dyck, 2007; Zeller et al., 2012). Predicted movement paths between source habitats can then be identified using analytical methods like least-cost path analysis (Adriaensen et al., 2003), circuit theory (McRae et al., 2008; 2016), and resistant kernels (Compton et al., 2007; Cushman et al., 2013). The following four-step workflow uses a resistant kernel approach to map predicted movement intensity and road impacts for each priority species.

Step 1. Specify Dispersal Parameters

The resistant kernel approach to connectivity modeling inherently reflects the dispersal limitation of a species, simulating how connectivity probability decays with distance and accumulated resistance to movement (Compton et al., 2007). To parameterize this model, it was necessary to first identify species-specific dispersal metrics from the literature, specifically either the mean dispersal distance for a species or the maximum reported dispersal distance. When multiple metrics were available in the literature, the largest published dispersal distance was selected to ensure a conservative estimate of species movement capacity. These literature-derived metrics were used to define the standard deviation (σ) of the modeled dispersal distance, a key parameter defining the model's spatial scale. The maximum dispersal distance (maxD) was assumed to be 3 × σ and was used to define the maximum modeled distance from any source point, a standard practice that is expected to capture approximately 99.7% of the kernel's density (Compton et al., 2007). Furthermore, the literature-derived mean net displacement was related to σ by the factor 1.5 × σ, accounting for movement persistence and directional bias inherent in many dispersal movements (Turchin, 1998).

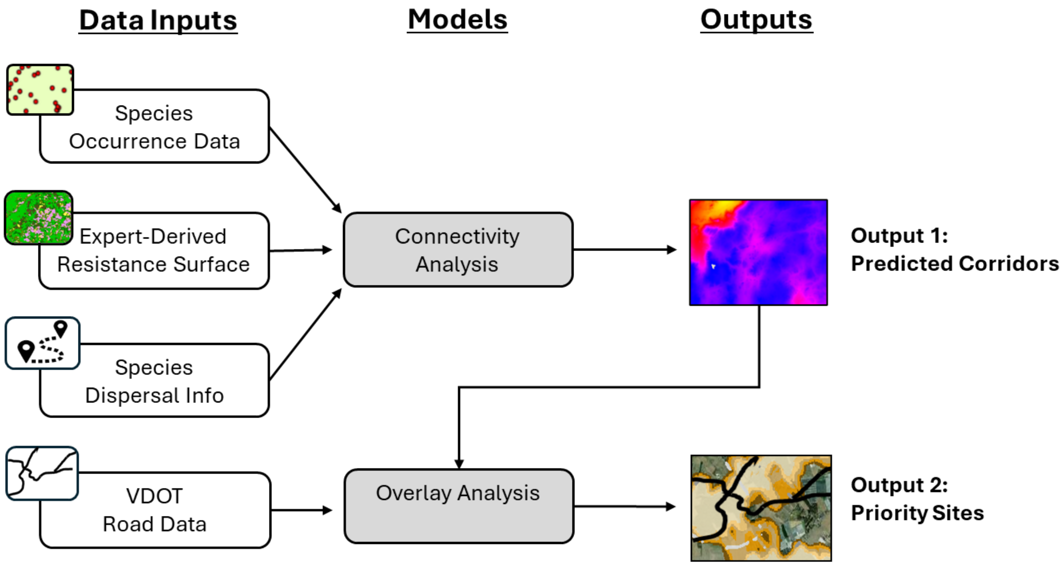
Step 2. Identify Source Locations

The next step in the connectivity modeling process was to designate source locations to serve as origins for the simulated movement of the target species. However, the completeness of existing occurrence data varied widely among species because of factors such as overall sampling effort and whether the species occupies discrete, well-defined patches versus more continuous habitats. These differences required three different approaches for defining source locations.

Species with Well-Documented, Discrete Distributions (Figure 1a)

GPS coordinates from original occurrence data were used as source points for species whose occurrence records were believed to be a reasonably complete representation of occupied sites. These source points were spatially thinned to retain one source point per grid cell, with the cell size defined by the standard deviation of the modeled dispersal distance (σ). This process prevents the overrepresentation of spatially clustered records in output maps and ensures each remaining point effectively represents a distinct, coarse-scale area of occupancy.

(a)



(b)

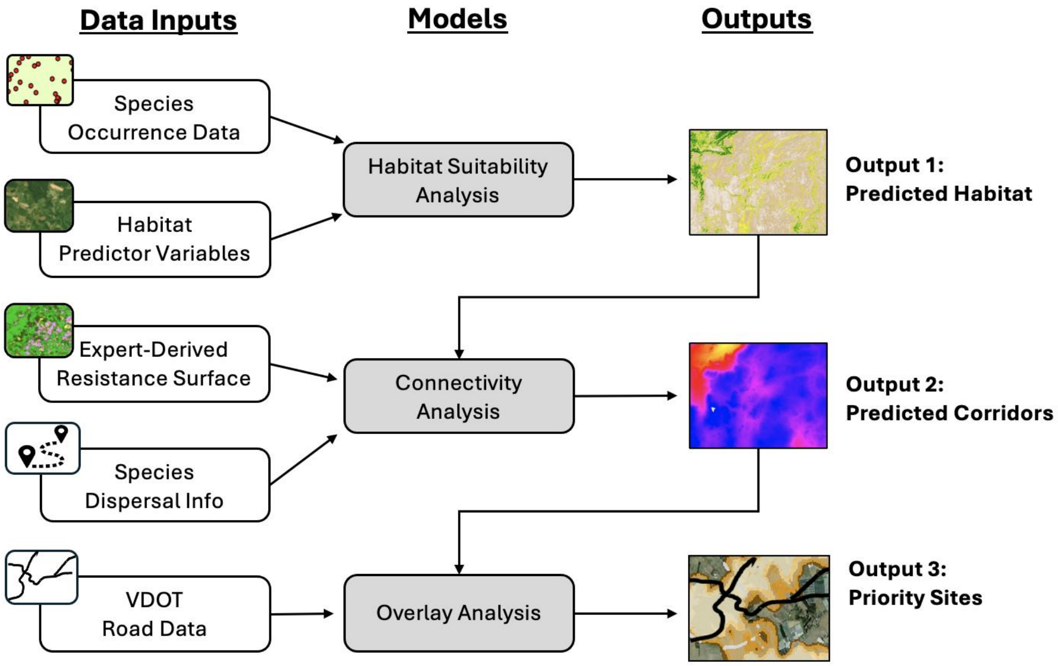


Figure 1. Conceptual Workflow for Species Connectivity Modeling in Google Earth Engine (Gorelick et al., 2017). Source points for connectivity analysis are generated using one of two strategies: (a) either by directly thinning raw occurrence data or (b) by using a habitat suitability model to simulate additional source points from predicted suitable habitat. These source points, along with expert-derived resistance surfaces and species dispersal information, are then used to predict species connectivity using a resistant kernel model (Compton et al., 2007). Researchers used an overlay analysis to compare connectivity maps built with and without road data to identify and prioritize road segments estimated to cause the greatest reductions in connectivity.

Species with Incomplete Occurrence Data but Mappable Habitat (Figure 1b)

For this group, the original occurrence data were preferentially used where available, following the same spatial thinning approach described previously, with additional source points simulated only to supplement and not replace the established records. Habitat suitability modeling was used to predict additional potential source areas for species with spatially incomplete occurrence data, but whose habitat could be effectively modeled as a function of environmental predictor variables represented by statewide GIS raster layers. If species experts recommended a suitable preexisting habitat suitability map (e.g., Feaga et al., 2024), this map product was used to add source points in likely habitat between original occurrence locations. For several species, however, novel habitat suitability maps were generated using Google Earth Engine and known occurrence locations (Gorelick et al., 2017), along with relevant predictor variables for each species, following the methods published in Crego et al. (2022). In summary, environmental predictor variables were matched to known occurrence points and a corresponding set of randomly generated "pseudo-absence" points across the study area. These data were used to train a random forest model that identified relationships between predictor variables and species presence, resulting in continuous maps of relative habitat suitability. Predictor variables were primarily selected for each species based on expert feedback or published literature and included a standardized suite of climate variables (WorldClim Bio Variables: bio01, bio07, bio12, bio15; Fick and Hijmans, 2017) and raw spectral information

(Landsat 8 Surface Reflectance, Bands 2-7; U.S. Geological Survey [USGS], 2019). The final Habitat Suitability Index (HSI) map for a given species was then used to generate additional source points in potential habitat as follows:

1. Potential areas for source point generation were restricted to habitat areas with a minimum habitat probability greater than 0.5.
2. The HSI map was smoothed using a majority filter at the scale of the species' home-range radius, retaining only pixels surrounded predominantly by habitat with HSI greater than 0.5. This filter removes isolated high-HSI pixels from consideration as potential sources.
3. The remaining habitat area was overlaid with a regular grid defined by the standard deviation of the modeled dispersal distance (σ).
4. For all grid cells not containing an original occurrence record, a single random point was selected within the cell.
5. The random selection of points was calibrated using the HSI value as its relative likelihood of selection, ensuring that proportionally more simulated source locations were allocated to areas of higher predicted habitat suitability.

This approach ensured that source points were generated only in biologically plausible source areas, maintained consistent spatial density based on the modeled dispersal scale (σ), and supplemented, rather than replicated, the original occurrence data.

The canebrake rattlesnake was treated as a special case because this species occurs in isolated habitat fragments embedded within highly urbanized landscapes and in some surrounding areas. For this species, additional constraints were applied to ensure the biological plausibility of simulated source locations. Only occurrence records from the past two decades were used as source points. Simulated sources were required to fall within a species-specific maximum distance (maxDistance) of a recent occurrence and to be connected to that occurrence by contiguous habitat with HSI greater than 0.5. In areas known to contain only a small number of extant habitat patches, simulated source points were not generated beyond the observed occurrences.

Species with Incomplete Occurrence Data but Difficult-to-Map Habitat

This third group consisted of species for which occurrence data were incomplete, but generating a reliable HSI map was prohibitively challenging. This limitation arose because critical habitat features, such as key hydrological characteristics, were not represented in reliable statewide GIS layers. For these species, no simulated source points were added to the predicted suitable habitat. Instead, spatially thinned occurrence data were used as source points—with the same grid-based thinning. Connectivity outputs for these species are considered to be limited in extent, representing only potential movement radiating from known source sites, rather than full, landscape-wide connectivity.

Step 3. Develop Resistance Surfaces

The generation of species-specific resistance surfaces was executed entirely within the Google Earth Engine platform, integrating expert-assigned resistance values with related GIS datasets layers to quantify the cost of movement for the target species at every point on the landscape. The final resistance surface output is a set of three multi-band raster images, one for each species expert, in which each image contains two bands: *withoutRoads* (baseline resistance without road impacts) and *withRoads* (total resistance, including road-related factors).

The initial step of this process involved assigning a base resistance value to every pixel on the landscape based on its land cover. All experts provided resistance values for each land cover class in the National Land Cover Dataset (NLCD) (Dewitz, 2023). However, because of the importance of aquatic features to many of the modeled species, the process prioritized assigning each pixel a cost based on its classification in the National Wetlands Inventory (NWI) dataset whenever an expert had elected to assign resistance values to NWI classes (U.S. Fish and Wildlife Service, 2018). Only the palustrine classes from NWI were included, based on expert consensus. If pixels lacked an NWI classification, pixels were then assigned a resistance value based on their water depth, provided that the expert had elected to assign different resistance values based on water depth. Depth was calculated by merging data from the National Oceanic and Atmospheric Administration’s Coastal National Elevation Database for coastal areas and the GLOBathy dataset for non-coastal water bodies (Khazaei et al., 2022; Thatcher et al., 2016). The depth values from these sources were assigned exclusively to existing NLCD open water pixels. All other open water locations not covered by NWI or water depth were assigned the resistance value associated with the shallow water depth class. Pixels not covered by either NWI or the specialized Water Depth datasets, or for experts who opted not to assign resistance values based on NWI or water depth, were assigned their base resistance values according to the NLCD land cover class.

Once a pixel’s base resistance surface was determined based on its land cover and corresponding expert resistance values, additional factors contributing to movement cost were added to the base resistance surface. Costs associated with topographic and landscape variables—including elevation and slope derived from National Aeronautics and Space Administration’s (NASA) Shuttle Radar Topography Mission (SRTM) (Jarvis et al., 2008), Euclidean Distance from streams filtered by order derived from the USGS (2019) National Hydrography Dataset, sand composition from the USGS Soil Survey Geographic Database resampling (Chaney et al., 2019), and shoreline type (Virginia Institute of Marine Science, 2014)—were assigned their corresponding expert-supplied resistance values and added to the base resistance. All linear vector data of roads and shorelines were converted to raster format, ensuring that no diagonal pixel gaps were present that would allow the connectivity simulation to avoid movement costs associated with those features. All geospatial layers were reclassified to expert-assigned resistance scores, with continuous layers (e.g., slope, distance to drainage) first being binned into discrete classes using expert-defined intervals before being assigned resistance values. At this stage, the resistance surface should reflect the total non-road related movement costs, which was saved as the withoutRoads resistance layer for each expert.

Road-related resistance values assigned by experts were then layered on top of the withoutRoads resistance surface. The Virginia road centerlines dataset (Virginia Geographic Information Network, 2025), which provides a vector representation of the road network, was used to define the spatial locations of road features. Road attributes, including traffic volume, speed limit, and road surface type (paved or unpaved), were sourced from internal datasets provided by VDOT (2022, 2024) and joined to the Virginia road centerlines dataset. Because many experts assigned resistance values based on the number of lanes, pavement width was converted into an approximate number of lanes by assuming one lane per 12 feet. Sound wall data were also sourced from VDOT (Hudnall, 2025). Annual average daily traffic was converted to average hourly traffic volume (AADT/24). To account for nocturnal movement in some species, the research team converted the annual average daily traffic to a crude estimate of hourly nighttime traffic volume based on hourly traffic being one-ninth of the 11% of total daily traffic volume during nighttime hours from 8 p.m. to 5 a.m. for a rural road in Arizona, based on Figure 3-3 in Federal Highway Administration (2013). Finally, for diamondback terrapin resistance surfaces, a process was implemented to override road costs associated with bridges by manually delineating water passages and replacing any land cover or road-related costs with a resistance value based on water depth. This step was applied only to the diamondback terrapin because many occurrence points for this species were in relatively wide estuarine waterways crossed by large bridges that are clearly not barriers to aquatic movement, whereas implementing comparable overrides for bridges and culverts statewide for other species would require considerably greater effort and involve more uncertainty about structure passability. All road-related features were reclassified to assign expert resistance scores, with continuous layers (e.g., traffic volume and elevation) first being binned into discrete classes using expert-defined intervals. The combined set of road resistance values was then added to the existing withoutRoads resistance surface to generate the final withRoads resistance surface.

This process was followed to create resistance surfaces, both with and without road resistance values, until GIS raster layers were generated for each expert and each species. In this way, separate resistance surfaces were generated that reflected each unique expert’s resistance values.

Step 4. Develop Maps of Predicted Connectivity

Resistant kernel modeling was used to develop maps of predicted movement intensity for each priority species. This technique, initially proposed and applied in a connectivity study with pond-breeding amphibians (Compton et al., 2007), uses a resistance surface to estimate the accumulated travel cost from each source pixel to all surrounding pixels, up to a maximum species-specific dispersal distance. This approach offers several benefits. It considers all possible movement pathways from source locations, explicitly accounts for dispersal limitation, and generally performs well when species movement is not highly biased toward a known destination (Kumar and Cushman, 2022). Although this method is computationally intensive, the research team developed a novel Google Earth Engine workflow that enabled the modeling process to be repeated with relative ease across 12 priority species and three expert-derived resistance surfaces per species.

For each expert, the withRoads and withoutRoads resistance surfaces derived from their suggested resistance values were first normalized by dividing them by the minimum terrestrial resistance value assigned by that expert. This step was required because the literature-derived dispersal distances (used to define σ) are measured as movement over land. Therefore, normalization sets the cost of movement in the least resistant terrestrial land cover to exactly one cost unit per meter, effectively scaling the resistance surface to be interpretable in units of terrestrial distance. A key by-product of this normalization was that aquatic land covers (NWI, water depth, or NLCD water pixels) that experts assigned a resistance value less than the terrestrial minimum (i.e., less than one normalized cost unit) became highly permeable. This measure allowed predicted movement to extend beyond the species' maximum terrestrial dispersal distance ($\mathrm{maxD} = 3 \times \sigma$) when moving through these highly permeable aquatic habitats. To ensure the resistant kernel calculations did not have a hard truncation at these aquatic movements, the maximum distance parameter was increased to encompass the full potential extent of aquatic dispersal.

The core of the resistant kernel method was then executed using the Google Earth Engine *cumulativeCost* function, which calculates the accumulated cost (or resistance) along the least-cost path from every source point to every pixel within the maximum dispersal distance. The accumulated cost at every pixel was then used to calculate the predicted movement intensity, while accounting for the expected decrease with distance, following a Gaussian decay function with σ as the scale parameter (Compton et al., 2007). Applying this calculation to both withRoads and withoutRoads cost surfaces for a given expert yielded two maps of predicted movement intensity: one map of predicted movement intensity for the current landscape with roads ($\mathrm{Kernel}_{\mathrm{withRoads}}$) and a second map for a scenario where no road costs were included in the underlying resistance surface ($\mathrm{Kernel}_{\mathrm{withoutRoads}}$).

To isolate the predicted effects of roads on connectivity for each species, the total loss of movement ($\mathrm{Kernel}_{\mathrm{Diff}}$) was calculated that represented the total predicted decrease in movement intensity due to all resistance factors introduced by the road network. This metric has been used previously to model the effects of linear infrastructure projects on predicted connectivity using a resistant kernel analysis for clouded leopards and can be thought of as a "road shadow" where less movement is expected on the far side of roads from source points (Kaszta et al., 2020). The calculation of $\mathrm{Kernel}_{\mathrm{Diff}}$ involves calculating the simple difference:

$$\mathrm{Kernel}_{\mathrm{Diff}} = \mathrm{Kernel}_{\mathrm{withoutRoads}} - \mathrm{Kernel}_{\mathrm{withRoads}}$$

A second measure of road impacts for this study (RoadEffect) was also developed that was intended to isolate the loss of connectivity specifically attributable to each road segment, excluding upstream reductions that are already incorporated because of other roads existing between a given road segment and the source point. This effort isolates the effect of an individual road pixel from the accumulated background reduction in movement prior to that point. This metric is derived by comparing the expected total loss of movement ($\mathrm{Kernel}_{\mathrm{Diff}}$) at a given road pixel with the minimum total loss in the 3-x-3 pixel neighborhood.

$$\mathrm{RoadEffect} = \mathrm{Kernel}_{\mathrm{Diff}} - \min(\mathrm{Kernel}_{\mathrm{Diff}})_{3 \times 3}$$

The RoadEffect metric isolates the marginal loss of connectivity—the reduction in predicted movement intensity caused by a single road pixel. This metric can be highly valuable for mitigation planning because it ensures that prior road effects upstream are accounted for in the total accumulated cost of movement before the marginal effect is calculated. Consequently, the metric assigns low priority to segments already separated from source habitats by a severe, nearly impermeable barrier (like a high-cost highway or urban land cover), allowing resources to be prioritized instead toward road segments where effective mitigation could maximize the final movement benefit. Segments with the highest RoadEffect values are thus predicted to be the most critical barriers because they combine high-resistance characteristics (e.g., high traffic volume or road width) with close proximity to a reachable source habitat for the given species.

The resistant kernel analysis for a given species resulted in a separate four-band raster image for each species expert, containing $\text{Kernel}_{\text{withRoads}}$, $\text{Kernel}_{\text{withoutRoads}}$, $\text{Kernel}_{\text{Diff}}$, and RoadEffect bands. An average of these rasters across all species experts generated a single four-band raster for each species. This averaging mitigates the influence of any single expert's resistance value selection assignments and is intended to produce a more robust, multi-expert ensemble prediction of movement intensity and road impacts. All final outputs were exported to a standard NLCD projection (Albers Equal Area for the continental United States, EPSG 5070) with a 30 m cell size.

RESULTS AND DISCUSSION

The results are categorized by each of the three major tasks in the work plan:

- Priority species selection.
- Literature review, sources of species occurrence, habitat, and connectivity data, and expert opinion.
- Species model development.

Priority Species Selection

A Small Species TAC was formed in July 2024 and comprised experts from VDWR, VDCR, and VDOT. Together, they identified 12 priority species of reptiles, amphibians, and small mammals. Table 2 includes five turtle, three snake, one salamander, and three mammal species. The primary rationale for selecting priority species was their classification as Virginia SGCN in the VDWR's (2025a) Wildlife Action Plan. Three of the selected species are also state threatened or endangered, and one is federally threatened. TAC focused on reptiles and amphibians regardless of life history traits because they are prone to negative road effects and are particularly susceptible to road mortality and habitat fragmentation (Rytwinski and Fahrig, 2015). Furthermore, reptiles and amphibians are generally underrepresented in habitat connectivity considerations despite their ecological status or conservation needs. Those selected mammal species were also considered particularly susceptible to habitat fragmentation or road mortality, or both. Aquatic and arboreal species were excluded.

Table 2. Priority Species Included in this Study and Their Conservation Status

Species	Scientific Name	Conservation Status^a	Conservation Status^b and Notes—VDCR/DNH Data
		Herpetofauna	
Bog turtle	*Clemmys muhlenbergii*	Federally threatened, endangered in VA, SGCN Tier 1a	G2G3, S2, LT/SA, LE
Wood turtle	*Glyptemys insculpta*	State threatened in VA, SGCN Tier 1a, Cites Appendix 2	G2G3, S2, LT
Spotted turtle	*Clemmys guttata*	SGCN, Tier 3a	*NA (not on VDCR's rare species or watch lists)*
Box turtle	*Terrapene carolina carolina*	SGCN Tier 3c, Cites Appendix 2	*NA (not on VDCR's rare species or watch lists)*
Mabee's salamander	*Ambystoma mabeei*	State threatened in VA, SGCN Tier 2a	G4, S1S2, LT
Northern diamondback terrapin	*Malaclemys terrapin terrapin*	SGCN Tier 2a, Cites Appendix 2	*A few records in watch list database but none in EC database*
Timber/canebrake rattlesnake	*Crotalus horridus*	State endangered in VA, SGCN Tier 2a (canebrake); SGCN 4a (timber).	Canebrake (Coastal Plain pop.): G4T4Q, S1, LE
Farancia snakes (mud and common rainbow)	*Farancia abacura abacura* and *erytrogramma erytrogramma*	SGCN Tier 4a	*A few records in watch list database but none in EC database*
		Mammals	
Eastern spotted skunk	*Spilogale putorius putorius*	SGCN Tier 4c	*On watch list but no records*
Fisher	*Martes pennanti pennanti*	SGCN Tier 4c	G5, S1 *3 records in EO database*
Allegheny woodrat	*Neotoma magister*	SGCN 4a	*On watch list but no records*

DNH = Division of Natural Heritage; EC = Element code; EO = Element occurrence; NA = not applicable; SGCN = Species of Greatest Conservation Need; VDCR = Virginia Department of Conservation and Recreation.
^{a} Based on state and federal status and SCGN classification and ranking from Virginia Department of Wildlife Resources (2025a). ^{b} Based on global rank, state rank, federal status, and state status from Roble (2025). Global ranks are G2 = imperiled, G3 = vulnerable, G4 = apparently secure, G5 = secure, and G4T4Q = taxon within species is apparently secure but "taxonomic distinctiveness…is questionable." State ranks are S1 = critically imperiled and S2 = imperiled. Federal ranks are LE = listed endangered, LT = listed threatened, and LT/SA = "listed as threatened due to similarity of appearance."

Literature Review, Review of Species Occurrence, Habitat, and Connectivity Data Sources, and Expert Opinion

Literature Review

A total of 532 peer-reviewed research papers were identified for the 12 target species, of which 391 papers had data that could be useful to inform the modeling and expert elicitation processes. The number of relevant papers per species varied from one for the Rainbow Snake to 59 for the Eastern Box Turtle. Figure 2 shows the number of papers that were found by a literature search for each of the focal species covering each of the primary data topics (habitat suitability, resource selection, connectivity, and movement). Data on these topics were extracted into a standardized database, and the papers were downloaded and saved for future access as needed. Considerably less data were available for species on the subject of habitat connectivity and selection, with an average of three and five papers per species, respectively, compared with an average of 19 papers per species on the subject of animal movement (Figure 2). For several species (notably the Mabee's salamander, eastern mud snake, and rainbow snake), no peer-reviewed information could be found on habitat selection or connectivity.

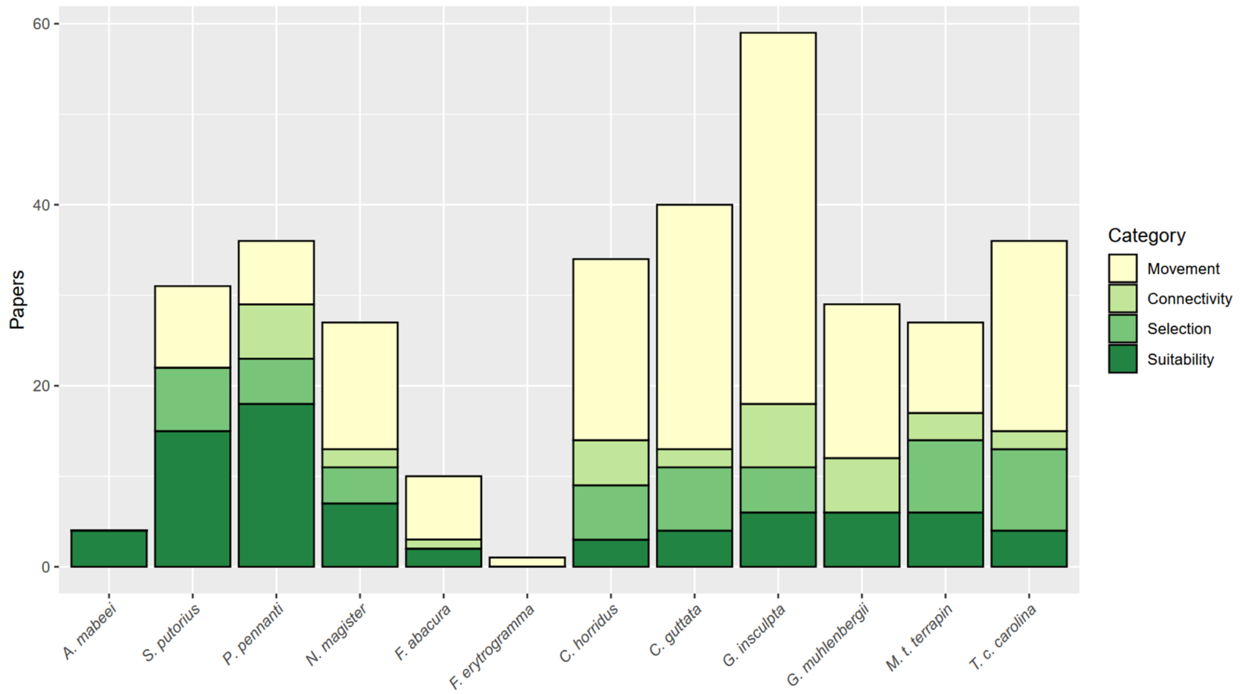


Figure 2. The Number of Scientific Papers with Relevant Information for Each Species Based on Habitat Suitability, Habitat Selection, Connectivity, and Movement

Literature on habitat suitability yielded an average of seven papers per species. These sources were used to identify covariates that could be used in HSI models, even when the values or significance of such covariates in the final models were not reported. Although no habitat suitability covariates were found for the Mabee's salamander, mud snake, and rainbow snake, an average of 26 potential covariates was available for each of the remaining species. These covariates were noted and provided to experts during the expert elicitation process to get their comments and importance rankings. Thus, although the literature review identified a substantial amount of relevant research, it also highlighted uneven coverage across species and a relative scarcity of studies focused on movement, habitat selection, and connectivity.

Species Occurrence, Habitat, and Connectivity Data

The best sources for occurrence data for the priority species were the two Virginia statewide datasets: the Natural Heritage Data Explorer (VDCR, 2025) and the Wildlife Environmental Review Map Service (VDWR, 2025b). These two datasets presented 4,813 observations covering all species except the box turtle. Individual experts on the spotted skunk, fisher, diamondback terrapin, mud snake, and rainbow snake also supplemented this data. Although data sharing was explored with all adjacent states to identify potential dispersal source locations close to Virginia borders, only North Carolina occurrence data were successfully integrated into the workflow because it was deemed critical for modeling connectivity for several range-restricted species in the southeastern Coastal Plain. The inclusion of adjacent source points was also considered a lower priority because key Virginia-specific GIS layers used to build the resistance surfaces were not available beyond the state line (e.g., road data). Because the Potomac River likely serves as a significant barrier for many of the modeled species, cross-border movement with Maryland is likely of low concern. However, caution is warranted when evaluating roads near the West Virginia border because adjacent areas of West Virginia should represent additional source areas for several species.

All publicly available iNaturalist and GBIF locations of species within the study area were also downloaded. However, many locations were either not available or had their GPS coordinates obscured because many of the focal species are targets of illegal poaching, and the majority of available GBIF locations were derived from iNaturalist data. In instances of obscured locations, particularly for less commonly observed species (e.g., fisher and Allegheny woodrat), individual iNaturalist users were contacted to solicit more exact location information. Although some users responded, many were unresponsive. Because of the research team's limited ability to make use of these data sources, GBIF and iNaturalist data were not integrated into the connectivity modeling process.

Unsurprisingly, more cryptic and less studied species had fewer observations in the VDCR and VDWR datasets, but conversations with experts during follow-up meetings indicated that the datasets for those species represented reasonable approximations of their known distributions in the state. In contrast, the bog turtle and spotted skunk experts suggested that although the occurrence dataset likely represented the best available data, important gaps exist between where they expect the species to be found and where surveys have been conducted. The fisher also presents a unique set of considerations because the species is actively expanding its distribution in the state, and output maps should be interpreted in this context. Ultimately, the Google Earth Engine-based workflow developed for connectivity modeling with this suite of priority species could be enhanced if meaningful future improvements were available in the completeness of underlying occurrence datasets that VDCR and VDWR manage.

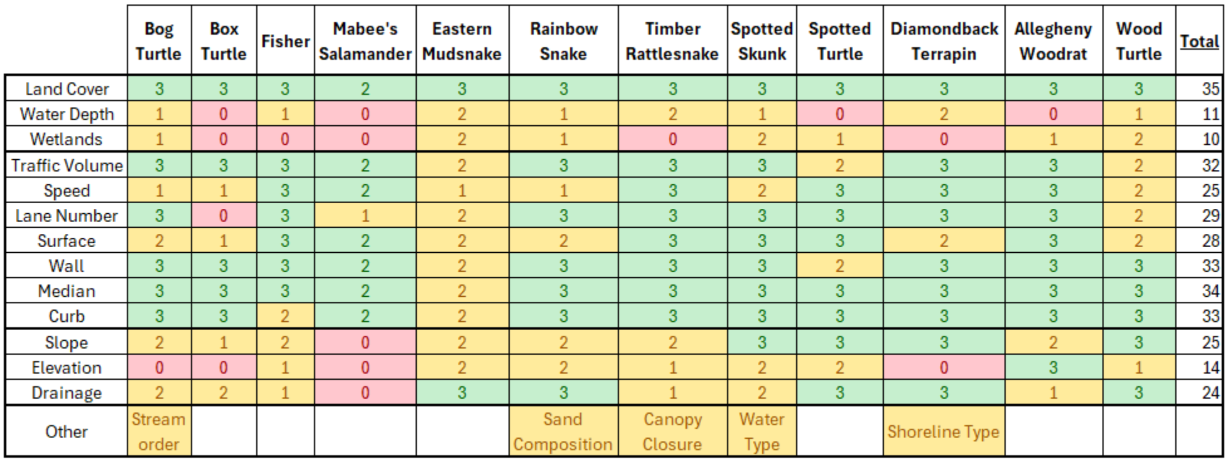
Expert Elicitation

Twenty-nine experts were identified across all species, and three participating experts were selected for each species, except for the Mabee's salamander, which had only two experts feeling qualified and agreeing to participate. Most experts covered only one species, but six experts covered two species. Of the 29 participating experts, 14 were affiliated with academic institutions, 10 with government agencies, and 5 with other non-governmental organizations. Twenty-four of the 29 experts participated in the live information sessions, with the remaining experts receiving the training via video. The majority of experts also participated in the follow-up meetings. Unfortunately, a follow-up meeting for the spotted skunk could not be held because of the delay caused by one expert withdrawing late in the process.

The follow-up meetings proved to be an important part of the process because many experts expressed a degree of uncertainty going into those meetings and expressed higher levels of confidence by the close of them. These meetings offered an opportunity for the research team to reiterate and clarify important mechanisms of the modeling process and led to the raising of species-specific ideas from individual experts that the others had not previously considered. Importantly, these meetings did not lead to a forced consensus because the revised worksheets provided by experts remained distinct quantifications of their individual experiences with the target species.

During follow-up meetings with experts, the research team reinforced the need to assign resistance values only to landscape components that were mechanistically meaningful to the species' movement. Although many experts initially provided scores for all available landscape categories, this subsequent clarification often led to a more focused set of final resistance assignments. However, the final resistance values did not reveal clear, consistent differences in the importance of specific landscape components across the individual species. Regardless, some general patterns were observed across resistance variables overall (Figure 3):

- Surrounding road features (walls, medians, and curves) were almost unanimously included.
- Traffic volume emerged as the most commonly included direct road consideration, with no species having less than two experts using it.
- Speed limit was the least used road feature but was still included in 25 of the 35 expert assessments.



	Bog Turtle	Box Turtle	Fisher	Mabee's Salamander	Eastern Mudsnake	Rainbow Snake	Timber Rattlesnake	Spotted Skunk	Spotted Turtle	Diamondback Terrapin	Allegheny Woodrat	Wood Turtle	Total
Land Cover	3	3	3	2	3	3	3	3	3	3	3	3	35
Water Depth	1	0	1	0	2	1	2	1	0	2	0	1	11
Wetlands	1	0	0	0	2	1	0	2	1	0	1	2	10
Traffic Volume	3	3	3	2	2	3	3	3	2	3	3	2	32
Speed	1	1	3	2	1	1	3	2	3	3	3	2	25
Lane Number	3	0	3	1	2	3	3	3	3	3	3	2	29
Surface	2	1	3	2	2	2	3	3	3	2	3	2	28
Wall	3	3	3	2	2	3	3	3	2	3	3	3	33
Median	3	3	3	2	2	3	3	3	3	3	3	3	34
Curb	3	3	2	2	2	3	3	3	3	3	3	3	33
Slope	2	1	2	0	2	2	2	3	3	3	2	3	25
Elevation	0	0	1	0	2	2	1	2	2	0	3	1	14
Drainage	2	2	1	0	3	3	1	2	3	3	1	3	24
Other	Stream order					Sand Composition	Canopy Closure	Water Type		Shoreline Type			

Figure 3. Summary of Expert Opinion Regarding the Relative Influence of Landscape and Road Components on Priority Small Animals. Resistance values were assigned for base land cover types (National Land Cover Dataset, National Wetland Inventory, and water depth), with additional resistance associated with road characteristics and other landscape features. Green cells indicate unanimous expert consensus to include the variable in the resistance surface, yellow cells indicate that a subset of experts supplied resistance values for the feature, and red cells indicate that the feature was excluded by all experts for that species.

Experts also regularly indicated that increasing levels of human development have the highest resistance values among the land use classes. The agricultural classes for cultivated crops and pasture also received some higher resistance values but not as consistently. Although this report focuses on the effects of roads, the data also provide insight into the non-road human barriers listed as a priority to identify in the WCAP.

Conversations during follow-up meetings regularly included how each feature contributed distinctly to resistance. For example, road surface type and width were perceived as potential novel or discomforting environments that species may behaviorally avoid, and traffic volume was more likely to affect the mortality risk for individual animals that attempt to cross. Several experts who decided to exclude traffic speed spoke to the idea that, for smaller species, drivers are unlikely to see and avoid a crossing animal, even at low speeds. As such, these experts felt that the resistance value of a road could then be more attributable to traffic volume than other factors.

During the follow-up meetings, experts also provided valuable insights into the potential mechanistic influence of both included and excluded landscape features. Discussions with species experts on these variables were insightful for identifying sources of, as well as gaps in, available data. For example, although mammal species were likely not restricted by any curb, multiple herpetofaunal species experts emphasized the importance of curb design and height in determining resistance to movement. Unfortunately, it was not possible to track down a source for fine-scale, statewide curb data. Experts also identified median walls and sound walls as important determinants of connectivity and road mortality. However, the type of barrier is important because each of the priority species would be able to pass under a guard rail with effectively no resistance, whereas a Jersey barrier would be an impenetrable barrier for most species. Unfortunately, the primary state dataset on median barriers does not provide distinctions between these barrier types. An attempt was made to use a separate guardrail-specific dataset in conjunction with the primary dataset to isolate Jersey barriers, but a mismatch in spatial representation prevented this effort because the guardrail data were not spatially aligned with road centerlines. Ultimately, the modeling workflow was able to capture some but not all road characteristics that experts identified as contributing to resistance. The development of comprehensive statewide data for median walls and curbs could meaningfully improve predictions of road impacts at fine spatial scales.

Although these features represent unmodeled barriers, several researchers also identified the presence of culverts and bridges as key road elements that have the potential to mitigate road impacts. This topic was discussed in follow-up meetings with experts on the fisher, mud snake, rainbow snake, and wood turtle species. Although point location data for these features exist, the data often lack detailed attributes necessary to assess species-specific passability, such as barrier size, material, water level, and position relative to the ground. Although the extent to which different species use these structures is unknown, incorporating existing structures into future connectivity assessments could provide valuable insights for the WCAP and would result in a more optimistic picture of habitat connectivity than our current maps depict.

Species Models

Source Selection

The resistant kernel analysis simulated movement from source sites for all 12 priority species and entailed different strategies for defining source locations depending on the particular species. Two species, the Mabee’s salamander and wood turtle, have a reasonably complete accounting of occurrence locations. Therefore, the known occurrence locations were used directly, and developing habitat suitability maps for identifying potential unmapped source sites was not needed. By contrast, the mud snake, rainbow snake, and spotted turtle were believed to be significantly undersurveyed. Although known source sites for these species were not comprehensive, the limitations of available predictor data made the creation of habitat suitability maps for unmapped sites impractical. Ultimately, because of either data completeness or limitations of predictive modeling, the team used observation points alone as the source locations for all five of these species in the connectivity analysis. To best capture the ecological dynamics of terrapin coming onto land for nesting, the GPS positions of a small number of terrapin occurrence points were edited to ensure they fall within the nearest likely "offshore" location the species might access, and subsequently generated connectivity outputs based on those modified source points.

Habitat suitability modeling was used to supplement known source locations in connectivity models for the remaining six species. For the bog turtle and box turtle, experts provided existing, published habitat suitability maps that were incorporated into the workflow. For the remaining four species (the fisher, spotted skunk, wood rat, and canebrake rattlesnake), HSI models were developed to identify additional supplemental source sites for connectivity modeling. An extensive set of potential predictor variables was evaluated and compiled to support the development of these HSI models. Table 3 shows the most highly ranked predictor variables for each species according to participating species experts and indicates which variables were ultimately incorporated into the HSI models for each species. Land use data were sourced from NLCD and supplemented by NWI for wetland type proportions and the NASA Tree Canopy dataset for canopy cover (Sexton et al., 2013). Elevation data were sourced from the NASA SRTM dataset and used to derive additional topographic variables such as slope, aspect, and topographic position index values. However, to represent potential cliff locations, the higher resolution USGS National Elevation Dataset, following the landform classification method of Theobald et al. (2015), was included. Road density for this portion of the workflow was based on the national Tiger lines dataset to include surrounding states (U.S. Census Bureau, 2025). Data for the presence of karst were sourced from the USGS National Map (Tobin and Weary, 2004). The resulting HSI models all performed well in accuracy assessments, with the following average area under the receiver operating characteristic curve values from a nine-fold cross-validation (Fawcett, 2006): canebrake rattlesnake = 0.969; spotted skunk = 0.902; fisher = 0.973; and Allegheny woodrat = 0.884.

Table 3. Variables Used (Green) and Considered (Gray) for Generating Habitat Suitability Index Models for Each of the Species for Which Custom Models were Generated[a]

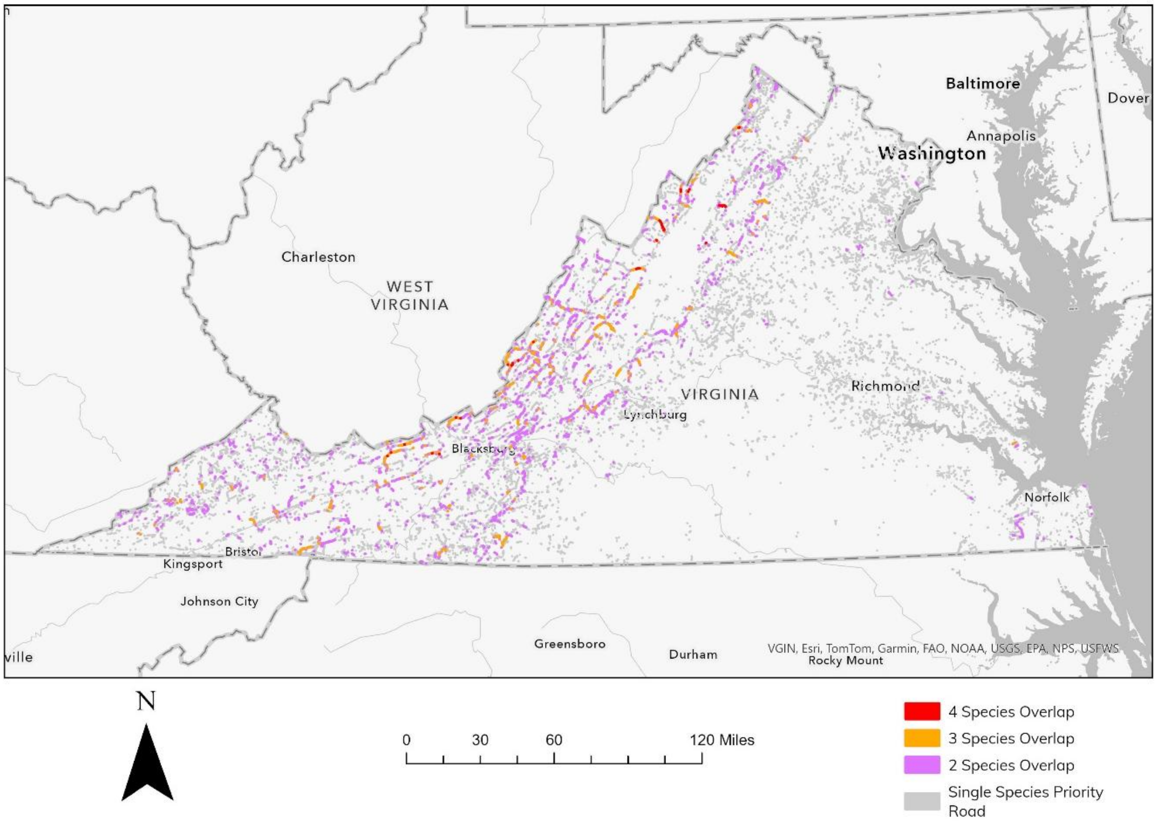
Timber Rattlesnake	Spotted Skunk
Elevation	Aspect
Slope	Elevation
Southness Index	Slope
Canopy Cover	Canopy Cover
Percent Forest Cover	Percent Forest Cover
Topographic Position Index	Percent Shrub Cover
Forest Patch Area (Combustion Limitation)	Trees (Presence) (Covered by Canopy)
Eastness Index (Covered by South)	Canopy Cover at Breast Height (Data Unavailable)

Timber Rattlesnake	Spotted Skunk
	Stand Age (Data Unavailable)
	Down Wood (Data Unavailable)
	Rocky Outcropping (Data Unavailable)
	Stand Size (Computation Limitation)
	Basal Area (Data Unavailable)
	Cover Woody Plants in Understory (Data Unavailable)
	Emergent and Colluvial Rock (Data Unavailable)
	Woody Mid and Understory Cover (Data Unavailable)
	Downed Woody Debris (Data Unavailable)
	Generalized Soil Order (Statistical Limitations)
Fisher	**Allegheny Woodrat**
Canopy Cover	Karstification
Percent Forest Cover	Distance to Urban
Percent Urban Cover	Distance to Cliffs
Road Density	Forest Type
Coarse Woody Debris (Data Unavailable)	Distance to Nearest Active Colony (Data Unavailable)
Commercial, 5 km Radius (Data Unavailable)	Pole Timber Density (Data Unavailable)
Forest Core (Computation Limitation)	Distance to Human Disturbance (> 50 Ha) (Statistical Limitations)
Size of Natural Fragments (Computation Limitation)	
Snag Basal Area (Data Unavailable)	

[a] Table 3 shows the most highly ranked predictor variables for each species according to participating species experts and indicates which variables were ultimately incorporated into the species distribution models for each species.

Connectivity map outputs were developed for all 12 priority species and were provided in a specialized file. Data sharing agreements do not allow this specialized file to be given to the public; rather, this file was given to the study champion and the technical review panel. These data are also shared as GIS raster data for each species, containing the bands for each of the four output products described in the Task 3 methods: the Predicted Movement Intensity with Roads (kernel_withRoads), the Predicted Movement Intensity without Roads (kernel_withoutRoads), the Total Change in Movement (Kernel$_{\text{Diff}}$), and the Marginal Road Effect (RoadEffect).

Species-specific maps are not included in this report because many of the priority species are at risk of illegal collection, and source sites can often be identified from the map outputs. Furthermore, derived products generated using state occurrence data for rare species (i.e., SGCN, threatened, or endangered) cannot be made publicly available without approval. Instead, Figure 4 is a single synthesis map that overlays priority road segments for the 12 priority species. It identifies road segments that are in the top 5% of segments predicted to cause the largest reductions in movement levels for either one, two, three, or four species across the state. This identification indicates several areas where high-risk road segments coincide across multiple species. The map also demonstrates that the southeastern Coastal Plain and the mountains of western Virginia (i.e., Blue Ridge, Ridge and Valley, and Cumberland Mountains) are key areas of potential impact to movement corridors for multiple species in Virginia. Specifically, south of Norfolk, with a relatively broad distribution of single species segments and several areas of species overlap, is an area of statewide importance for the range-restricted SGCN that occur there. Likewise, both extensive and concentrated coverage of single-species segments exist in the mountains of Virginia, with several regions therein, including segments affecting two to four species. The latter includes but is not limited to the northwestern corner of Virginia, several east-west road corridors and hotspots within the Ridge and Valley along the West Virginia border from Rockingham County in the north to Bland County south of Blacksburg, and a few isolated areas in the southern Blue Ridge.



VGIN, Esri, TomTom, Garmin, FAO, NOAA, USGS, EPA, NPS, USFWS

Figure 4. Priority Road Segments for 12 Selected Small Animal Species. This figure indicates that the southeastern Coastal Plain and the Blue Ridge, Ridge and Valley, and Cumberland Mountains are key areas of potential road impact for multiple species in Virginia. Gray areas indicate the top 5% road segments for single species. Purple, orange, and red areas indicate overlap of the top 5% road segments for two, three, and four species, respectively.

Spatial Patterns Among Predicted Movement Corridors and Implications for Management

This project provides connectivity map outputs for all 12 priority species as GIS raster data, and the specialized file contains specific map images. Figure 4 summarizes the spatial patterns related to species distributions and predicted movement corridors that are drawn from the assessment of individual species maps and the integration of model outputs across species.

Overall, the 12 species of small animals—8 reptiles (5 turtles and 3 snakes), 1 amphibian (salamander), 3 mammals (1 rodent and 2 carnivores)—differed considerably in several dimensions of ecology, life history, movement behavior, and range size and location, with some species having restricted distributions and others found across the entire Commonwealth. At one extreme, the Mabee's salamander is the smallest species with the smallest known extent of occurrence in Virginia. At the other extreme, the box turtle is within the general size range of the other turtles but has a distribution that appears to span the entire state. Between these two extremes are broadly distributed but patchy species, such as the Alleghany woodrat, or range-constricted species occupying a specific region, like the bog turtle.

The variation in species distributions and the extent of mapped movement corridors resulted in three general groupings of species outputs from the connectivity modeling process: (1) spatially compact movement zones; (2) regionally concentrated movement corridors; and (3) spatially diffuse movement corridors. Species that fall into these different categories likely require different management strategies for maintaining corridor connectivity and mitigating road impacts.

Spatially Compact Movement Zones (Highly Targeted Mitigation)

The Mabee's salamander was unique in its distribution among the selected small animals and, therefore, also in having model outputs that predict compact movement zones around a small number of extant source populations. Because the species is so narrowly distributed, the map products in the specialized file can be used to readily identify a small number of high-priority road segments that may be suitable for targeted, site-level mitigation—such as improving existing culvert passability or adding small-animal passages. This narrow scope means that the identified segments are potentially well suited for site-level study and mitigation measures. Although all species are predicted to experience reduced connectivity where barriers or roads occur, narrowly distributed species may be more vulnerable to population- or range-level effects within the state because a modest number of high-impact roads can potentially intersect a substantial portion of their limited range.

Regionally Concentrated Movement Corridors (Prioritized Mitigation)

Several species (e.g., the bog turtle, canebrake rattlesnake, wood turtle, diamondback terrapin, mud snake, rainbow snake, and fisher) had relatively larger but still regionally restricted distributions, with species likely exhibiting low density or patchy occurrences in many areas. Therefore, they had much broader but regionally concentrated movement corridors that intersected a modest number of important roads. The road impact prioritization metrics derived herein should reflect both proximity to key source habitats and road characteristics associated with high resistance to movement (e.g., high traffic volume and greater road width). As with the Mabee's salamander, road segment prioritization can enable site-level assessment and mitigation. However, for these more broadly distributed species that individually and collectively identify a much larger set of segments that are potentially suitable for mitigation, prioritization among species, ecosystems, settings, and road architecture and engineering considerations will likely be required to optimize resource allocation and management impact. With this concept in mind, Figure 4 demonstrates the spatial extent of high-priority road segments across the state, per single and multiple species impact, to potentially identify sites where the co-benefits of mitigation exist for multiple species.

Spatially Diffuse Movement Corridors (Design Standards or Best Practices)

Several species (i.e., the spotted skunk, Alleghany woodrat, spotted turtle, and box turtle) had broad distributions. Predicted corridors for these species were highly diffuse and intersected many roads over large portions of the state. The existence of so many priority road segments for these wide-ranging species and the widespread nature of concrete barriers, walls, and curbs means that the value of targeted site-level mitigation is likely to be proportionally less effective for the statewide population of these species. Mitigation efforts for such species could instead focus on roadway design standards that can be implemented at scale (e.g., regular use of fencing or curbing to funnel animals to existing structures and ensuring underpasses are compatible with small-animal use) rather than prioritizing individual crossing sites except where already identified and prioritized for other species.

Summary of Work Undertaken and Future Research Needs

The specific steps undertaken during this study and the resultant findings for each step led to the deliverables provided as GIS raster data and maps provided in a specialized file. These steps may be summarized as follows:

- *A TAC representing VDWR, VDCR, and VDOT identified 12 small priority species, all classified as Virginia SGCN, three that are also state threatened or endangered and one is federally threatened.* The species list includes reptiles, amphibians, and mammals vulnerable to road mortality and habitat fragmentation.

- *The literature review identified 532 peer-reviewed papers across the 12 focal species, with usable data from 391 studies, which were standardized into a searchable databas*e. Results revealed substantial information on species movement but limited research on habitat selection and connectivity, particularly for species such as the Mabee's salamander, eastern mud snake, and rainbow snake.

- *A panel of 29 experts from academic, government, and non-governmental organizations provided species-specific input on road and landscape resistance factors for focal species*. Their feedback identified traffic volume, medians, and curbs as critical to movement resistance and highlighted the need for more detailed roadway data on these features to better understand their potential as barriers and to identify mitigation opportunities.

- *HSI models formed the basis for modeled source locations for connectivity analysis for six species*. Analyses for two species, the bog turtle and eastern box turtle, utilized existing habitat suitability maps that species experts provided. For the remaining four species—the fisher, eastern spotted skunk, Allegheny woodrat, and timber rattlesnake—HSI models were created using expert-rated predictor variables for features such as land cover, elevation, and road features.

- *Connectivity analyses for six species were based on source locations defined using known occurrence points alone*. These species either: (1) had a complete accounting of occurrence locations (the Mabee's salamander and wood turtle); (2) were under surveyed to a degree that would make modeling inappropriate (the mud snake, spotted turtle, and rainbow snake); or (3) had reasonably widespread surveys conducted to identify source areas in aquatic habitat (the diamondback terrapin).

- *Priority road segments were identified and combined to map segments of the greatest potential effect to wildlife movement across Virginia (Figure 4)*. The top 5% of segments that caused the largest predicted reductions in movement were classified as priority segments for each species and were presented to illustrate overlap among one, two, three, or four species. The resulting map highlights the concentration of road effects on multiple species in the southeastern Coastal Plain and in western mountain regions, including the Ridge and Valley, Blue Ridge, and Cumberland Mountains.

- *Detailed connectivity map outputs for all 12 priority species have been placed in a specialized file*. For most species, two products exist: the Predicted Movement Intensity with Roads and the Predicted Movement Intensity without Roads. The Mabee's salamander also includes maps illustrating the Total Change in Movement ($\text{Kernel}_{\text{Diff}}$) and the Marginal Road Effect (RoadEffect).

This work also led to the identification of four future research needs:

- *The need for more basic movement ecology research and consistent reporting*. Limited studies on species movement, connectivity, and road impacts, especially for cryptic species, highlight the need for additional research in these areas. More consistent reporting of model outputs, descriptive statistics, and underlying data in published studies would also allow for more empirical data to be incorporated into future connectivity modeling efforts and would better inform conservation efforts.

- *The need for improved spatial data on existing infrastructure*. Enhanced datasets on road features, such as median walls, curbs, and culverts, would improve fine-scale predictions of road impacts for many small animal species. Integrating these data with future updates could provide more accurate assessments of road impacts and habitat connectivity.

- *The need for more comprehensive occurrence datasets*. Many species included in this study had relatively limited occurrence data available, which forced a modeling tradeoff between either underpredicting corridors and potential road impacts or using habitat suitability modeling to identify additional areas of potential source habitat and risking overprediction. Increasing the survey effort for most priority species and systematically tracking box turtle records would help fill this key data gap.

- *The need for empirical validation of connectivity and road impact predictions.* Field validation of connectivity model outputs, such as those developed in this study, is strongly needed. Field surveys could allow comparisons between observed and predicted patterns of road impacts. For example, roadkill surveys analyzed using site occupancy models have been used to estimate wildlife road crossing risk while identifying where mitigation may be most needed (Santos et al., 2018).

CONCLUSIONS

- *This project provided connectivity map outputs for 12 small priority species as GIS raster data and developed a consistent, repeatable workflow for assessing road impacts and connectivity across multiple locations in Virginia*. In addition to the GIS data, a primary deliverable for this effort—the species-specific road risk models and identification of road segments that pose a high risk to small priority species—are summarized in Figure 4 and detailed in a specialized file for the 12 priority species.

- *The connectivity map outputs address the WCAP priority of considering non-road barriers to movement*. The study explicitly accounted for other landscape features that impede movement, with experts assigning urban land covers consistently high resistance values across species. Drainage networks and topographic features were also important drivers of predicted connectivity in many species.

- *For the Mabee's salamander, which was unique in having compact movement zones predicted around a small number of extant source populations, a focused set of priority road segments was identified that may be suitable for site-level assessment and mitigation, such as improving existing culvert passability or adding targeted small-animal passages*.

- *Several species (i.e., the bog turtle, wood turtle, diamondback terrapin, mud snake, rainbow snake, and fisher) had much broader but regionally concentrated movement corridors that intersected a modest number of important roads*. Road risk segments for these species reflect both proximity to key source habitats and road characteristics associated with high resistance to movement (e.g., high traffic volume and greater road width).

- *For several widely distributed species (i.e., the spotted skunk, Alleghany woodrat, timber rattlesnake, spotted turtle, and box turtle), predicted corridors were diffuse and covered large portions of the state*. Mitigation efforts for such species may include roadway design considerations (e.g., the use of fencing or curbing to funnel animals to existing structures and ensuring that underpasses are compatible with small-animal use) rather than prioritizing individual crossing sites.

RECOMMENDATIONS

1. *VDOT's Environmental Division should coordinate with VDWR and VDCR to ensure that the species' habitat models and road risk areas identified in this study are incorporated into the prioritization of wildlife crossing opportunities for the updated WCAP.*

IMPLEMENTATION AND BENEFITS

The researcher and the technical review panel (listed in the Acknowledgments) for the project collaborate to craft a plan to implement the study recommendations and determine the benefits of doing so. This process is to ensure that the implementation plan is developed and approved with the participation and support of those involved with VDOT operations. The implementation plan and the accompanying benefits are provided here.

Implementation

Regarding Recommendation 1, VDOT's Environmental Division will work with the WCAP working group and consultant team to share and discuss the results and data outputs from this study within 6 months of the date of this report's publication. TAC species expert map review is underway, allowing for evaluation and revision before incorporating the maps into the WCAP.

Benefits

Incorporating the findings from this study into the updated WCAP will help satisfy the legislative mandate to list habitat identified as high quality for priority species, identify high road risk areas, and use that information to prioritize and recommend wildlife crossing projects that promote wildlife connectivity.

In addition to advancing the WCAP, other agencies and states will benefit from this study's application of a novel spatial analysis workflow to identify areas of suitable habitat and high-risk road segments for species with limited road mortality data or specialized habitat requirements, or both. Although states are increasingly adopting legislation or engaging in statewide efforts to address animal road mortality and habitat connectivity, research and implementation efforts that target small species are far less common than those for large mammals (Paul, 2023). Small species' evaluations must overcome the challenges of limited road mortality data, restricted species distributions, and spatial datasets that do not adequately capture the specialized or localized habitat requirements of these species.

By identifying both localized and landscape-scale movement constraints, this study provides agencies with a flexible, repeatable foundation for prioritizing mitigation efforts and incorporating wildlife connectivity into long-term transportation planning. Movement corridor maps for individual at-risk species may also be useful for other state conservation planning efforts, such as the Virginia Wildlife Corridor Action Plan.

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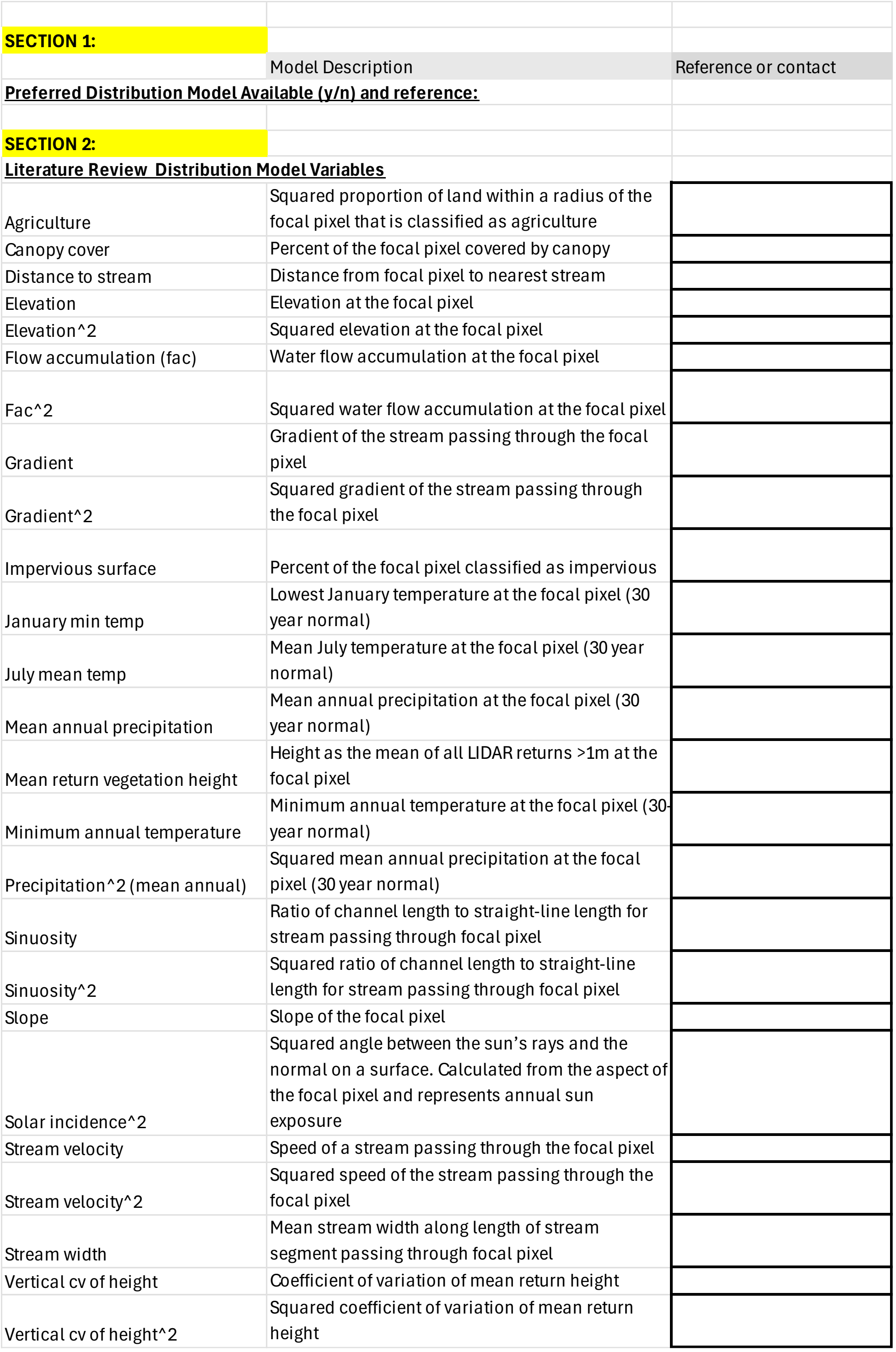
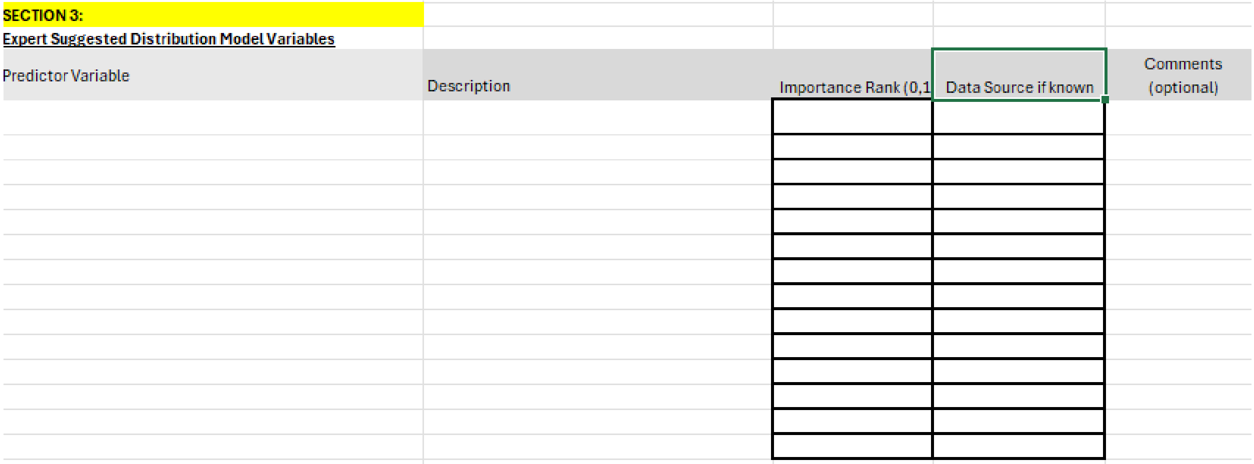
APPENDIX

Figures A1 and A2 show the expert elicitation worksheets, and Figure A3 shows the worksheet for resistance values used in model development.



SECTION 1:		
	Model Description	Reference or contact
Preferred Distribution Model Available (y/n) and reference:		
SECTION 2:		
Literature Review Distribution Model Variables		
Agriculture	Squared proportion of land within a radius of the focal pixel that is classified as agriculture	
Canopy cover	Percent of the focal pixel covered by canopy	
Distance to stream	Distance from focal pixel to nearest stream	
Elevation	Elevation at the focal pixel	
Elevation^2	Squared elevation at the focal pixel	
Flow accumulation (fac)	Water flow accumulation at the focal pixel	
Fac^2	Squared water flow accumulation at the focal pixel	
Gradient	Gradient of the stream passing through the focal pixel	
Gradient^2	Squared gradient of the stream passing through the focal pixel	
Impervious surface	Percent of the focal pixel classified as impervious	
January min temp	Lowest January temperature at the focal pixel (30 year normal)	
July mean temp	Mean July temperature at the focal pixel (30 year normal)	
Mean annual precipitation	Mean annual precipitation at the focal pixel (30 year normal)	
Mean return vegetation height	Height as the mean of all LIDAR returns >1m at the focal pixel	
Minimum annual temperature	Minimum annual temperature at the focal pixel (30-year normal)	
Precipitation^2 (mean annual)	Squared mean annual precipitation at the focal pixel (30 year normal)	
Sinuosity	Ratio of channel length to straight-line length for stream passing through focal pixel	
Sinuosity^2	Squared ratio of channel length to straight-line length for stream passing through focal pixel	
Slope	Slope of the focal pixel	
Solar incidence^2	Squared angle between the sun's rays and the normal on a surface. Calculated from the aspect of the focal pixel and represents annual sun exposure	
Stream velocity	Speed of a stream passing through the focal pixel	
Stream velocity^2	Squared speed of the stream passing through the focal pixel	
Stream width	Mean stream width along length of stream segment passing through focal pixel	
Vertical cv of height	Coefficient of variation of mean return height	
Vertical cv of height^2	Squared coefficient of variation of mean return height	

Figure A1. Worksheet for Ranking Predictor Variables for Model Development



SECTION 3:

Expert Suggested Distribution Model Variables

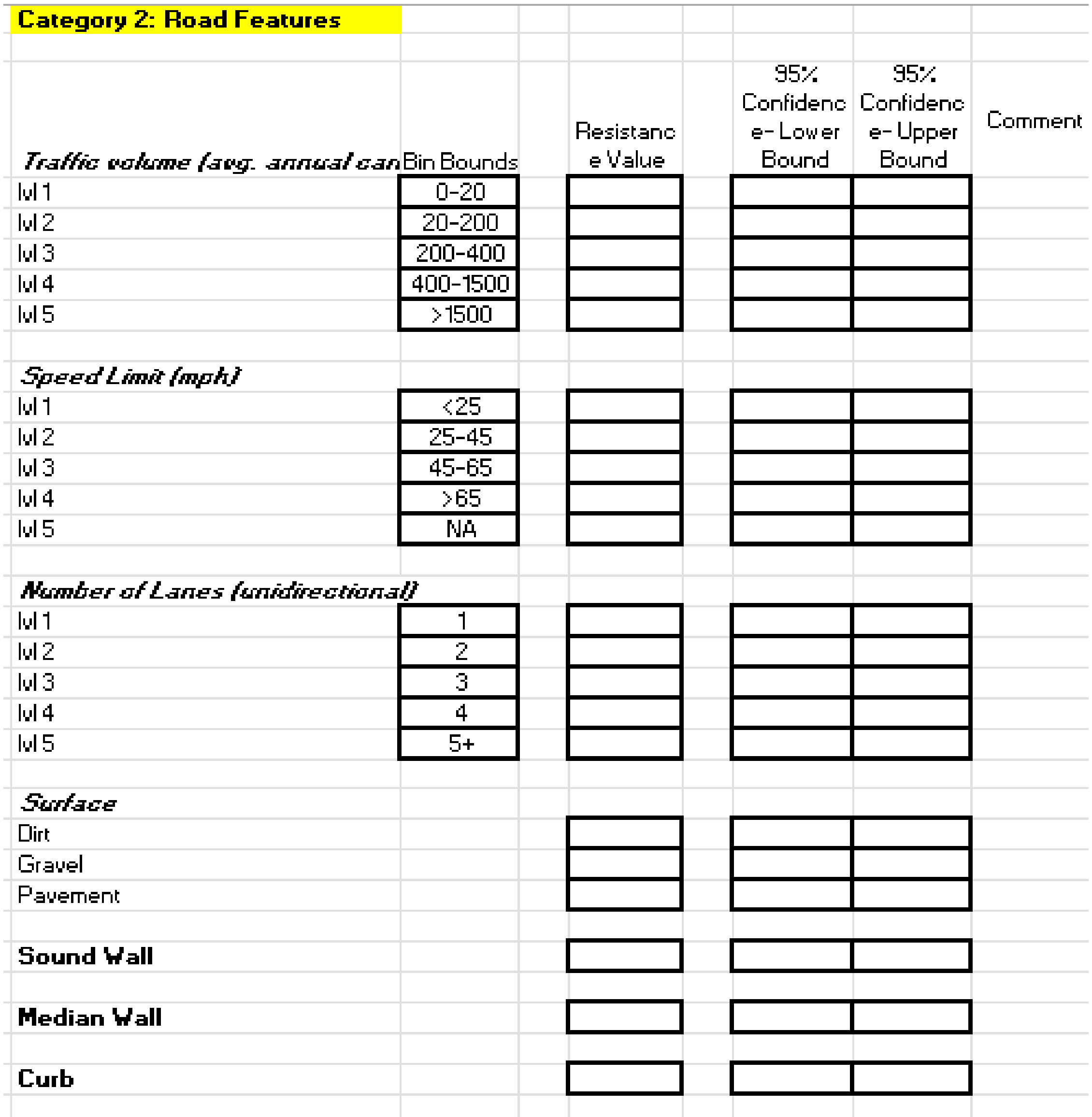
Predictor Variable	Description	Importance Rank (0,1	Data Source if known	Comments (optional)

Figure A2. Worksheet for Suggesting Predictor Variables for Model Development

Category 1: Land Use

Primary Classes (NLCD)		Resistance Value	95% Confidence-Lower Bound	95% Confidence-Upper Bound	Comment
Open water					
Developed open space					
Developed low intensity					
Developed medium intensity					
Developed high intensity					
Barren lands					
Deciduous forest					
Evergreen forest					
Mixed forest					
Shrub/scrub					
Grassland/herbaceous					
Pasture/hay					
Cultivated crops					
Woody wetlands					
Emergent herbaceous wetlands					
Subclasses					
Continuous Ex.					
Replacing: Open Water					
Subclass Category: Depth (m)					
Data Source (if known):	Bin Bounds				
M1	<5				
M2	>5				
Discrete Ex.					
Replacing: Wetland Classes					
Subclass Category: Wetland Type					
Data Source (if known): National Wetland Inventory					
NWI L1. Lacustrine, Limnetic					
NWI L2 shore. Lacustrine, Littoral					
NWI L2 bed. Lacustrine, Littoral					
NWI R1. Riverine, Tidal					
NWI R2 shore. Riverine, Lower perennial					
NWI R2 bed. Riverine, Lower perennial					
NWI R3. Riverine, Upper perennial					
NWI R4. Riverine, Intermittent					
NWI Pf. Palustrine, Farmed					
NWI PUB. Palustrine, Unconsolidated bottom					
NWI PAB. Palustrine, Aquatic bed					
NWI PUS. Palustrine, Unconsolidated shore					
NWI PEM. Palustrine, Emergent					
NWI PSS. Palustrine, Scrub-shrub					
NWI PFO. Palustrine, Forested					
NWI POW. Palustrine, Open water					

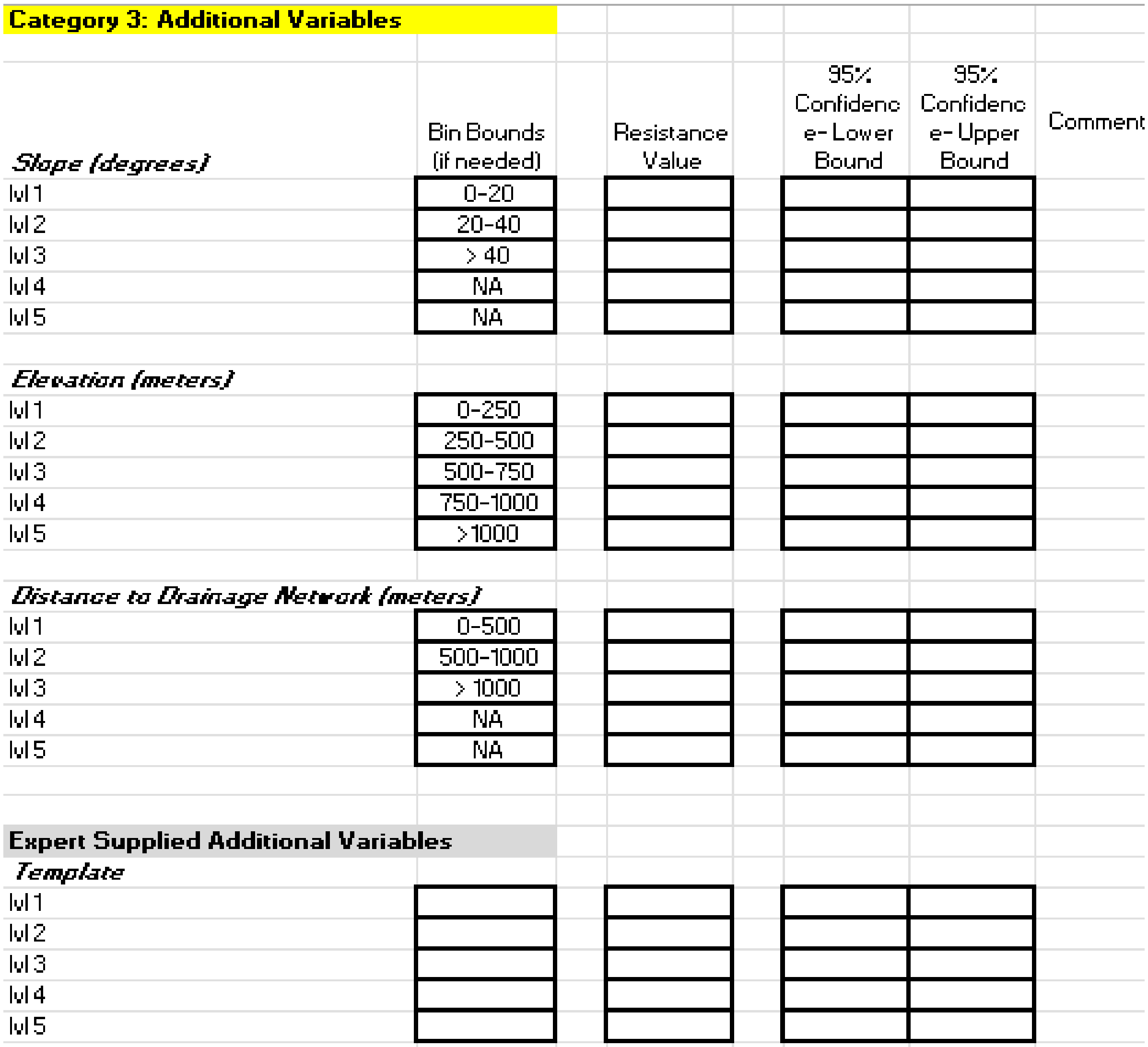
Figure A3. Worksheet for Assigning Resistance Values and Indicating Confidence Levels for Variables Considered Important for Species Movement



Category 2: Road Features

Traffic volume (avg. annual car	Bin Bounds	Resistance Value	95% Confidence- Lower Bound	95% Confidence- Upper Bound	Comment
lvl 1	0-20				
lvl 2	20-200				
lvl 3	200-400				
lvl 4	400-1500				
lvl 5	>1500				
Speed Limit (mph)					
lvl 1	<25				
lvl 2	25-45				
lvl 3	45-65				
lvl 4	>65				
lvl 5	NA				
Number of Lanes (unidirectional)					
lvl 1	1				
lvl 2	2				
lvl 3	3				
lvl 4	4				
lvl 5	5+				
Surface					
Dirt					
Gravel					
Pavement					
Sound Wall					
Median Wall					
Curb					

Figure A3 (continued). Worksheet for Assigning Resistance Values and Indicating Confidence Levels for Variables Considered Important for Species Movement



Category 3: Additional Variables

	Bin Bounds (if needed)	Resistance Value	95% Confidence- Lower Bound	95% Confidence- Upper Bound	Comment
Slope (degrees)					
lvl 1	0-20				
lvl 2	20-40				
lvl 3	> 40				
lvl 4	NA				
lvl 5	NA				
Elevation (meters)					
lvl 1	0-250				
lvl 2	250-500				
lvl 3	500-750				
lvl 4	750-1000				
lvl 5	>1000				
Distance to Drainage Network (meters)					
lvl 1	0-500				
lvl 2	500-1000				
lvl 3	> 1000				
lvl 4	NA				
lvl 5	NA				
Expert Supplied Additional Variables					
Template					
lvl 1					
lvl 2					
lvl 3					
lvl 4					
lvl 5					

Figure A3 (continued). Worksheet for Assigning Resistance Values and Indicating Confidence Levels for Variables Considered Important for Species Movement