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Improving roadway conservation investments in Vermont: Developing a prioritization screening framework for reducing road wildlife mortality and improving wildlife movement through bridges and culverts

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16. Abstract

Transportation structures like bridges, culverts, and underpasses provide permeability for wildlife across roadways, and structure improvements can encourage wildlife passage beneath roads. Investments in structure improvements can lead to benefits for wildlife by reducing the impacts of roads and allowing greater landscape connectivity for species. This project assessed the value of Vermont Agency of Transportation (VTrans) managed transportation structures for terrestrial mammal connectivity in Vermont. We developed a user-friendly, flexible spreadsheet tool that allows users to rank structures according to information on wildlife connectivity along with structure attributes, human development data, and protected lands data. We focused on 5,912 structures of potential interest for wildlife-based improvements based on input from VTrans and project partners. We used a new electrical circuit theory approach to model the movement of eight terrestrial mammal species at two spatial scales (statewide and structure level) using a combination of species occurrence data, expert-derived landscape resistance information, and coarse and fine scale land cover data. We also compiled information on structure attributes important to wildlife (structure width and length, bankfull width) and surrounding influences (amount of fine-scale human developed land cover, amount of adjacent protected lands). Results of each analysis were incorporated into a Terrestrial Passage Screening Tool: a linear programming decision-making framework that ranks each structure by its importance for terrestrial wildlife in Vermont. The Tool includes user-friendly features allowing managers to look up a structure by its ID number to view all associated data, adjust thresholds to rank a subset of structures, add weights to emphasize some data inputs more than others, and consider three different ranking options that evaluate structures by wildlife movement priority, structural condition, and amount of adjacent protected lands. We used game camera data, collected throughout multiple VTrans research projects, to assess some results. The Terrestrial Passage Screening Tool allows transportation and wildlife managers to quickly evaluate the value of a given structure for landscape connectivity that can inform decision-making related to mitigating the impacts of roadways on wildlife. The project is a collaboration between the University of Vermont, Vermont Fish and Wildlife Department, The Nature Conservancy of Vermont, and Vermont Agency of Transportation.

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Abstract

Transportation structures like bridges, culverts, and underpasses provide permeability for wildlife across roadways, and structure improvements can encourage wildlife passage beneath roads. Investments in structure improvements can lead to benefits for wildlife by reducing the impacts of roads and allowing greater landscape connectivity for species. This project assessed the value of Vermont Agency of Transportation (VTrans) managed transportation structures for terrestrial mammal connectivity in Vermont. We developed a user-friendly, flexible spreadsheet tool that allows users to rank structures according to information on wildlife connectivity along with structure attributes, human development data, and protected lands data. We focused on 5,912 structures of potential interest for wildlife-based improvements based on input from VTrans and project partners. We used a new electrical circuit theory approach to model the movement of eight terrestrial mammal species at two spatial scales (statewide and structure level) using a combination of species occurrence data, expert-derived landscape resistance information, and coarse and fine scale land cover data. We also compiled information on structure attributes important to wildlife (structure width and length, bankfull width) and surrounding influences (amount of fine-scale human developed land cover, amount of adjacent protected lands). Results of each analysis were incorporated into a Terrestrial Passage Screening Tool: a linear programming decision-making framework that ranks each structure by its importance for terrestrial wildlife in Vermont. The Tool includes user-friendly features allowing managers to look up a structure by its ID number to view all associated data, adjust thresholds to rank a subset of structures, add weights to emphasize some data inputs more than others, and consider three different ranking options that evaluate structures by wildlife movement priority, structural condition, and amount of adjacent protected lands. We used game camera data, collected throughout multiple VTrans research projects, to assess some results. The Terrestrial Passage Screening Tool allows transportation and wildlife managers to quickly evaluate the value of a given structure for landscape connectivity that can inform decision-making related to mitigating the impacts of roadways on wildlife. The project is a collaboration between the University of Vermont, Vermont Fish and Wildlife Department, The Nature Conservancy of Vermont, and Vermont Agency of Transportation.

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1. Project Overview

Road networks span great distances and contribute to fragmentation of the natural landscape (Beckmann and Hilty 2010). In Vermont, roads cover 25,428 kilometers, and the public travels an estimated 11.4 billion kilometers annually on those roads. Although roads are important for connecting human populations, they often inhibit the movement of wildlife across the landscape, leading to negative genetic and demographic consequences for species in most cases (Brady and Richardson 2017, Hostetler et al. 2009). Terrestrial mammals often experience direct mortality through wildlife-vehicle collisions, but also experience indirect mortality and reductions in fitness that can lead to less viable populations (Corlatti et al. 2009, Dodd and Gagnon 2011, Trombulak and Frissel 2000).

Transportation structures can facilitate safe wildlife movement across roadways and increase the permeability of these barriers (Simpson et al. 2016). Culverts, bridges, and underpasses provide opportunities for wildlife to navigate complex transportation networks and reduce the risk of collisions (Simpson et al. 2016). However, not all transportation structures are well suited to accommodate the movement of all species. The physical attributes of transportation structures, such as width, length, substrate, and material, may promote or deter wildlife use, depending on species size and preferences (Clevenger and Waltho 2000, 2005; Sawyer et al. 2016). Transportation and wildlife managers can improve existing structures to better accommodate a wide range of species. However, improvement projects are often costly, and developing a means of prioritizing structures for their value to wildlife connectivity can lead to more efficient and effective outcomes (Gurrutxaga and Saura 2014, Sawyer et al. 2016, Zeller et al. 2020a, 2020b).

We developed an approach to rank Vermont transportation structures by their connectivity value for eight terrestrial mammal species. We used a novel circuit-theory approach to model wildlife movement throughout the state at two spatial scales. Models along with information about structures and the surrounding landscape characteristics were then used to develop a spreadsheet tool that ranks structures. The project builds on two previous phases of research led by the Vermont Fish and Wildlife Department and The Nature Conservancy, and provides a science-based framework to inform decision making about the management of transportation structures in Vermont.

In this project, we:

1) Identified transportation structures across the state that met criteria related to wildlife movement, and compiled structure attribute information from multiple databases into a single dataset.
2) Modeled and mapped connectivity for eight terrestrial mammal species at two spatial scales (statewide and structure level).
3) Estimated the degree of fine-scale human development and adjacent protected lands around structures.
4) Developed a Terrestrial Passage Screening Tool to rank structures based on connectivity results, structure attributes, and amount of surrounding human development and protected lands.
5) Used game camera data collected before and during the project to evaluate connectivity assessments at a subset of locations.

The Terrestrial Passage Screening Tool (TPST) – a primary output from this project, allows managers to evaluate the relative value of a given transportation structure for connectivity, and inform decision-making related to mitigating the impacts of roadways on wildlife in Vermont. In this report, we provide an overview of the methods used to quantify the inputs to the TPST, including connectivity and information about structures and surrounding landscape characteristics. We also describe the development and use of the TPST.

2. Methods

Overview

We first identified a set of wildlife and transportation priorities to incorporate into the larger TPST framework based on input and consultation with all project partners. We began by identifying a set of state-managed transportation structure locations of potential practical use to wildlife based on size and replacement/retrofit potential. Locations were mapped and structure attributes recorded. We then modeled and mapped wildlife connectivity for eight species at two scales (statewide and structure) using a circuit theory approach that accounts for the relative distribution/abundance of species and the degree landscape conditions influence movement. Project partners further identified two other sets of information important to understanding patterns of wildlife movement at structures in addition to connectivity, including fine-scale human developments like houses, buildings, and impervious surfaces, and the amount of protected land around structures. We then developed the TPST framework in a user-friendly spreadsheet. The TSPT uses a linear-programming decision-making approach and integrates structure attributes, connectivity results, human development information, and protected area information to rank transportation structures according to their value for wildlife passage. The TSPT is flexible and allows for structures to be ranked according to constraints (e.g., only those larger than a specified size) and weights, which would allow managers to emphasize some inputs more than others if desired (e.g., structure level connectivity results over landscape level connectivity results). Below we describe each of the main project elements.

2.1. Structure Selection and Structure Attributes

Structure Selection

We compiled data from the Vermont Agency of Transportation and Stream Geomorphic Assessment inventories of state-managed transportation structures, including bridges, culverts (arch, box, and pipe) and other underpasses that may be of use to wildlife (Marangelo 2019, Vermont Agency of Natural Resources 2009, Vermont Agency of Transportation 2016A, 2016B, 2016C, 2017). Although there are over 88,000 state-managed transportation structures along Vermont roads, many structures (e.g., drainage culverts) are too small to be useful for wildlife passage and unlikely to be replaced or retrofitted to a larger size. To eliminate structures of no practical use for wildlife crossings, we selected structures from state databases that were at least three feet in diameter[1] located on state or federal highways, resulting in 5,912 structure locations (Figure 1). We created a new dataset for use in our analyses containing location and attribute information for these selected structures.

Additional steps were taken to ensure more accurate placement of structure points in our dataset, and to differentiate between multiple point locations associated with a single structure. To derive a point location for structures located over mapped streams, we followed the methodology of the Transportation Resiliency Project (Milone and MacBroom INC 2019).[2] For some analyses, it was important to link structures located at the same location that extended across the median of a divided highway: structures on or over divided highways that VTrans maps as a single structure were given unique IDs by adding a lane direction letter after

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[1] Structures lacking diameter information in state databases were eliminated from consideration.

[2] Some point assignments and attributes were manually adjusted if it was apparent from aerial photos that the incorrect structure had been selected.

the ID[3]. Conversely, bridges or culverts with unique IDs at the same divided highway location were assigned identical IDs in a separate attribute field by removing directional letters, or substituting one of the VTrans IDs[4]. In instances where a single structure appeared in more than one of the inventories with different ID numbers, identity was assumed based on proximity to the same stream-road intersection. Final structure IDs were based on original VTrans or ANR-AOP ID, ensuring each structure had a unique value.

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[3] Unique IDs were used when estimating development influence in a buffered circle surrounding each half of the structure.

[4] Consolidated IDs were used when identifying protected lands at a given distance from the outer lanes, so as not to include the median in the spatial analysis. These IDs were also used to identify analysis areas for wildlife movement analyses.

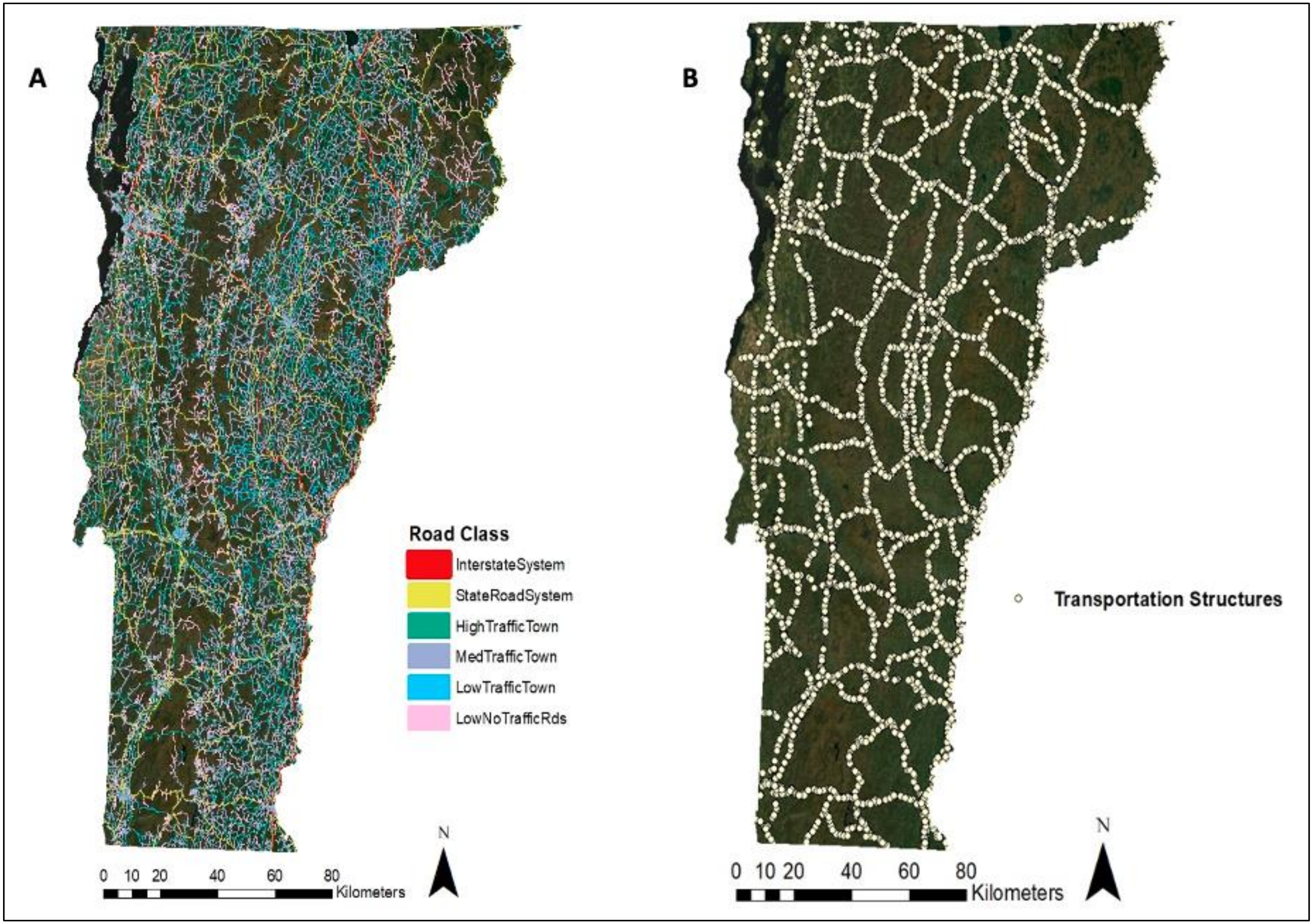

Figure 1. There are 25,428 km of roadway in Vermont that are generally classified into six categories (A). We focused our analysis on 5,912 transportation structure locations along state-managed roads (B).

Structure Attributes

We identified three structure attributes that were determined to be important for wildlife crossings in previous phases of the project: structure length, structure width, and bankfull width (Marangelo 2019). Data on structure length (Struc_Length) and width (Struc_Width) were obtained from the appropriate VTrans or ANR inventory databases. We obtained bankfull width data[5] (BkfWdth), estimated by catchment area equations, from the Transportation Resiliency Project (Milone and MacBroom INC 2019). We created a new attribute field to calculate the structure width to bankfull width ratio: Struc_Width / BkfWdth = SW_BKF. Structures located on unmapped streams that did not have a bankfull width value were assigned a SW_BKF value of 1, assuming water flow would be low to nonexistent during parts of the year.

2.2. Wildlife Connectivity Analysis

Overview

We modeled the movements of eight terrestrial mammal species: moose (*Alces alces*), white-tailed deer (*Odocoileus virginianus*), American black bear (*Ursus americanus*), eastern coyote (*Canis latrans*), eastern bobcat (*Lynx rufus*), red fox (*Vulpes vulpes*), raccoon (*Procyon lotor*), and striped skunk (*Mephitis mephitis*). These species frequently encounter roadways, and hold ecologic, economic, and cultural significance in Vermont (McCollister and Van Manen 2010, Vermont Fish and Wildlife Department 2015). They also span a large size range (from skunk to moose) and probably serve as representative surrogates for the larger mammal community in the state.

We used an electrical circuit theory approach to model predicted movements of each species in Vermont. This approach treats wildlife movement like the flow of electricity through a circuit: the landscape serves as the circuit which consists of various resistances, and wildlife act as electricity traveling throughout the circuit (McRae et al. 2008, 2016). We used the Omniscape program (Landau 2020, McRae et al. 2016) to carry out species-specific analyses. Omniscape uses a circuit theory-based algorithm to conduct connectivity analyses by combining two inputs: a *source-strength* input that determines the location and amount of electricity in the circuit, and a *resistance* input that influences how the electricity flows through the circuit. A moving window, sized according to the average home range size of the focal species, centers on each pixel of the landscape, and calculates connectivity (in units of electrical circuit density) from all pixels within the window to its center point (McRae et al. 2016). We carried out Omniscape analyses for each species at two spatial scales: first at the Landscape Scale[6] (statewide) using a coarser landcover dataset, and then at the Structure Scale[7] (around each individual transportation structure) using a fine-scale landcover dataset.

Inputs

For both spatial scales, we used wildlife occurrence maps (developed from models in Pearman-Gillman et al. 2020) as the source-strength input to designate areas in the landscape where electricity is emitted from. The source-strength layer serves to account for patterns of species distribution, which we assumed also reflects

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[5] Bankfull width measurements only exist for National Hydrography Dataset streams; all other structures have a null bankfull width value. Structures with a null bankfull width value were assigned a structure width:bankfull width ratio value of 1, under the assumption that these locations do not have streams, and therefore represent a consistently solid movement surface.

[6] To avoid edge effects at the Landscape Scale, we expanded our Omniscape analysis area with a 40-kilometer buffer into the neighboring states of New York, Massachusetts, and New Hampshire. Due to inconsistent landcover data, Canada was not included in the buffer and edge effects may occur on the VT-Canada border. Additionally, occupancy data were not available for NY, and therefore source electricity is not emitted from beyond the NY-VT border. Landscape Scale results were clipped to the boundary of Vermont.

[7] A buffer was not used at the Structure Scale, due to a lack of comparable 0.5-meter resolution landcover data in neighboring states/provinces. Some structures along the VT border may have smaller analysis areas at this scale due to the border intercepting analysis areas around border structures.

abundance. The wildlife occurrence models report the probability of species occurrence at each location in the landscape, based on the species' associations to natural landcover, climate, and other factors. Species-specific models and covariate information are reported in Appendix A. These models were built using a model selection process that evaluated the potential effects of 74 variables. Each model also tested well against independent species location data. In Omniscape, the electricity output at a given location is proportional to the occurrence probability of a species at that location. For example, a location with 90% probability of species occurrence will emit more electricity than a location with only 10% probability of occurrence. In other words, we expect more 'animals' to be moving out from high occupancy sites where abundance is most likely higher than low occupancy sites where abundance is most likely lower.

For the landscape resistance input, we elicited species-specific data on wildlife movement behavior from regional wildlife experts using an expert elicitation process (Figure 2). First, an online survey was developed that asked experts to score landcover variables in two datasets: the 30-meter resolution 2016 National Landcover Database (NLCD) for the Landscape Scale, and the 0.5-meter resolution 2016 Vermont Center for Geographic Information (VCGI) lidar dataset for the Structure Scale (Dewitz 2019, VCGI 2019; Appendix B). Both datasets were amended to include more detailed Vermont road class information, and roads were classified into six categories based on input from VTrans staff (Vermont Agency of Transportation 2016A). Experts scored each variable based on the relative resistance of each landcover type to the movement of the species. Landcover variables presenting less difficulty to movement receive a lower score on a 1-100 scale, and variables that are more difficult to move through receive a higher score. We averaged these initial species-specific expert opinion results for each variable in each landcover dataset, producing initial resistance inputs for each scale. Next, we ran preliminary Omniscape analyses for the full Landscape Scale extent (statewide) and around five test structures per species at the Structure Scale. To provide an opportunity for adjustments, we conducted one-on-one follow-up interviews with experts to present these preliminary maps (Dickson et al. 2013). After reviewing and discussing the maps, experts were given one opportunity to re-score variables if desired, and final landscape resistance inputs were created for each species using the re-averaged expert opinion values. In the Omniscape analyses, these final landscape resistance inputs determine how the species electricity flows throughout the landscape, and electrical current generally follows paths of less resistance, highlighting areas where wildlife are most likely to travel. Survey protocols were reviewed and approved by the Institutional Review Board at the University of Vermont (Appendix C).

Landscape Resistance Input: Expert Elicitation Process

Step 1: Online Expert Opinion Survey
- Experts view instructional video explaining Omniscape analysis.
- Experts score two landcover datasets (30m NLCD for *Landscape Scale*, 0.5m VCGI for *Structure scale*)
  - Scores based on 1-100 scale: 1 is least resistant to movement of the species, 100 is most resistant.

Step 2: Average Expert Values, Create Preliminary Maps
- Create preliminary resistance inputs for each species/each scale
  - Average expert opinion values for each variable
- Use expert-derived resistance inputs to create preliminary Omniscape maps
  - Statewide map for *Landscape Scale*, 5 test structures for *Structure scale.*

Step 3: Follow-up Interviews, Create Final Resistance Inputs
- Meet with experts individually to discuss preliminary maps for their species.
  - Experts given one opportunity to re-score variables.
- Average final expert opinion values to create final resistance inputs for each species at each scale.
- Final resistance inputs used in species-specific Omniscape analyses.

NLCD dataset (2016)

VCGI dataset (2016)

Figure 2. Expert elicitation process used to gather data to create landscape resistance inputs for species-specific Omniscape analyses at two spatial scales. Experts were asked to score landcover variables based on the degree to which they impede the movement of a given species.

Final Omniscape Analyses

For each spatial scale, the source-strength and final landscape resistance inputs were combined in Omniscape to determine probable movement patterns of each species throughout Vermont (Landscape Scale) or around each transportation structure location (Structure Scale; Figure 3). At the Landscape Scale, the movements of each species from any given location in the landscape were constrained by the average home range size for the species (Appendix D), so that the electricity emitted from any single location only travels as far as the species' average home range size would allow. For the structure scale, electricity travels throughout the full extent of the analysis area (100 meters) for all species.

Analyses at the structure scale were performed using the VermontTerrestrialPassageTool.jl package (Landau 2020). This package was specifically built to intake the fine-scale input data, clip the data to a 100-meter analysis area around each transportation structure, perform each Omniscape analysis, and summarize results within a 50-meter results area of each structure. This significantly reduced computing time by constraining the fine-scale analysis to only the immediate vicinity around structures. All Omniscape analyses were conducted on the Vermont Advanced Computing Core at the University of Vermont. From the eight species-specific Landscape Scale analyses, we recorded the mean electrical current density within 1 kilometer of each structure. From each collection of species-specific Structure Scale analyses, we recorded the mean electrical current density within 50 meters of each structure[8].

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[8] To avoid edge effects at the Structure Scale, results were clipped to half of the extent of the analysis area (clipped to 50m-radius from a 100m-radius analysis area).

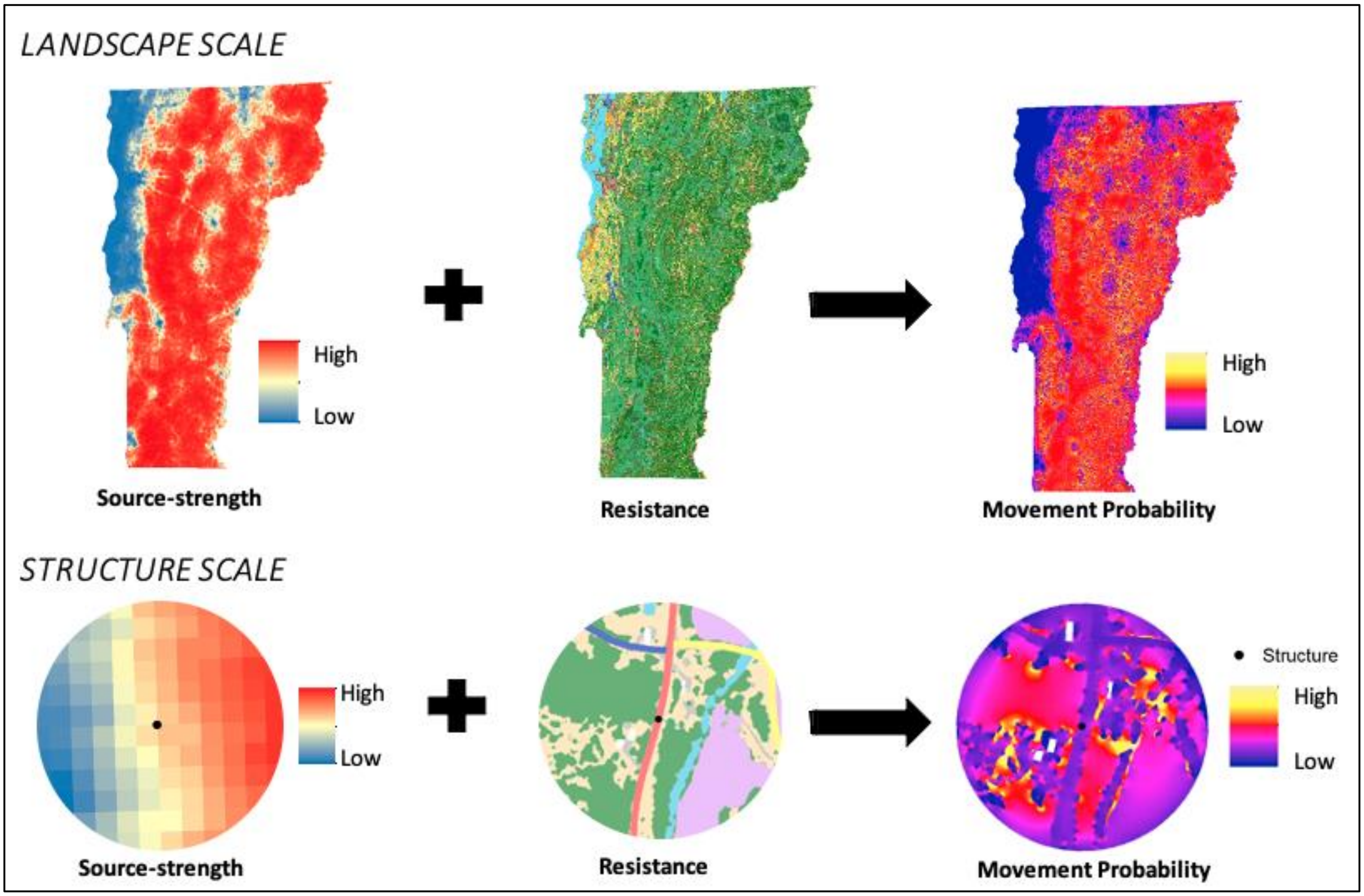

Figure 3. Visual depiction of the inputs and results for Omniscape analyses at the Landscape Scale (30-meter resolution) and Structure Scale (0.5-meter resolution) for American black bear. First, the source-strength input (wildlife occurrence data) determines where and how much electricity is emitted from each location in the landscape, based on occurrence probability of the species. Next, a landscape resistance layer (expert opinion and landcover data) determines how the electricity flows throughout the landscape, based on the composition of landcover and resistance of different landcover variables to the movement of each species. The result is a map of electrical current density, highlighting areas of increased predicted wildlife movement in yellow.

2.3. Human Development and Protected Lands Analyses

Human Development

While the physical footprint of buildings and homes act as barriers to wildlife movement, human activity associated with these human-made structures also influences wildlife behavior and movement around them. To estimate the influence of human activity from human-made structures near transportation structure locations, we summarized buffered human development zones within 150 meters of each structure (Figure 4).

First, we defined connectivity corridors of natural landcover through each structure location (excluding bridges over roads, railroads, or trails)[9]. For structures on mapped streams, connectivity corridors were buffered by 35

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[9] Since connectivity paths were difficult to define for bridges over roads, railroads or trails, these structures were evaluated based on total natural cover within 60 meters of the structure. Separate fields contain these results since they must be interpreted differently: RdNatAcres60,

meters on either side of the stream line passing through the structure. For structures on unmapped streams, artificial channels were manually constructed based on lidar data and buffered by 35 meters (Vermont Center for Geographic Information et al. 2018). For structures with no apparent stream channel, an arbitrary perpendicular path was created as a proxy for a connectivity corridor and buffered by 35 meters. We then summarized the natural landcover within these connectivity corridors. Natural landcover data were obtained from the Vermont High Resolution Landcover – Base Landcover dataset, a detailed 0.5-meter dataset developed by the University of Vermont Spatial Analysis Lab (UVM SAL; Vermont Center for Geographic Information 2019). We defined natural landcover within connectivity corridors, or NatAcres150, as [(tree canopy + shrub + wetland) – agriculture].

Next, we estimated the influence of human-made structures (buildings, homes) within the connectivity corridors using human development information from two datasets: E911 structures and the VCGI Impervious Surfaces dataset (Vermont Center for Geographic Information 2019). We buffered 50 meters around these points (E911 points or VCGI building footprints) to represent the human development influence around human-made structures and summarized these data within a 150-meter radius of transportation structure locations: DevAcres150. We then intersected the connectivity corridors (NatAcres150) and human development influence buffers (DevAcres150) within 150 meters of each transportation structure to determine the degree of human influence within the connectivity corridors. Within a 150-meter radius of each structure location, we divided the human development influence area by the natural landcover area within the connectivity corridor (DevAcres150/NatAcres150) to arrive at the percent of human development influence around a structure: PctDev150. This was then converted to a DevScore[10], or 1-PctDev150*100. A transportation structure received a DevScore of 100 if no human development influence existed within the connectivity corridor, and a DevScore of 0 if the entire corridor or buffer was influenced by development.

RdDevAcres60, and RdPctDev60. No development analysis was done for bridges over divided highways, as it was assumed these would have very low connectivity value.

[10] For structures over roads, railroads, or trails: DevScore = 1-RdPctDev60*100.

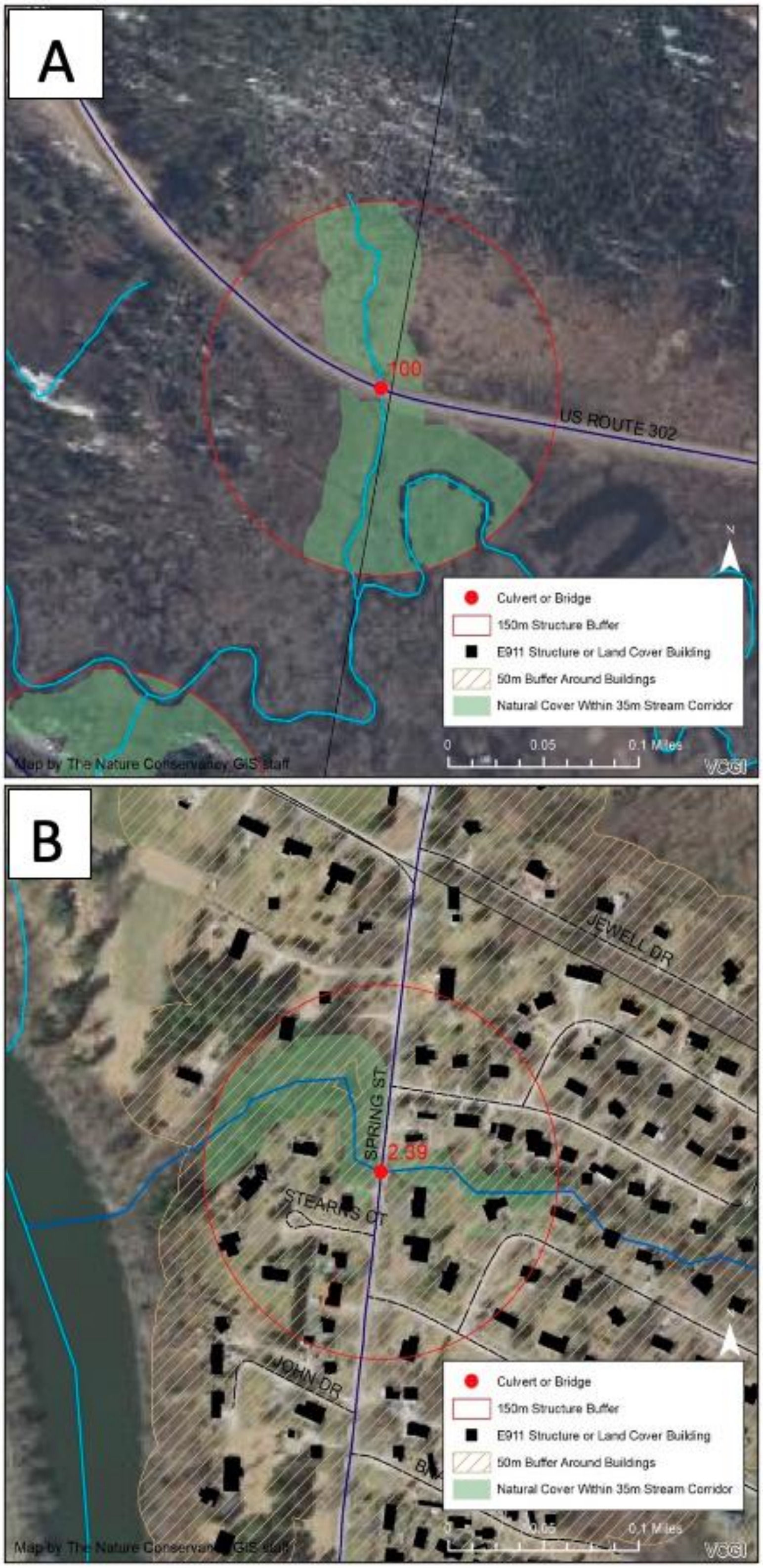

Figure 4. Examples of the human development analysis around two transportation structures, with natural landcover shown within connectivity corridors and human influence buffers around buildings. Map A shows a structure on VT Rt. 302 in Barre, VT with 0 human development influence. Map B shows a structure on VT Rt. 7 in Swanton, VT with high human development influence**.**

Protected Land

Protected lands adjacent to roadways are important to consider for wildlife movement, as they typically lack human development and serve as unimpeded movement corridors for many species. Transportation structures with adjacent protected lands on one or both sides of the roadway are well positioned to facilitate present and future wildlife movements across the roadway, since the surrounding landcover is unlikely to experience significant change. We summarized the amount and location of protected lands near transportation structure locations to create a protected land score.

We obtained protected lands information from an internal Nature Conservancy (TNC) Conserved Lands dataset derived from the Vermont Protected Lands Database, with other attribute and land additions (Vermont Center for Geographic Information 2021, TNC unpublished data). This dataset lists the GAP status of protected lands, which refers to the protection level of the parcel. The following GAP statuses are used in the Vermont Protected Lands Database:

GAP Status 1: Permanent protection from conversion, no interference.
GAP Status 2: Permanent protection from conversion, some interference allowed.
GAP Status 3: Permanent protection from conversion, some extraction allowed.
GAP Status 4: No known protection from conversion to unnatural land cover.

We included protected lands with GAP status 1, 2 and 3 from the TNC protected lands dataset in our analysis. Adjacent protected parcels were combined to represent contiguous blocks of protected lands. A road buffer (4 meters) was subtracted from protected blocks to eliminate slivers resulting from mismatched mapping of protected lands bordering roads. We summarized the protected lands data within a 150-meter buffer[11] of each transportation structure location, and split these circular buffers by the road centerline for separate protected lands calculations on either side of the roadway[12]. We created a ProtCount attribute to store data on the number of protected land blocks intersecting 0, 1, or 2 buffers splits, representing protected lands on neither, 1 or 2 sides of the road. The ProtMaxAcres attribute lists the area (acres) of the larger protected block, and the ProtMinAcres lists the area of the smaller block (recorded as 0 when only one block exists). The overall Protection Score (ProtScore) of a given structure is on a 0 to 100 scale based on criteria listed in Table 1. Structures with large blocks of protected land on both sides of the roadway would receive a better score than structures with smaller protected blocks, blocks on only one side of the roadway, or structures lacking protected land within the 150-meter buffer zone (Figure 5).

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[11] Buffers were dissolved for paired structures on a divided highway to ensure that the distance outward from the center of each set of lanes was consistent for two-lane roads.

[12] Buffer circles were split at roads and manually edited where necessary when structures near road junctions had more than two splits.

Table 1. Criteria used to determine the Protected Lands Score (ProtScore) at transportation structure locations. The score was based on the presence of protected lands on one or both sides of the roadway, and the size of protected land blocks.

Sides of Road with Protected Land	Size of Smaller Protected Block (acres)	Size of Larger Protected Block (acres)	ProtScore
0	0	0	0
1	0	0 - 2	12.5
1	0	2 - 5	50.0
1	0	5 - 15	56.3
1	0	>15	62.5
2	0 - 5	0 - 5	68.8
2	0 - 5	5 - 15	75.0
2	0 - 5	>15	81.3
2	5 - 15	5 - 15	87.5
2	5 - 15	>15	93.8
2	>15	>15	100.0

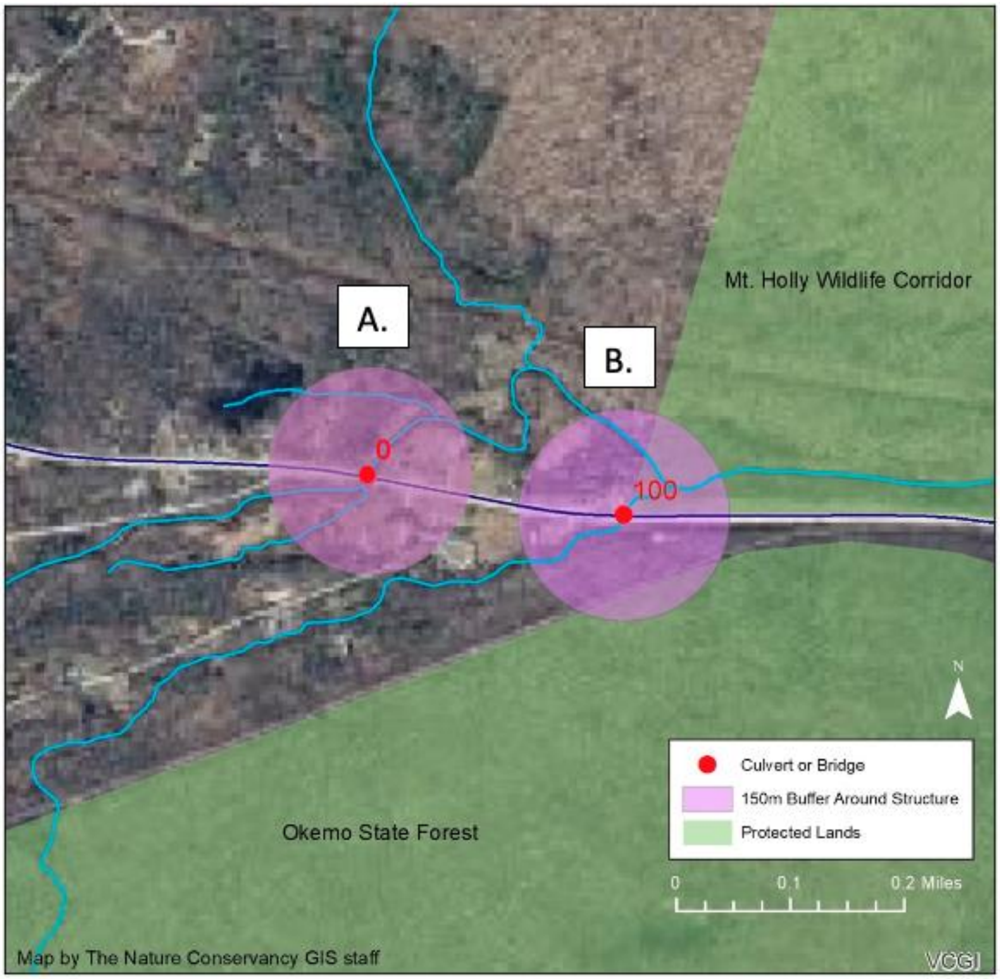

Figure 5. Protected lands analysis around two structures on VT Rt. 103 in Mt. Holly, VT. Structure A has no adjacent protected land blocks and receives a score of 0 based on the analysis criteria. Structure B receives a score of 100 due to the presence of two large blocks of protected land occurring on both sides of the roadway and within the buffered analysis area around the structure.

2.4. Terrestrial Passage Screening Tool Development

We developed a Terrestrial Passage Screening Tool (TPST): a decision-making framework used to assess the relative value of each transportation structure for wildlife connectivity. The TPST, modeled after linear-programming and SMART frameworks (Goodwin and Wright 2004), ranks structures by normalizing input data from each analysis and confronting those data against a set of user-defined constraints. The TPST integrates the five sets of information generated by the project (and described above) to score each structure. These include structure attributes, wildlife connectivity values (at two spatial scales), human development score, and protected lands score. We designed the TPST through multiple meetings with partners at the Vermont Agency of Transportation, Vermont Fish and Wildlife Department, The Nature Conservancy, and University of Vermont to ensure all wildlife and transportation priorities were addressed.

The TPST is built in a Microsoft Excel spreadsheet and contains four separate worksheets. The first sheet, *Structure Ranking Tool*, contains the Tool itself (Appendix E). The TPST goes through multiple steps to arrive at three separate structure rankings, from left to right in the spreadsheet. First, the results of each analysis (from the *Original Data* sheet) are normalized so that they are on the same 1-100 scale (columns A:I); this normalization of values allows each attribute to contribute evenly. Next, the normalized values are evaluated against a set of user-defined constraints (columns P:U). Thresholds can be set for these constraints (cells B2:B7) to influence which structures are ranked. For example, a user may choose to rank all structures less than 180 feet in length, if structures greater than 180 feet are deemed generally unusable for wildlife. Once the relevant attributes for each structure are evaluated against the constraints, structures receive three separate rankings:

1) **Wildlife Movement Priority (WMP):** This first rank assesses how important a given structure is for wildlife connectivity. It incorporates data from the wildlife connectivity analyses at the Landscape and Structure Scales, and the human development analysis. Structures that receive a higher WMP score receive a better overall rank. These structures are most important for wildlife based on predicted species movements, and the amount of human development surrounding the structure.
2) **Structure Characteristics:** This rank assesses the present condition of the structure for wildlife by evaluating two important attributes: structure length and bankfull width ratio. Structures that are shorter in length and have a wider bank for species to travel on would receive a higher score/better rank.
3) **Protected Lands:** This rank considers the amount of protected land surrounding a structure, and whether the protected land is present on one or both sides of the roadway. A structure with more protected lands on both sides would receive a higher score/better rank in this category, since this land would likely not experience human development in the future, and therefore a natural corridor may be maintained into the future.

The second sheet in the TPST is the *Structure ID Lookup*. Here, managers can type an ID of a structure they wish to evaluate, and all information associated with the structure will be retrieved: original results of each individual analysis, normalized attribute values, constraints, and rankings. The third sheet titled *Original Data* contains the non-normalized results of all analyses for each structure (structure attributes, wildlife connectivity scores, human development score, and protected lands score). The final sheet, *Metadata*, describes attributes from the *Original Data* sheet in more detail.

Lastly, we included the ability to weight some inputs more than others. A weight could be applied to an input, say the structure scale connectivity value, which would give more priority to this input relative to the others when generating rankings. Weights build-in more flexibility for users and provide a means of generating new scores and ranks if decision-making priorities change over time. Users also have the ability to simply rank structures according to landscape or structure connectivity values (using the raw or normalized scores for these inputs) without any of the other data inputs.

We developed a short training video that describes how the tool works. The video was designed for transportation practitioners/personnel and walks through the input data, optional constraint settings, optional weight settings, and calculations for scores and ranks. The video accompanies the data and TPST spreadsheet.

2.5. Game Camera Data

Game camera data were collected during two earlier, preceding projects led by the Vermont Fish and Wildlife Department and The Nature Conservancy of Vermont as well as this project and include wildlife images from 2015 to 2021 (Marangelo and Farrell 2016, Marangelo 2019). In total, wildlife presence/absence data were recorded at 52 sites across all three projects (Table 2, Figure 6). Ten sites were actively monitored during the current project, and additional data were recorded on human use and invasive species at these locations (see separate report). We used the species presence data from 50 of the camera sites to explore the relationship between occurrence probability and connectivity results. These sites were selected for cameras in earlier projects because they were considered to be areas where wildlife movement was expected to be high given the surrounding landscape (these sites were also selected to address other research objectives at the time). We summarized species presence at each site across years and estimated probability of occurrence for the focal species categorized into two groups: 1) ungulates (deer and moose) and 2) carnivores (bobcat, coyote, red fox, and skunk; raccoon was omitted from earlier project analyses and not included here). We expected that probability of occurrence for each group would be high and that connectivity scores would also be high relative to other unmonitored structures. Validating depictions of connectivity is exceptionally challenging (and rarely done) and our goal was simply to provide some independent data on wildlife occurrence at structures to evaluate relationships to connectivity measures.

Table 2. Fifty-two camera sites collected data on wildlife use at state-managed transportation structures during four phases of the project from 2016 to 2021. Detection and passage rate data at these locations were used to evaluate connectivity estimates of structures.

VTrans_AOP Structure ID	Site Name	Project	Town	Size class	Design Type
{2CC9B836-7EEF-4FB7-B03A-DBD346DF7CF2}	114-22	1	Brighton	Small	Box culvert
{63767A60-D4FB-4501-9D8F-3C6F86CB50F3}	I91bW	1	Sheffield	Small	Pipe culvert
{C7B53A59-81D5-4F86-A105-6CD4333560E2}	I91bE	1	Sheffield	Small	Pipe culvert
{CBC233DE-EC0B-4841-BEAB-56207521CE37}	15-76	1	Cambridge	Small	Old box culvert
200015008411172	30-84	1	Poultney	Medium/large	Span with footing shelf
200030005108102	15-51	1	Wolcott	Medium/large	Span
200091000503122	I91-101-2S	1	Sheffield	Small	Pipe culvert
200158000511232	73-5	1	Sudbury	Medium/large	Span
200241008312202	12-83	1	Worcester	Medium/large	Span
300020127E11091	4-12-17	1	Ira	Small	Pipe culvert
300028009012041	2-90	1	Cabot	Medium/large	Old concrete cattle pass
300037001410081	16-14	1	Glover	Small	Old box culvert
300091H12S03121	I91-101-3s	1	Sheffield	Small	Pipe culvert
300103000011222	103-53	1	Shrewsbury	Medium/large	V-bottom box culvert
300142001411091	4a-13	1	Ira	Medium/large	Span with footing shelf
300241009208041	12-92	1	Elmore	Small	Old box culvert
300251010203051	14-102	1	Hardwick	Small	Arch
300269002003081	114-20	1	Newark	Small	Span with footing shelf
500007000011162	7-110	1	Pittsford	Small	Old box culvert
{07FDB25F-4358-4CCF-A496-05A67DA45A07}	7-23-8	2	Manchester	Small	Pipe culvert
{D0DFC71D-743E-464E-B0BF-9C501A0F9D3D}	9-17	2	Woodford	Small	Pipe culvert
{D4AAA0B8-0F5E-4E4D-BB6F-DC0967919599}	I91a	1, 2	Sheffield	Small	Pipe culvert
200010025A02122	9-25a	2, 3	Searsburg	Medium/large	Span
200010025B02122	9-25b	2, 3	Searsburg	Medium/large	Span
200013007813092	100-78	2	Jamaica	Medium/large	Span
200020004214052	4-42	2, 3	Bridgewater	Medium/large	Span
200149000814122	100a-8	2	Plymouth	Medium/large	Span
300180001509141	113-15	2	Vershire	Small	Squash pipe
200180001909142	113-19	2	Vershire	Medium/large	Span
200200002401192	17-24	2	Starksboro	Medium/large	Arch
200200003212082	17-32	2	Waitsfield	Medium/large	Span
200200003612082	17-36	2	Waitsfield	Medium/large	Span
300013004713221	100-47	2	Wilmington	Medium/large	New precast box culvert
300015002213171	30-22	2	West Townshend	Small	Old box culvert
300015004702161	30-47	2	Winhall	Small	New precast box culvert
30001919-502151	7-19-5	2	Sunderland	Small	Squash pipe culvert
300022011811211	100-118	2, 3	Killington	Medium/large	New precast box
300037001310081	16-13	1, 2	Glover	Small	Pipe culvert
30009117-213131	I91-17-2	2	Putney	Medium/large	V-bottom box culvert
300133000611121	155-6	2	Mount Holly	Small	Pipe culvert
300141001411091	133-13	1,2	Ira	Medium/large	Span with footing shelf
300174001901161	125-19	2	Ripton	Small	New precast box culvert
300180001509141	113-15	2	Vershire	Small	Squash pipe culvert
300187001009021	12a-10	2	Braintree	Medium/large	Span
200089048512182	Little River	3	Waterbury	Medium/large	Span
200162001714152	73-17	3	Rochester	Medium/large	Span
200241007812102	12-78	3	Middlesex	Medium/large	Span
200251012310112	14-123	3	Irasburg	Medium/large	Span
30001919-602151	7-19-8	3	Sunderland	Medium/large	Span
30008950-404011	Pineo Brook	3	Bolton	Medium/large	V-bottom box culvert
*NO VTRANS_AOP ID**	Union St	2	Brandon	Medium/large	Span
*NO VTRANS_AOP ID**	122-24	2	Glover	Small	Old box culvert

*Structures lacking a VTrans_AOP ID were not tested against TPST rankings and connectivity models.

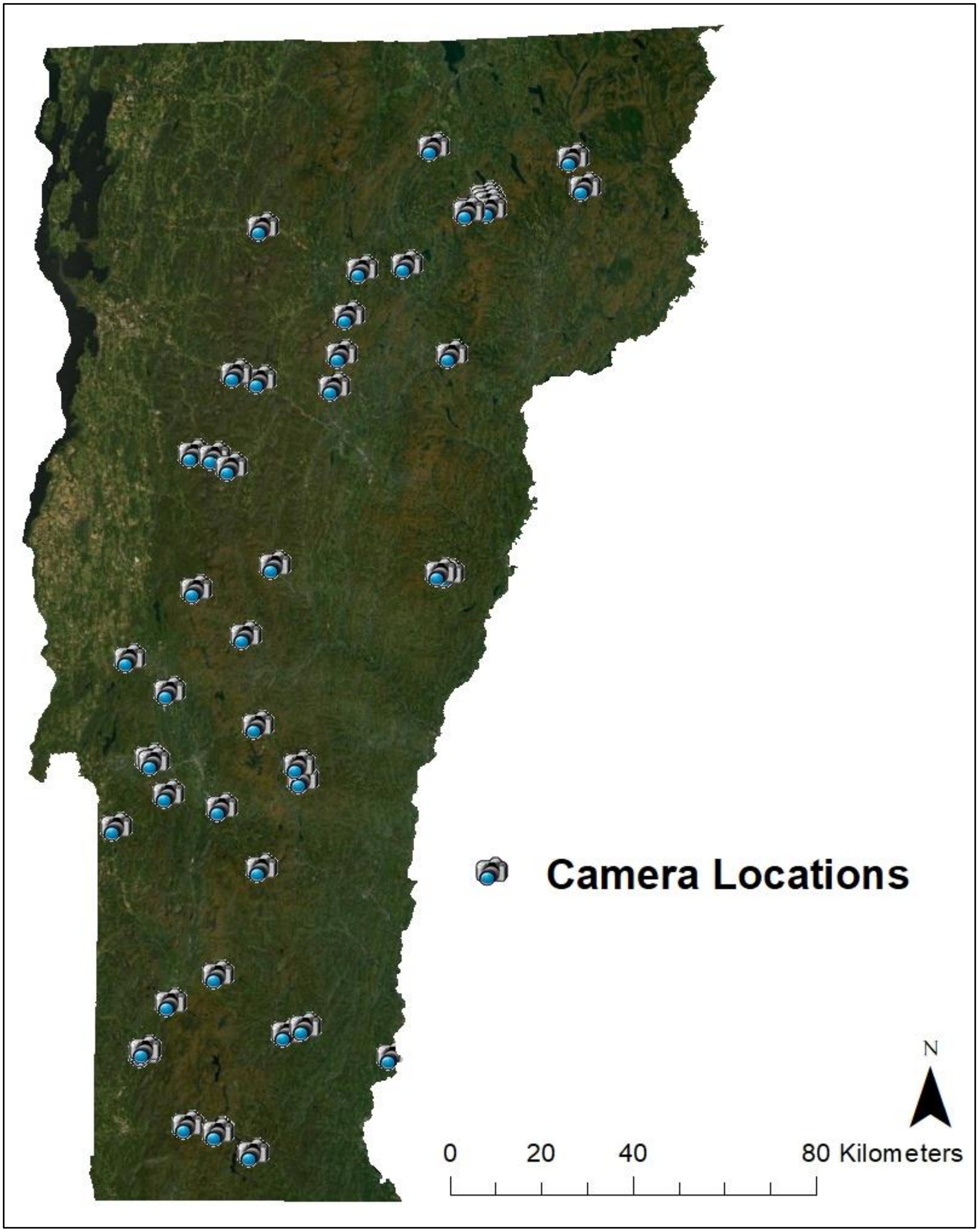

Figure 6. Locations of game cameras from three phases of wildlife and transportation research in Vermont (2015-2021).

3. Results

3.1. Structure Site Selection and Structure Attributes

We compiled information on 5,912 transportation structure locations from three state inventories (VTrans 2016B, 2016C, 2017) into a single shapefile dataset titled vt_culverts_statefed_3ft_final_AI051121. This combined dataset includes all attributes associated with each inventory, totaling 85 attributes related to structure characteristics (material, size, condition, location) and results of the human development and protected lands analyses, organized by the VTrans AOP-assigned ID of each structure. Metadata are available for the attributes used in and created for the TPST. Metadata are not available for all attributes carried over from the three VTrans structure inventories; however related descriptions can be found in Federal Report No. FHWA-PD-96-001 (US Department of Transportation 1995). Known attribute descriptions are available in the fourth sheet of the TPST Excel file.

Partners identified attribute constraints for the bankfull width ratio (BkfWdth) and structure length (Struc_Length) analyses. Structures with a bankfull width ratio of less than 0.4 are thought to have too much water to facilitate passage for most focal species, based on results of previous projects (Marangelo et al. 2019). Based on this cutoff, 92% of structures (5,465) have a bankfull width ratio greater than 0.4, and are therefore considered capable of facilitating wildlife movement for this metric. Structures greater than 180 ft in length are considered too long to facilitate wildlife passage, and 12% of structures are greater than 180 ft in length.

3.2. Wildlife Connectivity Analysis

The expert elicitation process to develop landscape resistance layers included input from ten regional wildlife experts, with 1-2 responses per species; some experts provided feedback for multiple species. Final landscape resistance values for each species and each spatial dataset are shown in Appendix F. Final landscape resistance inputs were combined with existing wildlife occurrence data to produce Omniscape analyses at each spatial scale for each species.

We created eight species-specific maps (Figure 7) and an all-species-combined map (Figure 8) of wildlife movement at the Landscape Scale, and 47,296 species-specific maps of wildlife movement at the Structure Scale (5,912 structure locations x 8 species). The mean electrical current density values from each species (recorded within 1 km and 50 m for the Landscape and Structure Scales, respectively) were summed to record all-species results at each structure.

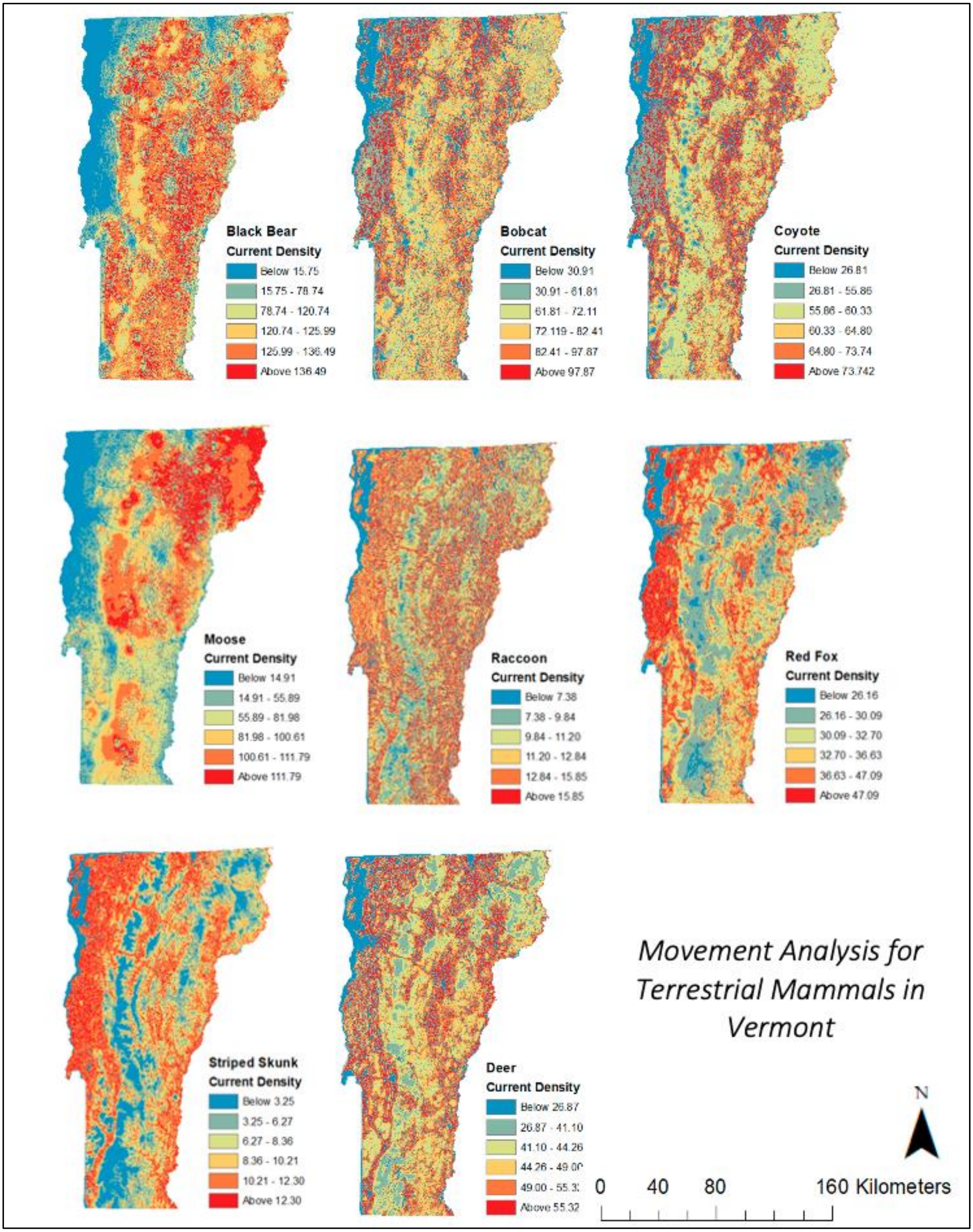

Figure 7. Maps of predicted wildlife movement throughout Vermont created with Omniscape. Areas of high electrical current density represent areas of more concentrated species movement.

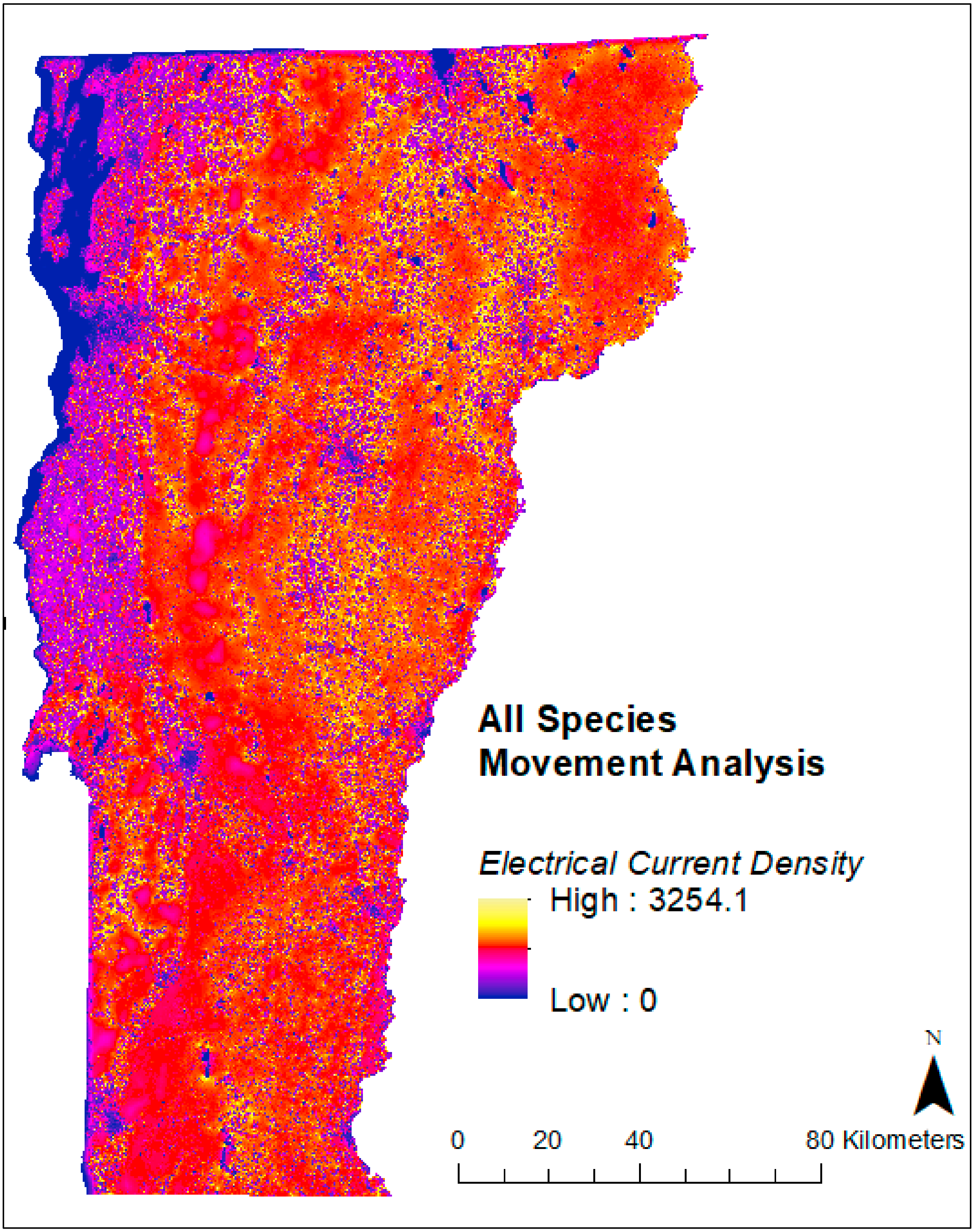

Figure 8. Map of predicted wildlife movement throughout Vermont for eight terrestrial mammal species combined created with Omniscape. Areas of high electrical current density represent areas of more concentrated species movement.

3.3. Human Development and Protected Lands Analyses

Over half of all structures considered (53%) received a DevScore over 80 (on 1-100 scale, where 100 means there is no human development in the connectivity corridor). These structures did not have high levels of human development influence within the connectivity corridor passing through the structure, and may be valuable sites for wildlife movement due to the reduced level of human activity near the potential crossing location.

Most structures (81%) had no protected lands on either side of the roadway. However, 12.8% of structures had protected land on one side of the roadway, and 5.4% of structures had protected lands on both sides of the roadway. These areas may be especially valuable for wildlife connectivity into the future, as they are less likely to experience human development on one or both sides of the roadway. Additionally, 4.5% of structures received the highest Protected Lands Score of 100; these structures have more than 15 acres of protected lands on both sides of the roadway surrounding the structure.

3.4. Terrestrial Passage Screening Tool

The TPST incorporated results of each analysis (structure attributes, wildlife connectivity at two scales, human development score, and protected lands score) to rank all 5,912 structure locations. The top 100 structures from the Wildlife Movement Priority rank are shown in Figure 9. These ranks were based on no constraints or input weightings, and it is important to note that including constraints and/or adding weights would result in different scores and rankings. Also, the other two ranking metrics (Structure Characteristics Rank and Protected Lands Rank) show different results as they incorporate different inputs. As one of the goals of the TPST was flexibility, the end user has the ability to consider the three ranking systems, view summary information for each input for individual structures and across all structures, and include constraints and weights into the analysis to suit their needs.

All input data for the TPST (structure shapefile with results of protected lands/human development analyses, species-specific and combined maps/results of Omniscape analyses), and the TPST spreadsheet itself, are stored on external hard drives provided to the Vermont Agency of Transportation and Vermont Fish and Wildlife Department. Additionally, we created an instructional video to accompany the TPST and associated datasets. The video explains the methods used in each analysis, and how to use the TPST and interpret results for use in decision-making around the management of transportation structures for wildlife. The video is also included on the hard drives.

Figure 9. The top 100 transportation structures identified by the Wildlife Movement Priority rank (no constraints or weights included). These structures are located in areas of more concentrated wildlife movement as predicted by the Landscape Scale and Structure Scale Omniscape analyses and have lower levels of human development influence.

3.5. Game Camera Data

Species-specific detection and through-passage data for the earlier, preceding projects are discussed in Marangelo and Farrell 2016 and Marangelo 2019. The impact of human use and invasive species at structure locations collected during the current project is available in a separate report.

Among the 50 monitored sites, we recorded 2,279 detections of the focal wildlife species (all except raccoon). Number of sites with species presence was 17 for coyote, 36 for deer, 3 for moose, 13 for bear, 10 for bobcat, 20 for red fox, and 14 for skunk. Probability of presence (or naïve occupancy probability) was 0.72 (or 72%) for ungulates and 0.76 (or 76%) for carnivores.

Estimated connectivity scores, which ranged 0-100 when standardized, were generally in agreement with the occupancy values for both ungulates and carnivores. The mean landscape scale connectivity score was 75.3 ± 7.9 SD and structure scale score was 72.1 ± 10.5 SD. Similarly, a total of 43 camera locations (86%) received above average WMP scores when compared with all 5,912 structures analyzed. Taken together these measures were largely expected given that monitored sites were originally chosen as sites with high potential for wildlife movement, and suggest that the connectivity results were generally accurate. However, important caveats to consider when interpreting these values: estimates of species occurrence did not account for detection probability, which can meaningfully affect probability estimates, cameras were only deployed a high value sites, and sample size was limited. Our assessment was not meant to serve as a full validation of the connectivity results, but to provide some simple measures from independent data to provide insight into accuracy.

Table 3. Game camera detections by site for each focal species (detection data for raccoon not recorded) and number of days the cameras were deployed per site.

					Number of Detections				
Site Name	**American Black Bear**	**Eastern Bobcat**	**Eastern Coyote**	**Moose**	**Red Fox**	**Striped Skunk**	**White-tailed deer**	**Site Total**	**No. Days**
114-22	0	0	1	0	1	0	7	9	756
I91bW	1	3	0	0	0	0	3	7	400
I91bE	1	0	7	1	0	0	5	14	400
15-76	0	0	0	0	0	0	9	9	442
30-84	0	1	0	0	8	2	161	172	477
15-51	0	0	2	0	2	0	0	4	748
I91-101-2S	0	0	0	0	0	0	1	1	401
73-5	9	1	0	9	8	0	49	76	410
12-83	0	0	0	0	0	1	7	8	758
4-12-17	0	2	0	0	0	1	9	12	440
2-90	0	0	0	0	1	2	0	3	750
16-14	0	0	0	0	8	16	1	25	741
I91-101-3s	0	0	0	0	0	0	0	0	401
103-53	0	1	0	0	0	1	3	5	435
4a-13	0	32	0	0	0	1	34	67	481
12-92	0	0	0	0	0	0	0	0	758
14-102	0	0	0	0	0	0	9	9	753
114-20	0	16	0	0	0	0	0	16	751
7-110	0	0	0	0	0	0	20	20	424
7-23-8	5	6	3	0	4	0	6	24	611
9-17	1	0	0	0	5	0	53	59	634
I91a	3	21	5	0	0	0	1	30	1649
9-25a	4	1	13	2	11	0	59	90	1136
9-25b	4	0	24	0	9	0	469	506	1686
100-78	0	0	0	0	0	0	0	0	453
4-42	1	2	24	0	6	1	409	443	961
100a-8	0	0	10	0	0	1	0	11	389
113-15	0	2	2	0	0	0	4	8	609
113-19	0	3	10	0	3	0	58	74	608
17-24	3	0	0	0	0	0	2	5	492
17-32	0	0	0	0	2	0	0	2	448
17-36	0	0	0	0	31	0	26	57	448
100-47	0	0	2	0	0	0	1	3	633
30-22	0	0	0	0	0	0	0	0	357
30-47	0	0	0	0	0	0	0	0	453
7-19-5	3	47	0	0	13	0	6	69	601
100-118	0	0	1	0	0	0	0	1	1161
16-13	0	1	1	0	13	18	4	37	1660
I91-17-2	0	1	0	0	0	0	35	36	630
155-6	0	0	0	0	0	0	0	0	428
133-13	0	44	14	0	8	1	83	150	1272
125-19	0	0	0	0	0	0	0	0	560
113-15	0	2	2	0	0	0	4	8	609
12a-10	1	0	0	0	0	1	2	4	611
Little River	0	0	0	0	1	0	16	17	510
73-17	0	0	5	0	0	0	0	5	549
12-78	0	3	0	0	7	1	148	159	549
14-123	0	0	0	0	5	1	1	7	548
7-19-8	1	0	0	0	0	0	1	2	545
Pineo Brook	0	0	0	0	0	0	15	15	358
Union St	0	30	0	0	0	2	9	41	573
122-24	2	1	1	0	1	7	20	32	1541

4. Discussion

Our goal was to assess the value of state-managed transportation structures for wildlife movement and landscape connectivity in Vermont. At the landscape scale we modeled the broader movement patterns of eight important species statewide, to highlight parts of the landscape and the road network that are important for connectivity. At the structure scale we introduced high-resolution landcover data to model wildlife movements in localized areas around individual transportation structures. This multi-scale view of wildlife movement and landscape connectivity was then combined with additional information on structure attributes and surrounding landscape influences to rank 5,912 state-managed transportation structures for these species. The eight species included in our analysis encompass a wide range of sizes and movement behaviors, and investments in transportation infrastructure for these species will likely benefit others in the state.

Wildlife Connectivity Analysis

We produced maps of wildlife movement at two spatial scales for each species using a novel circuit theory approach. The resulting maps incorporate validated data on wildlife occurrence in the state, home range information from local studies, as well as input from regional wildlife professionals with expertise in each focal species. These maps offer two important views of wildlife movement patterns: 1) species-level movements at a broader statewide level, and 2) detailed movements that individuals may make around transportation structures based on the fine-scale composition of landcover.

Terrestrial Passage Screening Tool

We developed an approach to rank transportation structures by overall connectivity value for terrestrial mammals in Vermont. The TPST incorporates data from multiple comprehensive datasets, including predicted wildlife movement patterns based on occupancy probability and landscape resistance, structure attributes relevant to wildlife, the influence of human development around structures, and location and amount of protected lands surrounding structures. The TPST also includes adjustable weights and constraints, which allows users to rank a subset of structures or adjust priorities in how the structures are ranked based on management objectives. Additionally, users have the ability to look up a structure by ID number and retrieve the data and ranking information associated with the structure. This feature is especially useful when managers need to assess a structure's value for wildlife connectivity during the planning stages of a construction project.

Game Cameras

We used game camera data at 50 structure locations with high movement potential to assess connectivity scores. Measures of species presence closely corresponded to landscape and structure scale connectivity scores and Wildlife Movement Priority scores, and were generally high and expected for sites considered by experts to be areas of high movement potential for larger mammal species. Taken together these results provide one line of evidence that suggest that connectivity results are reasonable. However, properly validating connectivity analyses is challenging (and rarely done) and often requires large independent data sets and fine-scale animal movement data (e.g., from radio-collars), both of which were unavailable for this project. Our sample size was small and only placed in high value locations. We also did not account for detection probability in our assessment of the data (due to sample size constraints). We recommend further investment in validating model predictions.

Conclusions

Maintaining and improving landscape connectivity for wildlife is a state priority in Vermont, which is centrally located in the Northern Appalachian-Acadian Region: an area containing multiple important wildlife movement corridors (Trombulak et al. 2008). Although roads contribute to fragmentation of the landscape, these barriers can be made more permeable by improving transportation structures to accommodate wildlife movement, which can lead to healthier, more viable populations. Investments in our existing transportation infrastructure can greatly benefit wildlife species, and prioritizing these investments in areas with higher predicted wildlife movement is a cost-effective approach to making road barriers more permeable (Zeller et al. 2020a, 2020b).

Our structure ranking tool will assist transportation managers in making science-informed decisions around the management of transportation structures for important wildlife species. However, these analyses of landscape connectivity represent a snapshot in time. As the Vermont landscape changes, continuing to assess how wildlife are moving across the landscape will be necessary to maximize benefit to wildlife and ensure a safe, effective, and well managed transportation system.

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Appendices

Appendix A. Species occurrence models from Pearman-Gillman et al. (2020), used as source-strength inputs for the connectivity analysis. Top model parameter estimates shown with standard error and upper (UCI) and lower (LCI) confidence intervals.

Species	Model, Covariates	β Estimate	SE	LCI	UCI
American Black Bear	Mean ~ prop_mature_forest + prop_all_roads + prop_forest_5k + mean_annual_precip_mm_5k + prop_fagugran_5k þ (1 | State) + (1 | Expert) + (1 | Site)				
	(Intercept)	25.64	11.34	3.42	47.86
	prop_mature_forest	3.27	0.86	1.59	4.95
	prop_all_roads	-12.47	2.15	-16.68	-8.26
	prop_forest_5k	6.16	0.88	4.43	7.90
	mean_annual_precip_mm_5k	-21.90	8.50	-38.57	-5.24
	prop_fagugran_5k	2.40	1.01	0.42	4.38
Eastern Bobcat	Mean ~ prop_developed + prop_forest_edge + prop_agriculture + (1 | Expert) + (1 | Site)				
	(Intercept)	0.22	0.36	-0.48	0.93
	prop_developed	-2.6	0.50	-3.58	-1.62
	prop_forest_edge	1.02	0.42	0.19	1.85
	prop_agriculture	1.42	0.52	0.40	2.44
Eastern Coyote	Mean ~ prop_waterbodies + prop_forest_edge + prop_major_roads_3k + prop_wetland_3k + prop_agriculture + (1 | Expert) + (1 | Site)				
	(Intercept)	1.42	0.72	0.01	2.82
	prop_waterbodies	-4.08	0.97	-5.99	-2.18
	prop_forest_edge	2.79	0.54	1.73	3.86
	prop_major_roads_3k	-32.05	9.94	-51.54	-12.56
	prop_wetland_3k	2.85	1.34	0.21	5.48
	prop_agriculture	1.31	0.71	-0.07	2.70
Moose	Mean ~ prop_young_forest + prop_developed + prop_shrubland + mean_fall_tmax_degC + prop_forest_5k + (1 | Expert) + (1 | Site)				
	(Intercept)	8.13	1.61	4.97	11.29
	prop_young_forest	7.02	2.93	1.27	12.76
	prop_developed	-4.59	0.78	-6.11	-3.06
	prop_shrubland	5.11	1.37	2.43	7.79
	mean_fall_tmax_degC	-73.71	8.98	-91.32	-56.1
	prop_forest_5k	3.52	0.65	2.25	4.79
Raccoon	Mean ~ prop_agriculture_500m + prop_mature_forest_500m + mean_DEM_km_500m + prop_oak_500m + prop_developed_500m + (1 | Expert) + (1 | Site)				
	(Intercept)	1.65	0.71	0.27	3.04
	prop_agriculture_500m	3.04	0.75	1.58	4.51
	prop_mature_forest_500m	1.21	0.54	0.15	2.27
	mean_DEM_km_500m	-2.09	0.66	-3.37	-0.80
	prop_oak_500m	1.66	0.83	0.03	3.3
	prop_developed_500m	2.26	0.60	1.07	3.44
Red fox	Mean ~ prop_agriculture + prop_high_dev + mean_winter_precip_mm_3k + prop_shrubland_3k + (1 | Expert) + (1 | Site)				
	(Intercept)	-3.16	1.77	-6.63	0.3

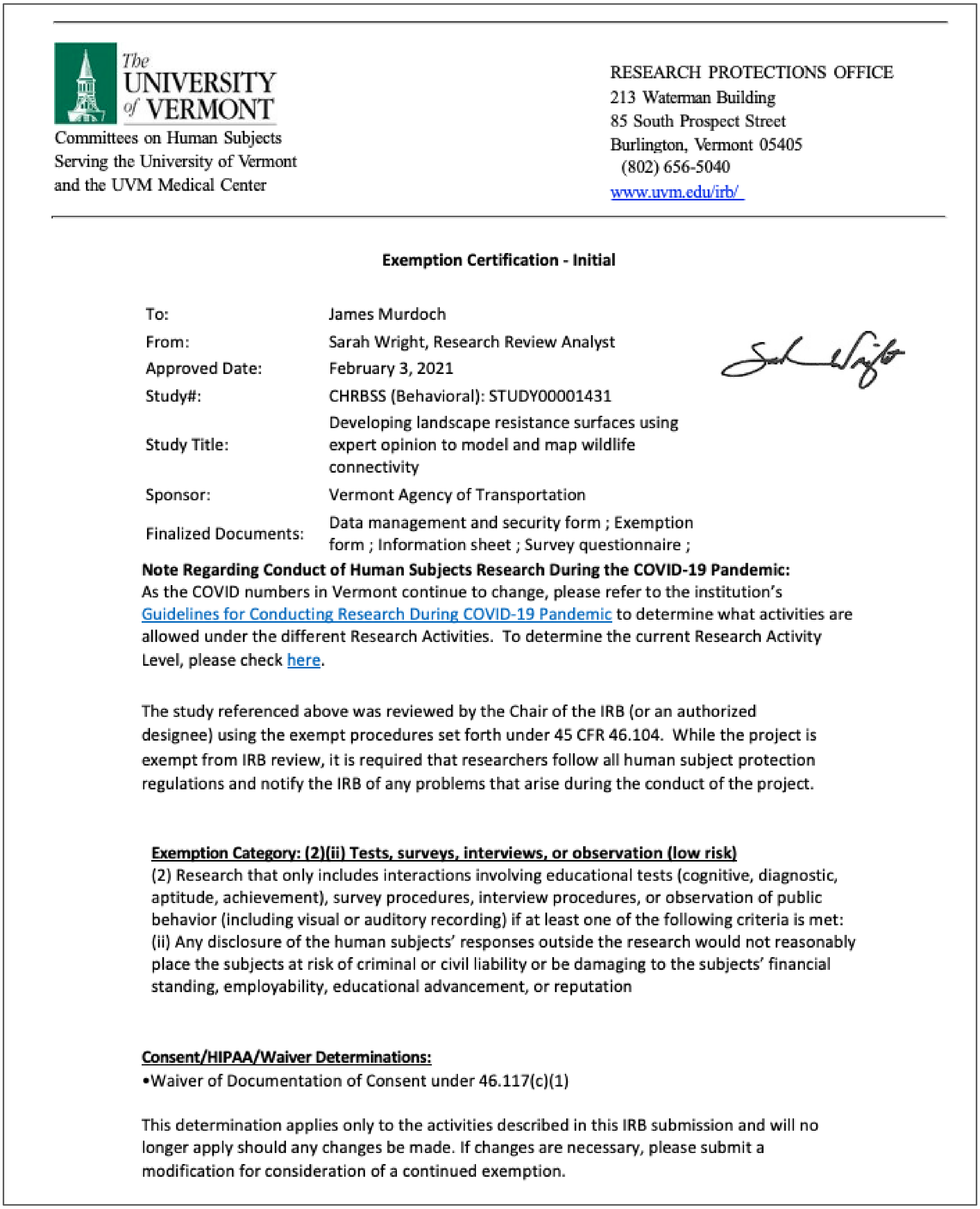
Species	Model, Covariates	β Estimate	SE	LCI	UCI
	prop_agriculture	3.28	0.61	2.09	4.47
	prop_high_dev	-3.23	1.21	-5.60	-0.86
Red Fox	mean_winter_precip_mm_3k	12.65	6.30	0.31	24.99
	prop_shrubland_3k	3.5	2.10	-0.63	7.62
Striped Skunk	Mean ~mean_DEM_km_500m + prop_mature_forest_500m + prop_agriculture_500m + prop_forest_edge_500m + (1 | Expert) + (1 | Site)				
	(Intercept)	1.91	0.79	0.36	3.45
	mean_DEM_km_500m	-6.25	0.60	-7.44	-5.07
	prop_mature_forest_500m	0.91	0.58	-0.23	2.06
	prop_agriculture_500m	3.40	0.76	1.91	4.88
	prop_forest_edge_500m	0.74	0.49	-0.22	1.70
White-tailed deer	Mean ~ prop_agriculture + prop_high_dev + prop_mature_forest + prop_hemlock_tamarack_cedar_3k + (1 | EcoRegion) + (1 | Expert) + (1 | Site)				
	(Intercept)	1.17	0.68	-0.17	2.5
	prop_agriculture	4.22	0.83	2.60	5.84
	prop_high_dev	-10.52	0.84	-12.17	-8.88
	prop_mature_forest	1.47	0.62	0.27	2.68
	prop_hemlock_tamarack_cedar_3k	10.5	1.69	7.18	13.82

Appendix B. Landcover and road class variables used in the creation of the landscape scale and structure scale resistance layers.

Variable Name	Attribute Name	Source
Landscape Scale		
Open water	NLCD 11	NLCD 2019
Developed open space	NLCD 21	NLCD 2019
Developed low intensity	NLCD 22	NLCD 2019
Developed medium intensity	NLCD 23	NLCD 2019
Developed high intensity	NLCD 24	NLCD 2019
Barren land	NLCD 31	NLCD 2019
Deciduous forest	NLCD 41	NLCD 2019
Evergreen forest	NLCD 42	NLCD 2019
Mixed forest	NLCD 43	NLCD 2019
Shrub/scrub	NLCD 52	NLCD 2019
Grassland/herbaceous	NLCD 71	NLCD 2019
Pasture/hay	NLCD 81	NLCD 2019
Cultivated crops	NLCD 82	NLCD 2019
Woody wetlands	NLCD 90	NLCD 2019
Emergent herbaceous wetlands	NLCD 95	NLCD 2019
Landscape and Structure Scale		
Interstate system	VTrans AOTCLASS>=50 and AOTCLASS<60 NHDOT Tier=1 NYSDOT ACC in 1, 2 MassDOT F_class=1	VTrans 2019, NHDOT 2020, NYSDOT 2020, MassDOT 2020
State road system	VTrans AOTCLASS>=30 and AOTCLASS<50 NHDOT Tier=2 NYSDOT ACC=3 MassDOT F_class=2	VTrans 2019, NHDOT 2020, NYSDOT 2020, MassDOT 2020
High traffic town	VTrans AOTCLASS in 1, 2 NHDOT Tier=3 NYSDOT ACC 4 MassDOT F_class in 3,5	VTrans 2019, NHDOT 2020, NYSDOT 2020, MassDOT 2020

Medium traffic town	VTrans AOTCLASS=3 NHDOT Tier=4 NYSDOT ACC=5 MassDOT F_class=6	VTrans 2019, NHDOT 2020, NYSDOT 2020, MassDOT 2020
Low traffic town	VTrans AOTCLASS=4 NHDOT Tier=5 NYSDOT ACC=6 MassDOT F_class=0	VTrans 2019, NHDOT 2020, NYSDOT 2020, MassDOT 2020
Low/no traffic town	VTrans AOTCLASS in 5, 6, 7, 8, 9, 96, 97 NHDOT Tier=6 NYSDOT FCC in A5, A7	VTrans 2019, NHDOT 2020, NYSDOT 2020,
Structure Scale		
Canopy cover	VT Base Land Cover, 1	VCGI 2019
Grass/shrub	VT Base Land Cover, 2	VCGI 2019
Bare soil	VT Base Land Cover, 3	VCGI 2019
Water	VT Base Land Cover, 4	VCGI 2019
Building	VT Base Land Cover, 5	VCGI 2019
Other paved	VT Base Land Cover, 7	VCGI 2019
Railroad	VT Base Land Cover, 8	VCGI 2019
Agriculture	VT Agriculture Land Cover, 1-3	VCGI 2019
Wetland	VT Wetlands Land Cover, 1-3	VCGI 2019

Appendix C. Expert opinion survey protocols were reviewed and approved by the Institutional Review Board at the University of Vermont.



The UNIVERSITY of VERMONT
Committees on Human Subjects
Serving the University of Vermont
and the UVM Medical Center

RESEARCH PROTECTIONS OFFICE
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Exemption Certification - Initial

To: James Murdoch
From: Sarah Wright, Research Review Analyst
Approved Date: February 3, 2021
Study#: CHRBSS (Behavioral): STUDY00001431
Study Title: Developing landscape resistance surfaces using expert opinion to model and map wildlife connectivity
Sponsor: Vermont Agency of Transportation
Finalized Documents: Data management and security form ; Exemption form ; Information sheet ; Survey questionnaire ;

Note Regarding Conduct of Human Subjects Research During the COVID-19 Pandemic:
As the COVID numbers in Vermont continue to change, please refer to the institution's Guidelines for Conducting Research During COVID-19 Pandemic to determine what activities are allowed under the different Research Activities. To determine the current Research Activity Level, please check here.

The study referenced above was reviewed by the Chair of the IRB (or an authorized designee) using the exempt procedures set forth under 45 CFR 46.104. While the project is exempt from IRB review, it is required that researchers follow all human subject protection regulations and notify the IRB of any problems that arise during the conduct of the project.

Exemption Category: (2)(ii) Tests, surveys, interviews, or observation (low risk)
(2) Research that only includes interactions involving educational tests (cognitive, diagnostic, aptitude, achievement), survey procedures, interview procedures, or observation of public behavior (including visual or auditory recording) if at least one of the following criteria is met:
(ii) Any disclosure of the human subjects' responses outside the research would not reasonably place the subjects at risk of criminal or civil liability or be damaging to the subjects' financial standing, employability, educational advancement, or reputation

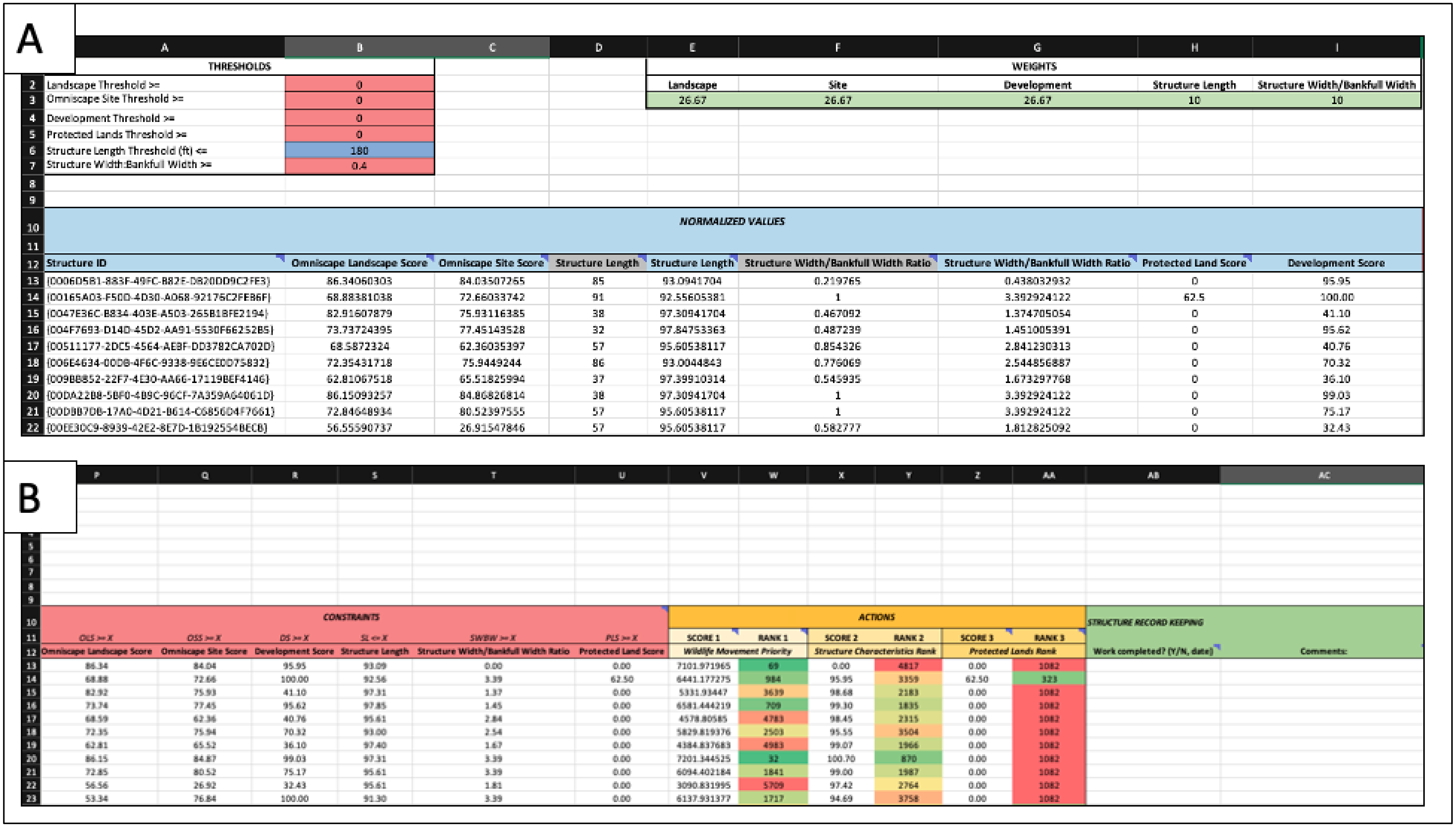
Consent/HIPAA/Waiver Determinations:
- Waiver of Documentation of Consent under 46.117(c)(1)

This determination applies only to the activities described in this IRB submission and will no longer apply should any changes be made. If changes are necessary, please submit a modification for consideration of a continued exemption.

Appendix D. Average home range size of each focal species used to determine moving window size in the landscape scale Omniscape analyses.

Species	**Mean Home Range for Adult Males/Females (km^2)**	**Moving Window Radius (m)**	**Study Location**	**Home Range Estimation Method**	**Reference**
Black bear	80.22	5053.20	Vermont	95% Kernel	Hammond (2002)
Eastern bobcat	46.90	3863.77	Vermont	UD	Donovan et al. (2011)
Eastern coyote	17.90	2387.00	Vermont	Harmonic mean, outliers removed	Person & Hirth (1991)
Moose	75.78	4911.37	Vermont	95% Fixed-kernel	Blouin et al. (2021)
Raccoon	0.83	514.00	Ontario	95% Fixed-kernel	Rosatte et al. (2010)
Red fox	14.70	2163.14	Maine	Convex polygon, outliers removed	Harrison et al. (1989)
Striped skunk	0.90	535.24	Ontario	100% MCP	Rosatte et al. (2011)
White-tailed deer	11.42	1906.59	Québec	95% MCP	Lesage et al. (2000)

Appendix E. The structure ranking section of the Terrestrial Passage Screening Tool spreadsheet built in Microsoft Excel. Image A shows the first part of the *Structure Ranking* spreadsheet, where original data from all analyses are normalized and where constraints and weights are set. Image B shows the second part of same sheet, where the data are evaluated against the constraints, then used to rank structures in three separate rankings: *Wildlife Movement Priority, Structure Characteristics,* and *Protected Lands.*



	A	B
	THRESHOLDS	
2	Landscape Threshold >=	0
3	Omniscape Site Threshold >=	0
4	Development Threshold >=	0
5	Protected Lands Threshold >=	0
6	Structure Length Threshold (ft) <=	180
7	Structure Width:Bankfull Width >=	0.4

E	F	G	H	I
WEIGHTS				
Landscape	Site	Development	Structure Length	Structure Width/Bankfull Width
26.67	26.67	26.67	10	10

NORMALIZED VALUES

12	Structure ID	Omniscape Landscape Score	Omniscape Site Score	Structure Length	Structure Length	Structure Width/Bankfull Width Ratio	Structure Width/Bankfull Width Ratio	Protected Land Score	Development Score
13	{0006D5B1-883F-49FC-B82E-D820DD9C2FE3}	86.34060303	84.03507265	85	93.0941704	0.219765	0.438032932	0	95.95
14	{00165A03-F50D-4D30-A068-92176C2FEB6F}	68.88381038	72.66033742	91	92.55605381	1	3.392924122	62.5	100.00
15	{0047E36C-B834-403E-A5D3-265B1BFE2194}	82.91607879	75.93116385	38	97.30941704	0.467092	1.374705054	0	41.10
16	{004F7693-D14D-45D2-AA91-5530F66252B5}	73.73724395	77.45143528	32	97.84753363	0.487239	1.451005391	0	95.62
17	{00511177-2DC5-4564-AEBF-DD3782CA702D}	68.5872324	62.36035397	57	95.60538117	0.854326	2.841230313	0	40.76
18	{006E4634-00DB-4F6C-9338-9E6CE0D75832}	72.35431718	75.9449244	86	93.0044843	0.776069	2.544856887	0	70.32
19	{009BB852-22F7-4E30-AA66-17119BEF4146}	62.81067518	65.51825994	37	97.39910314	0.545935	1.673297768	0	36.10
20	{00DA22B8-5BF0-4B9C-96CF-7A359A64061D}	86.15093257	84.86826814	38	97.30941704	1	3.392924122	0	99.03
21	{00DBB7DB-17A0-4D21-B614-C6856D4F7661}	72.84648934	80.52397555	57	95.60538117	1	3.392924122	0	75.17
22	{00EE3DC9-8939-42E2-8E7D-1B1925548ECB}	56.55590737	26.91547846	57	95.60538117	0.582777	1.812825092	0	32.43

	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC
10	CONSTRAINTS						ACTIONS						STRUCTURE RECORD KEEPING	
11	OLS >= X	OSS >= X	DS >= X	SL <= X	SWBW >= X	PLS >= X	SCORE 1	RANK 1	SCORE 2	RANK 2	SCORE 3	RANK 3		
12	Omniscape Landscape Score	Omniscape Site Score	Development Score	Structure Length	Structure Width/Bankfull Width Ratio	Protected Land Score	Wildlife Movement Priority		Structure Characteristics Rank		Protected Lands Rank		Work completed? (Y/N, date)	Comments:
13	86.34	84.04	95.95	93.09	0.00	0.00	7101.971965	69	0.00	4817	0.00	1082		
14	68.88	72.66	100.00	92.56	3.39	62.50	6441.177275	984	95.95	3359	62.50	323		
15	82.92	75.93	41.10	97.31	1.37	0.00	5331.93447	3639	98.68	2183	0.00	1082		
16	73.74	77.45	95.62	97.85	1.45	0.00	6581.444219	709	99.30	1835	0.00	1082		
17	68.59	62.36	40.76	95.61	2.84	0.00	4578.80585	4783	98.45	2315	0.00	1082		
18	72.35	75.94	70.32	93.00	2.54	0.00	5829.819376	2503	95.55	3504	0.00	1082		
19	62.81	65.52	36.10	97.40	1.67	0.00	4384.837683	4983	99.07	1966	0.00	1082		
20	86.15	84.87	99.03	97.31	3.39	0.00	7201.344525	32	100.70	870	0.00	1082		
21	72.85	80.52	75.17	95.61	3.39	0.00	6094.402184	1841	99.00	1987	0.00	1082		
22	56.56	26.92	32.43	95.61	1.81	0.00	3090.831995	5709	97.42	2764	0.00	1082		
23	53.34	76.84	100.00	91.30	3.39	0.00	6137.931377	1717	94.69	3758	0.00	1082		

Appendix F. Resistance values for landscape variables in the landscape scale and structure scale analyses by species. Expert opinion values for each species were derived through an expert opinion survey, with expert scores for each variable averaged together. Species listed include American black bear (ABB), eastern bobcat (EB), eastern coyote (EC), moose (M), raccoon (R), red fox (RF), striped skunk (SS), and white-tailed deer (WTD).

	Species-specific Resistance Values								
Variable	**ABB**	**EB**	**EC**	**M**	**R**	**RF**	**SS**	**WTD**	**Landcover Data Source**
Landscape scale analysis									
Open water	77	83	65	35	53	60	73	95	National Landcover Database (2019)
Developed open space	67	70	30	58	6	35	1	50	NLCD 2019
Developed low intensity	67	70	30	58	6	35	1	50	NLCD 2019
Developed medium intensity	67	70	30	58	6	35	1	50	NLCD 2019
Developed high intensity	85	98	65	74	38	65	40	95	NLCD 2019
Barren land	60	43	35	49	78	25	15	50	NLCD 2019
Deciduous forest	1	2	1	1	1	6	4	1	NLCD 2019
Evergreen forest	1	3	1	1	1	6	3	1	NLCD 2019
Mixed forest	1	2	1	1	15	6	3	1	NLCD 2019
Shrub/scrub	14	1	6	1	30	1	6	1	NLCD 2019
Grasslands/herbaceous	48	70	19	27	10	3	1	5	NLCD 2019
Pasture/hay	48	70	19	27	10	3	1	5	NLCD 2019
Cultivated crops	40	72	30	39	3	5	6	20	NLCD 2019
Woody wetlands	3	1	1	1	8	3	11	5	NLCD 2019
Emergent herbaceous wetlands	20	18	8	17	8	5	15	85	NLCD 2019
High-traffic town roads	53	80	43	58	70	38	61	50	Vermont Agency of Transportation (VTrans 2019)
Moderate-traffic town roads	33	78	38	40	50	37	40	30	
Low-traffic town roads	12	50	32	17	15	11	33	5	VTrans 2019
Low/no traffic roads	1	6	1	4	8	1	3	5	VTrans 2019
State road system	63	85	65	62	53	50	66	50	VTrans 2019
Interstate system	82	95	80	68	65	68	68	65	VTrans 2019

	Species-specific Resistance Values								
Variable	**ABB**	**EB**	**EC**	**M**	**R**	**RF**	**SS**	**WTD**	**Source**
Structure scale analysis									
Buildings	Null	Null	Null	Null	Null	Null	Null	Null	Vermont Center for Geographic information (VCGI 2019)
Canopy cover	1	1	1	1	1	1	6	1	VCGI 2019
Grass/shrub	35	12	11	4	13	1	1	1	VCGI 2019
Agriculture	45	65	12	20	3	5	5	10	VCGI 2019
Wetland	8	3	5	7	10	3	10	20	VCGI 2019
Bare soil	35	68	45	7	20	15	28	5	VCGI 2019
Water	38	53	30	26	5	48	50	95	VCGI 2019
Other paved	58	83	63	42	8	45	28	80	VCGI 2019
Railroad	32	10	6	20	8	8	12	80	VCGI 2019
High-traffic town roads	68	73	58	65	50	25	65	90	VTrans 2019
Moderate-traffic town roads	47	43	15	58	50	8	65	70	VTrans 2019
Low-traffic town roads	20	20	14	19	10	6	30	5	VTrans 2019
Low/no traffic roads	5	3	1	2	1	1	3	5	VTrans 2019
State road system	73	83	75	68	75	58	65	90	VTrans 2019
Interstate system	90	95	90	75	75	68	65	90	VTrans 2019