Proposing and Demonstrating an Improved Habitat Connectivity Assessment Framework

Photo Credit: Burnt Mountain, Vermont © TNC

A Group Project submitted in partial satisfaction of the requirements for the degree of Master of Environmental Science and Management for the Bren School of Environmental Science & Management, University of California, Santa Barbara

Authors:
Renee Albrecht, Becky Clow, Nelson Gould, Jamie Miller, Robert Saldivar

Faculty Advisor:
Dr. Frank Davis

March 2020

Signature Page

As authors of this Group Project report, we archive this report on the Bren School's website such that the results of our research are available for all to read. Our signatures on the document signify our joint responsibility to fulfill the archiving standards set by the Bren School of Environmental Science & Management.

Renee Albrecht

Becky Clow

Nelson Gould

Jamie Miller

Robert Saldivar

The Bren School of Environmental Science & Management produces professionals with unrivaled training in environmental science and management who will devote their unique skills to the diagnosis, assessment, mitigation, prevention, and remedy of the environmental problems of today and the future. A guiding principal of the School is that the analysis of environmental problems requires quantitative training in more than one discipline and an awareness of the physical, biological, social, political, and economic consequences that arise from scientific or technological decisions.

The Group Project is required of all students in the Master of Environmental Science and Management (MESM) Program. The project is a year-long activity in which small groups of students conduct focused, interdisciplinary research on the scientific, management, and policy dimensions of a specific environmental issue. This Group Project Final Report is authored by MESM students and has been reviewed and approved by:

Dr. Frank Davis

Date

Acknowledgements

This project would not have been possible without the guidance and support of many people. The authors of this project would specifically like to acknowledge the following individuals:

Clients:	Dirk Bryant, The Nature Conservancy - Adirondack Chapter Jessie Levine, The Nature Conservancy & The Staying Connected Initiative
Advisor:	Dr. Frank Davis, Bren School of Environmental Science & Management
External Advisors:	Dr. Bruce Kendall, Bren School of Environmental Science & Management Dr. Jochen Jager, Concordia University
Funding	Chubb Insurance
Guidance:	Sarah M. Walsh, Mohawk Hudson Land Conservancy Alissa Fadden, The Nature Conservancy Brian Lee, Bren School of Environmental Science & Management Dan Coker, The Nature Conservancy
Data:	Daniel Winters, State University of New York at Albany
Technical Support:	Dr. Ashley Larsen, Bren School of Environmental Science & Management Dr. James Frew, Bren School of Environmental Science & Management Dr. Allison Horst, Bren School of Environmental Science & Management Dr. Sarah Anderson, Bren School of Environmental Science & Management Steve Miley, Bren School of Environmental Science & Management

Table of Contents

Signature Page **ii**
Acknowledgements **iii**
Table of Contents **iv**
List of Figures **vi**
List of Tables **vii**
Acronyms **viii**
Abstract **ix**
Key Findings and Recommendations **x**
Significance **1**
Objectives **2**
Background **3**
- The Need for a Connected Landscape 3
- The Costs and Benefits of Maintaining a Connected Landscape 3
- Key Issues in Modeling Connectivity 4
- Northern Appalachian/Acadian Ecoregion (NAPA) 5
- The Staying Connected Initiative (SCI): 6
- Mohawk Valley Case Study 7

Methods for Developing the Framework **8**
- Evaluation of Approaches for TNC/SCI Partners 8

Part 1 - Framework for Improving Connectivity Models **9**
- Define Conservation Goals 11
- Identify and Communicate with Stakeholders 12
- Define Type of Connectivity to be Modelled 13
- Determine Availability of Empirical Species Data 13
- Define Resistance to Movement 14
- Define What is Being Connected 22
- Model and Map Connectivity 23
- Delineate Important Linkage Areas 27
- Validate Linkage Areas with Empirical Data 27
- Priority Setting 30
- Climate Connectivity Considerations 33

Part 2 - Monitoring Considerations **36**
- Establish Monitoring Objectives 36
- Determine Availability of Existing Data 36
- Determine Resource Availability to Conduct Monitoring 37
- Determine Questions to be Addressed by Monitoring 37
- Select Response Variables and Determine Appropriate Monitoring Frequency 37
- Design and Implement Monitoring Plan 40
- Evaluate and Refine Conservation Goals and Monitoring Strategy 41

Part 3 - Mohawk Valley Connectivity Analysis **46**
Methods and Results **47**
- Define Conservation Goals and Communicate with Stakeholders 47
- Define Type of Connectivity to be Modelled 47

Determine Availability of Empirical Species Data 47
Define Resistance to Movement 49
Define What is Being Connected and Model Connectivity 52
Delineate Linkage Area 55
Validate with Empirical Data 56
Priority Setting 58
Discussion 62
Data Bias and Representativeness Considerations 62
Balance the Costs and Benefits of Empirical Data Collection 62
Limitations of the Framework 63
Addressing Limitations 63
Conclusion 65
Further Reading 66
References 67
Appendix A. Linkage Area Report Summaries 79
Appendix B. Mapping Data Sources 86
Appendix C. Species Distribution Model Inputs 89
Appendix D. Species Distribution Model Outputs 92
Appendix E. Expert Opinion Resistance Values 95
Appendix F. Resistance Layers and Linkage Mapper Corridors 97
Appendix G. Potential Mohawk Valley Linkage Boundaries 106

List of Figures

Figure 1. Human development disconnecting Tug Hill and Adirondack Park. 4
Figure 2. SCI area of interest. 6
Figure 3. Current SCI linkage area creation framework. 7
Figure 4. Proposed framework for connectivity assessments. 10
Figure 5. Land surface translated into resistance surface. 15
Figure 6. Visual representation of resource selection functions. 22
Figure 7. Analysis processing extents and fisher detection points. 49
Figure 8. Least cost corridors and Omniscape cumulative current flow. 54
Figure 9. Potential linkage area boundaries. 55
Figure 10. Fisher detection points, random points, and normalized cumulative current. 57
Figure 11. Cumulative current of fisher detection points and random points. 58
Figure 12. Potential locations for connectivity improvements in the Mohawk Valley. 59
Figure 13. Detailed potential locations for connectivity improvements. 60

List of Tables

Table 1. Analytical approaches to create resistance layers. 20
Table 2. Theories and methods for modelling connectivity. 26
Table 3. Types of empirical species data. 38
Table 4. Response variables to evaluate corridor success. 39
Table 5. Summary of empirical species data collection methods. 42
Table 6. Habitat suitability sensitivity analysis iterations. 51

Acronyms

AHP - Analytical Hierarchy Process
eDNA - Environmental DNA
GBIF - Global Biodiversity Information Facility
GIS - Geographic Information System
GPS - Global Positioning System
HRSF - Home Range Selection Function
LCP - Least Cost Path
MHLC - Mohawk Hudson Land Conservancy
MSF - Matrix Selection Function
NAPA - Northern Appalachian/Acadian ecoregion
NGO - Non-Governmental Organization
NLCD - National Land Cover Database
PathSF - Path Selection Function
PSF - Point Selection Function
SCI - Staying Connected Initiative
SSF - Step Selection Function
TNC - The Nature Conservancy
WVC - Wildlife-Vehicle Collision

Abstract

Human infrastructure and urban development are increasingly fragmenting natural landscapes, threatening many species that require navigable landscapes for survival. Accordingly, many conservation organizations, such as The Nature Conservancy (TNC) and the Staying Connected Initiative (SCI), have begun modelling connectivity in an effort to integrate landscape connectivity into their broader conservation goals. Unfortunately, these organizations often lack a thorough framework to evaluate modelled connectivity and translate regional-scale connectivity assessments into local-scale conservation actions. At the request of TNC and SCI, we reviewed previous SCI connectivity assessments and connectivity literature to develop a framework that outlines how to: improve conservation outcomes through more specific conservation goals, build effective connectivity models, and establish methods for priority setting. We apply this framework to a case study in the Mohawk Valley of New York State, a new SCI linkage area. Our case study analysis revealed that our framework is applicable to connectivity modelling and decision making at both the regional (SCI linkage) scale and local scale of conservation actions. This project demonstrates how thoroughly understanding the conservation problem, carefully articulating goals, and responsibly using empirical species data can produce better models with greater leverage to maintain and improve landscape connectivity.

Key Words: Connectivity, Landscape Ecology, Connectivity Modelling, Species Movement, Conservation Planning

Key Findings and Recommendations

In this project, we developed a framework to guide the Staying Connected Initiative's (SCI) process of modelling connectivity and applied this framework to a case study in New York. Our findings revealed the following key recommendations:

- We found that SCI linkage area reports sometimes lacked precision in their definition of connectivity, which can impact the accuracy of connectivity model parameterization and interpretation. For future connectivity assessments, we recommend that SCI partners clearly define their connectivity goals and species' movement of interest (e.g. daily habitat, range shifts, migration, etc.), and thoughtfully reflect those decisions in the parameterization of connectivity models.
- In SCI linkage area assessments, most SCI partners used expert opinion to define how species move throughout the landscape. Expert opinion has been shown to less accurately reflect actual species movement through the landscape than empirically collected species data; however, most empirical species datasets in the Northern Appalachian/Acadian ecoregion (NAPA) region do not capture the landscape heterogeneity at the linkage area scale. Therefore, we recommend SCI partners continue to use expert opinion to model linkage areas, and use empirical species data to ground truth localized model results before connectivity projects are implemented.
- SCI partners modelled connectivity using termini-based algorithms (e.g. Circuitscape or Least-Cost Modelling), which have been shown to have biased results from the arbitrary placement of connectivity termini. Moving forward, we recommend SCI use connectivity models such as Moving Window or Wall-to-Wall analyses that predict connectivity throughout the landscape, rather than between a limited set of termini.
- In applying our framework to the Mohawk Valley case study, we determined that our framework is applicable to connectivity modelling and decision making at both the linkage scale and local scale of conservation actions. Therefore, we recommend SCI partners use this framework first at the regional scale to understand broad drivers of regional connectivity, but reiterate the framework at a landscape scale relevant to anticipated and actionable connectivity projects.

Significance

Maintaining a navigable landscape is imperative to the survival of many species; however, without accurate mapping and the consideration of feasible solutions, organizations can be stymied in their efforts to conserve or restore animal movement between habitat patches (Beier et al., 2008; Beier & Loe, 1992; Beier & Noss, 1998; Wade et al., 2015; Zeller et al., 2012). Habitat fragmentation, habitat loss, and direct human-caused deaths limit the ability of animals to move between resources in a landscape, which can lower the survival rates of affected species (Coffin, 2007; Fahrig, 2003). Additionally, as climates change and species' habitats shift in space, the reduction in survival due to movement barriers can be exacerbated (Hannah, 2011; Keeley et al., 2018a). Anthropogenic barriers to animal movement can also be a burden to humans, chiefly in the form of expensive WVCs along roadways (US Department of Transportation: Federal Highway Administration, 2008). In recognizing the benefits of increasing connectivity for wildlife, many organizations, including our clients The Nature Conservancy-Adirondack Chapter (TNC) and the Staying Connected Initiative (SCI), have begun to map connectivity between known habitat cores (e.g. protected areas) to support planning for projects that conserve or restore habitat connectivity (Anderson et al., 2016; McRae et al., 2016a; Theobald et al., 2012). SCI specifically has garnered financial and technical support from 57 partner organizations, including TNC, to map connectivity within the Northern Appalachian/Acadian ecoregion (NAPA); however, the utility and impact of SCI's nine regional connectivity assessments has been hindered by a lack of clear, actionable goals and the underuse of empirical species data for connectivity model calibration and validation (Appendix A).

Since SCI was initiated in 2009, more sophisticated and standardized methods to evaluate and model connectivity have been published (Anderson et al., 2016; Cushman et al., 2014; Cushman et al., 2013; McRae et al., 2016a; Wade et al., 2015; Zeller et al., 2011; Zeller et al., 2012). However valuable, these publications only either provide general recommendations to connectivity project design or specific explanations of model design. SCI, being an organization of partners with varying degrees of available resources, would benefit from a guidance document that both acknowledges the work SCI partners have completed and makes recommendations for future work SCI partners can feasibly complete. In this report, we adopt the general connectivity assessment framework described by Wade et al. (2015) along with other relevant synthesis papers (Beier et al., 2008; Rudnick et al., 2012; Zeller et al., 2012) to build a guidance document for future SCI connectivity assessments.

We illustrate this framework through a case-study connectivity assessment across the Mohawk Valley, New York. TNC, SCI, and the Mohawk Hudson Land Conservancy (MHLC), a local land trust, have expressed interest in beginning connectivity mitigation work across this region, but have not carried out formal analyses. Because our case study was limited by data availability, computing resources, and time constraints, our goal was to showcase how practitioners can use this conceptual framework under real-world limitations, not produce a definitive connectivity assessment for the area. We end our case study with recommendations for TNC and MHLC to conduct a more complete Mohawk Valley, NY connectivity assessment. These recommendations include: targeted monitoring, more advanced connectivity modelling, targeted connectivity model validation procedures, and the identification of priority areas for future mitigation work by TNC and the MHLC. We believe this case study and these recommendations will help contextualize the conceptual framework we outline, allowing SCI partners around the NAPA region to more efficiently carry out connectivity conservation and restoration.

Objectives

The primary goal of this project is to help the client, The Nature Conservancy, and a regional partnership, the Staying Connected Initiative, more effectively conserve and restore landscape connectivity in the Northern Appalachian/Acadian ecoregion. Our specific objectives include:

1. Improve the framework TNC and SCI use to model and mitigate barriers to connectivity by incorporating more emphasis on goal setting, the inclusion of empirically collected species data, and methods to make local decisions from regional connectivity maps.
2. Outline monitoring methods and considerations SCI partners can use to assess landscape connectivity for focal species within the NAPA region.
3. Demonstrate the improved framework through a case study in the Mohawk Valley of New York, a new SCI linkage area.
4. Offer recommendations for continued SCI connectivity assessments in the Mohawk Valley and the NAPA region.

Background

The Need for a Connected Landscape

Anthropogenic habitat destruction can lower the survival of species by reducing the total amount of resources available in a landscape and impeding access to the resources that remain (Allen et al., 1983; Butchart et al., 2010; Fahrig, 2003; Fischer & Lindenmayer, 2007). Limited resources within habitat patches can drive individuals to move between nearby patches to obtain adequate resources. However, land development can block passage between these patches (Figure 1). For many species, infrastructure such as roads, urban centers, and agriculture can act as physical barriers to movement (e.g. fencing; Jaeger & Fahrig, 2004), reduce a willingness-to-cross an area (e.g. avoidance of habitat edges; Pfeifer et al., 2017), or reduce the survival of individuals crossing an area (e.g. WVCs; Coffin, 2007). This development can also limit the ability of species to disperse through the landscape, reducing gene flow within or between populations (Cushman et al., 2006; Hanski & Gilpin, 1997; Saunders et al., 1991), and can prevent populations from completing seasonal migrations (Harris et al., 2009). The ability of species to disperse will be increasingly important under a changing climate (Hannah, 2011; Keeley et al., 2018a; Thomas et al., 2004). Collectively, the pressures associated with disconnected landscapes can have severe impacts on wildlife populations, making the preservation and restoration of connections within the landscape a pivotal segment of environmental stewardship (Keeley et al., 2018b; Rudnick et al., 2012; Wade et al., 2015).

The Costs and Benefits of Maintaining a Connected Landscape

Conservation scientists continue to debate how to best conserve or restore habitat connectivity and how connectivity initiatives should be woven into broader conservation goals. Although numerous studies outline the benefits of a connected environment (Dixon et al., 2006; Keeley et al., 2018b; Wade et al., 2015; Zeller et al., 2012), there are instances when improving habitat connectivity is not wholly beneficial. Studies have suggested that a connected landscape can encourage the spread of fires, pathogens, and invasive species and function as ecological traps or sinks for species (Simberloff et al., 1992; Simberloff & Cox, 1987). Moreover, the cost of implementation and the opportunity cost of forgone conservation investments may outweigh the ecological benefit of a connectivity project (Beier & Noss, 1998; Hodgson et al., 2009; Simberloff et al., 1992). For instance, it may not be worth the high cost of constructing a wildlife crossing structure along road segments with relatively few WVCs, when those funds could be used to conserve high-quality parcels. Because a connectivity projects' monetary and ecological trade-offs are often contingent on other environmental factors (e.g. surrounding habitat quality, presence of invasive species, or future local climate projections), many conservation organizations integrate connectivity into their broad conservation plans, rather than have connectivity be the lone focus (Anderson et al., 2016; Glen et al., 2013; Moore & Shadie, 2019).

Figure 1. Human development disconnecting Tug Hill and Adirondack Park. The Tug Hill Plateau habitat block (west) and the Adirondack Park habitat block (east) are in New York State. Disconnected forest habitat blocks can lower individual- and population-level survival rates for development-averse, forest-dwelling species. Source: Google Earth Pro.

Key Issues in Modeling Connectivity

Although connectivity is recognized as a valuable component of conservation plans, understanding connectivity has proven challenging (Zeller et al., 2012; Wade et al., 2015). Habitat connectivity can be an ambiguous term, defined by the spatial and temporal scale of interest, the species in question, and the species behavior in question. For instance, a landscape connected for relatively linear, seasonal ungulate migrations may not have enough dendritic connectivity to allow bears to move between dispersed berry patches. The first hurdle of connectivity assessments is to decide what organisms and associated behaviors should be the focus of connectivity improvements, and accurately reflect those organisms and behaviors in parameterizing connectivity models (Keeley et al., 2018b).

The second challenge is knowing whether you have effectively modelled actual wildlife connectivity. With many simple-to-run connectivity models (Calabrese & Fagan, 2004b; Kool et al., 2013; Wade et al., 2015), practitioners risk mis-parameterizing, misinterpreting, or overly trusting the outputs of these models (Wade et al., 2015; Zeller et al., 2012). Studies have addressed how to properly parameterize, run, and interpret these models (Calabrese & Fagan, 2004a; Wade et al., 2015; Zeller et al., 2012). However, these studies outline multiple viable options for parameterization and model selection, each of which carry their own toils and considerations. Ultimately, even the best designed connectivity model output is still an unconfirmed hypothesis until its predictions of connectivity are validated with relevant empirical data (Wade et al., 2015). Therefore, selecting appropriate models and model parameters is essential for conservation planners to avoid appropriating conservation dollars on projects in areas of projected high, but actually weak connectivity (Wade et al., 2015).

The third challenge emerges as conservation planners translate connectivity models into conservation action (Keeley et al., 2018b). Connectivity is often mapped over a conservation organization's region of interest (done in all SCI Linkage Area Reports, Appendix A; Anderson et al., 2016; Goetz et al., 2009; McRae et al., 2016a). Mapping over such extensive areas allows practitioners to infer movement of animals between known large core areas (SCI Linkage Area Reports) or across entire regions (Anderson et al., 2016; Goetz et al., 2009; McRae et al., 2016a). However, these broad scale connectivity assessments often culminate in predicted animal movement corridors that are kilometers or tens of kilometers wide (SCI Linkage Area Reports), which can be relatively large compared to the spatial extent of possible connectivity projects. If practitioners are not methodical in how they scale-down these broad connectivity maps, they may misappropriate conservation funds to areas of projected high regional animal movement, but actually weak local movement.

Northern Appalachian/Acadian Ecoregion (NAPA)

At 325,000 km^2, the NAPA ecoregion is home to over five million humans and abundant wildlife (blue line, Figure 2; Coker & Reining, 2013). The region covers portions of five U.S. states (New York, Massachusetts, New Hampshire, Vermont, and Maine) and three Canadian provinces (Quebec, New Brunswick, and Nova Scotia), and provides habitat for many far-ranging mammals, which are projected to be highly impacted by a disconnected landscape (Farrell et al., 2018). Currently, the NAPA region contains large intact forest blocks connected by variably intermittent forest corridors. However, human development is reducing the size of forest blocks and constricting forest corridors, which may impact species survival within the forest blocks and reduce connectivity between forest blocks (Anderson & Olivero-Sheldon, 2011). The disconnectedness of forest blocks will have an increasingly negative impact on species survival as climates change within North America, since the NAPA ecoregion is expected to be a critical corridor for many species' northward movement (Lawler et al., 2013). If connectivity between forest blocks is not retained, many species may be trapped in environments to which they are maladapted (Hannah, 2011; Hannah et al., 2007). Therefore, SCI and other organizations' work to ensure a navigable NAPA region is essential to safeguard impacted organisms from climate change.

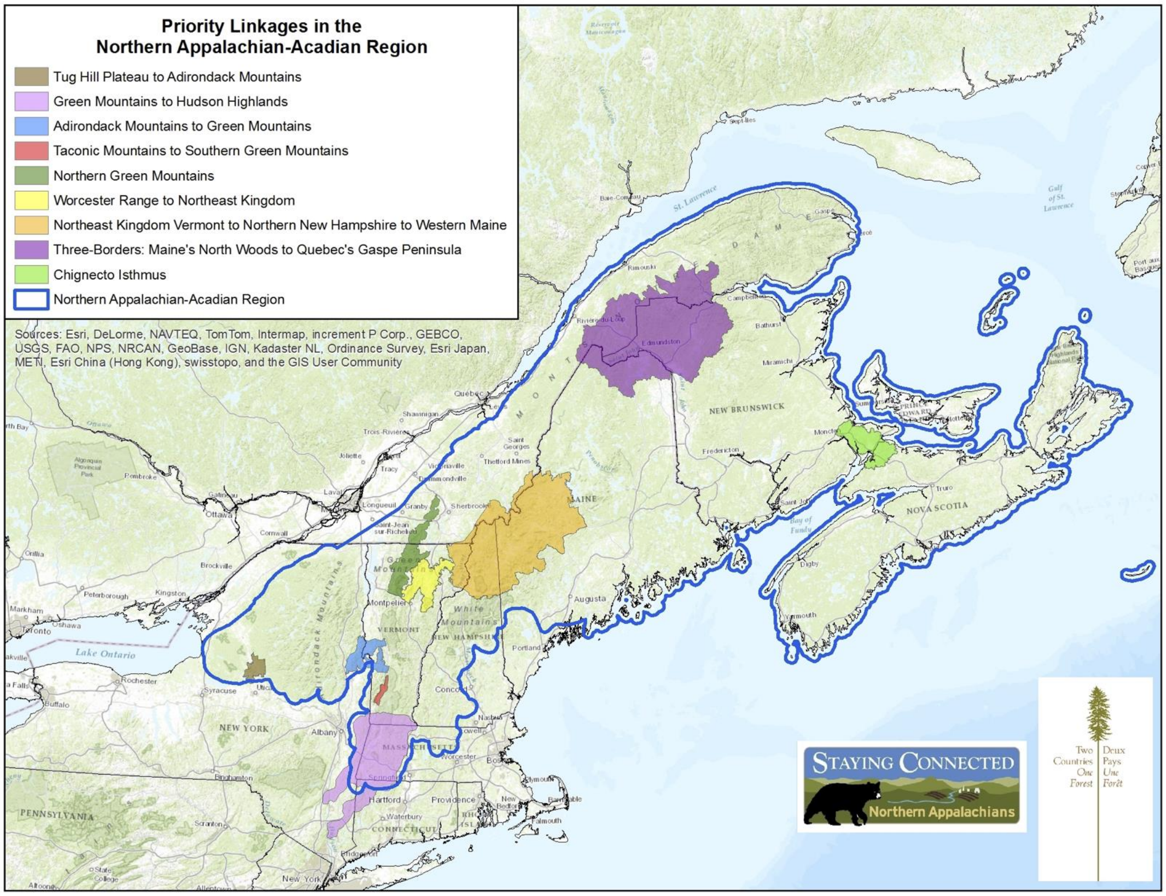


Figure 2. SCI area of interest. The Northern Appalachian/Acadian ecoregion (NAPA) is outlined in blue. SCI has delineated priority linkage areas (colored polygons) within the NAPA ecoregion. Although methods varied, expert opinion and literature review of animal movement patterns most often guided linkage area delineation. Source: Coker and Reining 2018.

The Staying Connected Initiative (SCI):

SCI is a 57-organization partnership that includes our client, The Nature Conservancy-Adirondack Chapter. Currently, SCI has delineated nine linkage areas, or corridors of modelled animal movement between protected areas, in the NAPA region (Figure 2; Coker & Reining, 2013; Meiklejohn et al., 2010). To understand what SCI has accomplished, we reached out to SCI partners to collect final reports or summary documents for their nine established linkage areas. SCI partners shared summary documentation for the following linkage areas: Adirondack Mountains to Green Mountains, Chignecto Isthmus, Green Mountains to Hudson Highlands, Tug Hill Plateau to Adirondack Mountains, Northern Green Mountains, Northeast Kingdom Vermont to Northern New Hampshire to Western Maine, and Three Borders. We did not receive reports for the Taconic Mountains to Southern Green Mountains linkage area or Worcester Range to Northeast Kingdom linkage area. We reviewed each report and recorded: how habitat connectivity was modelled, what the project goals were, what the focal species were, which environmental variables were used, and if empirical species data were included in the connectivity model (Appendix A).

Although all linkages are defined under the SCI umbrella, they differ in their geographic size, species-of-interest, connectivity model use, linkage delineation methods, and conservation prioritization methods (Appendix A). Despite their idiosyncrasies, each linkage area followed a similar process, which included: defining broad conservation goals, using expert opinion and literature review to estimate how animals move through various land types, modelling connectivity between two predetermined habitat core areas, and calling for future action (Figure 3). Although a good first step, these analyses rely heavily on expert opinion and literature review to define how animals use the landscape, which has been shown to reduce the accuracy of modelled connectivity maps and reduce the chance of conservation action (Keeley et al., 2018b; Zeller et al., 2012; Alissa Fadden, personal communication). Additionally, most SCI linkage area reports articulated only vague conservation goals and often lacked tangible next steps for boots-on-the-ground work after delineating a large-scale linkage area from the region-of-interest (Appendix A).

If SCI were to follow a more thorough conceptual framework, as we provide here, in their future connectivity assessments, their partner organizations may incite more prolific and effective connectivity mitigation work in the NAPA region.

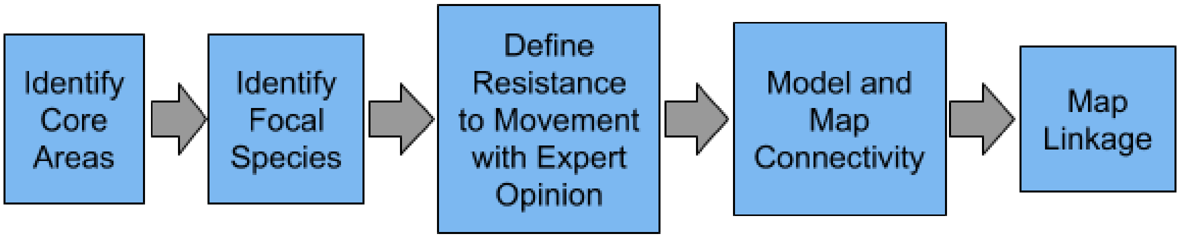


Figure 3. Current SCI linkage area creation framework. We identified this framework after reviewing SCI linkage area reports.

Mohawk Valley Case Study

To demonstrate the steps of the framework, we conducted a preliminary connectivity assessment in the Mohawk Valley of New York. SCI partners TNC and the Mohawk-Hudson Land Conservancy (MHLC) intend to integrate connectivity into their conservation plans within this region. The Mohawk Valley latitudinally separates the Adirondack Mountains and the Catskill Mountains, which are both large, preserved habitat cores (Figure 7). Maintaining and improving connectivity between these habitat cores will assist animals moving northward because of climate change from the Central Appalachian Mountains, via the Kittatinny Ridge (Dirk Bryant, personal communications), through the Catskill Mountains and to the Adirondack Mountains. The MHLC and TNC plan to complement each other's conservation work with MHLC focusing on acquiring land that improves connectivity through the region, while TNC implements road-barrier mitigation projects. Our framework is intended to address the emphases of both organizations by outlining how to identify priority land parcels for conservation and road segments for barrier mitigation in the Mohawk Valley.

Methods for Developing the Framework

Evaluation of Approaches for TNC/SCI Partners

Since the inclusion of empirically collected species data in connectivity models was a primary focus of this project, we compiled a preliminary review of existing data sources in the NAPA region that could be used in connectivity modelling. To conduct this investigation, we reached out to SCI partners in a general “request for data” email. We conducted targeted outreach to university-affiliated researchers or government agencies we identified as having high quality data, such as state departments of transportation and departments of environmental conservation. We also explored and catalogued publicly available data from iNaturalist, GBIF, and Movebank for black bear, moose, fisher, bobcat, marten, and lynx. We summarized these potential data sources and tracked which agencies/individuals were contacted for data and whether data were obtained.

Additionally, we identified factors that are likely to restrict the use and feasibility of the approaches described in the literature for incorporating species data in connectivity modeling for SCI and TNC (funding, data availability, computing power, etc.). Based on this information, we assessed the utility of different methods for incorporating empirical data into connectivity models based on their potential usefulness for TNC and SCI partners.

Part 1 - Framework for Improving Connectivity Models

The framework below outlines the process of creating a linkage area and highlights where empirical species data can be incorporated to more accurately model species movement (Figure 4).

To produce this framework, we reviewed the scientific literature concerned with the need for habitat connectivity, incorporating empirical species data into habitat connectivity modelling processes, goal setting and monitoring for connectivity assessments, and prioritizing areas for connectivity work. Ultimately, we relied heavily on key review papers, notably Wade et al., (2015) and Zeller et al., (2012), to guide our work. We focused our literature review on resistance-surface-based modelling as it was the most widely cited and researched option for incorporating empirical species data into habitat connectivity models. We tracked and summarized relevant literature in a spreadsheet and populated information for 17 attributes including: citation information, target species, key words, connectivity methods/tools, and a general summary.

To develop familiarity with monitoring techniques, we conducted a literature review in Google Scholar and Web of Knowledge. Search keywords included: performance monitoring, adaptive management, adaptive monitoring, targeted monitoring, and functional connectivity. We used Zeller et al., 2012 to determine the potential for various types of data to be included in resistance-surface based connectivity modelling. Based on this, we decided to further research the following types of data and collection methods: detection data (e.g. camera traps, roadkill, scat dog, tracks), movement data (e.g. GPS collar data) and genetic data (e.g. eDNA, tissue samples - hair snare, hunter/roadkill collection, blood samples).

Our resulting framework adds additional steps that we found missing in SCI's previous linkage creation processes and connectivity modelling including identifying tangible conservation goals, including empirical species data as a proxy for functional connectivity, and methods for identifying priority areas for management actions. This framework will help TNC and SCI more accurately model animal movement across landscapes through the addition of empirical species data, and can also help prioritize management areas by providing suggestions on how to use connectivity assessments to implement localized actions. In connectivity models, empirical species data can be incorporated in two ways: at the beginning of the process, by defining species resistance to movement through the creation of resistance surfaces, and at the end of the process, by validating the connectivity models with species data. When running connectivity assessments one or both of these procedures can be implemented depending on data robustness and conservation goals. This framework process can be conducted on any scale, including local and site connectivity assessments. Here we focus on the application of the framework on the linkage or regional scale but a more localized look at connectivity using the framework can also help to prioritize connectivity-based management actions.

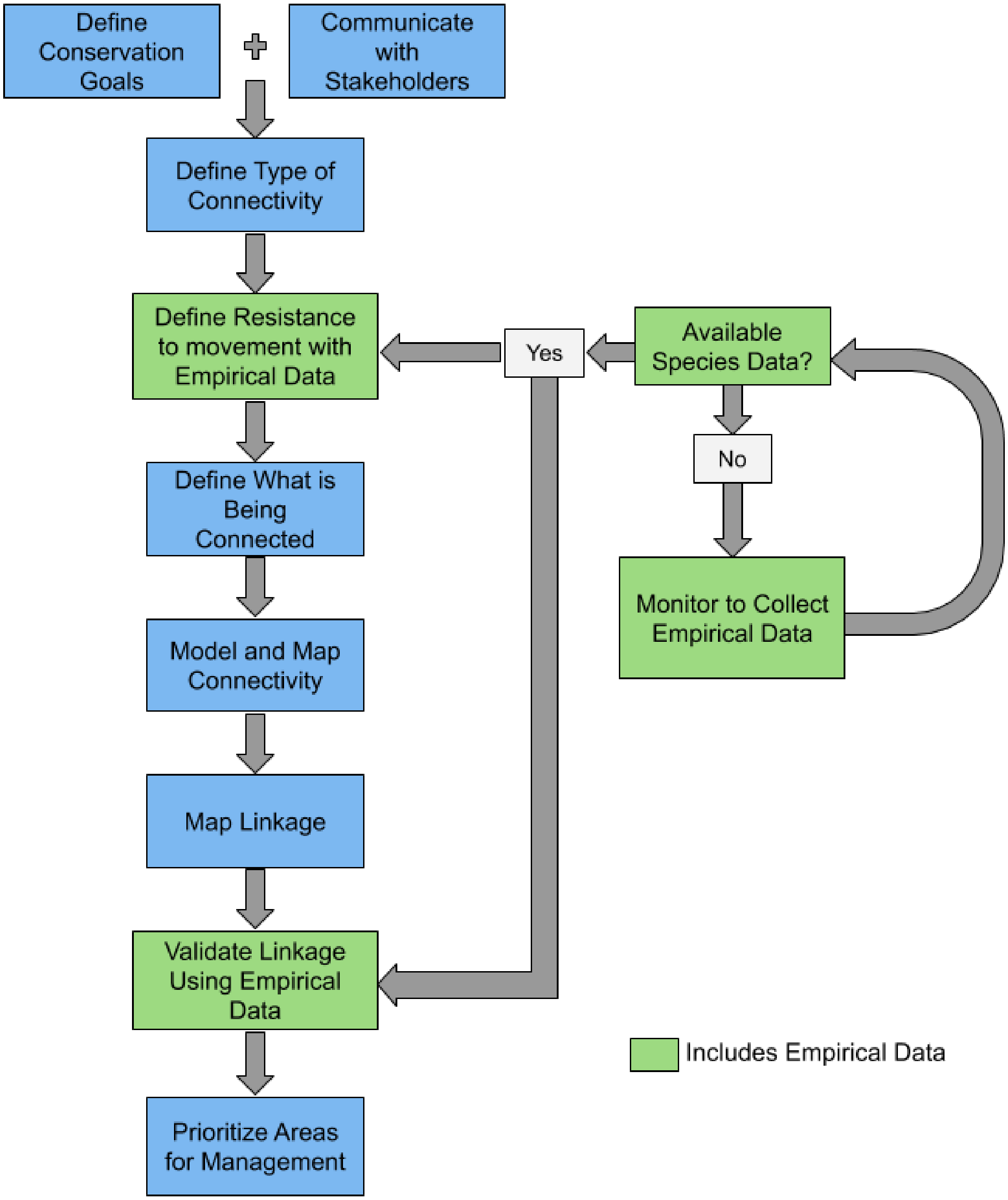


Figure 4. Proposed framework for connectivity assessments. This framework outlines the process and the steps that should be followed when conducting connectivity assessments. The steps in green represent areas where empirical species data can be incorporated into the process.

Define Conservation Goals

Without explicit conservation goals, organizations will be unable to measure progress and risk misappropriating limited resources. Therefore, the first step for any connectivity assessment is to establish clear conservation goals that articulate how partner organizations can mitigate specific conservation problems. Consequently, goals should be drafted to address problems that partner organizations have the interest and ability to mitigate and should shape the research questions that subsequent modelling will inform. Adequate goals should address a number of sub-considerations, including defining the conservation problem, selecting focal species, and aligning conservation goals with the organizational goals of all involved partner organizations. While the relevant considerations for conservation goal setting will vary across each organization and modelling scenario, we outline broadly applicable guidelines below.

Define the Conservation Problem

A clear understanding of the conservation problem provides a foundation to create carefully articulated conservation goals. Practitioners can use monitoring or existing research to define the conservation problem and determine if mitigating barriers to connectivity is a relevant solution. As part of a broader adaptive management strategy, iterative monitoring can help inform conservation goals and refine future monitoring efforts. For example, if monitoring or prior research reveals that there are barriers to animal movement, practitioners should identify what type of movement is compromised to effectively address the problem. Monitoring methods and considerations are described further in Part 2. Once the conservation problem has been identified, practitioners should carefully evaluate the relevance of connectivity to the issue. Typically, a thorough understanding of the conservation problem will suggest what type of connectivity is most relevant (further described in the section *Define Type of Connectivity to be Modelled*).

Select Focal Species

How species move within and between landscapes is idiosyncratic across species and individuals. The anatomy, physiology, and life history of individual species determine their connectivity needs and their ability to take advantage of specific interventions to improve connectivity (Wade et al., 2015). The focal species selection process should account for whether the possible mitigation strategies partner organizations can implement benefit a given species. Additionally, focal species should capture stakeholder values, if certain species are more socially valued or are of more conservation concern (e.g. if interested in reducing dangerous WVCs on roadways, select large, often struck species). Socially important species are also more likely to garner public support and funding.

Focal species can also be selected by how well they represent the movement patterns of a suite of species or connectivity types, if this is relevant to the conservation goal (Wade et al., 2015). It is beneficial, for example, to select focal species that are sensitive to habitat fragmentation and human development. Additionally, practitioners must consider whether focal species are likely to reside in a corridor versus just pass through a corridor, as this will influence modelling efforts.

It should be noted that large wide-ranging species, such as bear, ungulate, bovine, or cat species, are often negatively impacted by the loss of landscape connectivity, and are therefore strong candidates for focal species (Beier et al., 2008). Additionally, they may also garner more public support and funding as flagship species. However, habitat specialists with restricted mobility can also be heavily impacted by the loss of connectivity, so their inclusion as focal species can be beneficial (Beier et al., 2008).

Align Conservation Goals with Stakeholder Goals and Assess Feasibility:

To ensure continued support and successful action, there should be a strong alignment between stated conservation goals and the overall goals of organizations, partners, projects funders, and other stakeholders. These broad-picture goals may include:

- Organizational goals (e.g. acquiring land for conservation)
- Project funder goals (e.g. grant funding for a specific road mitigation project)
- Ecological goals (e.g. reintroduction of bobcats after local extirpation)
- Partner organization goals (e.g. Staying Connected Initiative mission)
- Goals of the community and general public

Additionally, it is important to make goals achievable with the resources (financial, time, personnel) available for the connectivity assessment and mitigation work.

Identify and Communicate with Stakeholders

Leveraging partnerships and engaging the community are critical steps to ensure the realization of conservation goals. In instances where resources are particularly limited or the conservation goal does not entirely align with an organization's broader mission, practitioners may be able to creatively engage stakeholders to achieve conservation goals. In the early stages of planning a conservation project, practitioners should identify the organizations, agencies, and community members who will be impacted by or may contribute to the conservation outcome. Such stakeholders include: land owners, indigenous peoples, university researchers, land trusts, NGOs, and state and federal agencies.

Practitioners should solicit opinions from a variety of partners and community members throughout the steps described in this framework. Doing so helps establish trust with the community and ensures that conservation efforts are supported and maintained over the long term. One valuable method for soliciting a variety of opinions and consolidating them is through the Analytical Hierarchy Process (AHP). The AHP is particularly beneficial in group decision making as it allows respondents to select between pairwise preferences and then synthesizes responses into a prioritization scheme. Using this method can be particularly valuable in complex decisions that may involve stakeholders such as determining focal species or finalizing conservation goals.

To establish and maintain community engagement and gather useful data, it may be valuable to set up a citizen science program. In addition to helping with data collection efforts, establishing a citizen science program can help the community become invested in the results of conservation initiatives.

Define Type of Connectivity to be Modelled

A landscape can be functionally connected or disconnected depending on the driver of animal movement for a given focal species. The conservation problem and associated goals will suggest the type of connectivity to be modelled (Wade et al., 2015). For example, if the conservation goal is to revive a population of bobcats in a location where they have been locally extirpated, this suggests the importance of modelling for demographic connectivity. Wade et al. (2015) describe six types of connectivity that can be modelled: structural connectivity and five types of functional connectivity. Structural connectivity describes the physical contiguity of habitat types and elements within a landscape and is not specific to any one species. Alternatively, functional connectivity is species specific and describes how the structure of the landscape supports species movement. Wade et al. (2015) describe five distinct types of functional connectivity:

- **Daily Habitat Connectivity** describes movements that animals make between resource patches to find daily food, water, and shelter (Wade et al., 2015).
- **Seasonal Migration Connectivity** describes movement to and from breeding areas, whether annually or seasonally (Sinclair, 1983)
- **Demographic movement Connectivity** describes animal movements that result in recruitment within a new population as a function of dispersal (Lowe & Allendorf, 2010)
- **Genetic movement Connectivity** describes animal movement between populations and subpopulations that maintains genetic variability (Lowe & Allendorf, 2010)
- **Range shift Connectivity** describes animal movement that allows species to move into new habitats in response to climate change or other disturbances (Wade et al., 2015).

It is critical that practitioners define which type of connectivity they are modeling. Without this level of specificity, there is no metric (genetics, specific movement patterns, etc.) by which to measure success toward conservation goals.

Determine Availability of Empirical Species Data

Determining which data are available to incorporate into connectivity models is foundational in informing which modelling approaches are feasible and responsible. If an organization does not already have readily available data, partners, university researchers, and state agencies may be willing to share data. Publicly available data can be found on iNaturalist, Movebank, GBIF and other citizen science repositories. With all data, caution must be exercised to assess the representativeness of the data and evaluate whether the data can be used responsibly for connectivity modelling. Evaluating the representativeness of a dataset should include an assessment of how many data points the dataset contains, whether the dataset matches the spatial and temporal scale of the conservation problem, and whether the data are representative of the actual population of a particular species. Ideal datasets should encompass a wide range of individuals, life stages, and sexes spanning as many relevant environmental variables as possible (Elith et al., 2011).

The different types of data that can be incorporated into models are described below. These data are briefly described here but more detail about each data type and different methods for collecting the data type can be found in Part 2 - Monitoring Considerations.

Detection Data

Detection data refer to data that are single locations for unidentified individuals. Detection data can take the form of presence-only data or presence-absence data. The data types differ because true absences cannot be assumed in presence-only data whereas absences can be inferred from presence-absence data (Zeller et al., 2012). Detection data can be collected via numerous collection methods, including: sightings, vocalizations, camera traps, mist nets, hair snares, scat, tracks, bait and trap, and telemetry studies. Detection data is often the most readily available and easily acquired data.

Relocation Data

Relocation data refers to data that are at least two sequential locations of the same animal (Zeller et al., 2012). The most common example is mark recapture studies, such as mist-netting birds. With relocation data, the time interval between data collections is not frequent enough to infer movement pathways.

Pathway Data

Pathway data describes at least two sequential locations of the same individual that are tracked frequently enough to treat the data as a movement pathway (Zeller et al., 2012). Movement rates are entirely species dependent and as such, there is no consensus on how frequent is frequent enough to interpret movement points as a pathway (Zeller et al., 2012). This particular type of data requires attaching GPS technology onto an animal.

Genetic Data

Genetic data are samples of genetic material collected at multiple locations. These data are used to estimate rates of gene flow between individuals or populations and then calculate genetic distance accordingly. These measures of genetic distance are then compared to geographic distance (Wade et al., 2015).

Expert Opinion Data (if empirical data are lacking)

While expert opinion is not empirical data, it is included here as it often must be used out of necessity when conservation action is urgent and representative empirical data is lacking. However, it is best to view expert opinion as a temporary solution until empirical data can be collected (Zeller et al., 2012). Research has established that expert opinion is generally less effective at correctly parameterizing environmental variables relative to empirical approaches (Clevenger et al., 2002; Seoane et al., 2005).

Define Resistance to Movement

Once animal data are collected (or not, see *Expert Opinion and Literature Review based*), practitioners need to infer how various environmental variables (e.g. land-use) influence a focal species' willingness-to-traverse an area, the physiological cost of traversing an area, and the reduction in survival for individuals crossing an area (Zeller et al., 2012; Wade et al., 2015). These inferences are often captured in a resistance to movement raster, or resistance layer, in which each cell holds a resistance to movement (or cost of movement) value (Wade et al., 2015). When inputted into a connectivity model, this resistance layer is used to predict how an animal might maneuver through a given landscape (Figure 5). Here we describe general considerations and outline methods to build a resistance layer with or without empirical data.

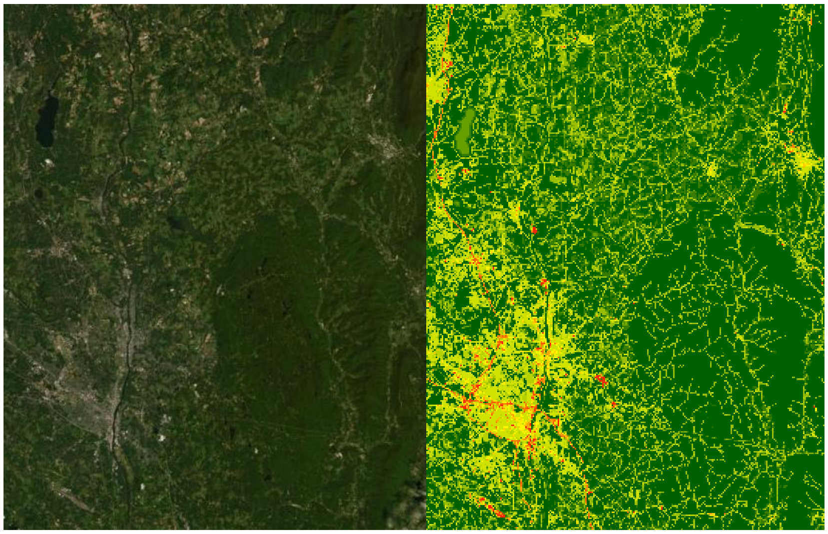


Figure 5. Land surface translated into resistance surface. The land surface is shown on the left and the resistance surface is shown on the right with resistance values increasing from green to red.

Initial Considerations

All methods to derive resistance to movement layers (Table 1) require the selection of a geographic study extent, a raster grain size, and environmental variables. In making these decisions, practitioners should select resistance layer parameters that reflect the biology of the focal species and reduce subsequent connectivity model bias. General considerations include:

Extent

- The extent of the resistance layer should be significantly larger than the region of interest to prevent connectivity models from falsely predicting barriers to animal movement at the edge of resistance layers (Wade et al., 2015).
- The extent selected should represent the species and connectivity type in question (Wade et al., 2015). For example, one should choose different extents if modelling how a species might climatically migrate over a long time scale versus modelling how the same species can presently access local foraging grounds.
- When creating a resistance layer with empirical data, practitioners should recalculate the layer with varying extents to better understand how sensitive the data are to study extent (Zeller et al., 2012).

Grain Size

- The grain size of the resistance layer should "be determined based on the scale at which the target species perceives and responds to heterogeneity in the environment (Wiens, 1989)" (Zeller et al., 2012). However, it should be noted that the lower limit of grain size is bound by the granularity of the underlying data, and that data with smaller grain sizes require more computational power and time to run than data with larger grain sizes (Wade et al., 2015).
- In building the resistance layer, practitioners can set different grain sizes for different environmental variables, if varying grain sizes makes ecological sense (Zeller et al., 2012). For instance, if interested in how an amphibian moves between small vernal pools, it may make sense for practitioners to capture the distribution of pools with more granularity than other variables, like temperature.

Environmental Variables

- The environmental variables practitioners select should be known to influence how the focal species interprets and moves through the landscape (Beier et al., 2008; Wade et al., 2015; Zeller et al., 2012). Consequently, the selection of these variables is contingent on the current knowledge of movement behavior in the focal species.
- Practitioners should consider the accuracy of data when selecting environmental variables (Wade et al., 2015; Zeller et al., 2012). Unreliable or inaccurate data should be avoided, or at the least acknowledged in the discussion of model reliability (Wade et al., 2015; Zeller et al., 2012).
- Practitioners should use caution when scaling environmental variables to a particular grain size, as some variables (e.g. categorical or classified variables) can become unreliable when scaled or scaled improperly (Wade et al., 2015; Zeller et al., 2012).

To be clear, these are general considerations. Before practitioners decide on parameters to build a resistance layer, we recommend they review Wade et al. (2015, pg. 19-21), Zeller et al. (2012, pg. 781-783) and Beier et al. (2008, pg. 841-842) for more thorough considerations and examples for selecting extent, grain size, and environmental variables.

Methods to Build Resistance Layer

There are multiple methods to assign resistance values; however, each method carries with it assumptions of animal behavior and limitations for model inference. Here, we describe the general categories these methods fall within, based on their initial data type, followed by a tabular summary of specific methods (Table 1, Figure 6). The method groups and most of the specific methods are from the Zeller et al. (2012) review of resistance layer creation. Here we discuss only general features and limitations of each model. Before practitioners use a particular model, they should review literature that more substantially details how to run and think about these models. We provide a preliminary list of literature available for each model in Table 1.

Expert Opinion and Literature Review

If adequate animal data are not available, practitioners can use expert opinion and literature review of focal species movement behaviors to define a resistance layer (Wade et al., 2015; Zeller et al., 2012). Often, expert opinions are gathered through a survey inquiring how the focal species might move through various land cover types at varying or specific life stages (e.g. tendency or willingness of a juvenile dispersing black bear to move through pastureland; Zeller et al., 2012). The survey results can be tabulated in a number of ways (Table 1) and cross referenced with published literature on movement behavior of the focal species to create a final resistance to the movement layer (Zeller et al., 2012).

Practitioners should take caution in using this method to create a resistance layer. Resistance layers based on expert opinion and literature review have been shown to be less reliable than those based on empirically collected data (Poor et al., 2012; Zeller et al., 2012), and may lower the likelihood for connectivity projects to reach a meaningful fruition (Keeley et al., 2018b; Jessica Levine, personal communications). If this method is chosen, practitioners should review and use standardized, objective methods for setting resistance values based on survey results, such as using Fuzzy logic systems (Pyke, 2005), Bayesian Belief Networks (Stiber et al., 2004), or an Analytical Hierarchy Process (Zeller et al., 2012).

Detection Data

Under the umbrella of Point-Selection Functions (PSFs), there are a handful of detection data-based techniques to define a resistance layer (Zeller et al., 2012). PSFs generally use presence or detection/non-detection points to build a habitat suitability or occupancy model for the focal species, which is then inverted to provide a resistance layer (inversion equation dependent on PSF used: for probability of occurrence models (1 - *probability value*), (Long, 2009); for habitat suitability models ((*Suitability* - (*Maximum value*)) x (-1) + (*Minimum value*)), see https://support.esri.com/en/technical-article/000006694; alternatively for habitat suitability models, practitioners can project random points within the area of interest and calculate a probability of occupancy for each point, then invert (1 - *probability value*) those probabilities, (Zeller et al., 2014). Consequently, in using PSFs to create a resistance layer, practitioners must make the assumption that areas of high predicted habitat suitability or predicted occupancy for the focal species are representative of animal movement patterns. This is a variably reasonable assumption to make, depending on the focal species and the type of connectivity being modelled (Long et al., 2011; Valerio et al., 2019; Wade et al., 2015; Zeller et al., 2012). For instance, habitat suitability may better infer movement patterns for a species of limited mobility fulfilling daily habitat use needs than a species requiring connectivity for a longer migration, in which habitat does not need to be of high quality to move through (Wade et al., 2015).

Detection data can also be used in a limited capacity within a Matrix Selection Function (MSF) to select between previously established expert opinion-based resistance layers (Wade et al., 2015; Zeller et al., 2012). The MSF selects the resistance layer that best predicts the ecological distance between observation points (Zeller et al., 2012).

Relocation Data

There are two methods that use relocation data to define a resistance layer. The first entails calculating movement or dispersal rates between relocation points and using a least cost path analysis to infer resistance values between points (FitzGibbon et al., 2007; Zeller et al., 2012). In the second method, relocation data are used to define species home ranges, which are then used to infer preferred habitat. Species habitat preferences are then extrapolated to the area of interest, which is then inverted to create a resistance layer (Zeller et al., 2012).

Pathway Data

Step-selection functions (SSF) and path-selection functions (PathSF), the only methods to use actual animal movement data (namely GPS-collar tracking data), are generally considered the most accurate methods of defining a resistance layer (Thurfjell et al., 2014; Zeller et al., 2012, 2016). Both functions select a surface of resistance values that best represents the animal's movement path. The model selects plausible resistance surfaces by comparing the cost distance between steps or paths to the cost distance of random steps or paths of equal length. The primary difference between SSFs and PathSFs is that SSFs compare only one step at a time, namely one recorded location and the subsequent recorded location, to equally long random steps, while PathSFs compare an entire pathway (e.g. all recorded points for a given day) to equally long random pathways (Zeller et al., 2012). PathSFs are considered of higher quality than SSFs, but require more frequent readings on the target animal’s location to ensure an accurate portrayal of the animal’s pathway. Both SSFs and PathSFs are susceptible to the bias of where random steps or paths are generated (termed *available habitat*). Both require iterations of sensitivity analyses on available habitat designation and time interval between steps. Practitioners should also be wary of using datasets with a small sample size of individuals, as idiosyncratic movement patterns may skew final resistance layers. Lastly, practitioners should ensure the movement data used in the SSF or PathSF represent the connectivity type established in their goals, namely by disentangling types of movement captured in the data (e.g. resting versus active, dispersal versus daily habitat use; Zeller et al., 2012).

Genetic Data

These methods use individual or population-level genetic relatedness analyses or a direct gene flow analysis to infer resistance to movement throughout a landscape (Cushman et al., 2006; Emaresi et al., 2011; Wang et al., 2009; Zeller et al., 2012). In any of the three method types, resistance layers are selected out of a pre-established set of resistance values for given environmental variables. The final resistance layer is the best predictor of the genetic distance between individuals or populations (on a cost-distance basis). In comparing these models, individual-based models are seen as more robust, but population models can be used if biologically relevant (e.g. population-based models were used in the Emaresi et al., 2009 assessment of genetic connectivity between relatively discrete newt populations) (Cushman & Landguth, 2010; Emaresi et al., 2011; Zeller et al., 2012). Zeller et al., (2012) note that gene flow-based models are appropriate only when migrations between populations can be accurately measured. For all genetic-based models, it is important to note that estimates of resistance to movement are rooted in historic movements and reflect how past generations of animals have moved through the landscape. Therefore, if the landscape has seen recent development relative to the generation time of the focal species, these genetic assessments may not be indicative of connectivity issues animals currently encounter.

Validating the Resistance Layer

Practitioners can validate the developed resistance layer with independent and relevant data, if those data are available (Zeller et al., 2012). Data used for validation should capture the behavior in question and heterogeneity of the relevant environmental variables in the region of interest. Generally, validation techniques involve overlapping species data on the resistance layer, and running simple analyses to verify

that the data correspond to logical resistance values. Because similar methods can be employed to validate a resistance layer and connectivity model output, the specific validation methods we discuss later on for connectivity linkage validation (see *Validate Linkage Areas with Empirical Data*) can be employed to validate resistance surfaces.

Table 1. Analytical approaches to create resistance layers. All approaches feature the use of empirical species data except "Expert Opinion and Literature Review".

Analytical Approach	**Example Models**	**Species Data Needed**	**Strengths**	**Limitations**	**Resources**
Expert Opinion and Literature Review	AHP, Bayesian Belief Networks, Fuzzy Logic Systems	None	• Allows for complex habitat relationships to be incorporated into resistance values • Can synthesize animal movement information from multiple studies	• Least quantitatively rigorous approach • Suboptimal parameterization	**Linkage Report:** Adirondack Mountains to Green Mountains (Tear et al., 2009) **Literature:** Aylward et al., 2018; Clevenger et al., 2002; Compton et al., 2007; Gantchoff & Belant, 2017; Gurrutxaga & Saura, 2014; Poor et al., 2012; Pyke, 2005; Stiber et al., 2004
Point Selection Function (PSF)	Maximum Entropy (i.e. Maxent), Occupancy Model	Spatially precise, current, unbiased detection data	• Can use multiple types of detection data • More intuitive than other models	• Infers movement resistance from non-movement data	**Linkage Reports:** Adirondack Mountain to Green Mountains (Long, 2009) **Literature:** Lele et al., 2013; Long et al., 2011; MacKenzie et al., 2002; Poor et al., 2012; Valerio et al., 2019; Zeller et al., 2014
Step Selection Function (SSF)	See Function Code in "Resources" column	Movement Data	• Based on movement data • Does not require short interval GPS location data	• Constrained by defined model parameters including available space (spatial and temporal) • Often only take into account preferred habitat and ignores avoided landscapes	**Linkage Reports:** NA **Literature:** Abrahms et al., 2017; Cushman & Landguth, 2010; Lele et al., 2013; Richard & Armstrong, 2010; Squires et al., 2013; Thurfjell et al., 2014; Zeller et al., 2016 **Function Code:** Brennan et al., 2018
Path Selection Function (PathSF)	See Function Code in "Resources" column	Movement Data	• Based on movement data • Considered most accurate because it takes into account the whole movement path	• Data intensive - requires frequently collected movement data • Modelling process less intuitive	**Linkage Reports:** NA **Literature:** Cushman & Lewis, 2010; Zeller et al., 2012, 2016 **Function Code:** Kathy Zeller's GitHub page **(**https://github.com/kazeller/PathSF-Data-Prep)

Analytical Approach	Example Models	Species Data Needed	Strengths	Limitations	Resources
Home Range Selection (HRSF)	NA	Relocation Data	• Conceptually close to actual resistance because it uses relocation data and home range	• Challenging to determine the "available environment" • Infers movement resistance from non-movement data	**Linkage Reports:** NA **Literature:** Graham, 2001; Kautz et al., 2006
Matrix Selection Function (MSF)	NA	Can use all data types, including Genetic Data	• Directly assesses environmental resistance • Does not require designation of "available environment"	• Ecological distance output highly correlated with geographic distance • Challenging to determine measure of ecological distance • Requires significant computing power	**Linkage Reports:** NA **Literature:** Braunisch et al., 2010; Chardon et al., 2003; Cushman et al., 2006, 2009; Desrochers et al., 2011
Individual-based Genetic Assessment	NA	Genetic Data	• Highlights reproductively successful movements of individuals • Can infer genetic relatedness between individuals	• Results reflect movements of prior generations, which may not reflect current movements	**Linkage Reports:** NA **Literature:** Cushman & Landguth, 2010
Population-based Genetic Assessment	NA	Genetic Data	• Highlights reproductively successful movements between populations	• Results reflect movements of prior generations, which may not reflect current species movements • Can only infer movements between populations	**Linkage Reports:** NA **Literature:** Emaresi et al., 2011
Gene-flow based Genetic Assessment	NA	Genetic Data	• Highlights how gene flows are impacted by the environment • Gene flow is directly measured, not inferred	• Results reflect movements of prior generations, which may not reflect current movements • Intensive to accurately measure gene flow	**Linkage Reports:** NA **Literature:** Wang et al., 2009

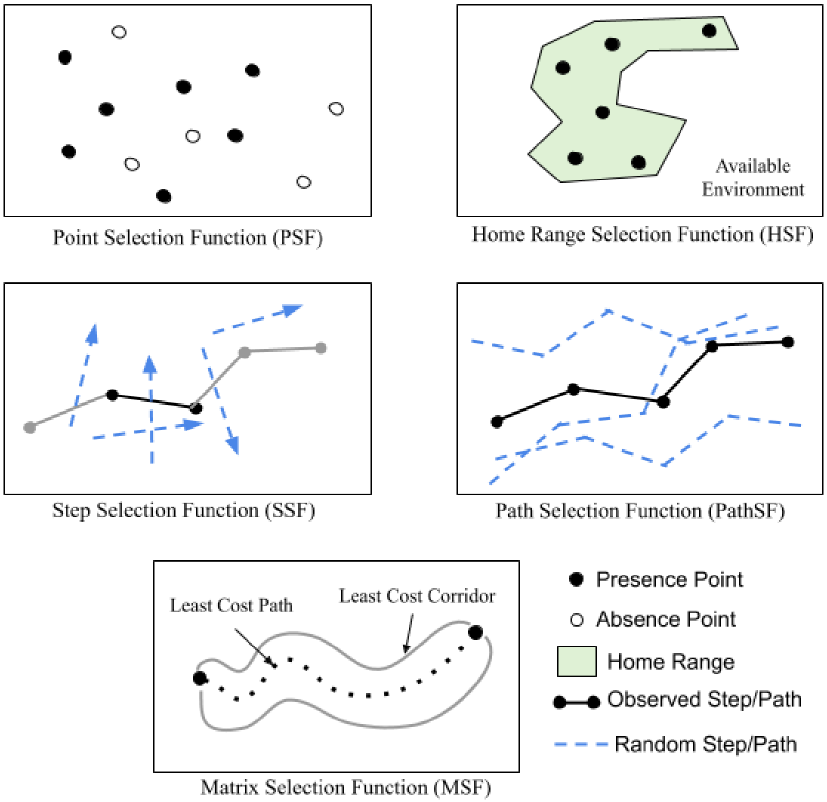


Figure 6. Visual representation of resource selection functions. Figure adapted from Zeller et al. (2012).

Define What is Being Connected

Before connectivity can be modelled, practitioners need to define what is being connected (Wade et al., 2015). Typically, the assigned termini, or movement destinations, of connectivity assessments are known habitat cores (e.g. large protected areas) or areas of concern for partner organizations (e.g. rare habitat); however, termini can also be defined by the current location of populations (Hannah, 2011). These termini are used in many of the available connectivity models as start or end points for animal movement (Wade et al., 2015). However, some of the novel and more synoptic connectivity models do not require explicit termini, but assess connectivity across a given region (Anderson et al., 2016; Cushman et al., 2014; McRae et al., 2016a; Pelletier et al., 2014).

For models that do require explicit core area termini, practitioners should consider the species biology when defining the termini. Core areas should be places where the focal species is currently found, or where viable habitat exists for the focal species. Additionally, practitioners should consider species home ranges and general movement patterns when choosing size and placement of core areas. Once the core areas are defined, practitioners must determine if connectivity will be assessed from the border or centroid of the defined core area. Note that modeling connectivity between the borders of the core areas assumes that habitat within the core area is homogeneous.

Assessments that only model connectivity between a few user-selected termini are increasingly recognized as rudimentary (Cushman et al., 2014; Pelletier et al., 2014). In these models, predicted connectivity can be biased by the location, size, and habitat composition of the core areas, and by the assumption that individuals of the focal species are moving between the termini. Therefore, these termini-based models may only weakly reflect real animal movement patterns, if core area termini do not reflect ecologically and behaviorally relevant areas to the target species in that region. As a result of these biases, more novel connectivity models do not use explicit core area termini as parameters (Anderson et al., 2016; Cushman et al., 2014; McRae, Shah, et al., 2016). Methods used to assess connectivity without core areas are discussed further in the *Model and Map Connectivity* section.

Model and Map Connectivity

Practitioners can model connectivity after they define a resistance layer and identify areas of interest. Although there are connectivity models that do not require a resistance layer (see http://conservationcorridor.org/corridor-toolbox/programs-and-tools/ for a comprehensive list), we only discuss resistance layer-based connectivity models because of their prevalence in the literature and in SCI's connectivity assessments.

Each connectivity model we discuss uses resistance values to assess the ecological "cost" of movement of the chosen species across the area of interest (Wade et al., 2015). Each connectivity model has different underlying theories, assumptions, and biases. It is important to use connectivity models that align with the type of movement being assessed and the biology of the focal species (McClure et al., 2016). This report highlights four of the most foundational and robust connectivity model types a) cost-weighted distance, b) circuit theory, c) resistance kernel, and d) centrality analysis (Table 2; Macdonald & Willis, 2013; Wade et al., 2015). Additionally, we highlight more novel, synoptic connectivity models that improve and build upon previous connectivity models by assessing regional connectivity without the need for core areas or termini.

Cost-weighted distance Modeling

Cost-weighted distance (also called least-cost modeling) treats the resistance layer as a cost layer and calculates the ecological cost an individual animal accumulates while moving between two termini (Table 2; Macdonald & Willis, 2013; McClure et al., 2016). This method results in a cost-surface map, where routes between the two termini are calculated according to an efficient search algorithm (Hart et al., 1968), and each cell retains the value of the least costly path that ran through it (some methods will reduce the cost-surface cells by the total cost of the least costly path, to scale the output). This method also produces a least-cost path, or the lowest ecological "cost" route between core area termini. Cost-weighted distance models assume that an animal has perfect knowledge of the landscape and, in the case of a least-cost path, that an animal will move through the landscape along the most efficient route. This assumption makes cost-weighted distance theories good for modeling large migrating animals because the population as a whole has previous knowledge of the landscape (McClure et al., 2016). For raster surfaces, the least cost path identified in cost weighted models is limited to a one-cell wide path, which is unrealistic because it assumes the animal stays on the most efficient route without deviations (Cushman et al., 2014).

Circuit Theory Modeling

Based on electric current theory, circuit theory connectivity models estimate animal movement through a landscape by treating habitat cores as source or ground nodes, and running current from one node to another across a resistance raster (Table 2; McClure et al., 2016; McRae et al., 2016b, 2008). Practitioners can infer animal movement or gene flow patterns from the modelled current distribution throughout the landscape (McRae & Beier, 2007). Circuit theory assumes an animal is a random walker in the landscape, meaning they have no knowledge of the landscape, and are making random movement decisions based on their immediate surroundings as they traverse the landscape (McClure et al., 2016). Circuit theory connectivity models are sensitive to not only the value of resistance but the distribution of resistance values. For example, current can disperse in areas of consistent low resistance, current can avoid areas of consistently high resistance, and current can be funneled through in areas of low resistance that are paralleled by areas of high resistance (Wade et al., 2015). Each of these results can suggest patterns of animal movement; for example, areas of high flow, or movement pinch points, may indicate places where animal movement is bottlenecked. However, practitioners should employ common sense to help interpret these maps. For instance, low flow may indicate areas of wide low resistance to movement, or it could indicate distance from the shortest path between habitat nodes. Ultimately, the value of current flow does not directly correlate to animal behavior, rather can help infer animal movement in the context of the model design and landscape in question.

Circuit theory may better represent animal movement patterns and gene flow than cost-based analyses because it takes into account movement throughout the whole region (McClure et al., 2016; McRae and Beier, 2007). However, there are inherent assumptions and biases within the model, including the placement and size of core area termini and the assumption that animals have no previous knowledge of the landscape.

Resistance Kernel Modeling

Resistance kernel connectivity modeling uses the same underlying theory as cost-weighted distance, but takes into account expected dispersal density of the species (Table 2; Compton et al., 2007; Wade et al., 2015). Resistance kernel assessments model dispersal of a population by using a dispersal function and resistance values to determine the populations expected outward movement from a focal cell (Buttrick et al., 2015). Each cell is given a score based on how far the species is able to grow or disperse from the focal cell. A higher score indicates a more permeable landscape with large possibility for dispersal. Similar to cost-weighted distance modeling, resistance kernel modeling assumes that the animal has perfect knowledge of the landscape and that the species is source and destination driven. Resistance kernel modeling is useful for modeling movement of species that have an explicit kernel, or starting dispersal location, such as amphibians in vernal pools, because they are moving from a specific location at a given time (Compton et al., 2007). This method is not as useful for species that move from shifting locations or are spread across the landscape, such as large mammals.

Synoptic Modelling Methods

As mentioned in the previous section, there are a handful of novel connectivity models that predict connectivity throughout the landscape, rather than between set termini. Each build upon connectivity models previously discussed, namely: circuit theory models, cost-weighted models, and resistant kernel models (Anderson et al., 2016; Compton et al., 2007; Cushman et al., 2014; Cushman et al., 2009; McRae, Hall, et al., 2016). These models have been shown to more accurately predict animal movement through a landscape, since they remove some of the termini biases from connectivity predictions (Cushman et al., 2014).

- *Moving Window Analysis*

  The Moving Window connectivity model (dubbed *Omniscape*) uses circuit theory to connect all viable cells within a given radial window to a target cell at the center of the window (McRae et al., 2016a; Landau, 2020). The viability of cells within the window is defined by a source layer—a 0-1 scale raster that sets each cell's weighted importance as a movement destination—where any source value of 0 or source value below a user-defined threshold is considered not a viable source. Typically, source rasters are set and interpreted as the likelihood an animal would move to or from a given cell. For instance, McRae et al. (2016a) set source values based on how natural a land-unit is, with more natural units receiving higher source values. To run the model, practitioners need to input a resistance raster and a source raster of equal extent and grain size and set various parameters, including window radius. It should be noted that this model can be computationally intensive, especially at relatively small grain sizes and large window sizes (McRae et al., 2016a; see Part 3). We discuss this method further in Part 3.

- *Wall-to-Wall Analysis*

  The Wall-to-Wall connectivity analysis (sometimes dubbed *Omnidirectional Connectivity*) uses circuit theory to connect randomly distributed termini along the latitudinal and longitudinal bounds of the region of interest (Anderson et al., 2016; Pelletier et al., 2014). Running current across the landscape outputs cumulative North-South and East-West connectivity maps, which can themselves be aggregated to infer multidirectional connectivity (Pelletier et al., 2014). If this method is used, practitioners can reduce the bias of node placement by offsetting the nodes from the region of interest by a set buffered distance (see Pelletier et al., 2014 for more thorough considerations).

- *Centrality Analysis*

  Centrality analyses use a network of nodes across the landscape as sources and destinations to model connectivity, predicting connectivity regionally instead of only between defined areas (Table 2, Wade et al., 2015). Centrality analysis can be conducted using cost-weighted distance, circuit, or resistant kernel connectivity algorithms.

- *Factorial Least-Cost Path Analysis*

  The Factorial Least-Cost Path analysis uses a resistance layer to compute the least cost path between a multitude (thousands or millions) of points within the landscape, which are then aggregated to show the density of least-cost paths throughout the landscape (Cushman et al., 2014; Cushman et al., 2009).

Table 2. Theories and methods for modelling connectivity. Each row contains attributes about different connectivity modelling approaches.

Model	**Underlying Theory**	**Assumptions**	**Inputs**	**Results**	**Programs**
Cost-Weighted Distance (least cost path)	Cost Distance	1. Perfectly efficient organism movement 2. Organism destination driven	1. Resistance Layer 2. Core Areas	1. Cost Weighted Distance Surface 2. Least Cost Path	ArcGIS Linkage Mapper LCP; LandScape Corridors, UNICOR
Circuit Theory	Circuit Theory	1. Organisms are random walkers 2. Organism destination driven	1. Resistance Layer 2. Core Areas	1. Current Flow 2. Pinch points	Circuitscape; Pinchpoint Mapper (in ArcGIS Linkage Mapper) GFlow; Omniscape
Resistance Kernel	Cost Distance	1. Perfectly efficient organism movement 2. Organism destination driven	1. Dispersal Function (distance of dispersal, etc.) 2. Resistance Layer	1. Resistant kernel map	ArcGIS Resistance Kernel toolbox
Moving Window	Circuit Theory	1. Organisms are random walkers	1. Source Layer 2. Resistance Layer	1. Current Flow	Omniscape (https://github.com/Circuitscape/Omniscape.jl).
Wall-to-Wall	Circuit theory	1. Organisms are random walkers	1. Regional Edge Termini Layer 2. Resistance Layer	1. Current Flow	Circuitscape
Centrality Analysis	Any	1. Depends on Theory	1. Habitat Quality or Resistance Layer	1.Depends on Theory	Connectivity Analysis Toolkit
Factorial-Least-Cost Path	Cost Distance	1. Perfectly efficient organism movement between nodes	1. Multiple Termini Layer 2. Resistance Layer	1. Aggregate Least Cost Path	ArcGIS Linkage Mapper LCP; LandScape Corridors, UNICOR

Delineate Important Linkage Areas

Linkage areas are mapped regions of predicted animal use and movement between habitat cores (Meiklejohn et al., 2010). Linkage areas are often binary polygons, making them an easy-to-use conservation tool. However, practitioners should be aware of how the arbitrary boundaries of a linkage area can either omit true animal corridors when corridor definition is too conservative, or overestimate animal use of the landscape when corridor definition is too liberal. Additionally, connectivity within a linkage area is likely to be more nuanced than a linkage map suggests. Therefore, practitioners should use linkage maps to inform broad conservation directives, but conduct more localized connectivity assessments before conducting specific connectivity projects.

Generally, linkage area boundaries are defined by a practitioner-set threshold of predicted connectivity (dependent on the connectivity model run), where all connectivity measures below the set threshold fall outside of the linkage area. Since linkage areas are often meant to connect two habitat cores, most linkage area assessments use termini-based connectivity models (although the relative novelty of synoptic methods may also account for the use of termini-based methods; Appendix A). Hence, thresholding the connectivity analysis bounds the corridor and area of conservation interest between habitat cores. Alternative to thresholding the connectivity analysis, practitioners can use prior ecological or practical knowledge of the region to define the linkage boundaries (see Green Mountains to Hudson Highlands Linkage Report, Applin & Marx, 2014). However, we do not recommend this method due to its excessively subjective assignment of linkage boundaries. Regardless of method, if connectivity for multiple species is being considered, each species should be accounted for when mapping the linkage. To aggregate multiple species connectivity, practitioners can either create a cumulative species connectivity map, preserving the predicted high-use corridors for each species, or preserve only corridors that are predicted high-use for all species. For example, protecting each species predicted high connectivity areas is important for specialist species that do not have overlapping habitat requirements while cumulative corridors with high predicted connectivity for all species are particularly useful for generalist species that prefer similar habitat.

Ultimately, linkage areas are constructed for human management purposes. Linkage boundaries are inherently biased and, therefore, should not be considered true boundaries to animal movement between core areas, but useful starting points for connectivity mitigation work. We recommend that in the construction and use of linkage areas, practitioners consider how these maps will be used before deciding on the threshold level, where boundaries should be drawn, and if linkage areas are a necessary step in a broader connectivity initiative. Regardless of how linkage areas are defined, all restoration or mitigation projects should be evaluated individually even if it falls outside of the linkage boundary.

Validate Linkage Areas with Empirical Data

Validating connectivity models with empirical species data, such as presence points or GPS movement paths, allows practitioners to understand with more certainty where and if species movement is occurring in areas of modeled high connectivity (McClure et al., 2016; Zeller et al., 2012). Validation results are particularly useful for connectivity models based on expert opinion, because empirical data can provide species-specific information in an area of interest. Validated models can be used with more certainty to prioritize and implement valuable and successful management decisions that positively impact landscape connectivity (Zeller et al., 2012).

Currently, there is no generally preferred method for validating connectivity models (Wade et al., 2015). Most methods are relatively similar, comparing the predicted movement flow of actual animal data points or lines to randomly generated points or lines. Ideally, practitioners should use an independent dataset from the data used to model connectivity to validate models; however, if independent data are not available, practitioners can withhold a portion of the original dataset to validate (Zeller et al., 2012; Wade et al., 2015). The data and method used for validation should align with the species, species behavior, and conservation goals outlined in the framework (Macdonald & Willis, 2013; McClure et al., 2016; Wade et al. 2015, Clevenger et al., 2002). For example, if the conservation goal is to mitigate road-barrier effects or to reduce WVCs, then detection data collected along roadways or WVC data would be useful to validate the connectivity model. Or, if the conservation goal is to improve or protect species migration routes, GPS-movement data captured during migrations would be useful for model validation (Wade et al. 2015). When using different data types for validation it is important to consider what that data represents and the limitations of each data type outlined in the *Define Resistance to Movement* section.

Before data are used to validate an entire connectivity assessment, practitioners should consider whether those data match the extent of the connectivity assessment or the heterogeneity of the extent's underlying environment variables. All methods of validation can evaluate the connectivity model outputs or the resistance layers. For each method we outline, validation can be conducted by either visually comparing the validation data to the connectivity model output or by conducting statistical tests, such as a t-test, on the underlying connectivity metrics or resistance values associated with the data.

Random Points versus Data Points

Practitioners can compare the underlying connectivity metric value (dependent on connectivity model run) of empirically-collected data points to randomly distributed points, and assess whether more or less connectivity is predicted where the empirically collected data were found (McClure et al., 2016; Walpole et al., 2012). The process to perform this validation method is as follows:

1. Create random points throughout the region of interest.
    a. The number of random points should be equivalent to the number of empirical data points.
    b. The location of the random points should be distributed in areas according to the empirical data collection methods. For instance, if detection data were collected along a particular road segment, random points should only be generated along that same road segment. Additionally, random points should only be distributed in areas the focal species could plausibly be found.

2. Visually compare the distribution of each type of data and/or perform appropriate statistical tests (e.g. t-test) on the connectivity metrics associated with the empirical species data and random points.
3. If the connectivity metric or visual comparison of the empirical species data are better than the random points, this validation process suggests the model represents species behavior well.

Note that this process can be done with multiple data types, including detection data or pathway data. To provide a more robust validation, practitioners can reiterate this comparison with multiple sets of actual species data and random points, if possible.

Buffer Method

Practitioners can use the buffer method, as described in Koen et al. (2014), to validate connectivity model outputs by comparing the connectivity metrics within buffered empirically-collected data points and buffered randomly generated data points. A buffer is created around each data point to capture how the individual animal uses the surrounding landscape and not just the recorded presence point. The buffer analysis assumes that species also move within the area surrounding the presence point. The size of the buffer area should correspond to how the species being assessed sees and uses the landscape. For example, a larger buffer should be used for a large, wide ranging species while a smaller buffer should be used for smaller species with limited home ranges.

After adding the buffer to real and random data points, the validation process is the same as *Random Points Versus Data Points,* except this method compares average, maximum, or minimum connectivity metrics within the buffered areas. Movement data can also be used in this process by comparing connectivity metrics within the recorded individuals home range versus outside the home range (Koen et al., 2014).

Withholding Test Data

Withheld data are a subset of the data used to model connectivity that are set aside for the purposes of validation. Validation with withheld test data is not explicitly a validation technique (rather sensitivity analyses; Wade et al., 2015); however, we include it here because of the inferences that can be made with withheld data. Generally, practitioners can use withheld data in any of the previous validation methods. Using withheld data ensures that the same underlying assumptions and connectivity goals are being assessed (Jarnevich et al., 2015). To be usable, withheld data need to be a subset of a dataset robust enough to adequately model connectivity and validate. Therefore, this process should only be considered if a large amount of representative, quality data are available.

Data Limitations and Considerations for Validation

Practitioners need to consider data robustness, data representativeness, and data collection techniques when choosing datasets for validation to ensure the validation is effectively representing focal species movement in the region of interest. The data used for validation need to be representative of the focal species presence or movement across the area of interest. The robustness or the amount of data needs to be substantial enough to represent the variation in the focal species land use and the spatial distribution of species movement. As mentioned earlier, the type of species data (presence, movement, genetic) and how it is collected is important to consider before it is used for validation because each data type will inform different aspects of connectivity models. Collection method is important to consider because limited scopes may bias what the data represent. For example, opportunistically collected citizen science data may be biased near major roads and parks because they are publicly accessible. This may not be fully representative of the region of interest, which limits the usefulness of the data for validation.

Validation in SCI Linkages

Various levels of validation with empirical data have been conducted for some SCI linkages. Some examples of validation conducted in SCI linkages can be found in the linkage reports of Northern Green Mountains Linkage, Green Mountains to Hudson Highlands, and Adirondacks Mountains to Green Mountains (Applin & Marx, 2014; Hawk et al., 2012; Marangelo, 2013). The Northern Green Mountain linkage team cross referenced the structural connectivity models with field data collected from the Critical Paths Project to infer functional connectivity (Hawk et al., 2012). The Green Mountains to Hudson Highlands and the Adirondack Mountains to Green Mountains linkages conducted post-hoc snow track data collection in modeled high connectivity areas to inform future decision making and ground truthing (Applin & Marx, 2014; Marangelo, 2013). The validation processes conducted throughout different linkages is a good starting point for incorporating empirical data into connectivity modelling to ensure that functional connectivity is occurring. Validating already modeled linkages provides a relatively simple way for SCI to assess functional connectivity and prioritize future mitigation measures.

Priority Setting

Define Regional Connectivity Drivers

Connectivity model outputs often appear abstract or absolute, making their contextualization necessary for useful interpretation. To effectively identify where connectivity work is most needed, practitioners should deduce the regional drivers of predicted connectivity in the landscape (Steinitz, 1994). We define regional connectivity drivers as landscape features or patterns that cause the connectivity patterns seen in connectivity model outputs. Practitioners can use analytical or visual methods to identify these regional connectivity drivers. A visual analysis of aerial land use images with the corresponding connectivity model layers can help contextualize the connectivity model patterns in the region of interest. A more analytical technique could include placing buffers around areas of predicted high or low flow and extracting the most prevalent land-use type within the buffered regions (practitioners could employ the connectivity programs PinchPoint Mapper and Barrier Mapper in ArcGIS's Linkage Mapper Toolbox to identify modelled pinch points or barriers in the landscape).

Use Linkage Map to Facilitate Local Projects and Decision Making (Step Down Process)

To conduct targeted connectivity work, practitioners need to step down broad regional linkage area maps to a scale of actionable local projects. The framework we have described to model and map connectivity at a large scale can be iterated through at project-relevant scales to ensure conservation budgets are not spent on inefficient connectivity work. Additionally, these focused iterations may allow practitioners to emphasize aspects of the framework that were not feasible at scale, such as focal species monitoring. It is worth noting that this step-down process was not absent from SCI partner work. In certain linkage areas, SCI partners conducted more localized monitoring and priority setting; however, many localized assessments did not inform specific localized conservation actions (Appendix A).

In this section, we describe general considerations for stepping down linkage areas to manageable scales, separating the process into two functional groups: stepping down to conserve or restore connectivity through land acquisition and stepping down to restore connectivity through road barrier mitigation. Each group will describe a general three step process: choosing a local area, conducting local monitoring efforts, and selecting sites for mitigation work.

Land acquisition

1. *Choose local area*

   In practicality, there are two methods to mitigate for a disconnected environment through land acquisition: conserving areas that currently allow connectivity through the landscape or restoring areas that currently act as barriers to connectivity. The value of each method depends on the landscape and conservation project in question. Below we briefly describe considerations for each method.

   Consideration 1: Conserving connectivity

   Most connectivity models predict where the focal species are likely to move within the landscape, making these model results a good starting point for local connectivity assessments. Along with simply visualizing where models predict animal movement, there are specific programs (e.g. Pinchpoint Mapper in Linkage Mapper or Normalized Cumulative Current Flow in Omniscape) that practitioners can use to identify areas that currently facilitate animal movement through the region. Practitioners can zoom-in to these areas of predicted high flow, creating a more localized region-of-interest for further connectivity analysis.

   Consideration 2: Restoring connectivity

   Parcels currently acting as barriers to movement can be acquired and restored to improve regional connectivity; however, restoring lands may come at a higher monetary cost than conserving higher-quality lands. From connectivity model outputs, practitioners can infer barriers through simple visualization of areas connectivity models avoid, or utilize programs built to identify barriers to movement (e.g. Barrier Mapper in Linkage Mapper or Normalized Cumulative Current Flow in Omniscape). Practitioners can zoom-in to these predicted barriers to identify local areas currently preventing landscape connectivity.

2. *Iterate through framework and conduct local monitoring*

   Once more local areas are targeted for land conservation, practitioners should iterate through the steps of this framework to reassess connectivity at the local management scale. This reiteration can help align local conservation goals between partners and improve connectivity models because models lose granular inferential value as their scale increases. This is particularly true of non-synoptic models. Additionally, practitioners should field-validate priority areas identified through modelling before any projects are implemented to address the possibility that a large-scale model may have incorrectly identified priority areas (commission error) or omitted important areas for connectivity (omission error). Committing either of these errors can lead to suboptimal use of limited resources. Broad considerations for monitoring are described in Part 2.

3. *Select land for acquisition*

   Although conserving the most direct connection between two core habitats may be the most effective conservation strategy to connect a landscape (Beier & Noss, 1998; Stewart et al., 2019), we understand that SCI partners acquire land or oversee easements opportunistically, and that conserving for connectivity is considered alongside other relevant conservation objectives (e.g. conserving climate refugia or preserving riparian corridors; Naiman et al., 1993; Rudnick et al., 2012). With that said, SCI partners should strive to conserve contiguous parcels rather than a spotty mosaic of parcels, since clusters of conserved lands better facilitate connectivity through a landscape than a dispersed stepping-stone arrangement (unless focal species has been shown to use stepping stones, e.g. migrating birds; Skagen et al., 1998; Stewart et al., 2019). And, through a broader conservation lens, larger conserved areas generally provide more ecological benefit and have lower management costs than sporadically conserved parcels (Armsworth et al., 2011; Burkey, 1989; Hannah, 2008).

Road barrier mitigation

There are two general methods to combat road-related movement issues: constructions that prevent all movement across the road (e.g. complete fencing, Jaeger & Fahrig, 2004) and constructions that allow safer passage across a road (e.g. over- or under-passes; Van der Ree et al., 2015). Although each carry their own ecological merit and trade-offs (either completely diminishing the population sink from road mortalities or allowing animals to move and breed across road boundaries), our discussion only pertains to projects that allow safe passage across a road.

1. *Choose local area*

   Practitioners can again use their connectivity model outputs to select road segments for localized connectivity analysis, identifying roadways that intersect areas of predicted bottlenecked flow. Studies have shown connectivity models to be relatively predictive of high animal road crossings (Koen et al., 2014; Valerio et al., 2019). Additional considerations could include: selecting a local site based on stakeholder interest or selecting a road segment based on the likelihood of government approval. Additionally, if there are known WVC hotspots, these may be good places to emphasize for conservation action.

2. *Iterate through framework and conduct local monitoring*

   Once road segments are selected for road barrier mitigation, practitioners should iterate through the steps of this framework to reassess connectivity along this road segment. Practitioners should consider including information that was previously not included into connectivity assessments, including WVC data. Considerations for monitoring initiatives that are specific to road mitigation structures are described in *Wildlife Crossing Structure Handbook Design and Evaluation in North America* by Clevenger & Huijser (2011).

3. *Select site for mitigation*

   Sites for mitigation should be selected based on the projected ecological value of a road barrier mitigation project, backing from stakeholders, and financial capabilities. Practitioners should focus on road segments that: bisect protected areas (as these will more likely contain animals looking to cross the road), have a high density of WVC, and contain infrastructure that are easily modified to permit wildlife road crossings (e.g. large culverts, long-bridges).

Ultimately, protecting land and reducing road barriers are not mutually exclusive conservation strategies. Organizations like SCI may have diverse partner expertise and management capabilities that can work synergistically. For instance, one partner limited to land acquisitions can preserve parcels bisected by a roadway, and another road-focused partner can build crossing structures along the same roadway, increasing the value of both partners' contribution. Such collaborations underscore the importance of communication and negotiation in the goal-setting and planning phases of this framework.

Climate Connectivity Considerations

Landscape connectivity allows for potential range shifts and movement along climate gradients, making connectivity projects important for future climate change resilience and species adaptation (Krosby et al., 2010; Wade et al., 2015). Thus far, the framework we describe does not explicitly address climate change; however, here we address how climate change connectivity can be addressed throughout the framework.

Conservation Goal

The identification of climate connectivity as a conservation goal will influence every step of the connectivity assessment framework (Costanza & Terando, 2019). To create actionable goals, practitioners should consider how a changing climate will affect areas at varying temporal and spatial scales, impact species idiosyncratically, and, due to political influences, only receive backing from select stakeholders or partners. Additionally, for focal species selection, practitioners should consider how sensitive a given species is to climate and land use changes and adjust connectivity assessments accordingly (Costanza & Terando, 2019; Keeley et al., 2018a).

Define Type of Connectivity

Large-scale climate connectivity assessments should focus on modeling migration and range shifts, because long-range movement patterns and species ranges are predicted to change with changing environmental conditions (Krosby et al., 2010). Daily habitat may not be a useful connectivity type to assess climate connectivity, because currently used habitat may not be suitable as climates change (Costanza and Terando 2019).

Define Resistance to movement

Larger spatial and temporal extents should be used when modeling climate connectivity to capture a larger diversity of projected changes including climate analogs and refugia. These larger extents should be used throughout the connectivity framework including in the evaluation of resistance values. When defining the resistance to movement with climate change, it is important to consider what environmental variables to use in each resource selection function. Each environmental variable chosen should attempt to capture changes in climate, land use, and habitat quality to provide resistance values that represent the future movement patterns of the focal species (Costanza and Terando, 2019; Keeley et al., 2018a; Wade et al., 2015). For example, species such as wolverines and martens are particularly sensitive to snow pack levels so it is important to include projections of snowpack levels within climate connectivity assessments (McKelvey et al., 2011). To determine the values of environmental variables under climate change (e.g. projected temperature, projected snowpack, projected precipitation etc.), various climate projections should be used to capture the range of potential change, including extreme and conservative projections. It is also important to consider how the resource selection model parameters or resistance should be adjusted to reflect movement under climate change. For example, species are likely to relocate to higher elevations with climate change because of the climate gradient associated with topography and such movements should be modelled with lower resistance values. (Keeley et al. 2018a).

Defining What is Being Connected/Modeling Connectivity/Mapping Linkage

When determining what should be connected, modelled, and mapped, practitioners must evaluate whether the areas being assessed are still likely to provide connectivity for the focal species under climate change. If core areas are being used, they should be chosen based on future climate projections (Wade et al., 2015). Core areas for climate connectivity should be projected future habitat, climate analogs of current habitat, or climate refugia for the focal species (Keeley et al. 2018a; Costanza and Terando 2019). When modeling climate connectivity, model parameters should be adjusted to reflect future climate such as focusing connectivity assessment on northward movement based on the projected northward movement of species (Keeley et al. 2018b). Connectivity modeling programs have been developed to take into account climate change including two add-ons to Linkage Mapper in ArcMap: Climate Linkage Mapper and Linkage Priority as well as an extension of Circuitscape called Gflow that includes climate analogs and climate gradients (Keeley et al. 2018a). Once climate connectivity is modelled, climate should be considered in the mapping of the linkage boundaries by including a diversity of habitat types, future climate projection, and climate refugia to give species the best chance at adapting to changes. The need to capture a larger variety of sites means the linkage boundaries should err on the side of being broader (Costanza and Terando 2019).

Validate Linkage

Validation of climate connectivity models is difficult because current species data may not represent future habitat preferences or movement patterns. Therefore, we consider it generally inappropriate to validate climate connectivity models created using future climate or land use projections with current species data.

Priority Setting

After running climate connectivity assessments, practitioners should prioritize areas that are projected to be important for connectivity under climate change for connectivity improvements and conservation action. It is important to consider changes in climate and land use to ensure that limited resources are directed towards projects with long term benefits to connectivity (Keeley et al. 2018a, Costanza and Terando 2019). A diversity of prioritization methods, mitigation projects, and climate projections improve the probability of actions being effective under climate change. These actions can include connecting sites that are projected to be climate analogs, climate refugia, connecting climate gradients, and protecting a diversity of habitats and projected climates (Costanza and Terando 2019; Keeley 2018b). It is also important to consider how species will move as the climate changes by identifying intermediate "stepping stone" habitat and sites of climate refugia that provide easier movement as the climate changes (Keeley et al. 2018a).

Since climate change projections and land use changes are constantly changing, it is important to continue to reevaluate connectivity assessments and linkage creation to ensure that potential linkages remain robust and effective with the changing world.

Part 2 - Monitoring Considerations

Practitioners can use empirically collected species data within this framework to: more accurately parameterize resistance-based models (compared to expert opinion; (Seoane et al., 2005; Zeller et al., 2012), validate the untested hypothesis of connectivity model outputs (Wade et al., 2015), and motivate funding and support for conservation projects (Keeley et al., 2018b). However, for empirical data to accurately inform sections of the framework, practitioners need to be meticulous and thoughtful in their data collection. Here we outline general best practices and considerations for the collection of species data through various monitoring methods that can be integrated into the broader framework we outline above. We preface this section by acknowledging that these guidelines will not uniformly apply to all monitoring programs and should not be used as more than initial considerations for monitoring program design.

Establish Monitoring Objectives

Practitioners must decide what a monitoring effort is intended to inform at the onset of a monitoring program. Clearly defined monitoring objectives ensure monitoring efforts address the most relevant issues and make optimal use of limited funding and resources. Also, well-articulated objectives make it easier to select appropriate response variables and focal species and determine the appropriate spatial and temporal scale for monitoring. The overall conservation goals of a connectivity project and the specific goals of a conservation action should inform the monitoring objectives (see "Determine Conservation Goals" and "Define Type of Connectivity to be Modelled" in the framework in Part 1, and "Priority Setting" in the framework in Part 1).

Select Focal Species for Monitoring

Practitioners should consider which focal species to monitor based on the goals of a particular corridor or a specific conservation intervention to restore connectivity. When selecting focal species to monitor, it is important to consider which species are most likely to provide a robust enough dataset to perform analyses and inform management decisions. Furthermore, it is beneficial to identify which focal species are the best indicators of changes relevant to the corridor or conservation project goal (Clevenger & Huijser, 2011). The focal species for monitoring will often be the same as the focal species used for modelling but this decision is dependent upon what monitoring is intended to inform.

Determine Availability of Existing Data

To save conservation resources, practitioners should determine if there are readily available, useful field data on the selected focal species in the region of interest. These data may be applied to various sections of the framework, including resistance layer creation and model validation, depending on their collection techniques, spatial scale and temporal scale. Recommended sources for data include: Movebank, GBIF, state or federal wildlife agencies, and academic researchers.

Determine Resource Availability to Conduct Monitoring

Monitoring plan design is contingent on the resources available to conduct a monitoring program. Therefore, conservation organizations should assess the availability of financial resources, technological resources, and staff time for monitoring. Additionally, practitioners should consider how to effectively leverage available resources to achieve monitoring objectives. In this step, it can be valuable to consider whether partners and stakeholders could assist with monitoring over large spatial or temporal scales. One option could be the establishment of a citizen science program in which community members assist with data collection. We describe which data collection methods may be most suitable for engaging citizen scientists in the “Potential for Citizen Scientist Participation” column of Table 5.

Determine Questions to be Addressed by Monitoring

Based on the monitoring objectives established, specific questions should be formulated that monitoring is intended to inform. Example questions may be “Does this corridor allow animals to disperse from one patch to another?” or “Is roadkill decreasing following the installation of a road overpass?”. At this step, specific thresholds or benchmarks may be defined that trigger management actions or indicate the success or failure of a corridor based on a specific movement goal (Clevenger & Huijser, 2011). For example, if a road mitigation measure results in less than a 40% reduction in roadkill based on baseline conditions, this could suggest that additional actions are needed (Clevenger & Huijser, 2011). Typically, a power analysis is needed to assess whether certain benchmarks can be reasonably detected by monitoring efforts (Clevenger & Huijser, 2011). Power analyses allow researchers to determine the minimum necessarily sample size given an expected effect size.

Select Response Variables and Determine Appropriate Monitoring Frequency

Response variables should be selected that correspond to the specific monitoring objectives and the overall goals of the corridor or conservation intervention. Example response variables include individual movement, animal presence in a corridor, gene flow, and patch occupancy (Gregory & Beier, 2014). Specific types of responses, for example movement of individuals from patch to patch, can be used to answer the questions posed in the previous step (Gregory & Beier, 2014). Once appropriate response variables are selected, practitioners should decide whether detection, relocation, genetic, or movement data would be the most appropriate to capture the relevant type of response. This decision, combined with an assessment of available resources, can be used to decide which monitoring technique would be most appropriate to address the monitoring objectives. Monitoring data types and methods are outlined in Table 3. Additional details and an evaluation of the specific data collection methods can be found in the conclusion of Part 2 in Table 5.

Table 3. Types of empirical species data. Additional details about data collection methods located in Table 5.

Data Type	**Description of Data Type**	**Collection Methods**	**Key Strengths**	**Key Limitations**
Detection	Detection data refer to single point locations for unidentified individuals. Detection data can take the form of presence-only data or presence-absence data. The data types differ because true absences cannot be assumed in presence-only data whereas absences can be inferred from presence-absence data (Zeller et al., 2012).	1. Camera traps 2. Scat dog 3. Track pads 4. Snow tracks 5. Sightings 6. Bait & Trap 7. Vocalizations 8. Mist nets 9. Telemetry 10.Hair snares	Often the least expensive data to collect and most readily available data type	These data do not give information about specific movement paths
Relocation	Sequential locations of the same individual that are not frequent enough to infer a pathway between them (Zeller et al., 2012).	1. Mark recapture 2. Mist Nets	These data can be used to find movement speeds, homing rates, dispersal rates, etc. between patches (Zeller et al., 2012)	Movement paths between patches must be inferred
Genetic	This type of data refers to genetic material (hair, tissue, eDNA) collected at multiple locations. This data is used to infer rates of gene flow between individuals or populations and then calculate genetic distance accordingly. These measures of genetic distance are then compared to geographic distance (Wade et al., 2015).	1. eDNA 2. Tissue Samples 3. Hair Snares 4. Scat	Requires assigning individuals to separate populations even if population is even distributed (Zeller et al., 2012)	Individual resistance to movement is not directly measured. Estimates of gene flow may not reflect the current landscape
Movement	Pathway data describes at least two sequential locations of the same individual that are tracked frequently enough to regard the data as a movement pathway (Zeller et al., 2012). This particular type of data requires attaching GPS technology onto an animal.	1. Telemetry	Captures actual paths of animal movement.	There is no consensus on how frequent is frequent enough to interpret movement points as a pathway as movement rates are species dependent (Zeller et al., 2012). Can be costly and impractical to put GPS collars on species.

Gregory and Beier (2014) outline common goals of conservation corridors and the response variables that could be used to assess whether the corridor is meeting the stated goal. The goals largely parallel the different types of functional connectivity described in *Define Type of Connectivity to be Modelled* of the framework outlined in part 1. The table below summarizes the potential corridor goals and response variables described by Gregory and Beier (2014).

Table 4. Response variables to evaluate corridor success. Table adapted from Gregory & Beier, 2014.

Conservation Corridor Goal	**Potential Response Variable**	**Type of Response that Indicates the Corridor is Effective**
Provide access to resources in two or more patches within a species' home range	Individual Movement	Movement between patches through the corridor
Maintain seasonal migration	Individual Movement	Movement between seasonal habitats through the corridor
Restore gene flow between patches	Gene Flow	See Gregory & Beier (2014) for information about corridor success index
Facilitate demographic rescue of isolated population	Patch occupancy	Greater occupancy within connected patches relative to isolated patches
	Gene Flow	See Gregory & Beier (2014) for information about corridor success index
	Individual Movement and Reproduction	Movement between patches through the corridor followed by reproduction in isolated patch
Facilitate patch recolonization after extirpation	Individual Movement	Movement between patches through the corridor
	Patch Occupancy	Greater occupancy rate within connected patches relative to isolated patches
	Gene Flow	Genetic samples suggest patch was recolonized by individuals from a separate patch connected via a corridor
Facilitate climate or disturbance-induced range shifts	Range shift	Range expansion occurs through the corridor during periods of environmental disturbance

Focal Species Biology Considerations

With the selection of response variables, it is critical to consider the intersection between the variable of interest, the desired goal, and the biology of focal species. These considerations can help inform the appropriate spatial and temporal scale for monitoring. For instance, monitoring efforts must occur over periods when rare movements, such as dispersal or migration, are occurring if these movements are relevant to the goal of the corridor (Beier & Loe, 1992). Considering species biology can also help inform which individuals of a species are most important to monitor. For example, if juvenile males of a particular species are known to be the individuals within a population to disperse, then GPS collaring should be careful to collar some juvenile males if dispersal is relevant to the goals of the corridor. At this step, it is critical to compile any relevant information about focal species biology if this information is not already known. Such information may include average home range, relevance of annual or seasonal migration, length of generation, lifespan, life cycle and sex associated with dispersal, and dispersal distance.

Design and Implement Monitoring Plan

Study Design

Practitioners must decide on a study design if monitoring is intended to measure performance or impact of a corridor or conservation intervention. A brief description of some study design options is outlined below in order of their inferential strength. Additional literature should be referenced before implementing any of the following study designs:

> **BACI -** This particular study consists of comparing impacted sites (I) with control sites (C) and evaluating how a variable of interest changes before (B) and after (A) a conservation action, such as connectivity barrier mitigation, is implemented (Stewart-Oaten et al., 1986).
>
> **BA -** This study design consists of sampling one site and assessing how a variable of interest responds before (B) and after (A) the impact of a conservation project, such as road barrier mitigation. This study design does not rule out the possibility that an observed difference between sites may have been caused by another variable than the conservation intervention (Clevenger & Huijser, 2011).
>
> **CI -** This study design consists of a comparison of impact (I) sites with control (C) sites. Data are only collected after a conservation project has been implemented (Clevenger & Huijser, 2011).

Establish Baseline Conditions (if relevant based on study design)

In this step, practitioners should measure relevant variables prior to the construction of a corridor or a conservation project. Depending on how the monitoring program is designed, these conditions will typically comprise the control or baseline for the monitoring study (Clevenger & Huijser, 2011). The relevant variables to measure at this step will vary widely depending upon what monitoring is intended to measure.

Identify Control and Treatment Areas (if relevant based on study design)

Practitioners must be careful to ensure that environmental conditions are similar in both control and treatment areas to reduce the potential influence of confounding variables. Factors such as habitat type, method of data collection, sampling intensity, and baseline population abundances ideally should be similar across sites (Clevenger & Huijser, 2011). Alternatively, any differences between control and treatment sites should be explicitly noted and controlled for in the analysis and interpretation of monitoring results.

Evaluate and Refine Conservation Goals and Monitoring Strategy

Practitioners should use the information collected through monitoring to inform and refine conservation goals and future monitoring objectives. Monitoring can be a useful strategy to evaluate the efficacy of corridors and conservation projects over time and adapt strategies to make future corridors and conservation projects more effective. Once the results of a monitoring program are interpreted, we recommend following through the framework described in Part 1 again with conservation goals and modelling objectives rooted in the findings of initial monitoring. Ideally, the data collected as part of the monitoring program will be suitable for use in the calibration and validation of connectivity models described in the Part 1 framework. Considerations for whether data are appropriate to use in this context is outlined in Part 1 and the discussion section.

Table 5. Summary of empirical species data collection methods. These data types and collection methods were selected based on their potential to provide insights about habitat connectivity.

Data Type	Data Collection Method	Relative Cost (Highest Cost Aspect)	Data Robustness	Strengths	Limitations	Potential for Citizen Scientist Participation	Resources
Detection	Camera Traps	Labor - camera deployment and photo sorting	**Spatial Scale:** Small, typically focused on a single feature **Temporal Scale:** Dependent on study	1. Captures multiple species 2. Captures species at the actual time of the survey 3. Efficient for rapid inventory assessments	1. Camera failure 2. Samples a single point 3. Rely on lures or opportunistic detection 4. Laborious photo processing 5. Limited detection of small species	Citizen scientists may be able to assist with sorting camera trap photos, particularly if focal species are easily identified.	Long et al., 2007; Rafferty et al., 2016; Tobler et al., 2008
	Scat dog	Dogs & Training: Major costs coming from leasing the dog and training a handler for the dog. A dog can also be purchased if it is going to be used often	**Spatial Scale**: Can survey an area of 22ha in a single visit. **Temporal Scale:** Impossible to tell when the animal of interest was at the site.	1. Can detect the presence of elusive animals 2. Mitigates bias of other detection methods that use baits and lures 3. A site can be surveyed in a single visit	1. Does not capture the actual time of species presence 2. A false positive can be identified if animals with similar scat are in the same region.	Specialized training required for dogs and handlers. Not appropriate for citizen scientists.	Long et al., 2007a, 2007b

Data Type	Data Collection Method	Relative Cost (Highest Cost Aspect)	Data Robustness	Strengths	Limitations	Potential for Citizen Scientist Participation	Resources
	Tracks	Labor - time of the person doing the survey. minor cost - track plates	**Spatial Scale:** Can cover the range of the species habitat **Temporal Scale:** Survey can capture the time of species presence. Depends on how frequently tracks are surveyed	1. Can detect the presence of elusive animals 2. Baited track pads can bring in a large number of animals	1. Difficulty in identification of old and similar tracks 2. Does not capture the time of animal presence 3. The ground may not be suitable for leaving tracks	Specialized training is needed to identify similar tracks. Citizen scientist may be able to assist with capturing the track (e.g. via track pad or photograph)	Bull et al., 1992; Evans et al., 2009; Zielinski & Kucera, 1995
	Traps (i.e. mark recapture, banding, mist netting)	Labor- trap deployment, checking, and processing	**Spatial Scale:** Dependent on study **Temporal Scale:** Dependent on study	1. Individual identification 2. Can tag individual animals to assess movement overtime	1. Only effective for some species (i.e. small species) 2. Difficult to extrapolate movement 3. Labor Intensive 4. Potential negative effect on individual animals	Handling and trapping wildlife often requires specialized training and licensure. Not appropriate for citizen scientists.	Clevenger and Huijser, 2011
Movement	GPS Collars	High upfront cost to purchase collars and tag individuals. Cost is dependent on species of interest	**Spatial Scale:** Spatial scale is determined by the movements of individual species. **Temporal Scale:** Dependent on the study and battery life of collar	1. Captures actual movement paths of individuals 2. High resolution movement data	1. Small sample size 2. Data may be skewed by idiosyncratic behavior. 3. Labor intensive	Attaching GPS collars to wildlife requires training. Not appropriate for citizen scientists.	Chetkiewicz & Boyce, 2009; LaPoint et al., 2013; Squires et al., 2013; Wattles et al., 2018a, 2018b

Data Type	**Data Collection Method**	**Relative Cost (Highest Cost Aspect)**	**Data Robustness**	**Strengths**	**Limitations**	**Potential for Citizen Scientist Participation**	**Resources**
Roadkill	Roadkill/ Wildlife-Vehicle Collisions	Little to none because usually collected by Department of Transportation Agencies or Citizen Science groups	**Spatial scale:** Usually by state **Temporal scale:** Dependent on state records - often multiple decades for major roads and wildlife	1. Can infer movement 2. Publicly available 3. Opportunities for genetic samples 4. Road mitigation prioritization 5. Informs human and wildlife safety	1. Only capturing individuals that are getting hit (i.e. unsuccessful movement) 2. Sampling only biased around highly human influenced areas such as roads	Citizen scientists may be able to report locations of roadkill	Olson et al., 2014; Shilling et al., 2015; *UC Davis Road Ecology Center*, 2019; Vercayie & Herremans, 2015
Genetic	eDNA	Lab DNA Tests - high initial investment, cost-effective overtime	**Spatial scale:** Dependent on study design **Temporal scale:** Dependent on study design	1. Non-invasive 2. Species-specific detection 3. Easy to standardize	1. False Negatives: Non-detection does not imply absence 2. False Positives: Detection does not always mean presence due to transport 3. Detection rates and detection efficiency need to improve 4. Standardization of methodology is challenging	Genetic material requires professional processing. Citizen scientists may be able to collect genetic samples from hare snares or hunting specimens.	Rees et al., 2014; Roussel et al., 2015; Ruppert et al., 2019; Thomsen & Willerslev, 2015

Data Type	Data Collection Method	Relative Cost (Highest Cost Aspect)	Data Robustness	Strengths	Limitations	Potential for Citizen Scientist Participation	Resources
	Tissue Samples	Sample Storage and Lab DNA Processing	**Spatial scale:** Dependent on study design **Temporal scale:** Capturing individual genetics, population movement, or historic genetic movement	1. Data on animal presence and DNA sample 2. Identifies individuals	1. Species specific 2. Lab analysis and processing require expertise or expensive lab tests	Genetic material requires professional processing. Citizen scientists may be able to help with tissue collection by reporting the locations of road kill and/or collecting samples from hunting specimens.	Hebert & Gregory, 2005; Hedgecock et al., 2007; Lowe & Allendorf, 2010

Part 3 - Mohawk Valley Connectivity Analysis

We illustrate our framework through a case study in the Mohawk Valley in eastern New York State. This is the location of a new SCI linkage area located between the Catskill Mountains and Adirondack Mountains (Figure 7). Improving and maintaining connectivity within the Mohawk Valley can assist animals' northward migration due to climate change by connecting the NAPA region to the Central Appalachians via the Kittatinny Ridge (Dirk Bryant, personal communications). Our case study culminates in a preliminary linkage area and recommendations for future action in the region. Future connectivity work in the Mohawk Valley Linkage Area will be spearheaded by TNC-Adirondack Chapter and the MHLC.

The Mohawk Valley consists of a patchwork of agricultural lands, forests, and urban and suburban development. The suspected largest barriers to connectivity in the region are clustered urban centers, Interstate 90 (connecting Albany to Buffalo), the Erie Canal adjacent to Interstate 90, and Interstate 88 (connecting Schenectady to Binghamton). Preliminary field assessments by SCI partners have identified two areas where Interstate 90 is potentially permeable to wildlife movement: Glenville Hill, between Schenectady and Amsterdam in the eastern portion of the linkage, and an area known locally as "The Noses" in the western portion of the linkage. In both of these areas, there are large Interstate underpasses that may be permeable to animal movement, or may become permeable with modification (Dirk Bryant, personal communication).

Within the Mohawk Valley, the Mohawk Hudson Land Conservancy (MHLC) has protected over 12,000 acres of land. MHLC's mission is to "enhance the quality of life in the Mohawk and Hudson River valleys by preserving natural, scenic, agricultural and historic landscapes, and conserving habitats, in partnership with landowners, not-for-profit organizations, businesses, and governments for the benefit of current and future generations." (Mohawk Hudson Land Conservancy: The Capital Region's Land Trust, 2020). MHLC is interested in connecting their work to the broader NAPA ecoregion to create collective impact with their conservation areas. As a member of SCI and a key stakeholder in the Mohawk Valley, MHLC will be the lead entity of the new SCI Mohawk Valley Linkage area. TNC, a long-standing SCI partner, is interested in complementing MHLC's connectivity work across the Mohawk Valley by retrofitting existing infrastructure, namely culverts, to better provide safe passage for animals crossing Mohawk Valley roads.

Methods and Results

Define Conservation Goals and Communicate with Stakeholders

To help guide the definition of conservation goals, we spoke with Sarah Walsh, Conservation Director of MHLC, about the priorities and interests of MHLC in the region. As a land trust, MHLC works to preserve landscapes through land acquisition and conservation actions. MHLC is interested in setting priorities for conservation at the local scale, so that connectivity can be improved at the landscape scale within the linkage area. MHLC identified three focal species to assess in a linkage analysis between the Adirondacks Mountains and the Catskill Mountains: black bears (*Ursus americanus*), bobcats (*Lynx rufus*), and fishers (*Pekania pennanti*). These three species were selected because they are wide-ranging carnivores that represent a range of habitat preferences and movement patterns (Tear et al., 2006). We applied the priorities and interests of MHLC throughout our application of the framework. MHLC is actively engaged with key community stakeholders and conservation partners, and communicated their intentions to magnify their conservation impact through their partnership with SCI.

Define Type of Connectivity to be Modelled

This analysis models connectivity for demographic movements and daily habitat movements for the three target species: fishers, black bears, and bobcats. We modelled connectivity for demographic movement to ensure that animals can disperse throughout the Mohawk Valley landscape and between the habitat cores of the Adirondack Mountains and Catskill Mountains. This is of particular importance as animals shift their ranges into higher latitudes in response to climate change, including moving north from the Catskill Mountains to the Adirondack Mountains (Lawler et al., 2013). Note that we did not include future climates or climate-driven habitat displacements in any of our models. TNC analysts in other areas have begun to explicitly account for linkages that confer more climate resilience (e.g., Schloss et al., 2012).

In addition to modelling connectivity for demographic movements, we also modelled connectivity at a local scale to predict species daily habitat movements within their home range, since animals living inside the linkage need to maintain access to resource patches within their home range.

Determine Availability of Empirical Species Data

To obtain the empirical species data for the linkage area case study, we contacted several SCI partners with known research projects in the NAPA region and explored online repositories for publicly-available data. While partners and PIs were supportive of our efforts, most were unable or unwilling to share their data within our project timeline. Ultimately, we utilized publicly available datasets and one non-publicly available detection dataset for the three focal species: fishers, black bears, and bobcats (Appendix B, Table 1).

The fisher detection data came from research-grade observations (e.g. observations with photos) submitted to the citizen science data collection application iNaturalist (*GBIF Occurrence Download*, 2019), camera trap observations from Albany Area Camera Trapping Project (LaPoint et al., 2013; *Martes pennanti LaPoint New York-reference data*, 2013), and the Albany-based Lisha Kill Preserve Fisher Study (Daniel Winters, personal communication). These points were located throughout the NAPA region; however, primarily located in Vermont, Massachusetts, and the Albany region (Figure 7). The bear and bobcat detection data were from iNaturalist through the GBIF server. The bear and bobcat points are also spatially distributed across the NAPA region. We used detection data in this case study because it was the most widely available for the focal species.

The species detection data we obtained were limited by the availability of data sources and their spatial spread across the region. The detection data from citizen science sources and Albany-based data collection projects are not representative of the potential Adirondacks to Catskills linkage area. Most of the data points are clumped around the city of Albany or were outside of the linkage region in other states, including Vermont and Massachusetts. This resulted in a spatially unrepresentative data sample that did not accurately capture animal movement across the region of interest. Another limitation of the citizen science data from iNaturalist is that some of the location data were imprecise, reducing the robustness of the dataset. In our analysis we used the detection points that were at 1 km precision or lower to ensure that the data accurately corresponded to locations environmental variables reducing the number of detection points that were usable. The collection methods of the data also resulted in data biases. The nature of citizen science data (i.e. iNaturalist) results in observations collected only in areas with public access, therefore skewing the data towards roads, public parks, and hiking trails. The fisher camera traps were placed in targeted fisher habitat to determine presence, limiting the potential for detection points in unexpected locations. To remove bias from over-sampling, camera trap observations were reduced so that each camera location that detected fishers only corresponded with one fisher observation, not several. Given their territoriality and the corresponding GPS collar data, we assumed that each camera was collecting images of only one fisher during the study (Allen et al., 1983; LaPoint et al., 2013). We did not account for territory overlap because that was beyond the scope of our analysis. These limitations and biases restricted the robustness of the analysis we could conduct in the Adirondack to Catskills potential linkage area using detection data alone.

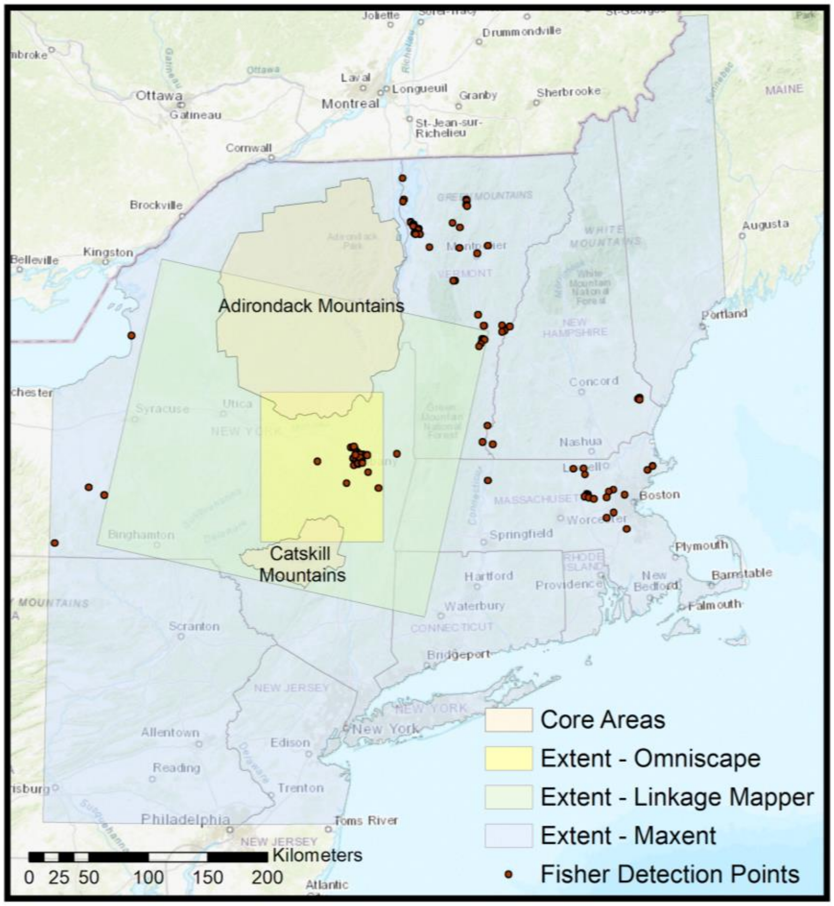


Figure 7. Analysis processing extents and fisher detection points. The Maxent species distribution model extent was applied to all Maxent environmental layers and the fisher detection points. The expert opinion habitat suitability models and Linkage Mapper analyses were run in the green extent. Habitat suitability rasters and the source layer were clipped to the yellow extent for the Omniscape analysis.

Define Resistance to Movement

The resistance to movement for the focal species was defined using two methods: species distribution modeling based on detection data (fishers only) and species-specific habitat suitability modeling based on expert opinion habitat suitability scores. We only conducted species distribution modelling for fishers, as the fisher detection data was the only data set robust enough to use in modelling. Species-specific modelling based on expert habitat ratings was conducted for all three target species. Processing extents for each analysis are shown in Figure 7.

Species Distribution Model

The species distribution model was created for fishers with the maximum entropy (Maxent) modeling method with fisher observations with location precision of one kilometer or less and environmental variable layers (Phillips et al., 2006; Appendix B, Table 2). Environmental layers were drawn from the 2016 National Land Cover Database (NLCD) land cover classes (Appendix C, Figure 1), elevation and slope layers derived from USGS 1 arc-second, Digital

Elevation Model (DEM) data (Appendix c, Figures 2 and 3), and BioClim precipitation and temperature data (Appendix B, Table 2). Fishers inhabit dense coniferous and mixed forests with high canopy closure which are represented by the land cover and precipitation layers (Allen et al., 1983; Zielinski et al., 2004). Forested areas with higher precipitation will presumably have increased vegetation growth. Slope and temperature data were included in the Maxent model because Davis et al. (2007) demonstrated that topographic relief, forest structure, and mean annual precipitation predicted fisher presence in California. Since fishers are limited by deep snowpack because they are unable to effectively forage, BioClim precipitation data from the wettest month (BIO13), wettest quarter (BIO16), and coldest quarter (BIO19), and temperature data from coldest month (BIO6), wettest quarter (BIO8), and coldest quarter (BIO11) were used as a proxy for snowpack depth (Jensen & Humphries, 2019; Krohn, 1995).

Maxent (version 3.3.3; Philips et al., 2017) was run with fisher detection data twice: once including all environmental variables and once only including NLCD land cover data. The modeled fisher distribution from all the environmental layers was heavily skewed towards areas surrounding the detection points (Appendix D, Figure 1). Though several variables that measure the same aspect of the environment (e.g. precipitation, temperature, topography) were used in the model and Maxent is able to handle correlated variables, the model does require an unbiased sample of species data (Elith et al., 2011). The detection data were clustered around a few areas and the Maxent output yielded an unrealistic representation of known fisher habitat. Therefore, Maxent was then run with only the NLCD layer. The modeled fisher distribution appeared more representative of known fisher habitat requirements (Appendix D, Figure 2). The Maxent model based only on NLCD had a better model fit (AUC = 0.706) than the model based on all layers (AUC = 0.953) (Appendix D, Figure 3). The difference in AUC values between the models suggests that the all-layer model overestimated fisher presence around the detection points and underestimated presence throughout the modeled region (Merow et al., 2013).

The all-layer and NLCD-only Maxent outputs were inverted to create resistance layers used in subsequent connectivity analyses (Appendix F, Figures 1 and 2). Resistance layers from both the Maxent species distribution model and the expert opinion habitat suitability model were generated with the expression:

$$((\mathit{SuitabilityRaster} - (\mathit{Maximum\ value})) \times (-1) + (\mathit{Minimum\ value}))$$

Habitat Suitability Model

Habitat suitability models were created for each species using resistance values for 2016 NLCD land cover classes based on two different wildlife connectivity analyses. Values were derived from expert opinion assessments for the Nature Conservancy Canada Chignecto Isthmus linkage report (Nussey & Noseworthy, 2018; Appendix E, Table 1) and the TNC Green Mountains to Adirondacks linkage report (Tear et al., 2006; Appendix E, Table 2). The resistance values from the Chignecto Isthmus report were derived from a habitat suitability matrix that scored multiple forest and land cover types with a value of 100 signifying the most suitable habitat (Nussey & Noseworthy, 2018). The resistance values from the Green

Mountains to Adirondacks report assessed land cover in terms of cover suitability and hardness of barriers on a scale of one to 10 with a value of 10 representing the most suitable habitat or impenetrable barrier, respectively. The land cover classification categories in the linkage reports did not cleanly match the NLCD land cover classes, so the resistance values were applied to analogous classes from the linkage reports.

The habitat suitability models included additional road resistance values, between 50 and 1000, that were added to the NLCD layer (Nogeire et al., 2015; Appendix E, Table 3). Five resistance rasters with varying road resistance values were developed, to test the sensitivity of the connectivity assessment to small changes in resistance values (Table 6). The first iteration was run for each species with the resistance values for each of the linkage areas without an additional roads layer. The second iteration combined resistance values from the Chignecto Isthmus and the moderate (resistance values of 50-100) additional roads layer. The next iteration combined resistance values from the Green Mountains to Adirondacks and the moderate (resistance values of 50-100) additional roads layer. The final iterations combined the resistance from the respective NLCD layers and extreme road values (resistance values of 1000).

Table 6. Habitat suitability sensitivity analysis iterations.

Run	**NLCD Resistance Source**	**Species**	**Additional Road Resistance**	**Appendix F Figure**
1	Nussey & Noseworthy, 2018; Tear et al., 2006	Fisher, Bobcat, Bear	None	*Not included*
2	Nussey & Noseworthy, 2018	Fisher	Moderate (50-100)	Figure 3
2	Nussey & Noseworthy, 2018	Bobcat	Moderate (50-100)	Figure 4
2	Nussey & Noseworthy, 2018	Bear	Moderate (50-100)	Figure 5
3	Nussey & Noseworthy, 2018	Fisher	Extreme (1000)	Figure 6
4	Tear et al., 2006	Fisher	Moderate (50-100)	Figure 7
5	Tear et al., 2006	Fisher	Extreme (1000)	Figure 8

Each of the resistance rasters were different enough that the mapped connectivity changed when resistance values were adjusted (Appendix F, Figure 9). The rest of the connectivity analysis centered around the resistance values from Run 2 with resistance values from the Chignecto Isthmus with moderate road values because the underlying layer appeared to most realistically predict how easily each species would move through the landscape. Though the resistance values from the Green Mountains to Adirondacks were applied to a spatial extent closer to the Mohawk Valley, the resistance value crosswalk process was more complex than that for the Chignecto Isthmus. The iterations that included extreme road values shifted the range of resistance values such that the nuance to land cover change across the landscape was lost. While roads are certainly a large barrier, these extreme values were unnecessary in further analysis.

Define What is Being Connected and Model Connectivity

We ran two different connectivity models, one using a termini-based model to predict how animals might move directly between the Catskill and Adirondack Mountains, and one that took a synoptic view of the landscape to predict how animals use the habitat for daily movements.

The Linkage Mapper tool in ArcGIS (Cost-Weighted Distance model; *ArcGIS*, 2019 version 10.7.1; *Linkage Mapper Connectivity Analysis Software*, 2019 version 2.0.0) was used to predict species dispersal across the Mohawk Valley. We assigned the Adirondack and the Catskill Mountains as core area termini. Core area polygons were drawn based on polygons from federal and state protected areas (Appendix B, Table 3; McRae et al. 2016b). Linkage Mapper runs were conducted with resistance layers created from Maxent habitat suitability models using fisher detection points and expert opinion-based resistance values for all three focal species. Maxent-based fisher resistance layers were not used for the rest of the linkage creation process because the Linkage Mapper result showed similar connectivity trends to the expert opinion models, but was more generalized (Appendix F, Figure 9). It showed direct, straight-line paths between core areas, whereas the expert opinion models produced a more detailed prediction of movement probability through the region. Though the resistance layers for the Maxent and expert opinion models appeared similar, the corridors predicted by the expert opinion models were more detailed, therefore more useful in making concrete land management decisions.

Omniscape, a circuit theory-based moving window analysis, was used to assess connectivity for all three species within a set window size, using expert opinion-based resistance layers (Landau, 2019/2020; McRae, Hall, et al., 2016). Set at 5.4 km, the window radius encompasses what could be considered daily habitat use movements, but not longer dispersal movements. Moving window analysis such as Omniscape can assess connectivity across a region, but does not require the distinction of core areas. Omniscape also requires an inputted source layer, which we defined as a binary layer, where any natural land cover type received a source value of 1, and non-natural land cover received a source value of 0. We assigned these source values as these species are generally considered human-averse and prefer more natural environments (Long et al., 2011). Resistance and source rasters were aggregated to 90-meter cell size, maintaining the maximum cell value underlying the 90m cell. Additionally, we set the block size–a computational shortcut–to five cells wide. Omniscape outputs include a cumulative current map, a regional flow potential map (a rerun of the analysis with all resistances having a value of one), and a normalized cumulative current map (the result of dividing the cumulative current by flow potential; McRae et al., 2016a).

To assess potential corridors that would encompass habitat requirements for all three focal species, Linkage Mapper and Omniscape were run on the resistance values derived from Nussey and Noseworthy (2018) with the additional moderate roads layer (Run 2). The corridors predicted by Linkage Mapper exhibited similar patterns for all three species (Figure

8). Predicted movement for bears and bobcats followed a narrower corridor than movement for fishers. The bear corridor incorporated a small side branch to the east between Schenectady and Albany. The bobcat corridor had a similar, but larger, side branch to the west through a mosaic of agricultural areas. The fisher corridor appears progressively limited by the network of roads and rivers throughout the region. The Omniscape cumulative current output for bears and bobcats were remarkably similar, showing high current flow through natural areas and low flow through developed areas. Since fishers are more specialized in their habitat requirements, the areas of high current flow are more pronounced (Allen et al., 1983). The overlap between the predicted corridors and current flow maps for all focal species can guide the development of linkage area boundaries that will simultaneously address a range of habitat needs and focus management resources to appropriate locations. When assessing potential linkage areas with resistance raster-based tools such as Linkage Mapper, the resistance value placed on each cell can drastically alter the location of potential boundaries (Appendix F, Figure 9). Combining outputs for a suite of species yields a more comprehensive and unbiased view of a landscape's management potential.

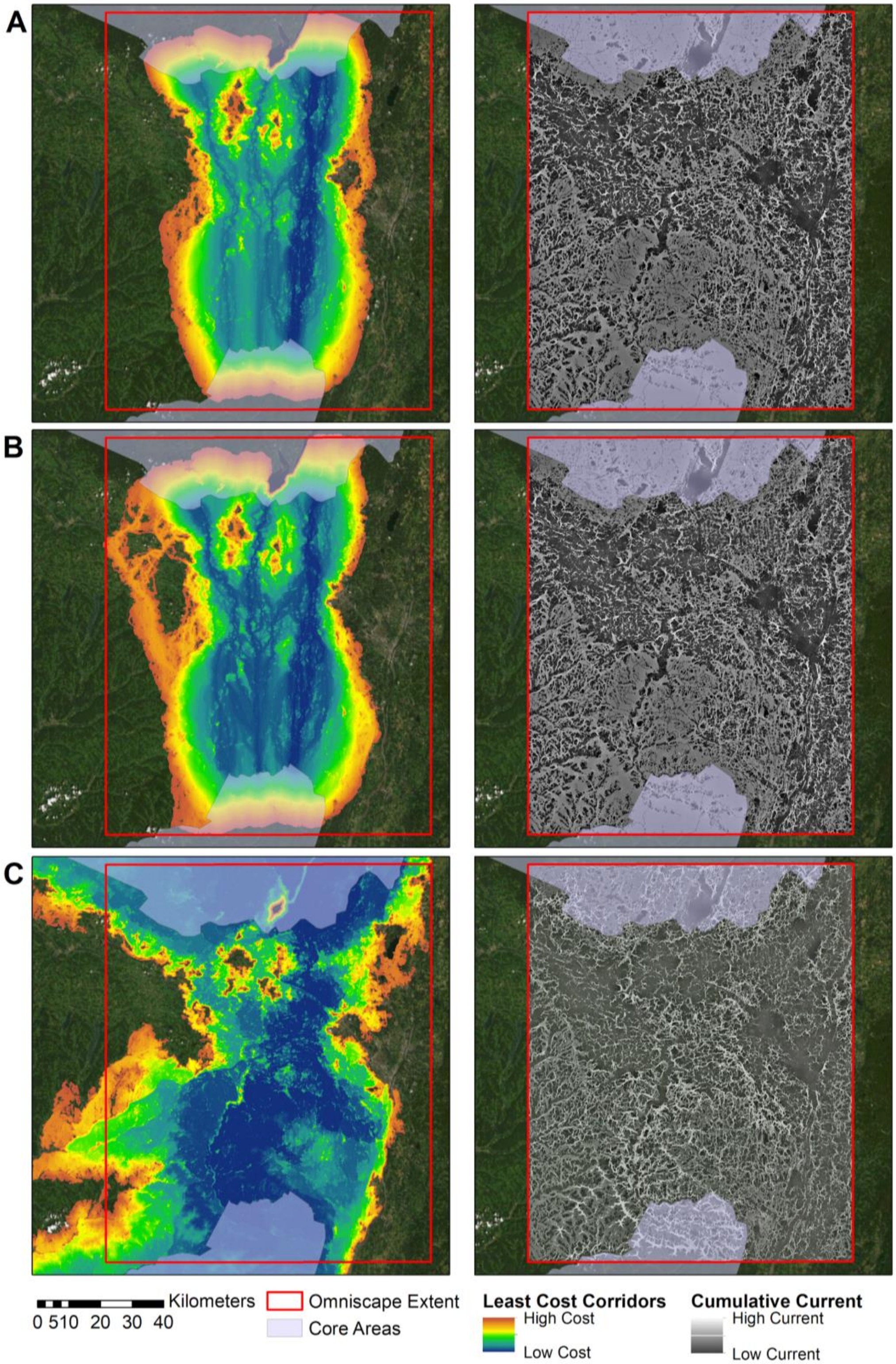


Figure 8. Least cost corridors and Omniscape cumulative current flow. Predicted least cost corridors (left) and Omniscape cumulative current flow (right) for bears (A), bobcats (B), and fishers (C). Least cost corridors are truncated at a travel cost value of 200,000.

Delineate Linkage Area

To delineate the linkage area boundaries between the Adirondacks and the Catskills, we aggregated the expert opinion-based Linkage Mapper corridor maps for all three focal species. We aggregated the corridor maps by adding together each current map using Raster Calculator in ArcGIS. The three maps were summed to produce a current map that captures the important areas for connectivity for all three species. We initially truncated the aggregated linkage area at four different cost-weighted corridor values to varyingly refined linkage boundaries (200,000; 400,000; 600,000; and 800,000). Lesser truncation values bound the linkage area to a narrower extent, while larger truncation values result in a wider extent (Figure 9). We presented these four preliminary linkage boundaries to MHLC to receive their input on whether they are more concerned with potential omission of important connectivity areas in a more truncated linkage area, or potential overestimate of connectivity in a less truncated linkage area.

Through talks with the MHLC, we defined the linkage area at the 800,000-truncation value, as it encompassed more opportunities for parcel acquisition. We found this request for a wider linkage area acceptable, since we also ran Omniscape over the region of interest to contextualize local connectivity throughout the large linkage area.

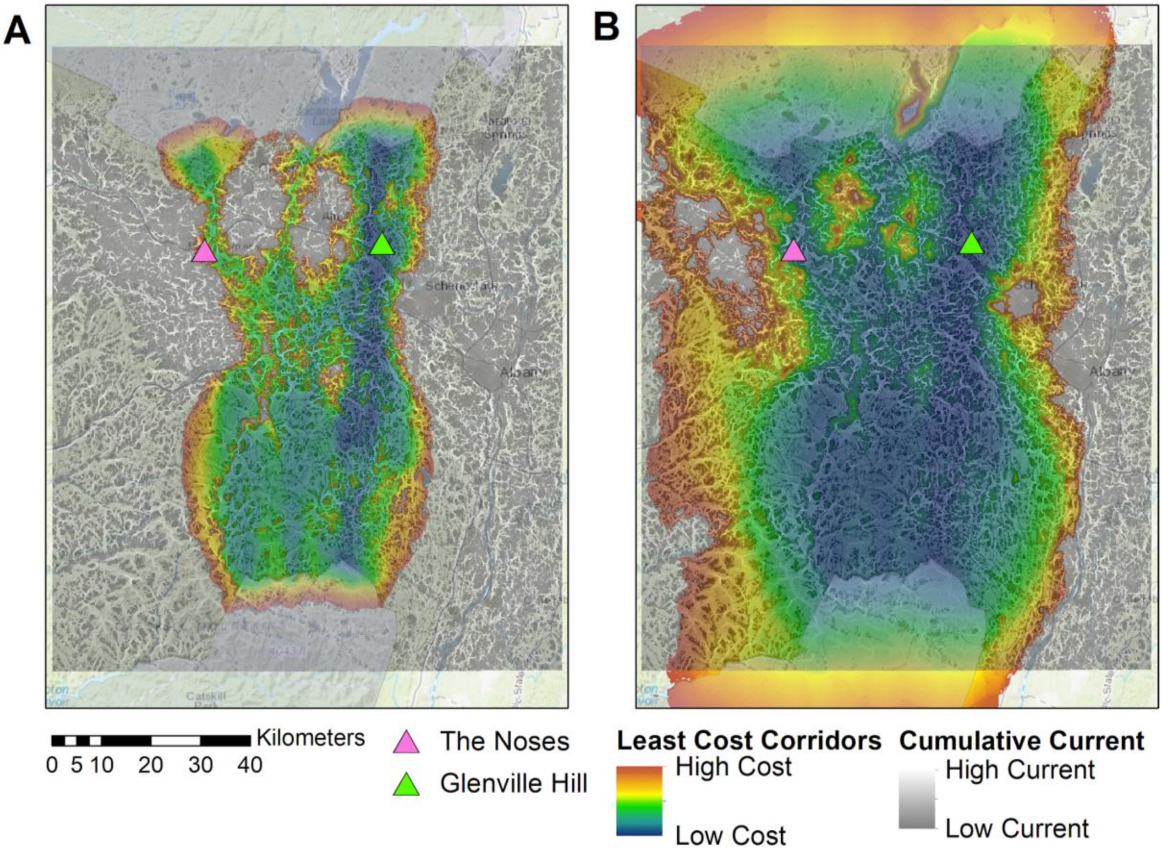


Figure 9. Potential linkage area boundaries. Boundaries were modeled with a combination of Linkage Mapper and Omniscape. Boundaries were truncated at a relative travel cost of 200,000 (A) and 800,000 (B).

Validate with Empirical Data

Due to species data limitations and unrepresentativeness across the region between the Adirondacks and the Catskills, we limited our validation to the local scale by focusing on the Omniscape results in the Albany region. Validating the whole region with unrepresentative and potentially biased species data would lead to irresponsible and biased results. Therefore, we refined our validation to the Albany area to demonstrate how validation techniques are useful with targeted data at the local scale. This local validation can support local project decision making. Detection data points for fishers were compared to randomly distributed points to perform local validation.

To validate the Albany area, we compared the underlying Omniscape Normalized Cumulative Current values between fisher presence data from Lisha Kill Preserve Fisher Study (n=10), Albany Camera Trapping Project (n=23), and iNaturalist (n = 1) with points randomly generated within the extent of the presence data (n=34; Create Random Points tool, ArcGIS; Figure 10). We extracted the connectivity metric values for the both sets of data points using the Extract Multi-Values to Points tool in ArcGIS. We ran a two-tailed, unpaired two-sample student’s t-test to test for a significant difference in predicted current flow between the real and random groups.

Our results suggest that the fisher presence data had significantly higher normalized cumulative current values than the randomly distributed points, (t (61.1) = 2.24, p = 0.029; Figure 11). This indicates that the fisher expert opinion Run 2 Omniscape Normalized Cumulative Current model is predictive of actual fisher presence in the Albany area.

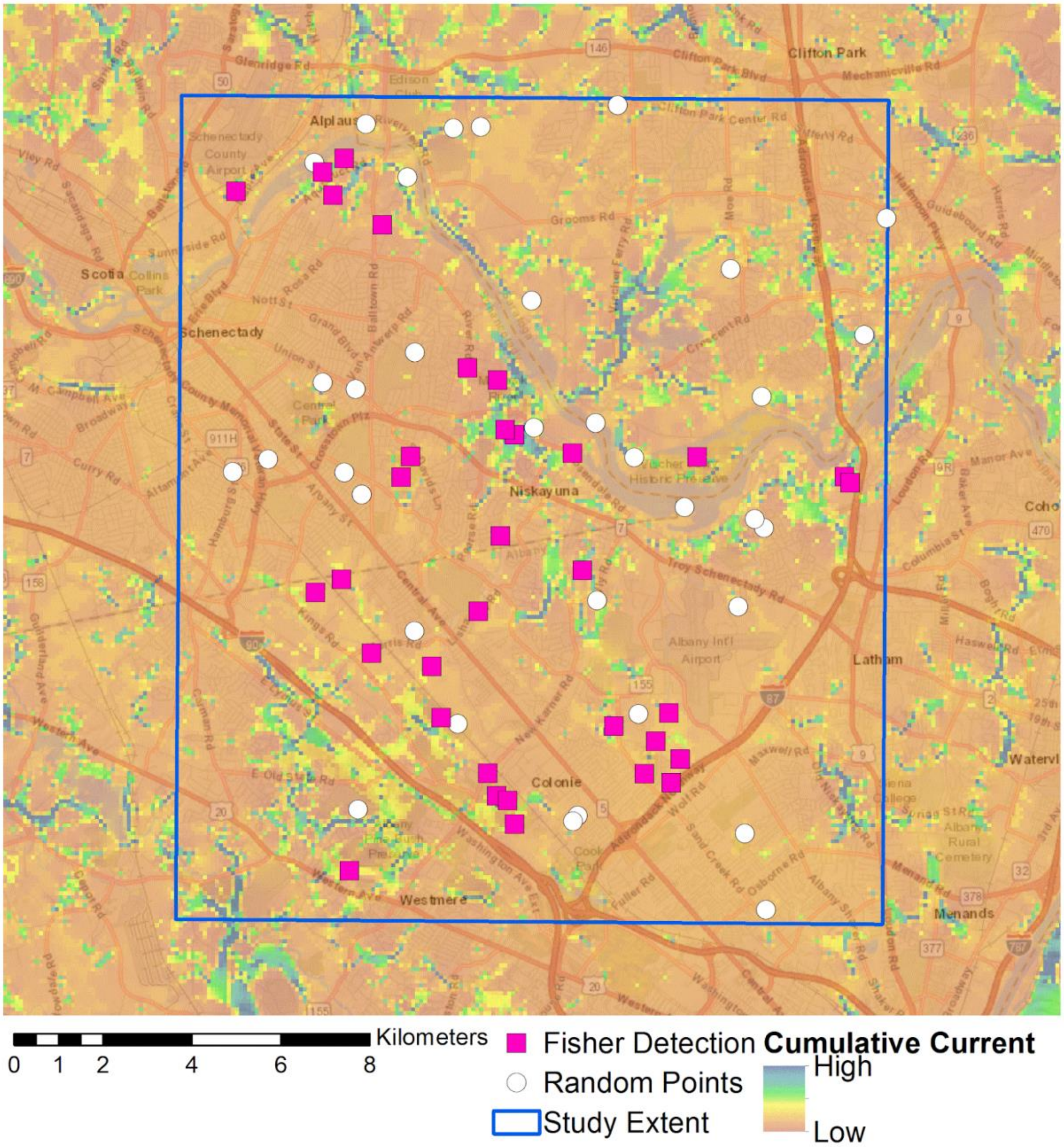


Figure 10. Fisher detection points, random points, and normalized cumulative current. Fisher detection points (pink) and randomly distributed points (white) near Albany, NY are overlaid on Normalized Cumulative Current results. The higher cumulative current is shaded blue and green and the lower current is shaded yellow and orange. On average, fisher detection points had higher underlying cumulative current values than random points, suggesting this Omniscape output is predictive of fisher presence in the Albany area.

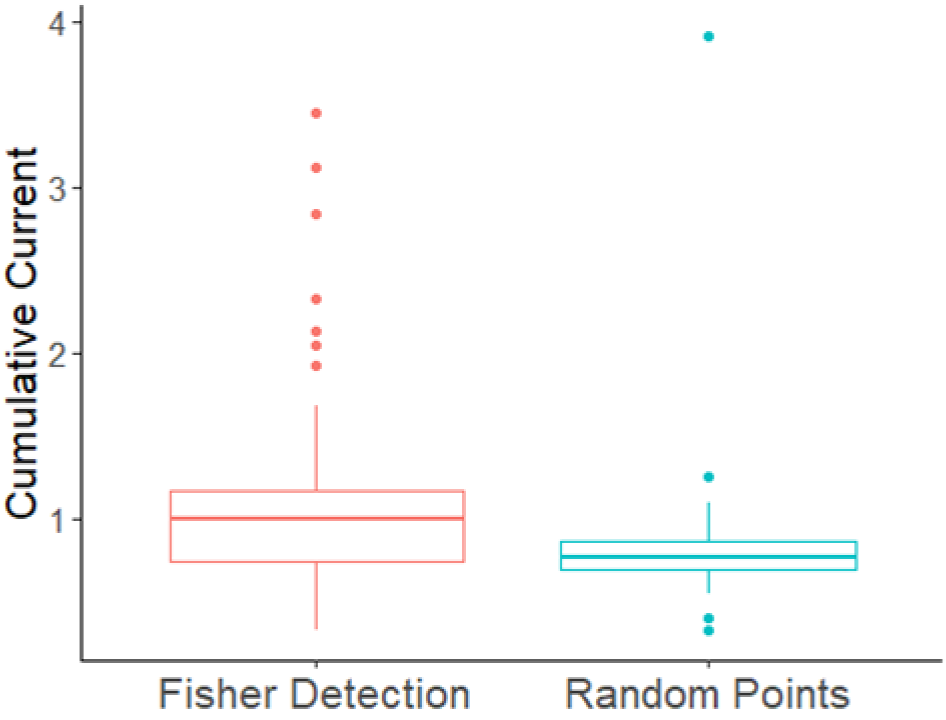


Figure 11. Cumulative current of fisher detection points and random points. The fisher detection points have a higher average current flow (mean = 1.23) than the random points (mean = 0.87, t (61.1) = 2.24, p = 0.029).

Priority Setting

Define Regional Connectivity Drivers

To analyze what is driving the modelled connectivity in the region, the Omniscape Normalized Cumulative Current layer for each of the focal species was overlaid on the world imagery base map in ArcGIS to visually compare patterns of high and low current flow. This process also showed that all three of the focal species generally have a similar modeled connectivity response to landscape features with some minor differences. For each species, locations of modelled high current flow tend to be in contiguous forested areas. Predicted low current flows tend to be near urban, suburban and agricultural areas. One of the large areas of modelled low current flows for all species are the agricultural fields surrounding I-90 that cause the high current flows to become patchy and narrow creating pinch points. These pinch points along I-90 may be good areas to refine connectivity assessments and implement subsequent connectivity projects.

Use Linkage Map to Facilitate Local Projects and Decision Making (Step Down Process)

Due to an incomplete understanding of MHLC and SCI's priorities and management abilities, this analysis can only make very preliminary suggestions of where MHLC and SCI might want to conserve land or restore the landscape through road barrier mitigation (Figure 12 and 13).

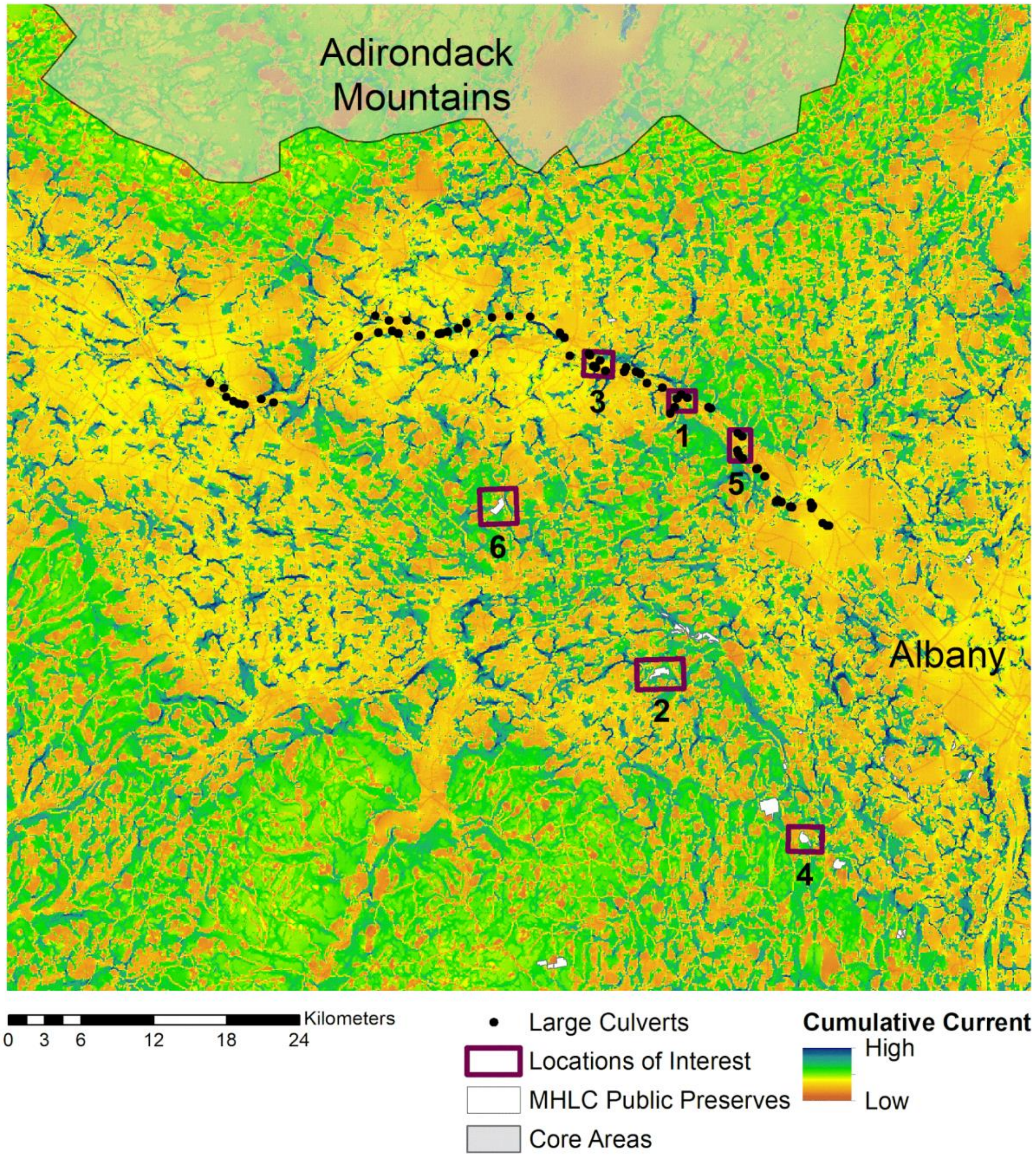


Figure 12. Potential locations for connectivity improvements in the Mohawk Valley. Boxed locations are potential sites for road barrier mitigation projects or land conservation. The cumulative current represented in this map is a combined normalized cumulative current for all of the species.

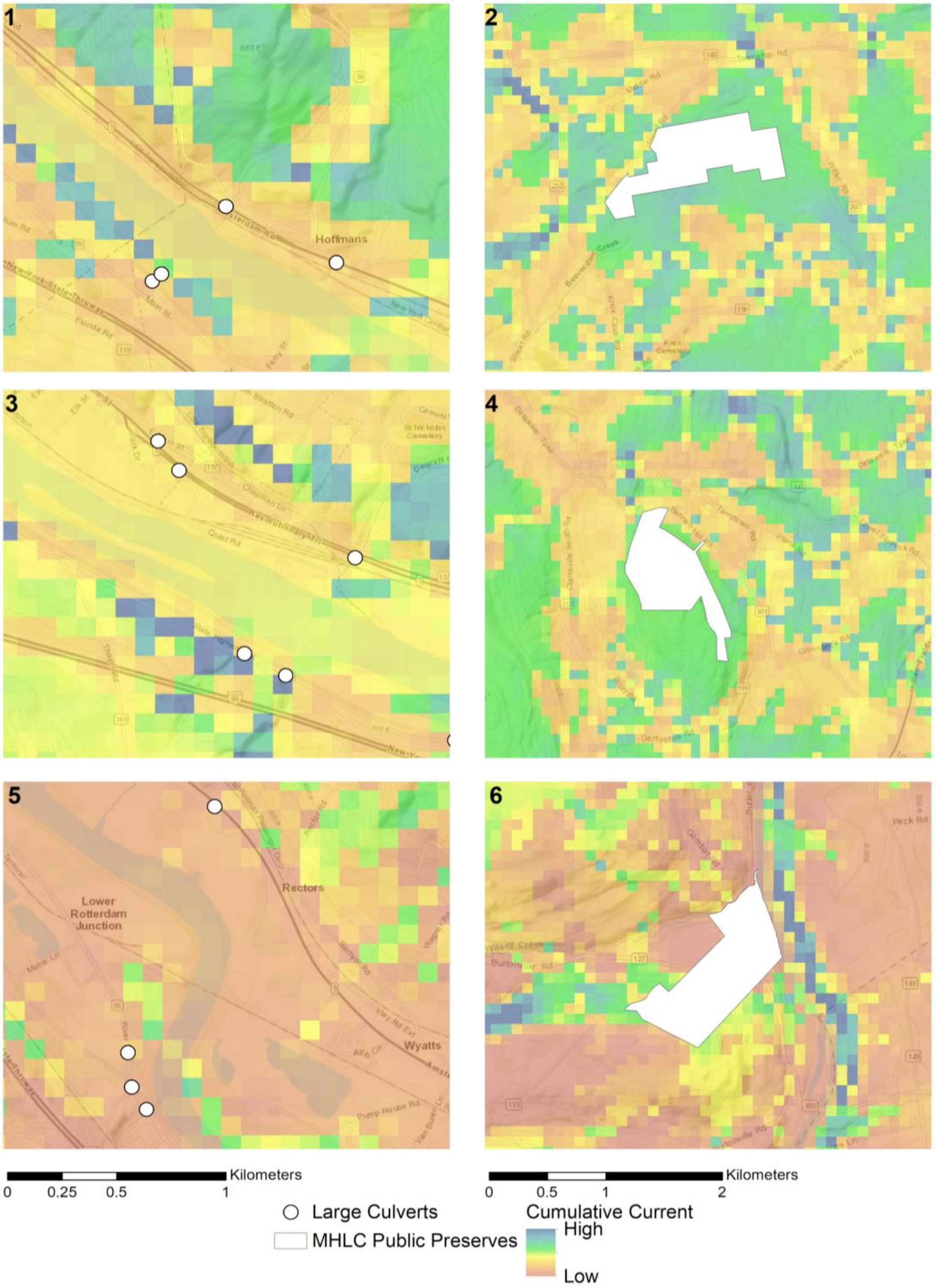


Figure 13. Detailed potential locations for connectivity improvements. Numbers in the upper left corner of maps correspond to boxed areas in Figure 12. These boxes show potential locations where connectivity could be improved for bears (top row), bobcats (middle row), and fishers (bottom row). The left column (boxes 1, 3, and 5) shows locations for potential road barrier mitigation near existing culvert locations (white circles). The right column (boxes 2, 4, and 6) shows potential locations for land conservation near existing MHLC preserves (white polygons) adjacent to predicted high current flow.

However, one land conservation strategy to maintain connectivity and preserve species habitat is to expand protection around existing conserved areas. We illustrated this approach by overlaying a selection of MHLCs protected lands on the fisher Omniscape normalized current output (Appendix B, Table 4). Areas with predicted high current flow adjacent to MHLC preserves, if monitoring corroborated the model, could be preserved to increase fisher movement through the Mohawk Valley. We recommend MHLC consider reiterating this approach with models for additional species and include all protected lands to facilitate better animal movement in the Mohawk Valley at potentially lower management costs.

To illustrate how TNC can identify road segments for road mitigation, we focused on State Route 5, as it is a MHLC-identified priority road segment in the region. In communications with TNC, we realized their interest in improving existing culverts to be more passable by wildlife. To determine where culvert retrofits should occur, we overlaid the large culvert points (2019 shapefile from the New York Department of Transportation; Appendix B, Table 4) on the Omniscape Normalized Cumulative Current layers for each species. Culverts along roadways that bisect projected high connectivity areas could be prioritized for future monitoring and road mitigation projects, since the road may act as a barrier to movement between high connectivity habitat patches. Culvert improvements could include adding substrate or shelving to the culvert to make it more passable, or installing fencing around the culvert to funnel animals into the culvert, instead of crossing the road.

We recommend TNC and MHLC monitor high priority areas before executing a connectivity project to verify results of the connectivity models or better assess project feasibility. Additionally, this framework can be reiterated at a more localized scale before specific high priority areas are identified to refine connectivity models and conduct more localized monitoring.

Discussion

In any connectivity modelling effort, there are assumptions and potential errors introduced at multiple steps of the modelling process. In this section, we highlight limitations of our proposed connectivity assessment framework and how potential sources of uncertainty, error, and bias can influence model results. The goal of this section is to provide a foundation for appropriate model use in support of conservation planning and decision making.

Data Bias and Representativeness Considerations

Our case study modelling connectivity in the Mohawk Linkage demonstrates how the data used to calibrate and validate models has the potential to bias model results. This occurs when the data is not representative of the population or the scale of the relevant conservation problem. These biases can often arise as a function of how and where the data were collected relative to the conservation goal. This was evident in our case study when data collected by citizen scientists were biased towards locations where people are most likely to be relative to where the animals are actually most likely to be found. Our findings underscore the importance of thoroughly evaluating the representativeness of a dataset whenever it will be used to calibrate and validate connectivity models (Anderson & Gonzalez, 2011; Jarnevich et al., 2015).

Additionally, our findings highlight the importance of exercising caution with inferences and extrapolation of data. Fisher detection points centered around Albany could not be used to extrapolate habitat suitability over the full range of other land use, land cover, and other environmental variables in the broader Mohawk Valley (Appendix D, Figure 1 and 2). While some extrapolation will be necessary in modelling because all species in all locations cannot be monitored, the spatial and temporal scale of the data should be aligned as closely as possible to the modelling extent and the scale of the ecological process relevant to the conservation goal (Rudnick et al., 2012). Similarly, the use of proxies will often be necessary in modelling, however, practitioners should carefully consider the accuracy of proxies and how their use may influence model results (Wade et al., 2015). This includes, for example, the use of umbrella species as proxies for the movement of many animals and the use of detection data to model movement behaviors.

Balance the Costs and Benefits of Empirical Data Collection

In evaluating the representativeness of a dataset, practitioners may arrive at the conclusion that a limited or biased dataset is inappropriate to use for the calibration and/or validation of a connectivity model. This raises the question of whether it would be worthwhile to proceed with additional collection of empirical data. While this question is largely context dependent, it can be valuable to consider how much additional data would be needed as well as what the modelled linkage would be informing. Models based on sparse data still have value for the purposes of comparing different scenarios and creating generalized, regional maps of connectivity (Rudnick et al., 2012). Models based on sparse or biased data are more problematic when they are intended to inform management priorities and specific mitigation actions (Rudnick et al., 2012). When models are intended for comparison purposes or for the creation of generalized regional maps, a naturalness-based (structural connectivity) approach to modelling may be sufficient (Krosby et al., 2015). Research contrasting a focal species modelling approach with a naturalness-based approach found that the naturalness-based approach modelled connectivity for many species (particularly large generalist species) as effectively as 3-4 focal species (Krosby et al., 2015). These research findings demonstrate that it may not be worthwhile to spend limited resources on additional empirical data collection if modelling is not intended to inform localized priorities and management actions.

Limitations of the Framework

In addition to the challenges that can arise due to biased or unrepresentative data, there are multiple places where error and bias can be introduced into the modelling process. Although this is not an exhaustive list of potential errors, biases, and uncertainties, practitioners should consider which of the following may be most relevant to their modelling process in an effort to be explicit about knowledge gaps and potential modelling inaccuracies.

Potential Errors

- Misrepresentation of focal species biology and habitat requirements
- Omission of a key environmental variable in the modelling process
- Inappropriate data extrapolation (Rudnick et al., 2012)

Potential Sources of Model Bias

- Selection of focal species
- Classification and selection of environmental variables
- Biased data used for the calibration and validation of models
- Assumptions of modelling method (e.g. model assumes species move between core areas)

Potential Uncertainties

Collectively, sources of error and model bias, such as those highlighted above, will lead to uncertainties about the accuracy of a model. Additional uncertainties in the modelling process include:

- Incomplete understanding of the conservation problem
- Incomplete understanding of the relevant ecosystem and focal species biology
- Uncertainties about future land cover and land use
- Uncertainties about climate change and future disturbances

Addressing Limitations

While it is impossible to address all sources of error, bias, and uncertainty in connectivity modelling, acknowledging the ways in which these limitations may be influencing model results is paramount. Collectively, many small errors and data biases may amount to major inaccuracies in modelled corridors. When these potential sources of error and bias are carefully accounted for, it may suggest the need for additional empirical data collection or signal that practitioners should proceed with caution if the model is intended to inform conservation actions (Rudnick et al., 2012).

Conducting a sensitivity analysis can be a valuable method to explore how sources of uncertainty in model inputs influence model results. In the case study, we performed a sensitivity analysis by comparing different expert opinion models and adjusting resistance values for roads. Other questions to explore through a sensitivity analysis may include an evaluation of how sensitive the model results are to the quality of the ecological variable data or the cell size of the resistance layer (Wade et al., 2015). Evaluating where sources of uncertainty may be influencing model results can help inform future research and approaches to address uncertainties in the future.

Conclusion

Our framework and corresponding case study are intended to help TNC and SCI refine their existing connectivity modelling approach. In our review of SCI connectivity modelling efforts, we identified key areas where the existing SCI framework could be improved. These key areas were creating more clearly defined connectivity goals and specifying which animal movement behavior is of interest in modelling efforts, incorporating empirical species data into connectivity modelling, and implementing a procedure for local priority setting and connectivity improvements based on linkage-scale modelling efforts. We incorporated each of these key areas into our suggested framework.

While our framework highlights the value of incorporating empirical data into habitat connectivity models, our case study analysis revealed some of the limitations of this approach. We found that most empirical species datasets in the NAPA region for wide-roaming mammals are not representative enough of the landscape heterogeneity at the linkage scale and are likely to bias model results. While we do not recommend extrapolating localized datasets to model connectivity across a broad region, limited datasets can be valuable for modelling connectivity across a smaller region to inform conservation actions. Given the scarcity of representative empirical species datasets for the purpose of modelling connectivity at the linkage scale, we recommend SCI partners continue to use expert opinion to model linkage areas. Empirical data can be collected and used to model connectivity at local scales to inform priority setting and decision making.

In applying our framework to the case study, we determined that our framework is applicable to connectivity modelling and decision making at both the linkage scale and local scale of conservation actions. Therefore, we recommend SCI partners use this framework first at the regional scale to understand broad drivers of regional connectivity, but reiterate the framework at a scale relevant to anticipated and actionable connectivity projects.

Our analysis revealed how thoroughly understanding the conservation problem, carefully articulating goals, and using empirical data responsibility has the capacity to produce better models with greater leverage to address the conservation problem at hand (Wade et al., 2015). Furthermore, a detailed process to step down regional models into localized conservation projects helps transition abstract problems into concrete actions. Implementing this framework will help SCI define success, based on well-articulated goals, and measure progress towards those goals with targeted monitoring and local actions to improve connectivity.

Further Reading

Throughout this project, the following published materials provided invaluable insight. We recommend that practitioners looking for more information on the topics described in our framework and case study review the following:

Beier, P., Majka, D. R., & Spencer, W. D. (2008). Forks in the Road: Choices in Procedures for Designing Wildland Linkages: Design of Wildlife Linkages. *Conservation Biology*, 22(4), 836–851. https://doi.org/10.1111/j.1523-1739.2008.00942.x

Clevenger, A., & Huijser, M. (2011). *Wildlife Crossing Structure Handbook Design and Evaluation in North America* (FHWA-CFL/TD-11-003; p. 224). U.S. Department of Transportation Federal Highway Administration.

Cushman, S. A., McRae, B., Adriaensen, F., Beier, P., Shirley, M., & Zeller, K. (2013). Biological Corridors and Connectivity. In D. W. Macdonald & K. Willis (Eds.), *Key Topics in Conservation Biology 2* (First Edition). John Wiley & Sons, Ltd.

Hilty, J. A., Keeley, A. T. H., Jr, W. Z. L., & Merenlender, A. M. (2019). *Corridor Ecology, Second Edition: Linking Landscapes for Biodiversity Conservation and Climate Adaptation* (Second Edition, New edition). Island Press.

Keeley, A. T. H., Basson, G., Cameron, D. R., Heller, N. E., Huber, P. R., Schloss, C. A., Thorne, J. H., Merenlender, A. M. (2018). Making habitat connectivity a reality. *Conservation Biology*, 32(6), 1221–1232. https://doi.org/10.1111/cobi.13158

Rudnick, D. A., Ryan, S. J., Beier, P., Cushman, S. A., Dieffenbach, F., Epps, C. W., Gerber, L. R., Hartter, J., Jenness, J. S., Kintsch, J., Merenlender, A. M., Perkl, R. M., Preziosi, D. V., & Trombulak, S. C. (2012). The role of landscape connectivity in planning and implementing conservation and restoration priorities. *Issues in Ecology*, 21.

Wade, A. A., McKelvey, K. S., & Schwartz, M. K. (2015). *Resistance-surface-based wildlife conservation connectivity modeling: Summary of efforts in the United States and guide for practitioners* (RMRS-GTR-333). U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. https://doi.org/10.2737/RMRS-GTR-333

Zeller, K. A., McGarigal, K., & Whiteley, A. R. (2012). Estimating landscape resistance to movement: A review. *Landscape Ecology*, *27*(6), 777–797. https://doi.org/10.1007/s10980-012-9737-0

References

Abrahms, B., Sawyer, S. C., Jordan, N. R., McNutt, J. W., Wilson, A. M., & Brashares, J. S. (2017). Does wildlife resource selection accurately inform corridor conservation? *Journal of Applied Ecology*, *54*(2), 412–422. https://doi.org/10.1111/1365-2664.12714

Allen, A. W., Fish, U. S., Road, R., & Collins, F. (1983). *Habitat Suitability Index Models: Fisher* (p. 29). US Fish and Wildlife.

Anderson, M. G., Barnett, A., Clark, M., Prince, J., Sheldon, A. O., & Vickery, B. (2016). *Resilient and Connected Landscapes for Terrestrial Conservation* (p. 161). The Nature Conservancy, Eastern Conservation Science, Eastern Regional Office.

Anderson, M. G., & Olivero-Sheldon, A. (2011). *Conservation Status of Fish, Wildlife, and Natural Habitats in the Northeast Landscape* (p. 292). The Nature Conservancy, Eastern Conservation Science.

Anderson, R. P., & Gonzalez, I. (2011). Species-specific tuning increases robustness to sampling bias in models of species distributions: An implementation with Maxent. *Ecological Modelling*, *222*(15), 2796–2811. https://doi.org/10.1016/j.ecolmodel.2011.04.011

Applin, J., & Marx, L. (2014). *Wildlife connectivity in western Massachusetts: Results and recommendations from a 2013-14 study of wildlife movement in two corridors*. 73.

ArcGIS (Version 10.7.1). (2019). [Computer software]. Environmental Systems Research Institute.

Armsworth, P. R., Cantú-Salazar, L., Parnell, M., Davies, Z. G., & Stoneman, R. (2011). Management costs for small protected areas and economies of scale in habitat conservation. *Biological Conservation*, *144*(1), 423–429. https://doi.org/10.1016/j.biocon.2010.09.026

Aylward, C. M., Murdoch, J. D., Donovan, T. M., Kilpatrick, C. W., Bernier, C., & Katz, J. (2018). Estimating distribution and connectivity of recolonizing American marten in the northeastern United States using expert elicitation techniques. *Animal Conservation*, *21*(6), 483–495. https://doi.org/10.1111/acv.12417

Beier, P., & Loe, S. (1992). In My Experience: A Checklist for Evaluating Impacts to Wildlife Movement Corridors. *Wildlife Society Bulletin (1973-2006)*, *20*(4), 434–440. JSTOR.

Beier, P., Majka, D. R., & Spencer, W. D. (2008). Forks in the Road: Choices in Procedures for Designing Wildland Linkages: *Design of Wildlife Linkages*. *Conservation Biology*, *22*(4), 836–851. https://doi.org/10.1111/j.1523-1739.2008.00942.x

Beier, P., & Noss, R. F. (1998). Do Habitat Corridors Provide Connectivity? *Conservation Biology*, *12*(6), 12.

Braunisch, V., Segelbacher, G., & Hirzel, A. H. (2010). Modelling functional landscape connectivity from genetic population structure: A new spatially explicit approach:

MODELLING LANDSCAPE CONNECTIVITY FROM GENETIC DATA. *Molecular Ecology*, *19*(17), 3664–3678. https://doi.org/10.1111/j.1365-294X.2010.04703.x

Brennan, A., Hanks, E. M., Merkle, J. A., Cole, E. K., Dewey, S. R., Courtemanch, A. B., & Cross, P. C. (2018). Examining speed versus selection in connectivity models using elk migration as an example. *Landscape Ecology*, *33*(6), 955–968. https://doi.org/10.1007/s10980-018-0642-z

Bull, E. L., Holthausen, R. S., & Bright, L. R. (1992). Comparison of 3 Techniques to Monitor Marten. *Wildlife Society Bulletin (1973-2006)*, *20*, 6.

Burkey, T. V. (1989). Extinction in Nature Reserves: The Effect of Fragmentation and the Importance of Migration between Reserve Fragments. *Oikos*, *55*(1), 75. https://doi.org/10.2307/3565875

Butchart, S. H. M., Walpole, M., Collen, B., van Strien, A., Scharlemann, J. P. W., Almond, R. E. A., Baillie, J. E. M., Bomhard, B., Brown, C., Bruno, J., Carpenter, K. E., Carr, G. M., Chanson, J., Chenery, A. M., Csirke, J., Davidson, N. C., Dentener, F., Foster, M., Galli, A., … Watson, R. (2010). Global Biodiversity: Indicators of Recent Declines. *Science*, *328*(5982), 1164–1168. https://doi.org/10.1126/science.1187512

Buttrick, S., Popper, K., Schindel, M., McRae, B. H., Unnasch, B., Jones, A., & Platt, J. (2015). *Conserving Nature's Stage: Identifying Resilient Terrestrial Landscapes in the Pacific Northwest*. The Nature Conservancy, Portland Oregon.

Calabrese, J. M., & Fagan, W. F. (2004). A comparison-shopper's guide to connectivity metrics. *Frontiers in Ecology and the Environment*, *2*(10), 529–536. https://doi.org/10.1890/1540-9295(2004)002[0529:ACGTCM]2.0.CO;2

Chardon, J. P., Adriaensen, F., & Matthysen, E. (2003). Incorporating landscape elements into a connectivity measure: A case study for the Speckled wood butterfly (Pararge aegeria L.). *Landscape Ecology*, *18*(6), 561–573. https://doi.org/10.1023/A:1026062530600

Chetkiewicz, C.-L. B., & Boyce, M. S. (2009). Use of resource selection functions to identify conservation corridors. *Journal of Applied Ecology*, *46*(5), 1036–1047. https://doi.org/10.1111/j.1365-2664.2009.01686.x

Clevenger, A., & Huijser, M. (2011). *Wildlife Crossing Structure Handbook Design and Evaluation in North America* (FHWA-CFL/TD-11-003; p. 224). U.S. Department of Transportation Federal Highway Administration.

Clevenger, A., Wierzchowski, J., Chruszcz, B., & Gunson, K. (2002). GIS-Generated, Expert-Based Models for Identifying Wildlife Habitat Linkages and Planning Mitigation Passages. *Conservation Biology*, *16*, 503–514. https://doi.org/10.1046/j.1523-1739.2002.00328.x

Coffin, A. W. (2007). From roadkill to road ecology: A review of the ecological effects of roads. *Journal of Transport Geography*, *15*(5), 396–406. https://doi.org/10.1016/j.jtrangeo.2006.11.006

Coker, D., & Reining, C. (2013). *A Measures Framework for Staying Connected in the Northern Appalachians* (p. 126).

Compton, B. W., McGARIGAL, K., Cushman, S. A., & Gamble, L. R. (2007). A Resistant-Kernel Model of Connectivity for Amphibians that Breed in Vernal Pools. *Conservation Biology*, *21*(3), 788–799. https://doi.org/10.1111/j.1523-1739.2007.00674.x

Costanza, J. K., & Terando, A. J. (2019). Landscape Connectivity Planning for Adaptation to Future Climate and Land-Use Change. *Current Landscape Ecology Reports*, *4*(1), 1–13. https://doi.org/10.1007/s40823-019-0035-2

Cushman, S. A., & Landguth, E. L. (2010). Scale dependent inference in landscape genetics. *Landscape Ecology*, *25*(6), 967–979. https://doi.org/10.1007/s10980-010-9467-0

Cushman, S. A., & Lewis, J. S. (2010). Movement behavior explains genetic differentiation in American black bears. *Landscape Ecology*, *25*(10), 1613–1625. https://doi.org/10.1007/s10980-010-9534-6

Cushman, S. A., McKelvey, K. S., Hayden, J., & Schwartz, M. K. (2006). Gene Flow in Complex Landscapes: Testing Multiple Hypotheses with Causal Modeling. *The American Naturalist*, *168*(4), 486–499. https://doi.org/10.1086/506976

Cushman, S. A., Mckelvey, K. S., & Schwartz, M. K. (2009). Use of Empirically Derived Source-Destination Models to Map Regional Conservation Corridors. *Conservation Biology*, *23*(2), 368–376. https://doi.org/10.1111/j.1523-1739.2008.01111.x

Cushman, S. A., Shirk, A. J., & Landguth, E. L. (2013). Landscape genetics and limiting factors. *Conservation Genetics*, *14*(2), 263–274. https://doi.org/10.1007/s10592-012-0396-0

Cushman, S., Lewis, J., & Landguth, E. (2014). Why Did the Bear Cross the Road? Comparing the Performance of Multiple Resistance Surfaces and Connectivity Modeling Methods. *Diversity*, *6*(4), 844–854. https://doi.org/10.3390/d6040844

Davis, F. W., Seo, C., & Zielinski, W. J. (2007). Regional Variation in Home-Range-Scale Habitat Models for Fisher (martes Pennanti) in California. *Ecological Applications*, *17*(8), 2195–2213. https://doi.org/10.1890/06-1484.1

Desrochers, A., Bélisle, M., & Bourque, J. (2011). Integrating GIS and homing experiments to study avian movement costs. *Landscape Ecology*, *26*, 47–58. https://doi.org/10.1007/s10980-010-9532-8

Dixon, J. D., Oli, M. K., Wooten, M. C., Eason, T. H., McCOWN, J. W., & Paetkau, D. (2006). Effectiveness of a Regional Corridor in Connecting Two Florida Black Bear Populations: Evaluating a Regional Black Bear Corridor. *Conservation Biology*, *20*(1), 155–162. https://doi.org/10.1111/j.1523-1739.2005.00292.x

Elith, J., Phillips, S. J., Hastie, T., Dudík, M., Chee, Y. E., & Yates, C. J. (2011). A statistical explanation of MaxEnt for ecologists: Statistical explanation of MaxEnt. *Diversity and Distributions*, *17*(1), 43–57. https://doi.org/10.1111/j.1472-4642.2010.00725.x

Emaresi, G., Pellet, J., Dubey, S., Hirzel, A. H., & Fumagalli, L. (2011). Landscape genetics of the Alpine newt (Mesotriton alpestris) inferred from a strip-based approach. *Conservation Genetics*, *12*(1), 41–50. https://doi.org/10.1007/s10592-009-9985-y

Evans, J. W., Evans, C. A., Packard, J. M., Calkins, G., & Elbroch, M. (2009). Determining Observer Reliability in Counts of River Otter Tracks. *Journal of Wildlife Management*, *73*(3), 426–432. https://doi.org/10.2193/2007-514

Fahrig, L. (2003). Effects of Habitat Fragmentation on Biodiversity. *Annual Review of Ecology, Evolution, and Systematics*, *34*(1), 487–515. https://doi.org/10.1146/annurev.ecolsys.34.011802.132419

Farrell, L. E., Levy, D. M., Donovan, T., Mickey, R., Howard, A., Vashon, J., Freeman, M., Royar, K., & Kilpatrick, C. W. (2018). Landscape connectivity for bobcat (Lynx rufus) and lynx (Lynx canadensis) in the Northeastern United States. *PLOS ONE*, *13*(3), e0194243. https://doi.org/10.1371/journal.pone.0194243

Fischer, J., & Lindenmayer, D. B. (2007). Landscape modification and habitat fragmentation: A synthesis. *Global Ecology and Biogeography*, *16*(3), 265–280. https://doi.org/10.1111/j.1466-8238.2007.00287.x

FitzGibbon, S. I., Putland, D. A., & Goldizen, A. W. (2007). The importance of functional connectivity in the conservation of a ground-dwelling mammal in an urban Australian landscape. *Landscape Ecology*, *22*(10), 1513–1525. https://doi.org/10.1007/s10980-007-9139-x

Gantchoff, M. G., & Belant, J. L. (2017). Regional connectivity for recolonizing American black bears (Ursus americanus) in southcentral USA. *Biological Conservation*, *214*, 66–75. https://doi.org/10.1016/j.biocon.2017.07.023

GBIF Occurrence Download. (2019, October 21). GBIF.Org. https://doi.org/10.15468/dl.ms6vgg

Glen, A. S., Pech, R. P., & Byrom, A. E. (2013). Connectivity and invasive species management: Towards an integrated landscape approach. *Biological Invasions*, *15*(10), 2127–2138. https://doi.org/10.1007/s10530-013-0439-6

Goetz, S. J., Jantz, P., & Jantz, C. A. (2009). Connectivity of core habitat in the Northeastern United States: Parks and protected areas in a landscape context. *Remote Sensing of Environment*, *113*(7), 1421–1429. https://doi.org/10.1016/j.rse.2008.07.019

Graham, C. (2001). Factors Influencing Movement Patterns of Keel-Billed Toucans in a Fragmented Tropical Landscape in Southern Mexico. *Conservation Biology*, *15*, 1789–1798. https://doi.org/10.1046/j.1523-1739.2001.00070.x

Gregory, A. J., & Beier, P. (2014). Response Variables for Evaluation of the Effectiveness of Conservation Corridors: Evaluating Conservation Corridors. *Conservation Biology*, *28*(3), 689–695. https://doi.org/10.1111/cobi.12252

Gurrutxaga, M., & Saura, S. (2014). Prioritizing highway defragmentation locations for restoring landscape connectivity. *Environmental Conservation*, *41*(2), 157–164. https://doi.org/10.1017/S0376892913000325

Hannah, L. (2008). Protected Areas and Climate Change. *Annals of the New York Academy of Sciences*, *1134*(1), 201–212. https://doi.org/10.1196/annals.1439.009

Hannah, L. (2011). Climate Change, Connectivity, and Conservation Success: Climate Change and Connectivity. *Conservation Biology*, *25*(6), 1139–1142. https://doi.org/10.1111/j.1523-1739.2011.01788.x

Hannah, L., Midgley, G., Andelman, S., Araújo, M., Hughes, G., Martinez-Meyer, E., Pearson, R., & Williams, P. (2007). Protected area needs in a changing climate. *Frontiers in Ecology and the Environment*, *5*(3), 131–138. https://doi.org/10.1890/1540-9295(2007)5[131:PANIAC]2.0.CO;2

Hanski, I., & Gilpin, M. E. (Eds.). (1997). *Metapopulation biology: Ecology, genetics, and evolution*. Academic Press.

Harris, G., Thirgood, S., Hopcraft, J., Cromsight, J., & Berger, J. (2009). Global decline in aggregated migrations of large terrestrial mammals. *Endangered Species Research*, *7*, 55–76. https://doi.org/10.3354/esr00173

Hart, P., Nilsson, N., & Raphael, B. (1968). A Formal Basis for the Heuristic Determination of Minimum Cost Paths. *IEEE Transactions on Systems Science and Cybernetics*, *4*(2), 100–107. https://doi.org/10.1109/TSSC.1968.300136

Hawk, R., Miller, C., Reining, C., & Gratton, L. (2012). *Staying Connected in the Northern Green Mountains: Identifying Structural Pathways and other Areas of High Conservation Priority*. Staying Connected Initiative.

Hebert, P. D. N., & Gregory, T. R. (2005). The Promise of DNA Barcoding for Taxonomy. *Systematic Biology*, *54*(5), 852–859. https://doi.org/10.1080/10635150500354886

Hedgecock, D., Barber, P., & Edmands, S. (2007). Genetic Approaches to Measuring Connectivity. *Oceanography*, *20*(3).

Hodgson, J. A., Thomas, C. D., Wintle, B. A., & Moilanen, A. (2009). Climate change, connectivity and conservation decision making: Back to basics. *Journal of Applied Ecology*, *46*(5), 964–969. https://doi.org/10.1111/j.1365-2664.2009.01695.x

Jaeger, J. A. G., & Fahrig, L. (2004). Effects of Road Fencing on Population Persistence. *Conservation Biology*, *18*(6), 1651–1657. https://doi.org/10.1111/j.1523-1739.2004.00304.x

Jarnevich, C. S., Stohlgren, T. J., Kumar, S., Morisette, J. T., & Holcombe, T. R. (2015). Caveats for correlative species distribution modeling. *Ecological Informatics*, *29*, 6–15. https://doi.org/10.1016/j.ecoinf.2015.06.007

Jensen, P. G., & Humphries, M. M. (2019). Abiotic conditions mediate intraguild interactions between mammalian carnivores. *Journal of Animal Ecology*. https://doi.org/10.1111/1365-2656.13024

Kautz, R., Kawula, R., Hoctor, T., Comiskey, J., Jansen, D., Jennings, D., Kasbohm, J., Mazzotti, F., McBride, R., Richardson, L., & Root, K. (2006). How much is enough? Landscape-scale conservation for the Florida panther. *Biological Conservation*, *130*(1), 118–133. https://doi.org/10.1016/j.biocon.2005.12.007

Keeley, A. T. H., Ackerly, D. D., Cameron, D. R., Heller, N. E., Huber, P. R., Schloss, C. A., Thorne, J. H., & Merenlender, A. M. (2018a). New concepts, models, and assessments of climate-wise connectivity. *Environmental Research Letters*, *13*(7), 073002. https://doi.org/10.1088/1748-9326/aacb85

Keeley, A. T. H., Basson, G., Cameron, D. R., Heller, N. E., Huber, P. R., Schloss, C. A., Thorne, J. H., & Merenlender, A. M. (2018b). Making habitat connectivity a reality: Habitat Connectivity. *Conservation Biology*, *32*(6), 1221–1232. https://doi.org/10.1111/cobi.13158

Koen, E. L., Bowman, J., Sadowski, C., & Walpole, A. A. (2014). Landscape connectivity for wildlife: Development and validation of multispecies linkage maps. *Methods in Ecology and Evolution*, *5*(7), 626–633. https://doi.org/10.1111/2041-210X.12197

Kool, J. T., Moilanen, A., & Treml, E. A. (2013). Population connectivity: Recent advances and new perspectives. *Landscape Ecology*, *28*(2), 165–185. https://doi.org/10.1007/s10980-012-9819-z

Krohn, W. B. (1995). Relations among fishers, snow, and martens: Development and evaluation of two hypotheses (W. B. Krohn, K. D. Elowe, & R. B. Boone, Trans.). *Forestry Chronicle*, *v. 71*(1), 97–105. PubAg. https://doi.org/10.5558/tfc71097-1

Krosby, M., Breckheimer, I., John Pierce, D., Singleton, P. H., Hall, S. A., Halupka, K. C., Gaines, W. L., Long, R. A., McRae, B. H., Cosentino, B. L., & Schuett-Hames, J. P. (2015). Focal species and landscape "naturalness" corridor models offer complementary approaches for connectivity conservation planning. *Landscape Ecology*, *30*(10), 2121–2132. https://doi.org/10.1007/s10980-015-0235-z

Krosby, M., Tewksbury, J., Haddad, N. M., & Hoekstra, J. (2010). Ecological Connectivity for a Changing Climate: Ecological Connectivity. *Conservation Biology*, *24*(6), 1686–1689. https://doi.org/10.1111/j.1523-1739.2010.01585.x

Landau. (2020). *Omniscape.jl: An efficient and scalable implementation of the Omniscape algorithm in the Julia scientific computing language, vX.Y.Z* [Julia]. Circuitscape. https://github.com/Circuitscape/Omniscape.jl (Original work published 2019)

LaPoint, S., Gallery, P., Wikelski, M., & Kays, R. (2013). Animal behavior, cost-based corridor models, and real corridors. *Landscape Ecology*, *28*(8), 1615–1630. https://doi.org/10.1007/s10980-013-9910-0

Lawler, J. J., Ruesch, A. S., Olden, J. D., & McRae, B. H. (2013). Projected climate-driven faunal movement routes. *Ecology Letters*, *16*(8), 1014–1022. https://doi.org/10.1111/ele.12132

Lele, S. R., Merrill, E. H., Keim, J., & Boyce, M. S. (2013). Selection, use, choice and occupancy: Clarifying concepts in resource selection studies. *Journal of Animal Ecology*, *82*(6), 1183–1191. https://doi.org/10.1111/1365-2656.12141

Linkage Mapper Connectivity Analysis Software (Version 2.0.0). (2019). [ArcGIS].

Long, R. A. (2009). *Predicting Occurrence and Assessing Connectivity for Wide-Ranging Carnivores in the Greater Southern Lake Champlain Region of New York*. The Nature Conservancy.

Long, R. A., Donovan, T. M., Mackay, P., Zielinski, W. J., & Buzas, J. S. (2007). Comparing Scat Detection Dogs, Cameras, and Hair Snares for Surveying Carnivores. *Journal of Wildlife Management*, *71*(6), 2018–2025. https://doi.org/10.2193/2006-292

Long, R. A., Donovan, T. M., MacKay, P., Zielinski, W. J., & Buzas, J. S. (2011). Predicting carnivore occurrence with noninvasive surveys and occupancy modeling. *Landscape Ecology*, *26*(3), 327–340. https://doi.org/10.1007/s10980-010-9547-1

Lowe, W. H., & Allendorf, F. W. (2010). What can genetics tell us about population connectivity? *Molecular Ecology*, *19*(15), 3038–3051. https://doi.org/10.1111/j.1365-294X.2010.04688.x

Macdonald, D. W., & Willis, K. J. (2013). *Key topics in conservation biology 2*. John Wiley & Sons Inc.

MacKenzie, D. I., Nichols, J. D., Lachman, G. B., Droege, S., Andrew Royle, J., & Langtimm, C. A. (2002). Estimating site occupancy rates when detection probabilities are less than one. *Ecology*, *83*(8), 2248–2255. https://doi.org/10.1890/0012-9658(2002)083[2248:ESORWD]2.0.CO;2

Marangelo, P. (2013). *Development of Spatial Priorities for Habitat Connectivity Conservation Between the Green Mountains and Adirondacks* (p. 20). The Nature Conservancy Vermont Chapter.

Martes pennanti LaPoint New York-reference data. (2013, July 2). http://hdl.handle.net/10255/move.329

McClure, M. L., Hansen, A. J., & Inman, R. M. (2016). Connecting models to movements: Testing connectivity model predictions against empirical migration and dispersal data. *Landscape Ecology*, *31*(7), 1419–1432. https://doi.org/10.1007/s10980-016-0347-0

McRae, B., Dickson, B. G., Keitt, T. H., & Shah, V. B. (2008). Using circuit theory to model connectivity in ecology, evolution, and conservation. *Ecology*, *89*(10), 2712–2724. https://doi.org/10.1890/07-1861.1

McRae, B. H., & Beier, P. (2007). Circuit theory predicts gene flow in plant and animal populations. *Proceedings of the National Academy of Sciences*, *104*(50), 19885–19890. https://doi.org/10.1073/pnas.0706568104

McRae, B., Hall, K., Ken, P., Unnasch, B., Jones, A., Platt, J., & Schindel, M. (2016a). *Conserving Nature's Stage: Mapping Omnidirectional Connectivity for Resilient Terrestrial Landscapes in the Pacific Northwest*. The Nature Conservancy. http://nature.org/resilienceNW

McRae, B., Shah, V., & Edelman, A. (2016b). *Circuitscape: Modeling landscape connectivity to promote conservation and human health*. https://doi.org/10.13140/RG.2.1.4265.1126

Meiklejohn, K., Ament, R., & Tabor, G. (2010a). *Habitat Corridors & Landscape Connectivity: Clarifying the Terminology*. Center for Large Landscape Conservation.

Merow, C., Smith, M. J., & Silander, J. A. (2013). A practical guide to MaxEnt for modeling species' distributions: What it does, and why inputs and settings matter. *Ecography*, *36*(10), 1058–1069. https://doi.org/10.1111/j.1600-0587.2013.07872.x

Mohawk Hudson Land Conservancy: The Capital Region's Land Trust. (2020). Mohawk Hudson Land Conservancy. https://mohawkhudson.org/

Moore, P., & Shadie, P. (2019). Connectivity Conservation: International Experience in Planning, Establishment and Management of Biodiversity Corridors. *IUCN Background Paper*. https://doi.org/IUCN-Rep-2007-008

Naiman, R. J., Decamps, H., & Pollock, M. (1993). The Role of Riparian Corridors in Maintaining Regional Biodiversity. *Ecological Applications*, *3*(2), 209–212. https://doi.org/10.2307/1941822

Nogeire, T. M., Davis, F. W., Crooks, K. R., McRae, B. H., Lyren, L. M., & Boydston, E. E. (2015). Can Orchards Help Connect Mediterranean Ecosystems? Animal Movement Data Alter Conservation Priorities. *The American Midland Naturalist*, *174*(1), 105–116. https://doi.org/10.1674/0003-0031-174.1.105

Nussey, P., & Noseworthy, J. (2018). *A Wildlife Connectivity Analysis for the Chignecto Isthmus* (p. 33). The Nature Conservancy Canada.

Olson, D. D., Bissonette, J. A., Cramer, P. C., Green, A. D., Davis, S. T., Jackson, P. J., & Coster, D. C. (2014). Monitoring Wildlife-Vehicle Collisions in the Information Age: How Smartphones Can Improve Data Collection. *PLOS ONE*, *9*(6), e98613. https://doi.org/10.1371/journal.pone.0098613

Pelletier, D., Clark, M., Anderson, M. G., Rayfield, B., Wulder, M. A., & Cardille, J. A. (2014). Applying Circuit Theory for Corridor Expansion and Management at Regional Scales: Tiling, Pinch Points, and Omnidirectional Connectivity. *PLoS ONE*, *9*(1), e84135. https://doi.org/10.1371/journal.pone.0084135

Pfeifer, M., Lefebvre, V., Peres, C. A., Banks-Leite, C., Wearn, O. R., Marsh, C. J., Butchart, S. H. M., Arroyo-Rodríguez, V., Barlow, J., Cerezo, A., Cisneros, L., D'Cruze, N., Faria, D., Hadley, A., Harris, S. M., Klingbeil, B. T., Kormann, U., Lens, L., Medina-Rangel, G. F., … Ewers, R. M. (2017). Creation of forest edges has a global impact on forest vertebrates. *Nature*, *551*(7679), 187–191. https://doi.org/10.1038/nature24457

Philips, S., Dudik, M., & Schapire, R. (2017). *Maxent software for modeling species niches and distributions* (Version 3.3.3) [Computer software]. http://biodiversityinformatics.amnh.org/open_source/maxent/

Phillips, S. J., Anderson, R. P., & Schapire, R. E. (2006). Maximum entropy modeling of species geographic distributions. *Ecological Modelling*, *190*(3–4), 231–259. https://doi.org/10.1016/j.ecolmodel.2005.03.026

Poor, E. E., Loucks, C., Jakes, A., & Urban, D. L. (2012). Comparing Habitat Suitability and

Connectivity Modeling Methods for Conserving Pronghorn Migrations. *PLoS ONE*, *7*(11), e49390. https://doi.org/10.1371/journal.pone.0049390

Pyke, C. R. (2005). Assessing Suitability for Conservation Action: Prioritizing Interpond Linkages for the California Tiger Salamander. *Conservation Biology*, *19*(2), 492–503. https://doi.org/10.1111/j.1523-1739.2005.00018.x

Rafferty, A., Brady, J., Patric, D., & Hilke, J. (2016). *Wildlife Cameras in the Northern Appalachians: Uses and Lessons Learned*. Staying Connected Initiative. http://stayingconnectedinitiative.org/assets/SCI-Camera-Summit-White-Paper.pdf

Rees, H. C., Maddison, B. C., Middleditch, D. J., Patmore, J. R. M., & Gough, K. C. (2014). REVIEW: The detection of aquatic animal species using environmental DNA - a review of eDNA as a survey tool in ecology. *Journal of Applied Ecology*, *51*(5), 1450–1459. https://doi.org/10.1111/1365-2664.12306

Richard, Y., & Armstrong, D. P. (2010). Cost distance modelling of landscape connectivity and gap-crossing ability using radio-tracking data: Cost distance modelling of landscape connectivity. *Journal of Applied Ecology*, *47*(3), 603–610. https://doi.org/10.1111/j.1365-2664.2010.01806.x

Roussel, J.-M., Paillisson, J.-M., Tréguier, A., & Petit, E. (2015). The downside of eDNA as a survey tool in water bodies. *Journal of Applied Ecology*, *52*(4), 823–826. https://doi.org/10.1111/1365-2664.12428

Rudnick, D. A., Ryan, S. J., Beier, P., Cushman, S. A., Dieffenbach, F., Epps, C. W., Gerber, L. R., Hartter, J., Jenness, J. S., Kintsch, J., Merenlender, A. M., Perkl, R. M., Preziosi, D. V., & Trombulak, S. C. (2012). The role of landscape connectivity in planning and implementing conservation and restoration priorities. *Issues in Ecology*, 21.

Ruppert, K. M., Kline, R. J., & Rahman, M. S. (2019). Past, present, and future perspectives of environmental DNA (eDNA) metabarcoding: A systematic review in methods, monitoring, and applications of global eDNA. *Global Ecology and Conservation*, *17*, e00547. https://doi.org/10.1016/j.gecco.2019.e00547

Saunders, D. A., Hobbs, R. J., & work(s):, C. R. M. R. (1991). Biological Consequences of Ecosystem Fragmentation: A Review. *Conservation Biology*, *5*(1), 18–32.

Schloss, C. A., Nunez, T. A., & Lawler, J. J. (2012). Dispersal will limit ability of mammals to track climate change in the Western Hemisphere. *Proceedings of the National Academy of Sciences*, *109*(22), 8606–8611. https://doi.org/10.1073/pnas.1116791109

Seoane, J., Bustamante, J., & Diaz-Delgado, R. (2005). Effect of Expert Opinion on the Predictive Ability of Environmental Models of Bird Distribution. *Conservation Biology*, *19*(2), 512–522. https://doi.org/10.1111/j.1523-1739.2005.00364.x

Shilling, F., Perkins, S., & Collinson, W. (2015). *Handbook of Road Ecology*. John Wiley & Sons, Ltd. https://escholarship.org/uc/item/2p7927vt

Simberloff, D., & Cox, J. (1987). Consequences and Costs of Conservation Corridors. *Conservation Biology*, *1*(1), 63–71. https://doi.org/10.1111/j.1523-

1739.1987.tb00010.x

Simberloff, D., Farr, J. A., Cox, J., & Mehlman, D. W. (1992). Movement Corridors: Conservation Bargains or Poor Investments? *Conservation Biology*, *6*(4), 493–504. https://doi.org/10.1046/j.1523-1739.1992.06040493.x

Sinclair, A. R. E. (1983). The function of distance movements in vertebrates. In *The Ecology of Animal Movement* (pp. 240–258). Clarendon Press.

Skagen, S. K., Melcher, C. P., Howe, W. H., & Knopf, F. L. (1998). Comparative Use of Riparian Corridors and Oases by Migrating Birds in Southeast Arizona. *Conservation Biology*, *12*(4), 14.

Squires, J. R., DeCesare, N. J., Olson, L. E., Kolbe, J. A., Hebblewhite, M., & Parks, S. A. (2013). Combining resource selection and movement behavior to predict corridors for Canada lynx at their southern range periphery. *Biological Conservation*, *157*, 187–195. https://doi.org/10.1016/j.biocon.2012.07.018

Steinitz, C. (1994). A framework for theory and practice in landscape planning. *Ekistics*, *61*(364).

Stewart, F. E. C., Darlington, S., Volpe, J. P., McAdie, M., & Fisher, J. T. (2019). Corridors best facilitate functional connectivity across a protected area network. *Scientific Reports*, *9*(1), 1–9. https://doi.org/10.1038/s41598-019-47067-x

Stewart-Oaten, A., Murdoch, W. W., & Parker, K. R. (1986). Environmental Impact Assessment: “Pseudoreplication” in Time? *Ecology*, *67*(4), 929–940. https://doi.org/10.2307/1939815

Stiber, N. A., Small, M. J., & Pantazidou, M. (2004). Site-Specific Updating and Aggregation of Bayesian Belief Network Models for Multiple Experts. *Risk Analysis*, *24*(6), 1529–1538. https://doi.org/10.1111/j.0272-4332.2004.00547.x

Tear, T., Brown, M., Stratton, B., Seleen, K., & Marangelo, P. (2006). *An Analysis of Habitat Connectivity for Wide Ranging Mammals between the Green Mountains and Adirondacks of the Southern Lake Champlain Valley*. The Nature Conservancy Eastern New York Chapter.

Theobald, D. M., Reed, S. E., Fields, K., & Soulé, M. (2012). Connecting natural landscapes using a landscape permeability model to prioritize conservation activities in the United States: Connecting natural landscapes. *Conservation Letters*, *5*(2), 123–133. https://doi.org/10.1111/j.1755-263X.2011.00218.x

Thomas, C. D., Cameron, A., Green, R. E., Bakkenes, M., Beaumont, L. J., Collingham, Y. C., Erasmus, B. F. N., de Siqueira, M. F., Grainger, A., Hannah, L., Hughes, L., Huntley, B., van Jaarsveld, A. S., Midgley, G. F., Miles, L., Ortega-Huerta, M. A., Peterson, A. T., Phillips, O. L., & Williams, S. E. (2004). *Extinction risk from climate change*. *427*, 4.

Thomsen, P. F., & Willerslev, E. (2015). Environmental DNA – An emerging tool in conservation for monitoring past and present biodiversity. *Biological Conservation*, *183*, 4–18. https://doi.org/10.1016/j.biocon.2014.11.019

Thurfjell, H., Ciuti, S., & Boyce, M. S. (2014). Applications of step-selection functions in ecology and conservation. *Movement Ecology*, *2*(1), 4. https://doi.org/10.1186/2051-3933-2-4

Tobler, M., Carrillo-Percastegui, S. E., Leite Pitman, R., Mares, R., & Powell, G. (2008). An evaluation of camera traps for inventorying large- and medium-sized terrestrial rainforest mammals. *Animal Conservation*, *11*, 169–178. https://doi.org/10.1111/j.1469-1795.2008.00169.x

UC Davis Road Ecology Center. (2019). https://roadecology.ucdavis.edu/

US Department of Transportation: Federal Highway Administration. (2008). *Wildlife-Vehicle Collision Reduction Study: Report To Congress*. https://doi.org/FHWA-HRT-08-034

Valerio, F., Carvalho, F., Barbosa, A. M., Mira, A., & Santos, S. M. (2019). Accounting for Connectivity Uncertainties in Predicting Roadkills: A Comparative Approach between Path Selection Functions and Habitat Suitability Models. *Environmental Management*, *64*(3), 329–343. https://doi.org/10.1007/s00267-019-01191-6

Van der Ree, R., Smith, D. J., & Grilo, C. (Eds.). (2015). *Handbook of road ecology*. John Wiley & Sons, Inc.

Vercayie, D., & Herremans, M. (2015). Citizen science and smartphones take roadkill monitoring to the next level. *Nature Conservation*, *11*, 29–40. https://doi.org/10.3897/natureconservation.11.4439

Wade, A. A., McKelvey, K. S., & Schwartz, M. K. (2015). *Resistance-surface-based wildlife conservation connectivity modeling: Summary of efforts in the United States and guide for practitioners* (RMRS-GTR-333). U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. https://doi.org/10.2737/RMRS-GTR-333

Walpole, A. A., Bowman, J., Murray, D. L., & Wilson, P. J. (2012). Functional connectivity of lynx at their southern range periphery in Ontario, Canada. *Landscape Ecology*, *27*(5), 761–773. https://doi.org/10.1007/s10980-012-9728-1

Wang, I. J., Savage, W. K., & Bradley Shaffer, H. (2009). Landscape genetics and least-cost path analysis reveal unexpected dispersal routes in the California tiger salamander (*Ambystoma californiense*). *Molecular Ecology*, *18*(7), 1365–1374. https://doi.org/10.1111/j.1365-294X.2009.04122.x

Wattles, D. W., Zeller, K. A., & DeStefano, S. (2018a). Response of moose to a high-density road network: Road Avoidance by Moose. *The Journal of Wildlife Management*, *82*(5), 929–939. https://doi.org/10.1002/jwmg.21459

Wattles, D. W., Zeller, K. A., & DeStefano, S. (2018b). Range expansion in unfavorable environments through behavioral responses to microclimatic conditions: Moose (Alces americanus) as the model. *Mammalian Biology*, *93*, 189–197. https://doi.org/10.1016/j.mambio.2018.05.009

Wiens, J. A. (1989). Spatial Scaling in Ecology. *Functional Ecology*, *3*(4), 385–397. JSTOR. https://doi.org/10.2307/2389612

Zeller, K.A., Nijhawan, S., Salom-Perez, R., Potosme, S. H., & Hines, J. E. (2011). Integrating occupancy modeling and interview data for corridor identification: A case study for jaguars in Nicaragua. *Biological Conservation*, *144*(2), 10. https://doi.org/10.1016/j.biocon.2010.12.003

Zeller, Katherine A., McGarigal, K., Beier, P., Cushman, S. A., Vickers, T. W., & Boyce, W. M. (2014). Sensitivity of landscape resistance estimates based on point selection functions to scale and behavioral state: Pumas as a case study. *Landscape Ecology*, *29*(3), 541–557. https://doi.org/10.1007/s10980-014-9991-4

Zeller, Katherine A., McGarigal, K., Cushman, S. A., Beier, P., Vickers, T. W., & Boyce, W. M. (2016). Using step and path selection functions for estimating resistance to movement: Pumas as a case study. *Landscape Ecology*, *31*(6), 1319–1335. https://doi.org/10.1007/s10980-015-0301-6

Zeller, Katherine A., McGarigal, K., & Whiteley, A. R. (2012). Estimating landscape resistance to movement: A review. *Landscape Ecology*, *27*(6), 777–797. https://doi.org/10.1007/s10980-012-9737-0

Zielinski, W. J., & Kucera, T. E. (1995). *American marten, fisher, lynx, and wolverine: Survey methods for their detection* (PSW-GTR-157; p. PSW-GTR-157). U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. https://doi.org/10.2737/PSW-GTR-157

Zielinski, W. J., Truex, R. L., Schmidt, G. A., Schlexer, F. V., Schmidt, K. N., & Barrett, R. H. (2004). Resting habitat selection by fishers in California. *Journal of Wildlife Management*, *68*(3), 475–492. https://doi.org/10.2193/0022-541X(2004)068[0475:RHSBFI]2.0.CO;2

Appendix A. Linkage Area Report Summaries

Table 1. Adirondack Mountains to Green Mountains Linkage Area report summary.

Linkage Name	**Adirondack Mountains to Green Mountains**
Report Referenced	Marangelo, Paul (2013). Development of Spatial Priorities for Habitat Connectivity Conservation Between the Green Mountains and Adirondacks. The Nature Conservancy - Vermont Chapter.
Year Completed	2013
Species Included	Bobcat Black Bear Fisher
Rationale for Connectivity Work	Maintain or restore gene flow (implied)
Project Goals	Road barrier mitigation, land-use planning, parcel prioritization
Environmental Variables	Land cover
Methods to create resistance layer/species behavior parametrization	**Multiple methods:** 1. Tear et al. (2006) - Expert Opinion and Literature Review 2. Long (2007) - Inverted Occupancy Models for individual focal species based on monitoring conducted throughout Vermont (Long et al., 2011) 3. Middleman and Marangelo (2009) - Borrowed from Tear et al. (2006) or Long (2007); unclear. 4. Zeh (2010) - Expert Opinion and Literature Review
Connectivity model	1. Tear et al. (2006) - Least Cost Path 2. Long (2007) - Least Cost Path 3. Middleman and Marangelo (2009) - Circuitscape 4. Zeh (2010) - FunConn (not used to create final linkage map)
Model validation with species data	Road segments intersecting areas of high predicted animal movement were surveyed for "habitat attributes that were most likely to enable wildlife road crossing." The habitat attributes were not defined. A subset of these identified road segments were visited in a winter tracking exercise to identify mammal movement along or across the road segment. The surveys were considered preliminary and the authors advised future monitoring before road barrier mitigation work takes place.

Table 2: Chignecto Isthmus Linkage Area report summary.

Linkage Name	**Chignecto Isthmus**
Report Referenced	Nussey, Patrick and Noseworthy, Josh (2018). A Wildlife Connectivity Analysis for the Chignecto Isthmus. Final Report for The Nature Conservancy - Canada
Year Completed	2018
Species Included	Moose Black Bear Red Fox Bobcat Snowshoe Hare Fisher Northern Flying Squirrel Barred Owl Northern Goshawk Pileated Woodpecker Yellow Warbler Brown Creeper Ruffed Grouse Boreal Chickadee Blackburnian Warbler
Rationale for Connectivity Work	Not explicitly stated
Project Goals	Not explicitly stated
Environmental Variables	Land cover
Methods to create resistance layer/species behavior parametrization	Expert opinion and literature review
Connectivity model	Linkage Mapper Pinchpoint Mapper Habitat suitability
Model validation with species data	None
Notes	The least cost maps for the 15 species were combined and run through a kernel density analysis to provide a map of areas of high connectivity convergence.

Table 3: Green Mountains to Hudson Highlands Linkage Area report summary.

Linkage Name	**Green Mountains to Hudson Highlands**
Report Referenced	Applin, Jessica and Marx, Laura (2014). Wildlife connectivity in western Massachusetts: Results and recommendations from a 2013-14 study of wildlife movement in two corridors. SCI Final Linkage Report
Year Completed	2014
Species Included	None
Rationale for Connectivity Work	Not explicitly stated
Project Goals	Road barrier mitigation
Environmental Variables	None
Methods to create resistance layer/species behavior parametrization	None
Connectivity model	None
Model validation with species data	Conducted camera-trap and snow-tracking surveys along select roadways within structural corridors identified by UMass Amherst Conservation Assessment and Prioritization System. Collected species data meant to inform general future conservation decisions.
Notes	"The linkage was delineated using TNC matrix forest blocks identified in the Lower New England Ecoregional Plan (Barbour et al., 2003), ecoregional boundaries, and TNC's regional resistant kernel analysis (Anderson et al., 2012). We also looked at orthoimagery and base data layers like roads and rivers to understand the landscape context, especially in the Hudson River valley." Applin and Marx (2014)

Table 4: Tug Hill Plateau to Adirondack Mountains Linkage Area report summary.

Linkage Name	**Tug Hill Plateau to Adirondack Mountains**
Report Referenced	Brown, Michelle, Cheeseman, Craig, Garrett, Linda, Dunham, Todd, Bryant, Dirk (2009). Adirondack-Tug Hill Connectivity Project–Final Report. SCI Final Linkage Report
Year Completed	2009
Species Included	Black Bear American marten Cougar Canada Lynx Moose River Otter Scarlet Tanager
Rationale for Connectivity Work	Maintain or restore gene flow, promote climate change range shifts
Project Goals	Road barrier mitigation, community outreach, land-use planning
Environmental Variables	Land cover
Methods to create resistance layer/species behavior parametrization	Expert opinion and literature review
Connectivity model	Least Cost Path FunConn
Model validation with species data	None

Table 5: Norther Green Mountains Linkage Area report summary.

Linkage Name	**Northern Green Mountains**
Report Referenced	Hawk, R., Miller, C., Reining, C., Gratton, L. (2012). Staying Connected in the Northern Green Mountains: Identifying Structural Pathways and other Areas of High Conservation Priority. Staying Connected Initiative Final Report
Year Completed	2012
Species Included	None
Rationale for Connectivity Work	Promote climate change range shifts (implied)
Project Goals	Parcel prioritization
Environmental Variables	Land cover
Methods to create resistance layer/species behavior parametrization	Expert opinion and literature review
Connectivity model	Structural connectivity analysis with least cost path Identified Habitat Block Core Areas (HBCA)
Model validation with species data	Modelled results were cross referenced with field data from the Critical Paths Project
Notes	Authors used structural pathways analysis to inform and avoid “Bridges to Nowhere” and refine the linkage boundary.

Table 6: Northeast Kingdom Vermont to Northern New Hampshire to Western Maine Linkage Area report summary.

Linkage Name	**Northeast Kingdom Vermont to Northern New Hampshire to Western Maine**
Report Referenced	Steckler, P. & Bechdtel, D., 2013. Staying Connected in the Northern Appalachians, Northeast Kingdom to Northern New Hampshire Linkage: Implementation Plan to Maintain and Enhance Landscape Connectivity for Wildlife. New Hampshire Chapter of The Nature Conservancy. Concord, NH
Year Completed	2013
Species Included	**Ridgeline using species:** American marten (habitat specialist, area sensitive) Black bear (habitat generalist) Bobcat (area sensitive) Canada lynx (habitat specialist, area sensitive) Fisher (habitat generalist) **Riparian dependent species:** Long-tailed weasel (habitat generalist) Mink (habitat specialist) Otter (habitat specialist) Wood turtle (barrier sensitive) **Other Species:** Porcupine (habitat generalist, barrier sensitive) Snowshoe hare (habitat specialist)
Rationale for Connectivity Work	Promote climate change range shifts (implied)
Project Goals	Road barrier mitigation, restoration, parcel prioritization
Environmental Variables	Land cover, proximity to roads and riparian areas, slopes, ridgelines
Methods to create resistance layer/species behavior parametrization	Expert opinion and literature review
Connectivity model	Cost-distance modelling
Model validation with species data	Modelled connectivity validated with roadside winter tracking

Table 7: Three Borders Main Northwoods to Quebec's Gaspe Peninsula Linkage Area Report.

Linkage Name	**Three Borders: Maine Northwoods to Quebec's Gaspe Peninsula**
Report Referenced	*Morrison, Margo and Noseworthy, Josh (2018). Identifying Connectivity Networks across the Three Borders Region - New Brunswick, Quebec, and Maine. Final Report to The Nature Conservancy - Canada.*
Year Completed	2018
Species Included	Moose Black Bear White-Tailed Deer Canada Lynx American Marten American Mink Wood Turtle
Rationale for Connectivity Work	Not explicitly stated
Project Goals	Parcel prioritization
Environmental Variables	Land cover
Methods to create resistance layer/species behavior parametrization	Expert opinion and literature review
Connectivity model	Linkage Mapper PinchPoint Mapper Kernel Density Model (used to combine least-cost path of six species)
Model validation with species data	None

Appendix B. Mapping Data Sources

Table 1. Species detection data used in the Maxent species distribution model and validation process.

Species	**Project**	**Type**	**Year**	**Source**	**Location**	**Link/Citation**
Fisher	iNaturalist Fisher Observations	Tab-delimited CSV	2010-2019	Global Biodiversity Information Facility (GBIF)	United States, North East Region	GBIF.org (21 October 2019) GBIF Occurrence Download https://doi.org/10.15468/dl.ms6vgg
Fisher	Albany Area Camera Trapping Project	Camera trap observations	2011-2012	eMammal	United States, North East Region	https://emammal.si.edu/analysis/data-download
Fisher	Lisha Kill Preserve Fisher Study	Camera trap observations	2019	Dan Winters, SUNY Albany	Albany, New York	
Bear	iNaturalist Bear Observations	Tab-delimited CSV	2010-2019	Global Biodiversity Information Facility (GBIF)	United States, North East Region	GBIF.org (21 October 2019) GBIF Occurrence Download https://doi.org/10.15468/dl.ms6vgg
Bobcat	iNaturalist Bobcat Observations	Tab-delimited CSV	2010-2019	Global Biodiversity Information Facility (GBIF)	United States, North East Region	GBIF.org (21 October 2019) GBIF Occurrence Download https://doi.org/10.15468/dl.ms6vgg

Table 2. Environmental data used in the Maxent species distribution model and expert opinion habitat suitability model.

Layer	**Data Type**	**Time-frame**	**Source**	**Location/ Extent**	**Resolution**	**Link/Citation** **(filename if applicable)**
State Boundaries	Shapefile, .shp	2018	United States Census Bureau	United States	5 meters	https://www.census.gov/geographies/mapping-files/time-series/geo/carto-boundary-file.html (cb_2018_us_state_5m.shp)
National Land Cover Database (NLCD) 2016	Raster, .img	2016	Multi-Resolution Land Characteristics Consortium	United States	30x30 meters	https://www.mrlc.gov/data (NLCD_2016_Land_Cover_L48_20190424)
Digital Elevation Model (DEM)	Raster, .img	2019	USGS NED	Lat: N41 – N46 Long: W71 – W77	1 arc-second, 1 x 1 degree	https://viewer.nationalmap.gov/basic/#startUp (nXXwXXX IMG 2019)
WorldClim – BioClim Temperature and Precipitation	Raster	1960-2000	WorldClim	Global	30 second	https://www.worldclim.org/current
TIGER Primary and Secondary Roads	Shapefile, .shp	2019	United States Census Bureau	United States, NY, VT, NH, MA, CT, RI	NA	https://www.census.gov/cgi-bin/geo/shapefiles/index.php

Table 3. Protected area boundary layers used to create core areas.

Layer	**Type**	**Year**	**Source**	**Link/Citation**
United States Protected Area Database (PAD-US), Edition 2.0	Shapefile, .shp	2018	USGS	https://www.usgs.gov/core-science-systems/science-analytics-and-synthesis/gap/science/pad-us-data-download?qt-science_center_objects=0#qt-science_center_objects
New York Protected Areas Database (NYPAD)	Shapefile, .shp	2018	New York Natural Heritage Program	http://nypad.org/Download/GDBv1.4
New York Department of Environmental Conservation Lands	Shapefile, .shp	2018	New York Department of Conservation	https://gis.ny.gov/gisdata/inventories/details.cfm?DSID=1114
New York Office of Parks, Recreation, and Historic Preservation (OPRHP)	Shapefile, .shp	2018	New York OPRHP	https://gis.ny.gov/gisdata/inventories/details.cfm?DSID=430

Table 4. Protected areas prioritization layers.

Layer	**Type**	**Year**	**Source**	**Link/Citation**
Large Culverts Feb 2019	Shapefile, .shp	2019	New York State Department of Transportation	https://gis.ny.gov/gisdata/inventories/details.cfm?DSID=1255
MHLC Public Preserves 2019	Shapefile, .shp	2019	Mohawk Hudson Land Conservancy	Communication with MHLC

Appendix C. Species Distribution Model Inputs

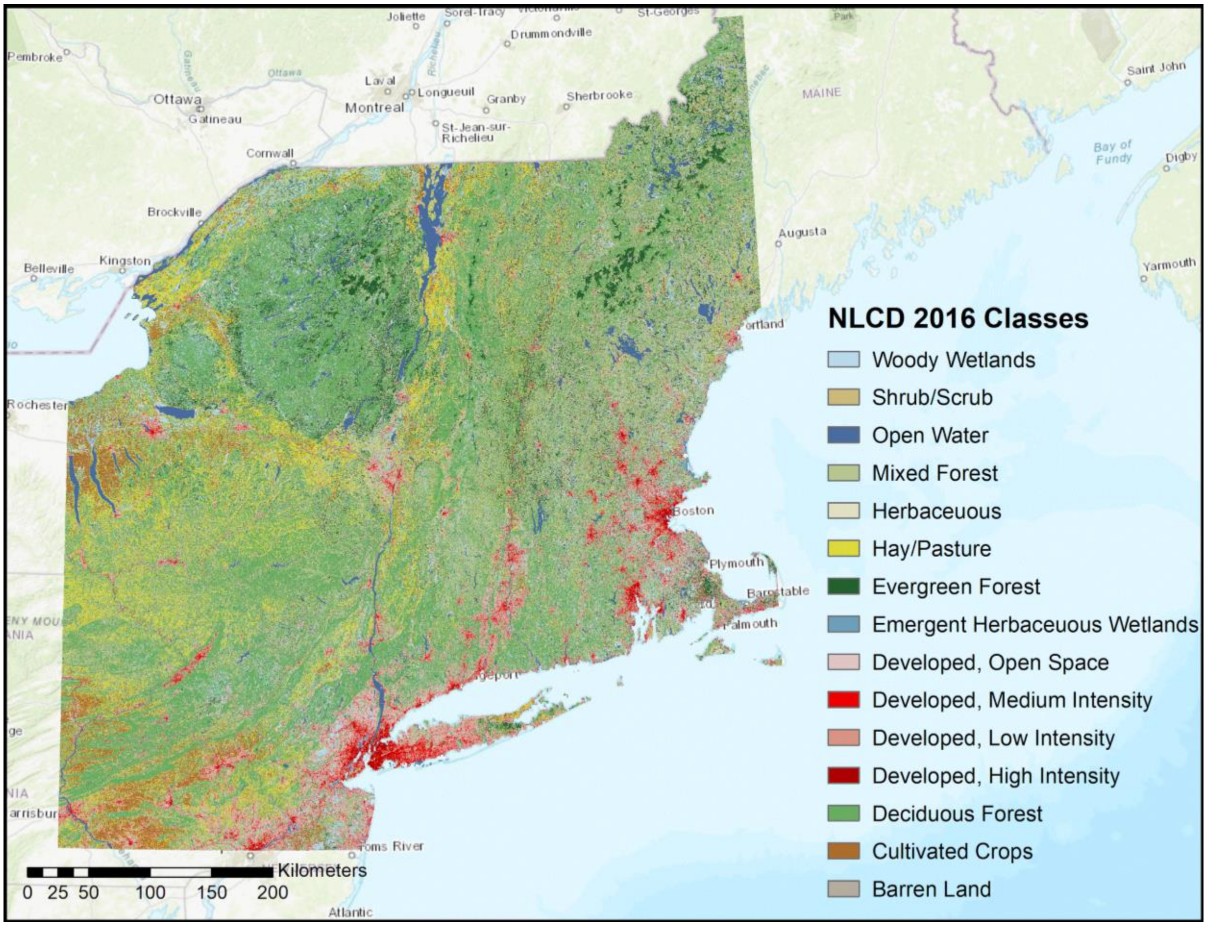


Figure 1. NLCD land cover classes in the Maxent processing extent.

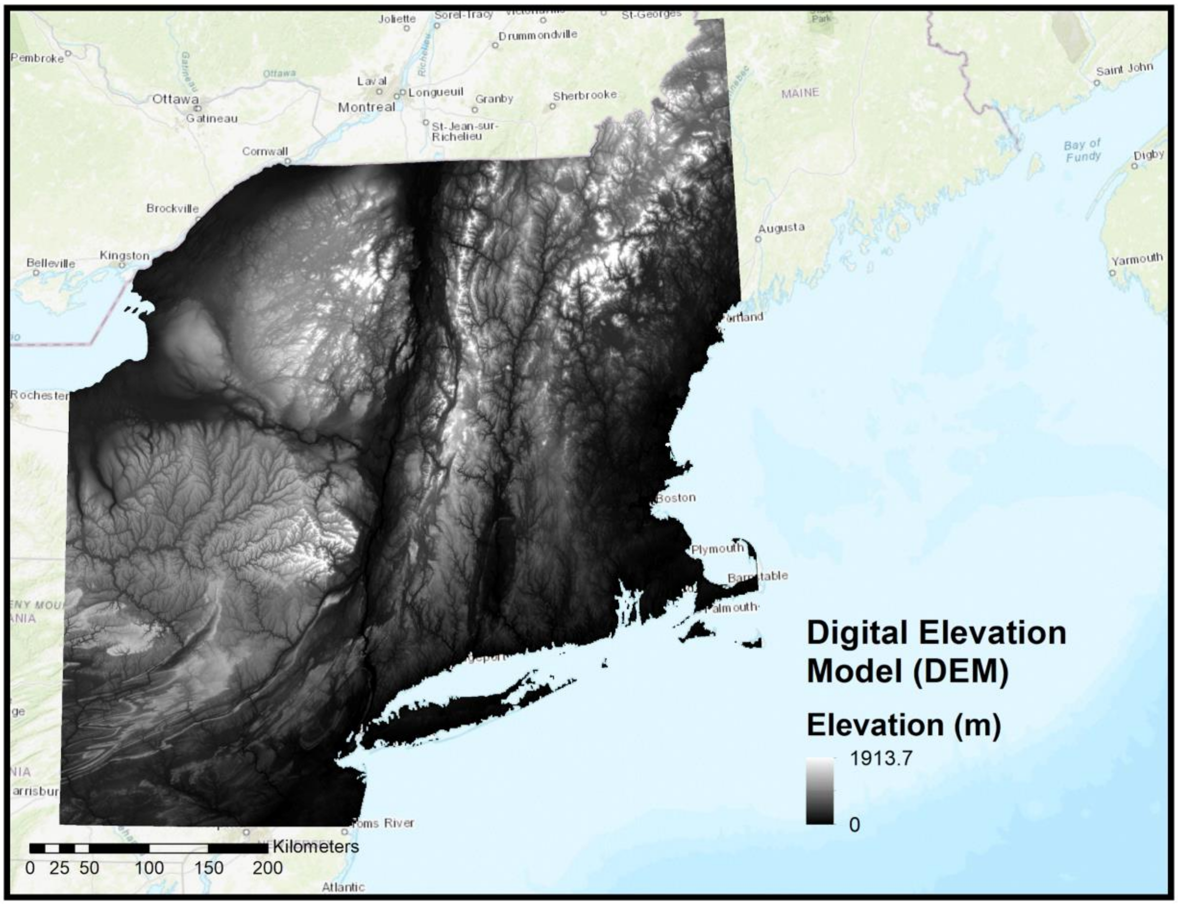


Figure 2. Digital elevation model (DEM) in the Maxent processing extent.

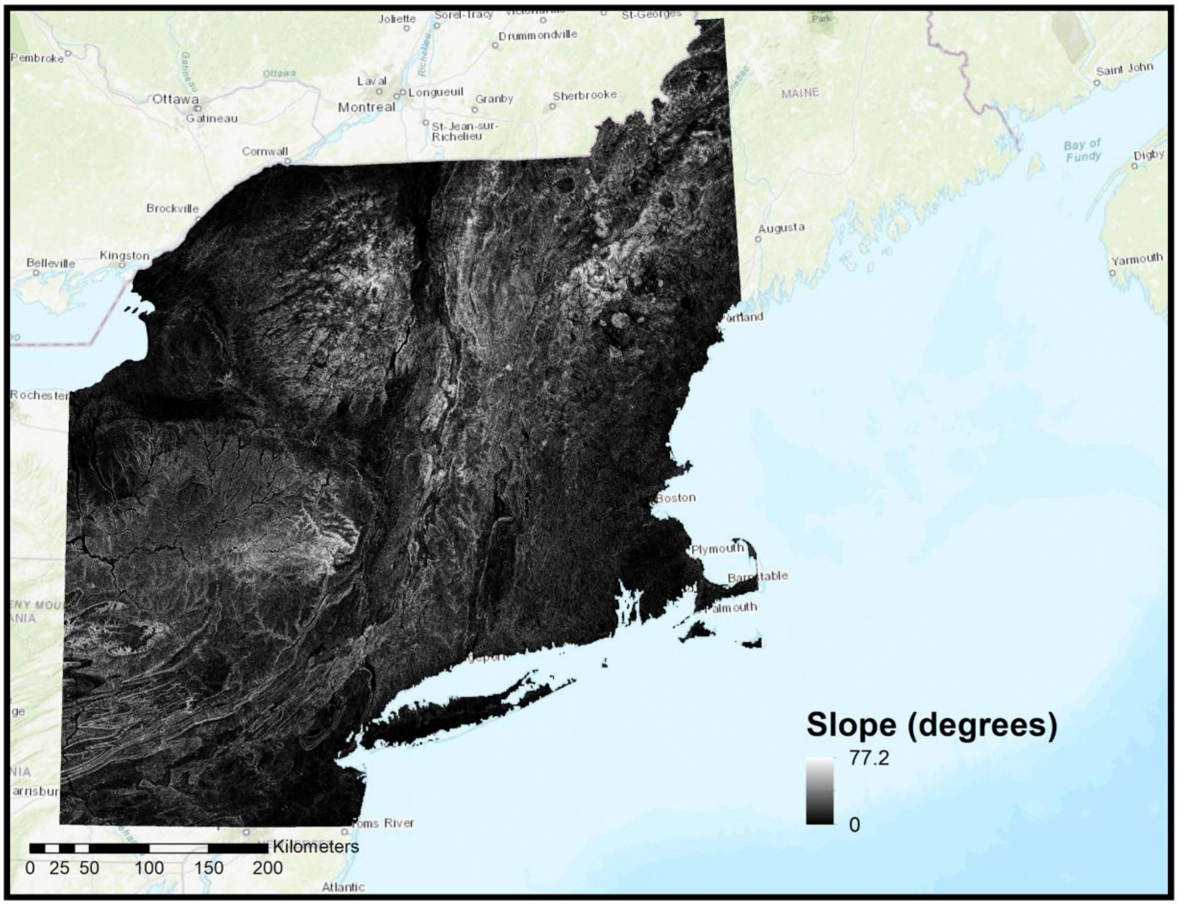


Figure 3. Slope in degrees derived from the digital elevation model (DEM) in the Maxent processing extent.

Appendix D. Species Distribution Model Outputs

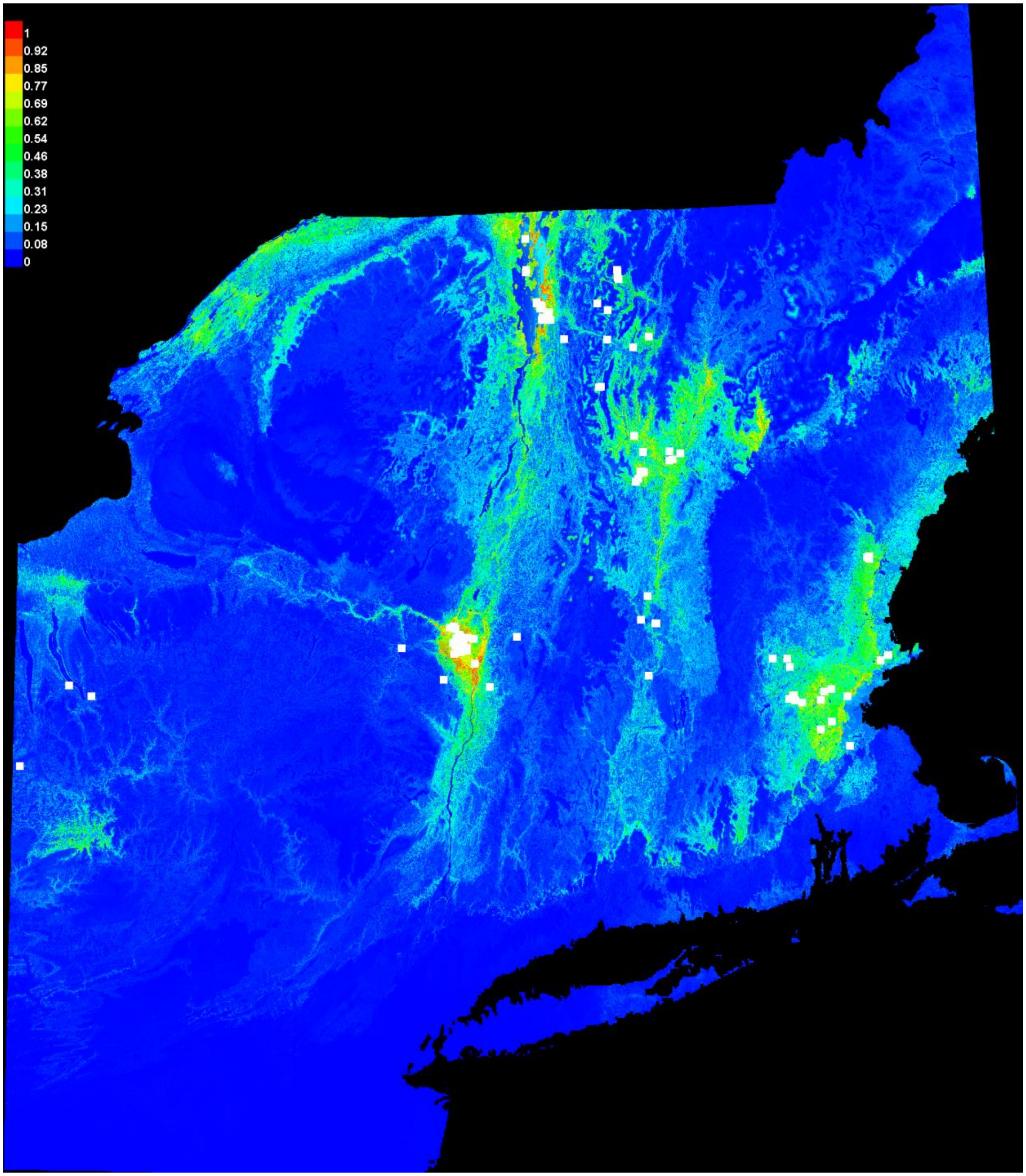


Figure 1. Maxent output from fisher observation points and all environmental layers. Red to green areas show locations with conditions that better predict fisher presence. Bluer areas poorly predict fisher presence. White dots represent presence data locations used for model training.

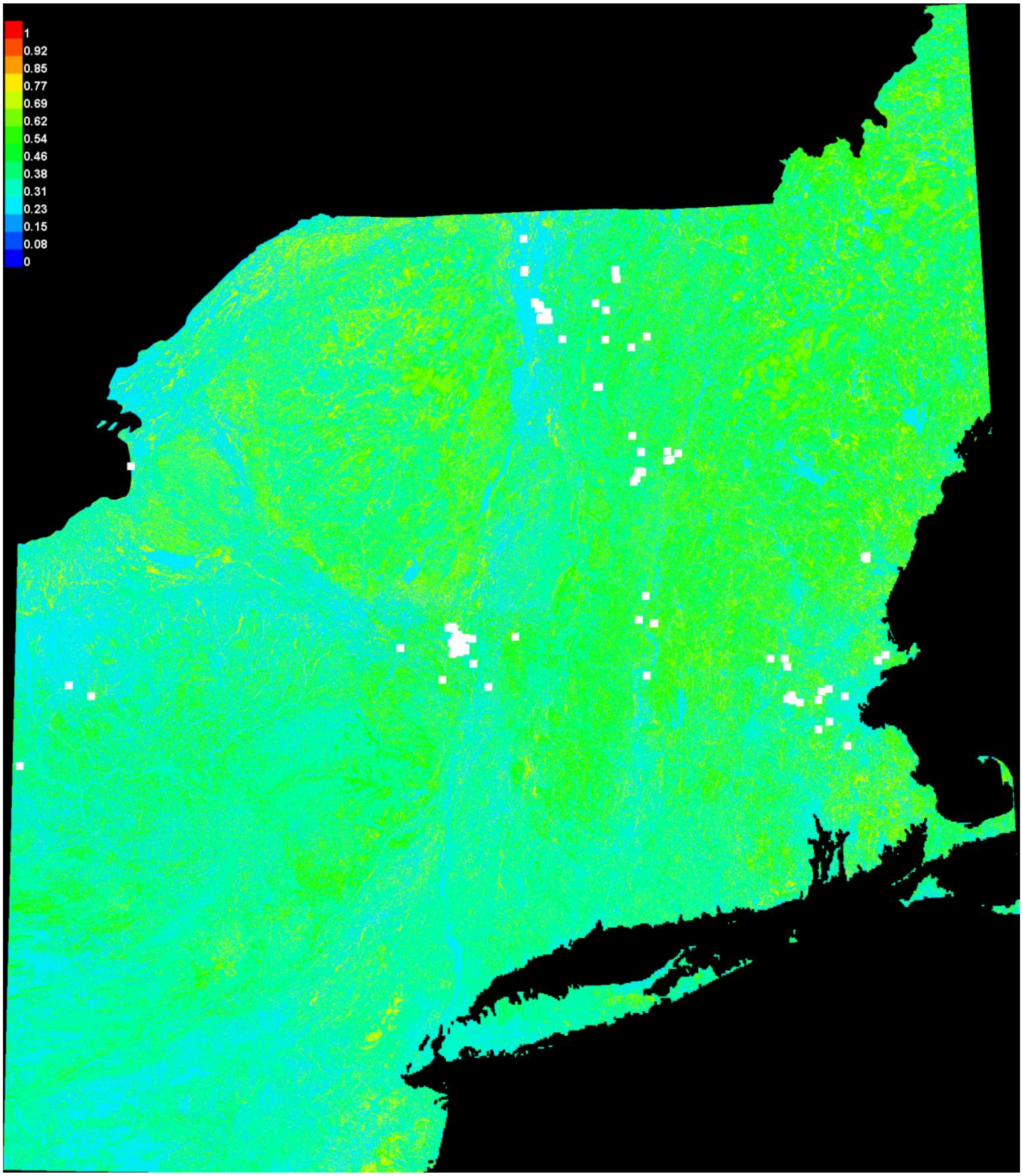


Figure 2. Maxent output from fisher observation points and NLCD environmental layer. Red to green areas show locations with conditions that better predict fisher presence. Bluer areas poorly predict fisher presence. White dots represent presence data locations used for model training.

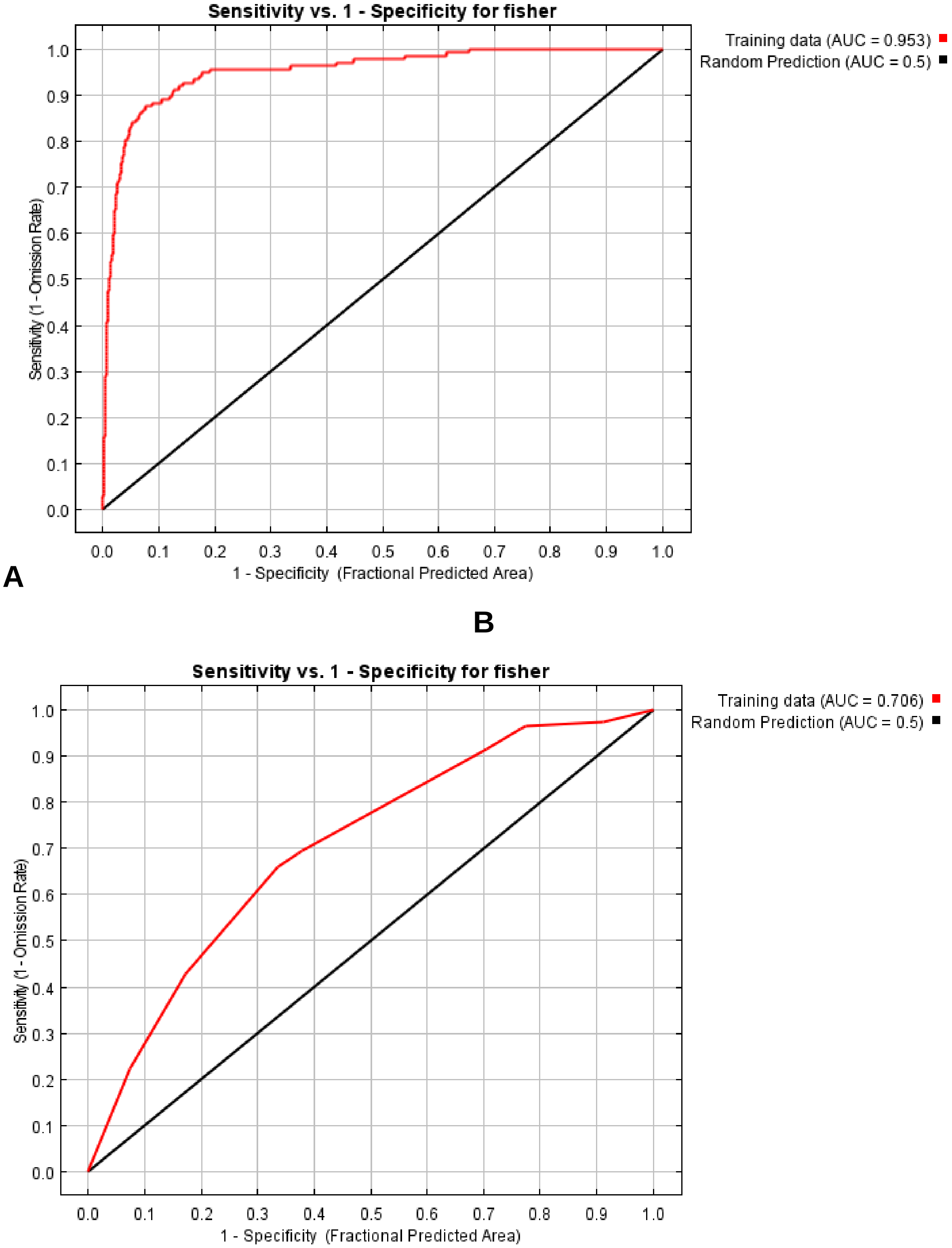


Figure 3. Model fit graphs for the Maxent models generated with (A) all environmental layers and (B) NLCD only.

Appendix E. Expert Opinion Resistance Values

Table 1. NLCD resistance values based on Nussey and Noseworthy (2018) were used in expert opinion runs 2 and 3.

		Habitat Suitability Score (Values 0 - 100)			Resistance Value (100 - Suitability Score)		
NCC Land Classification Crosswalk	**NLCD Land Cover Type**	**Fisher**	**Bear**	**Bobcat**	**Fisher**	**Bear**	**Bobcat**
Lake or Pond	Open Water	20	20	10	80	80	90
Human Settlement	Developed, Open Space	0	0	0	100	100	100
Human Settlement	Developed, Low Intensity	0	0	0	100	100	100
Human Settlement	Developed, Medium Intensity	0	0	0	100	100	100
Human Settlement	Developed, High Intensity	0	0	0	100	100	100
Soil / Gravel Extraction	Barren Land	20	20	10	80	80	90
*	Deciduous Forest	90	90	90	10	10	10
*	Evergreen Forest	100	90	90	0	10	10
*	Mixed Forest	100	90	90	0	10	10
Shrubland	Shrub/Scrub	70	90	100	30	10	0
**	Herbaceous	20	20	20	80	80	80
Agriculture	Hay/Pasture	0	30	40	100	70	60
Agriculture	Cultivated Crops	0	30	40	100	70	60
Forested Wetland	Woody Wetlands	50	90	80	50	10	20
Emergent Wetland	Emergent Herbaceous Wetlands	30	45	50	70	55	50

* Values assigned from maximum habitat suitability in forest category.

**Values assigned 20 as though similar to Barren Land.

Table 2. NLCD resistance values based on Tear et al. (2006) were used in expert opinion runs 4 and 5.

		Habitat Suitability Score (Values 0 - 100)			Resistance Value (100 - Suitability Score)		
Tear et al. 2006 Classification Crosswalk	**NLCD Land Cover Type**	**Fisher**	**Bear**	**Bobcat**	**Fisher**	**Bear**	**Bobcat**
Lakes[a, b]	Open Water	30	47	10	70	53	90
Developed[b]	Developed, Open Space	0	0	0	100	100	100
Developed[b]	Developed, Low Intensity	0	0	0	100	100	100
Developed[b]	Developed, Medium Intensity	0	0	0	100	100	100
Developed[b]	Developed, High Intensity	0	0	0	100	100	100
Developed/Paved Roads[b]	Barren Land	30	20	20	70	80	80
Upland/Lowland deciduous forest	Deciduous Forest	70	100	60	30	0	40
Upland/Lowland coniferous forest[d]	Evergreen Forest	100	70	100	0	30	0
Upland/Lowland mixed forest[d]	Mixed Forest	100	90	80	0	10	20
Upland scrub/ shrub	Shrub/Scrub	50	80	80	50	20	20
Grassland (hayfield) [b,e]	Herbaceous	50	35	47	50	65	53
Cultivated (agriculture/ crop rows)[c]	Hay/Pasture	30	30	47	70	70	53
Cultivated (agriculture/ crop rows)[c]	Cultivated Crops	30	30	47	70	70	53
Shrub Swamp/Riparian (mean)	Woody Wetlands	40	70	80	60	30	20
Open Wetland	Emergent Herbaceous Wetlands	30	50	30	70	50	70

Values based on Tear et al. 2006, multiplied by 10.

[a] Mean of values for large, medium, and small lakes.

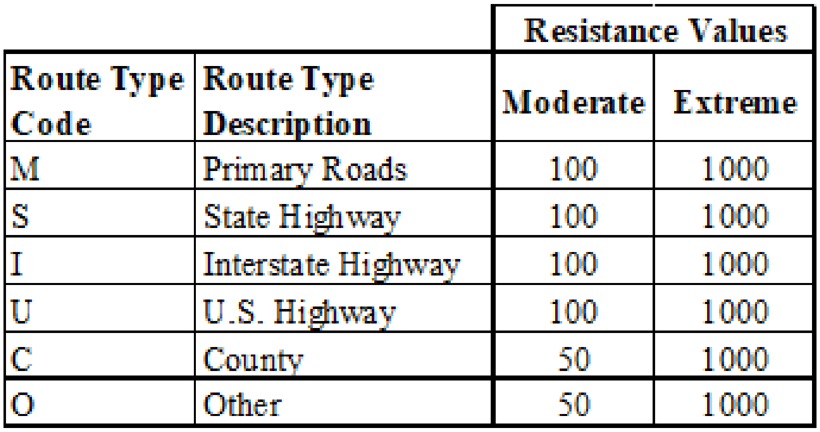
[b] No suitability score given so either assigned the inverse of barrier hardness value or zero.

[c] Fisher: Mean of values for all cultivated area widths. Bobcat: Mean of values for all buffered distances.

[d] Bear: Mean of upland and lowland values.

[e] Bear: Mean of values >75m or <75m from forest cover.

Table 3. Additional road resistance values added to the Linkage Mapper analysis. Moderate resistance values were added to Runs 2 and 4. Extreme road values were added to Runs 3 and 5 based on analysis done by Nogiere et al. (2015).



		Resistance Values	
Route Type Code	**Route Type Description**	**Moderate**	**Extreme**
M	Primary Roads	100	1000
S	State Highway	100	1000
I	Interstate Highway	100	1000
U	U.S. Highway	100	1000
C	County	50	1000
O	Other	50	1000

Appendix F. Resistance Layers and Linkage Mapper Corridors

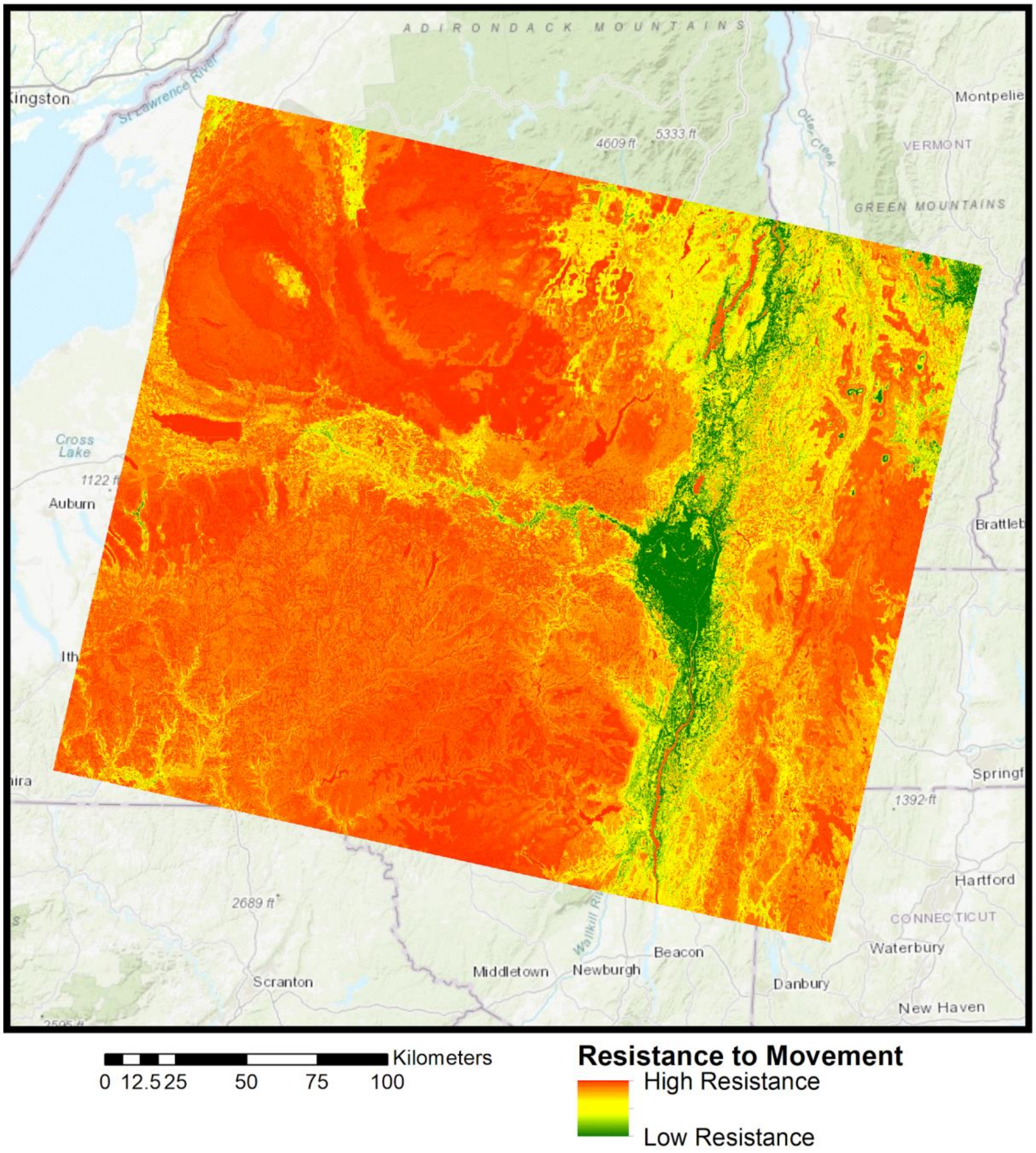


Figure 1. Resistance layer from Maxent species distribution model with all environmental layers.

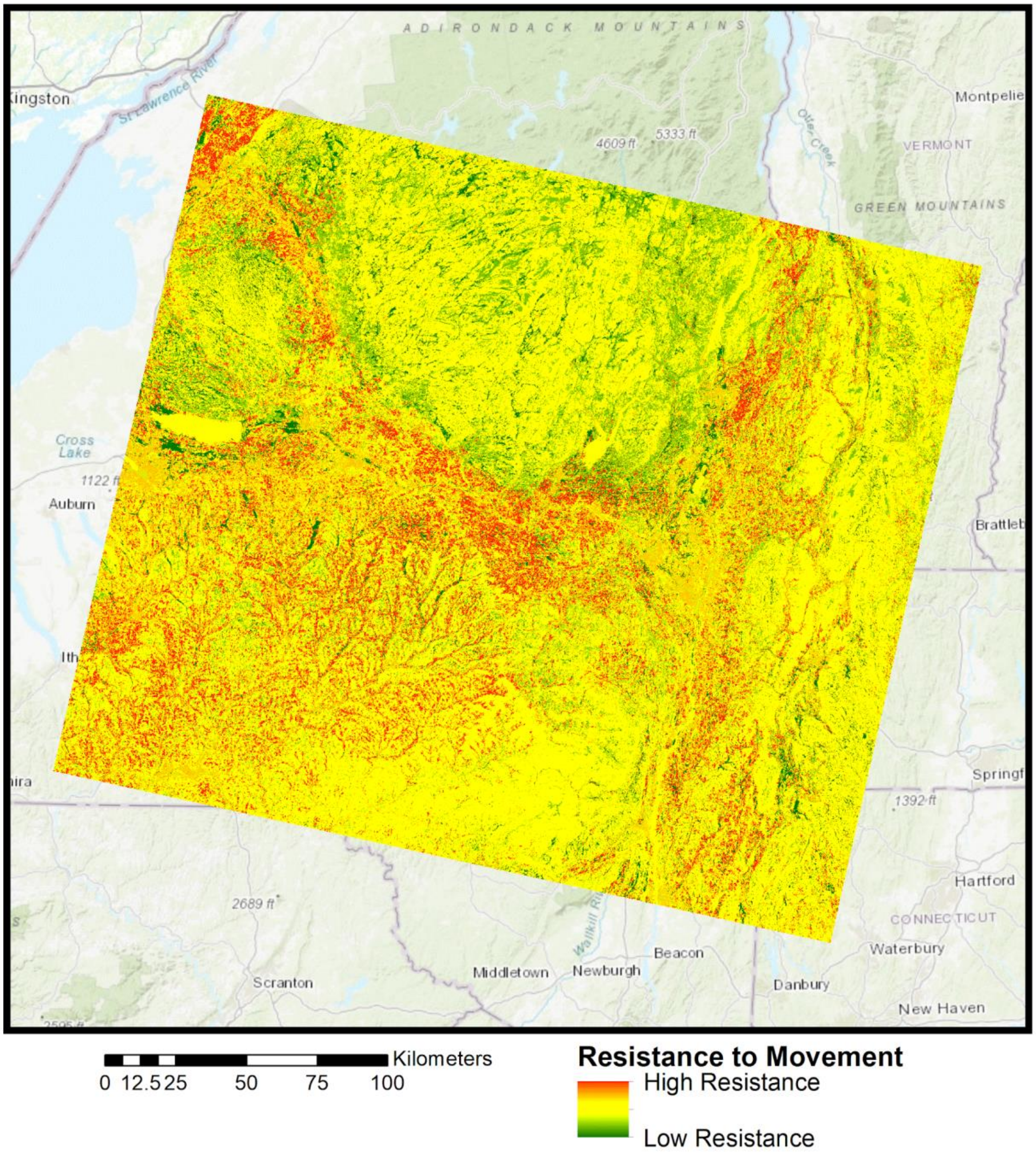


Figure 2. Resistance layer from Maxent species distribution model with only NLCD.

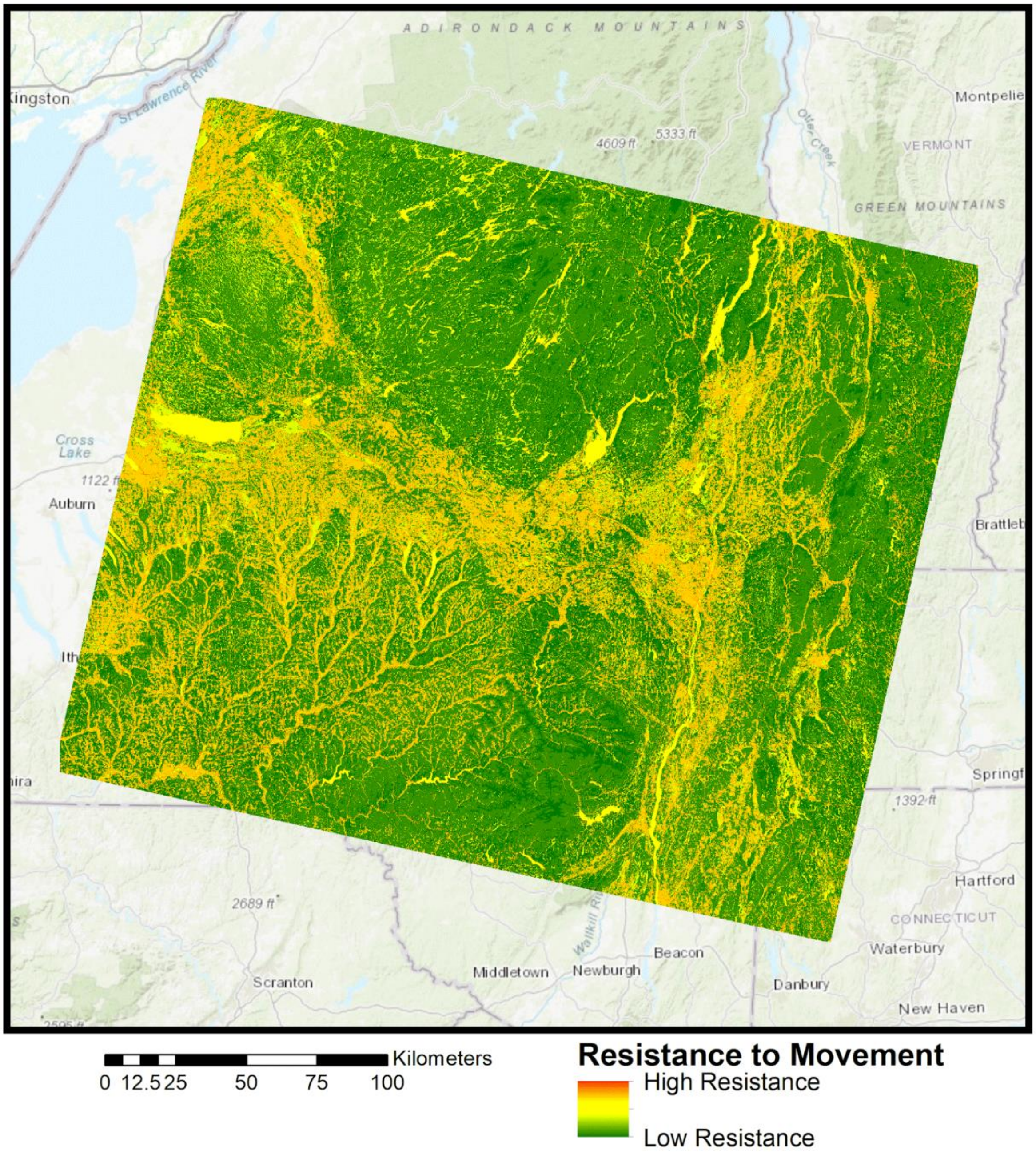


Figure 3. Resistance layer from fisher expert opinion model using NLCD resistance values derived from Nussey and Noseworthy (2018) and the additional moderate roads layer (Run 2).

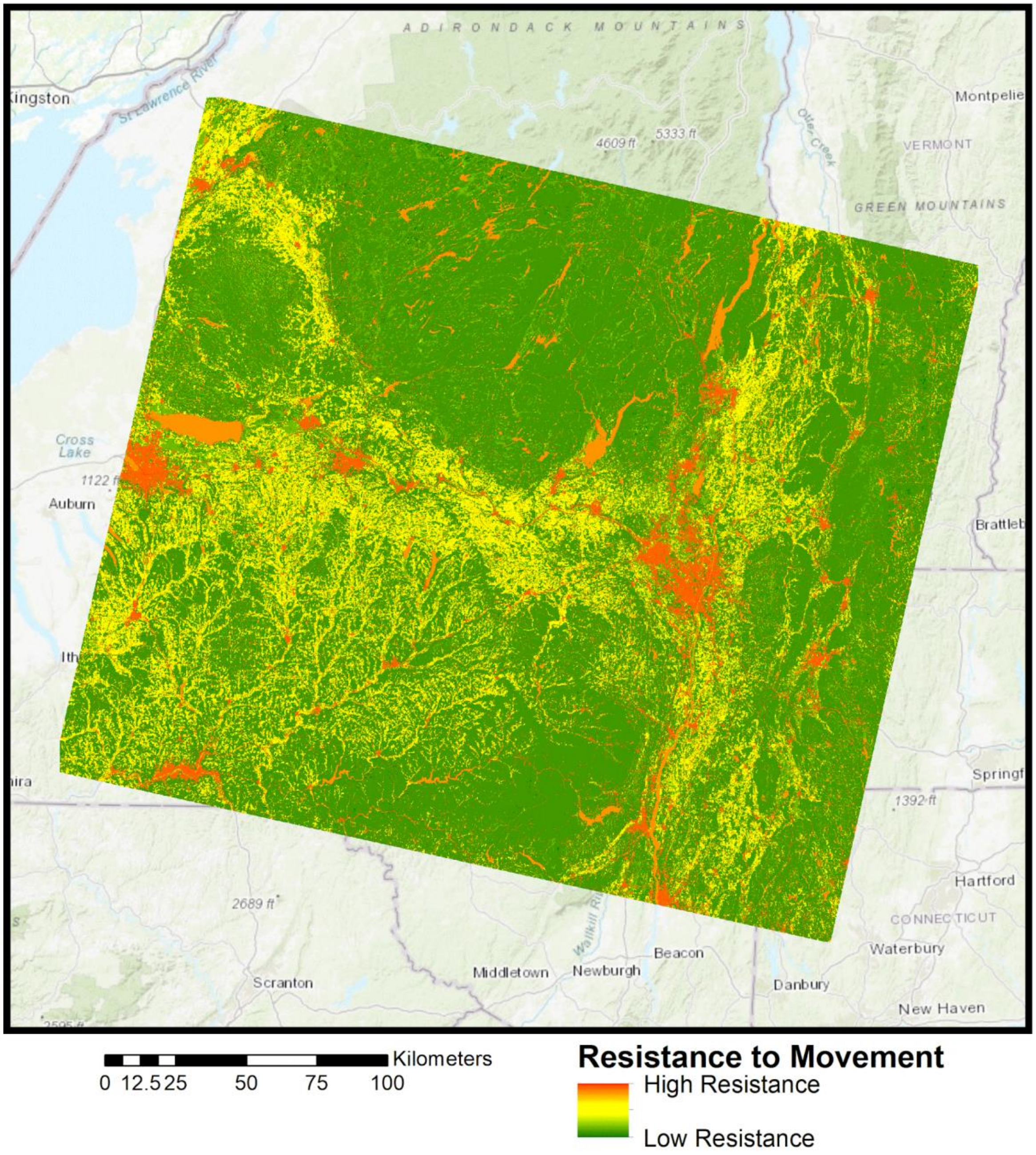


Figure 4. Resistance layer from bobcat expert opinion model using NLCD resistance values derived from Nussey and Noseworthy (2018) and the additional moderate roads layer (Run 2).

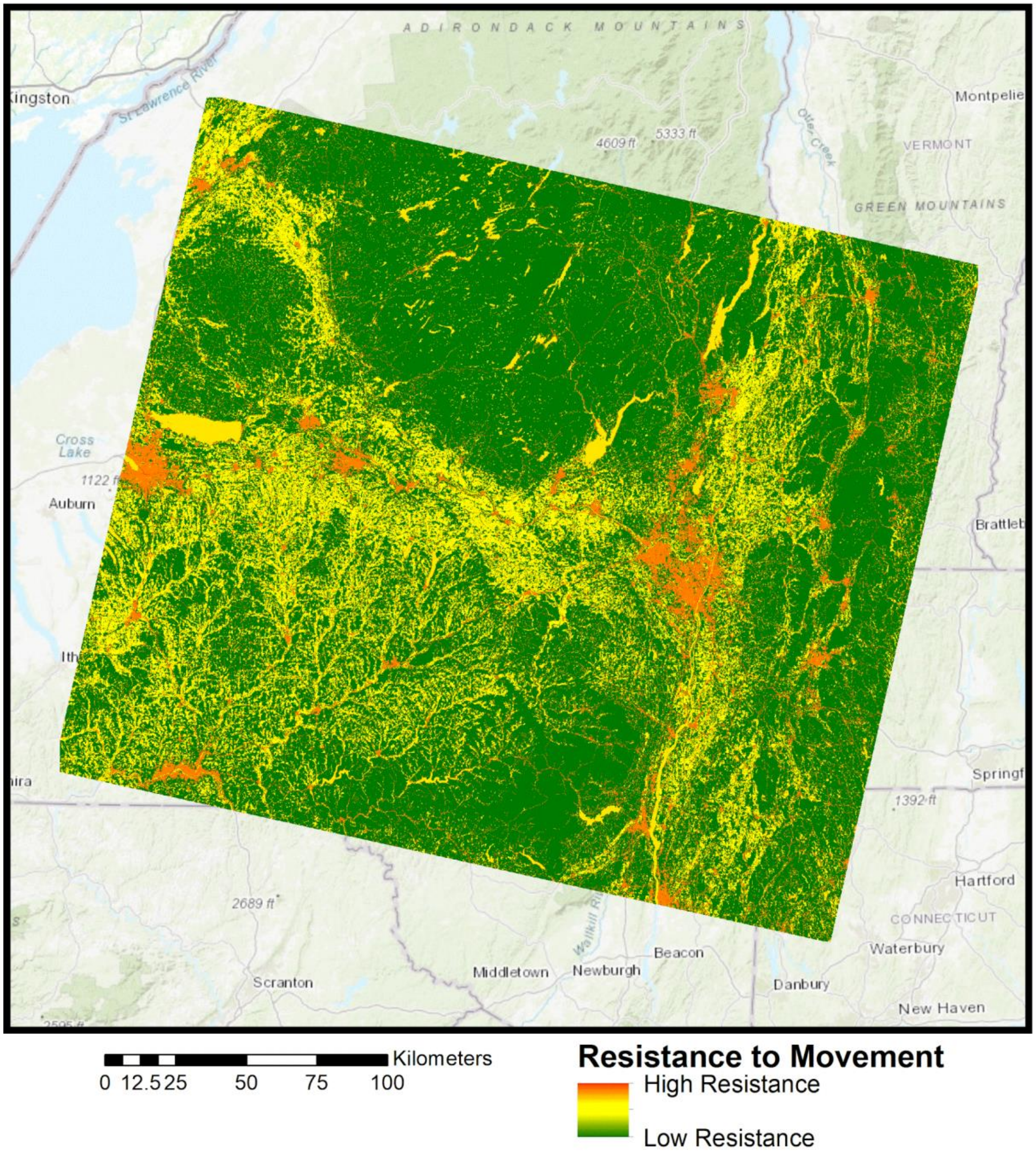


Figure 5. Resistance layer from bear expert opinion model using NLCD resistance values derived from Nussey and Noseworthy (2018) and the additional moderate roads layer (Run 2).

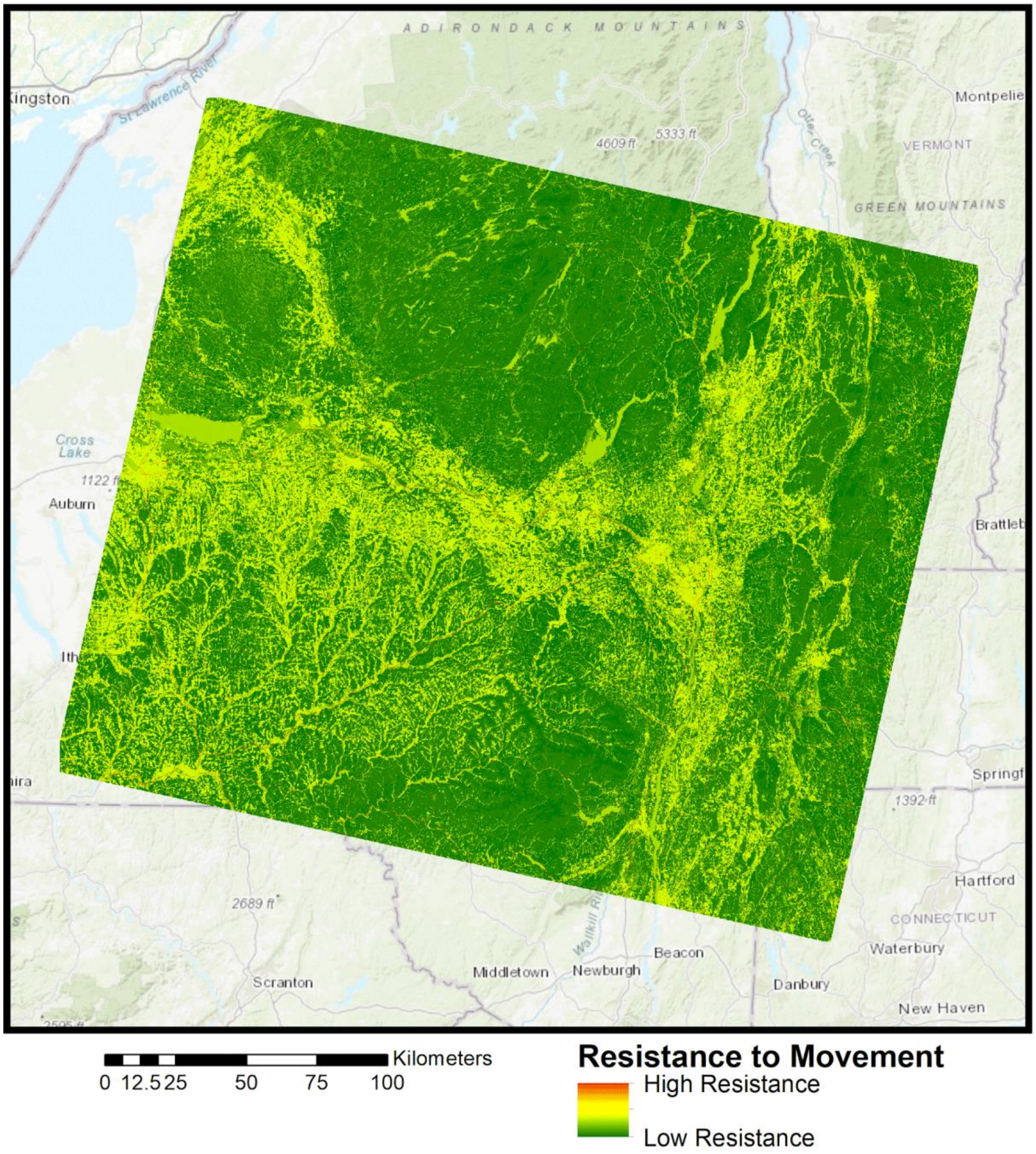


Figure 6. Resistance layer from fisher expert opinion model using NLCD resistance values derived from Nussey and Noseworthy (2018) and the additional extreme roads layer (Run 3).

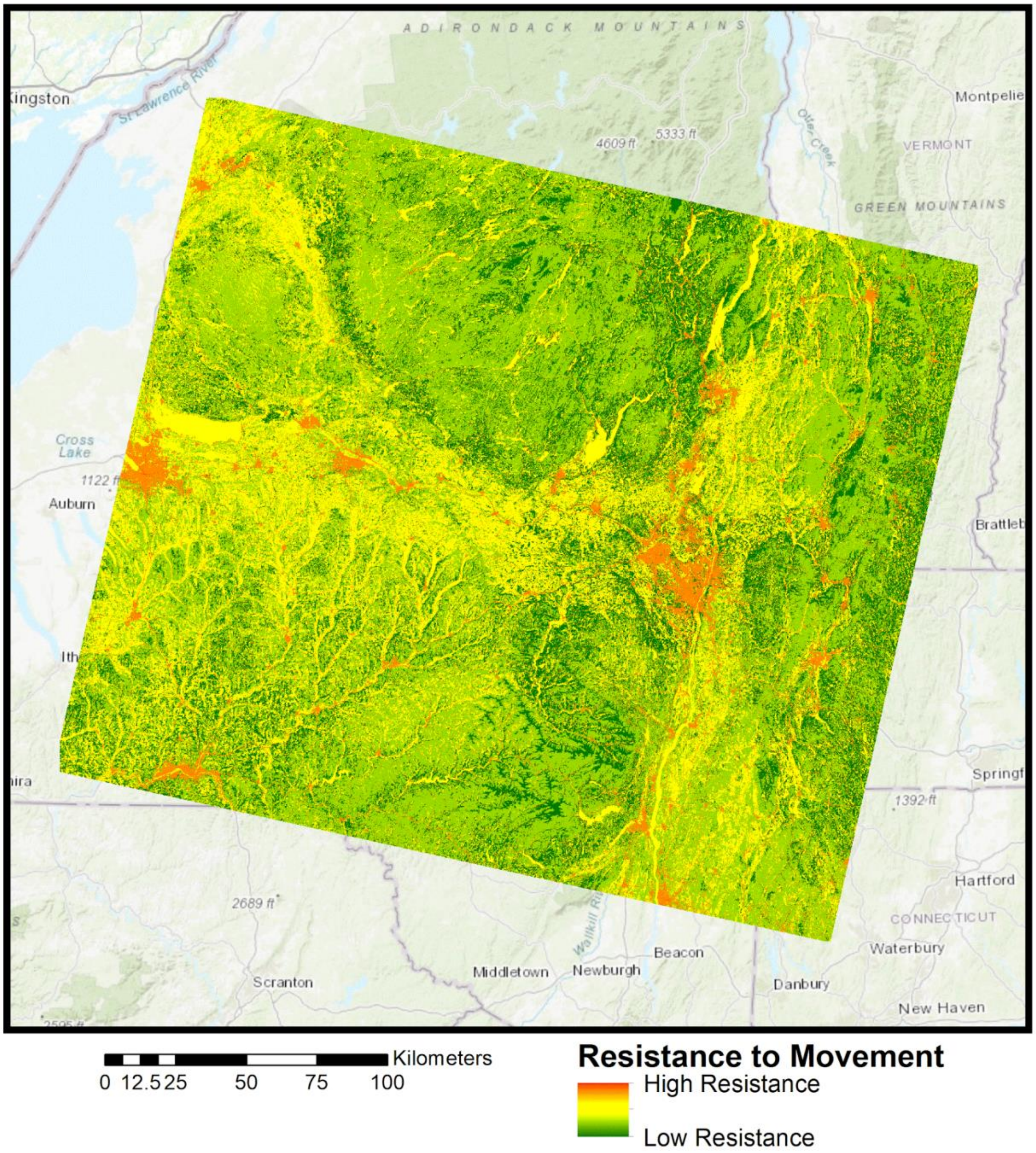


Figure 7. Resistance layer from fisher expert opinion model using NLCD resistance values derived from Tear et al. (2006) and the additional moderate roads layer (Run 4).

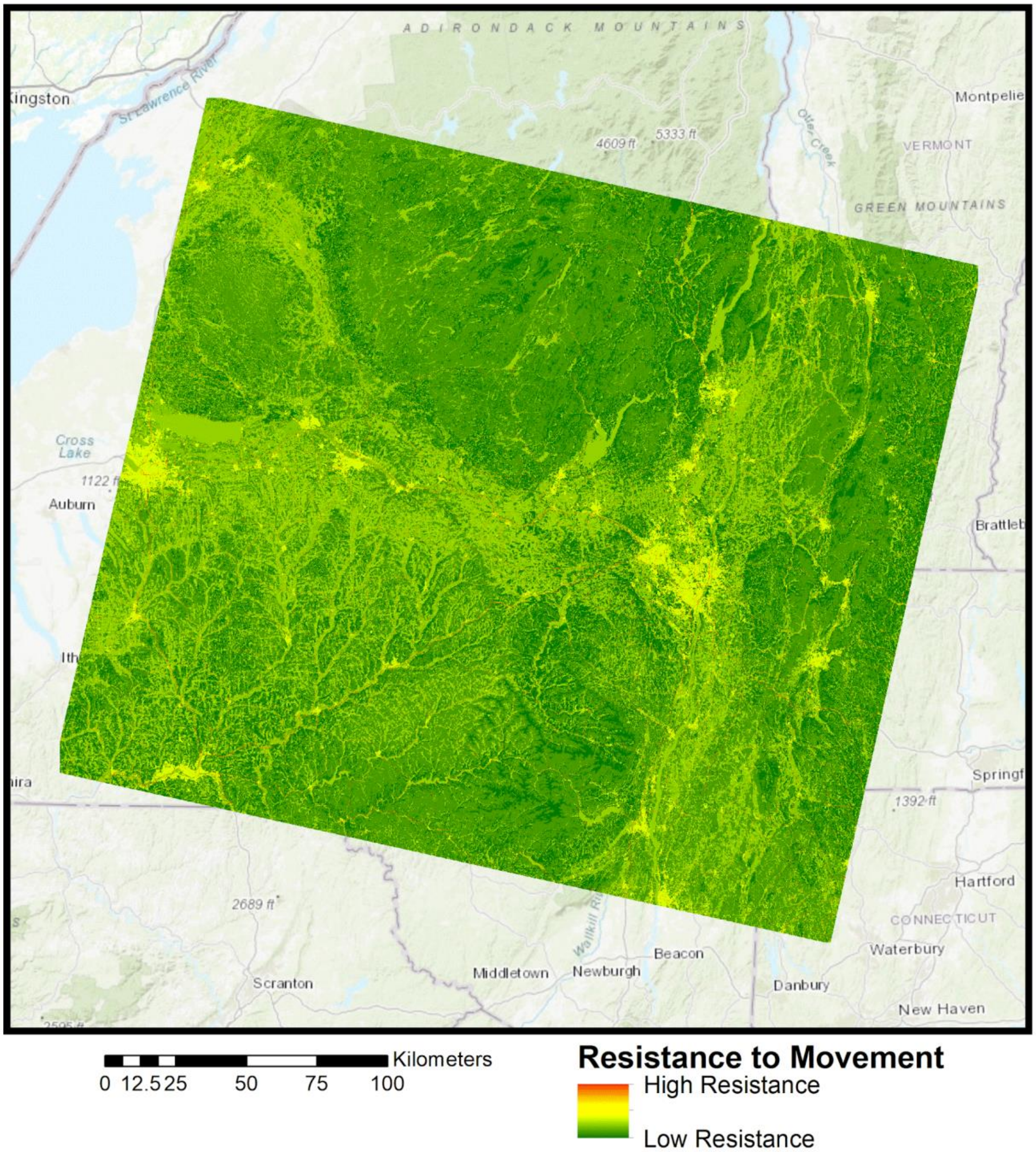


Figure 8. Resistance layer from fisher expert opinion model using NLCD resistance values derived from Tear et al. (2006) and the additional extreme roads layer (Run 5).

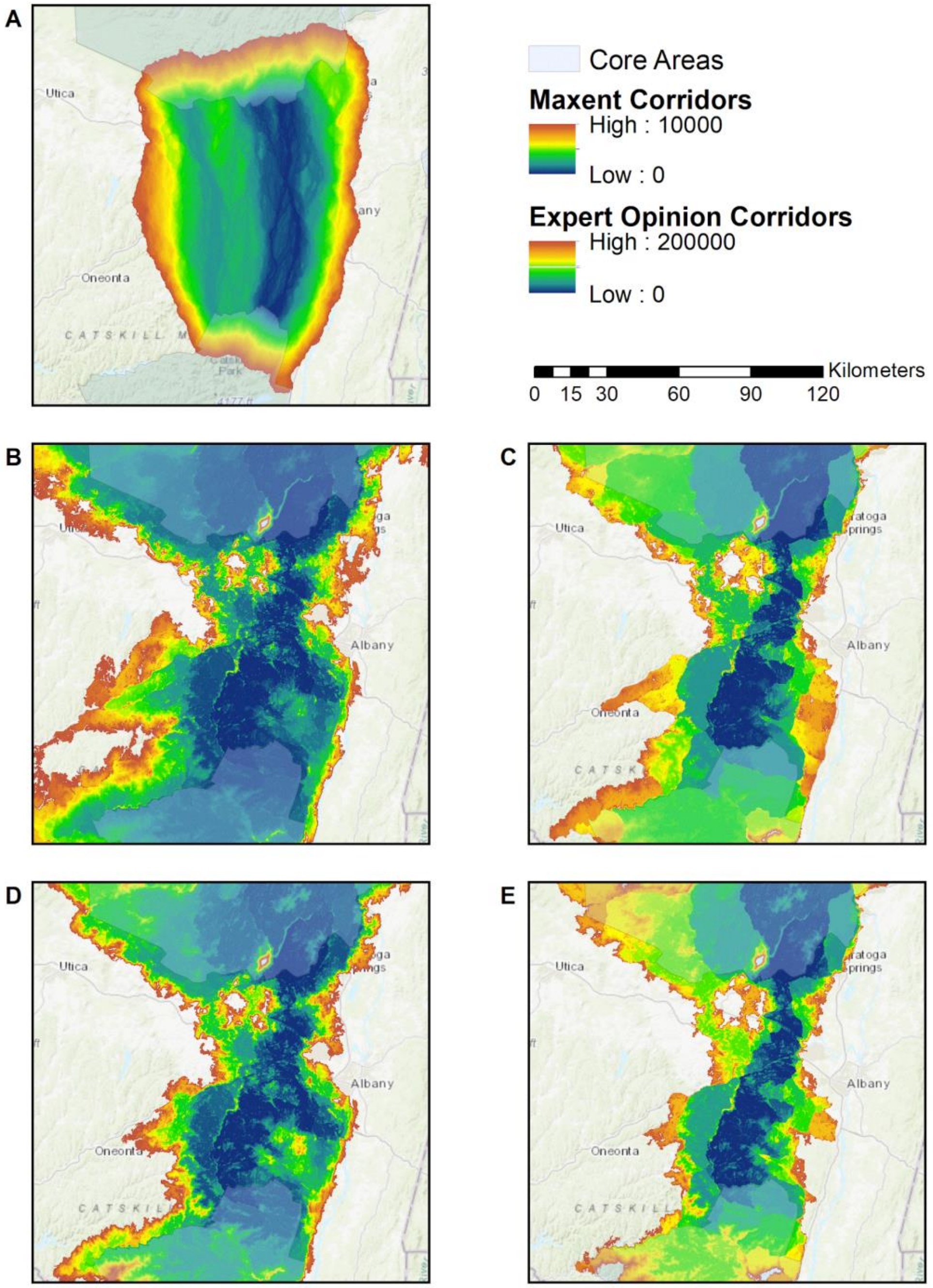


Figure 9. Predicted corridors for fisher derived from sensitivity analysis resistance layers. Corridor (A) was derived from the NLCD-only Maxent resistance layer (Appendix F, Figure 2) and truncated at a relative travel cost value of 10,000, so the corridor boundaries were comparable with the expert opinion-based corridors. The expert opinion-based corridors were automatically truncated at a relative travel cost value of 200,000. Corridors (B) and (C) were derived from the Nussey and Noseworthy (2018) land cover resistance values and the additional moderate (B; Run 2; Appendix F, Figure 3) and extreme (C; Run 3; Appendix F, Figure 6) road layers. Corridors (D) and (E) were derived from the Tear et al. (2006) land cover resistance values and the additional moderate (D; Run 4; Appendix F, Figure 7) and extreme (E; Run 4; Appendix F, Figure 8) road layers.

Appendix G. Potential Mohawk Valley Linkage Boundaries

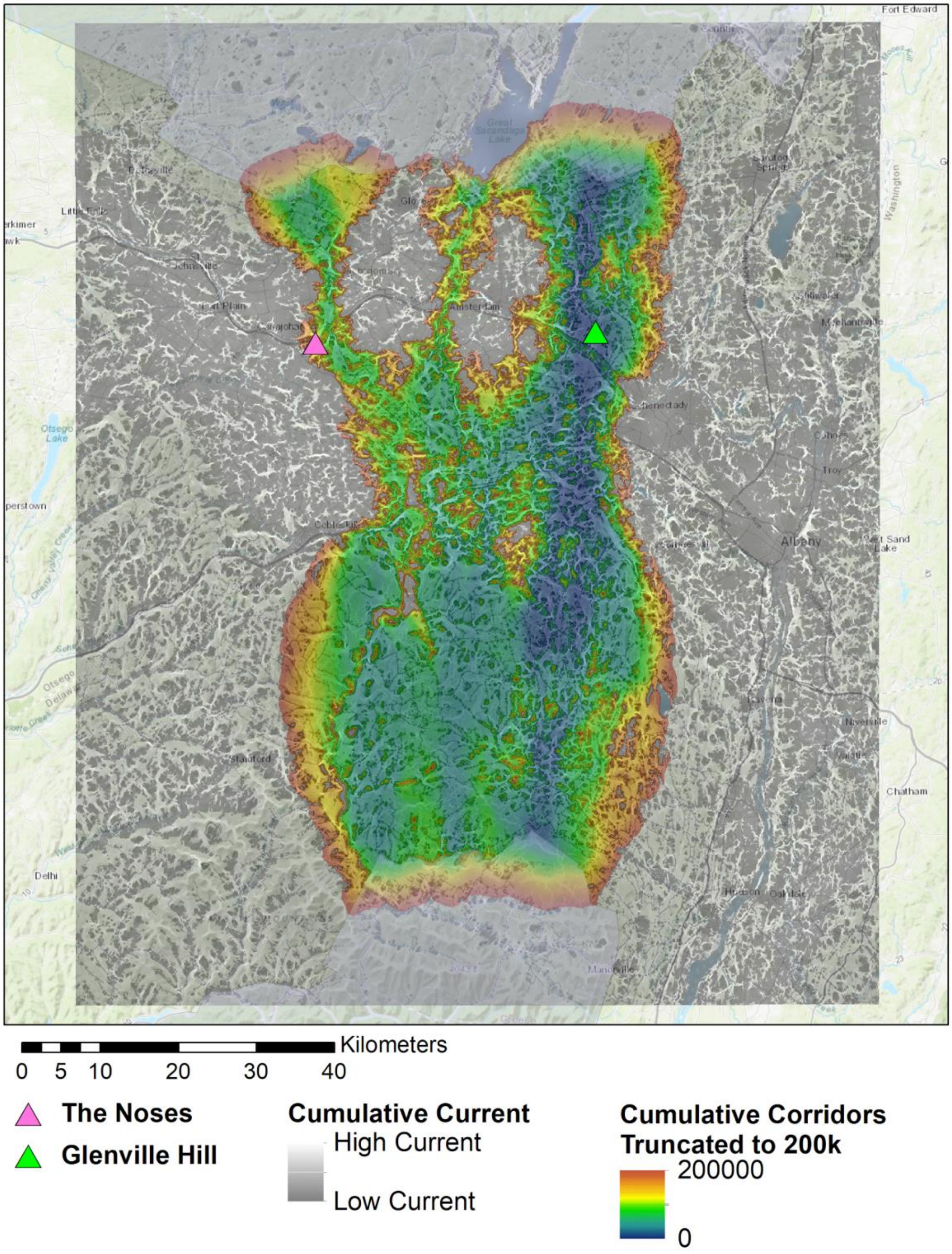


Figure 1. Linkage Mapper and Omniscape outputs for all three focal species were combined to visualize proposed linkage area boundaries. Cumulative least cost corridors are truncated to a travel cost of 200,000.

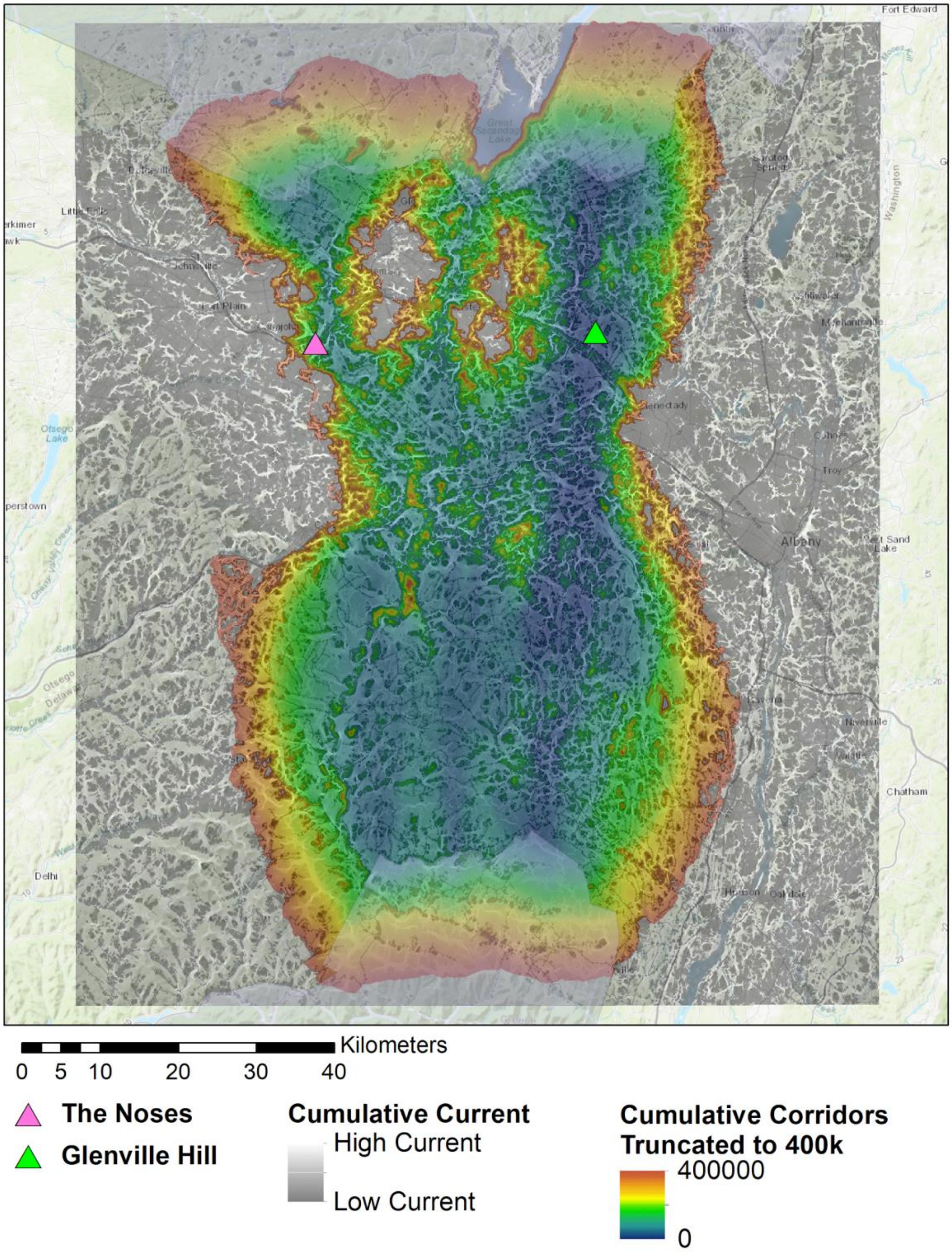


Figure 2. Linkage Mapper and Omniscape outputs for all three focal species were combined to visualize proposed linkage area boundaries. Cumulative least cost corridors are truncated to a travel cost of 400,000.

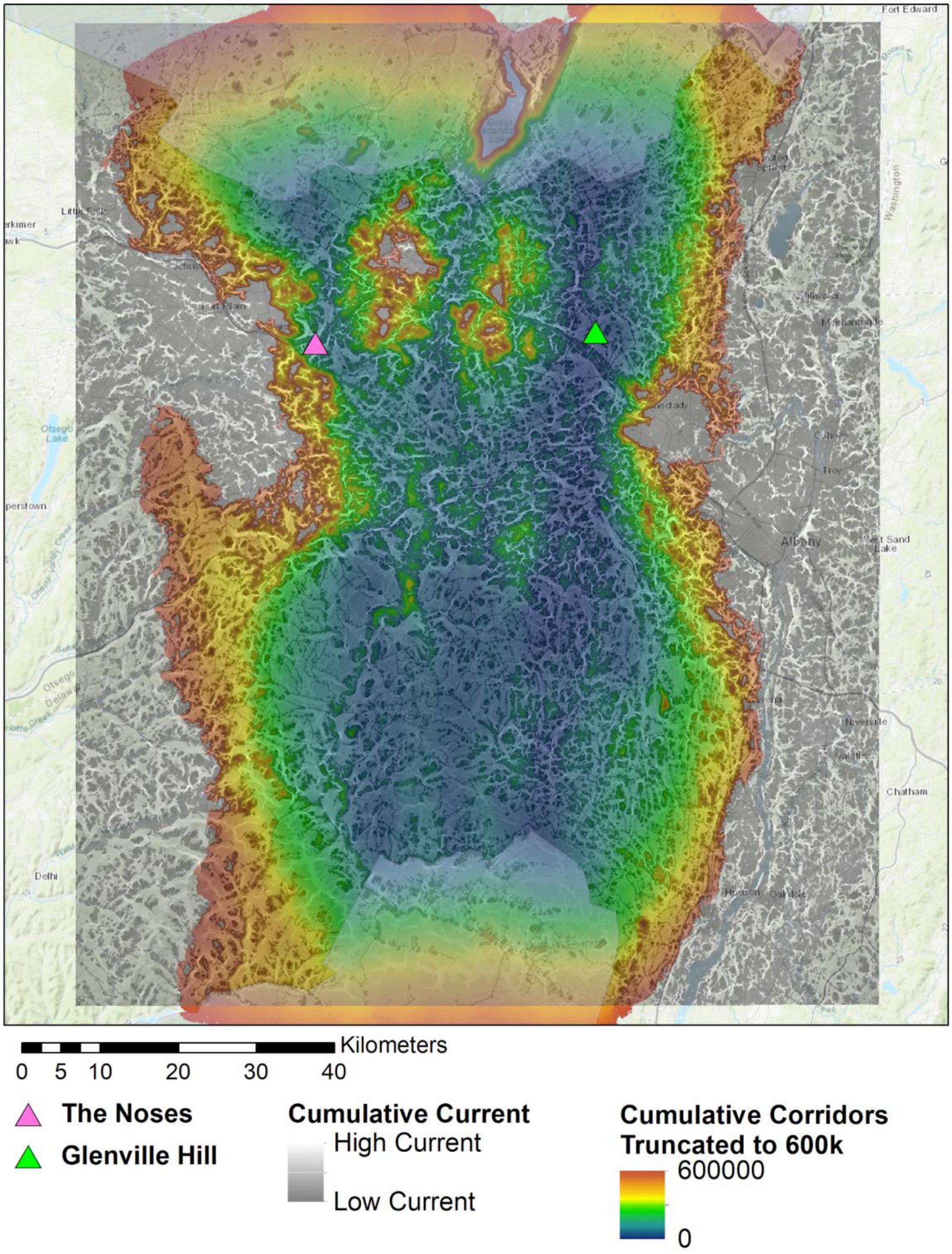


Figure 3. Linkage Mapper and Omniscape outputs for all three focal species were combined to visualize proposed linkage area boundaries. Cumulative least cost corridors are truncated to a travel cost of 600,000.

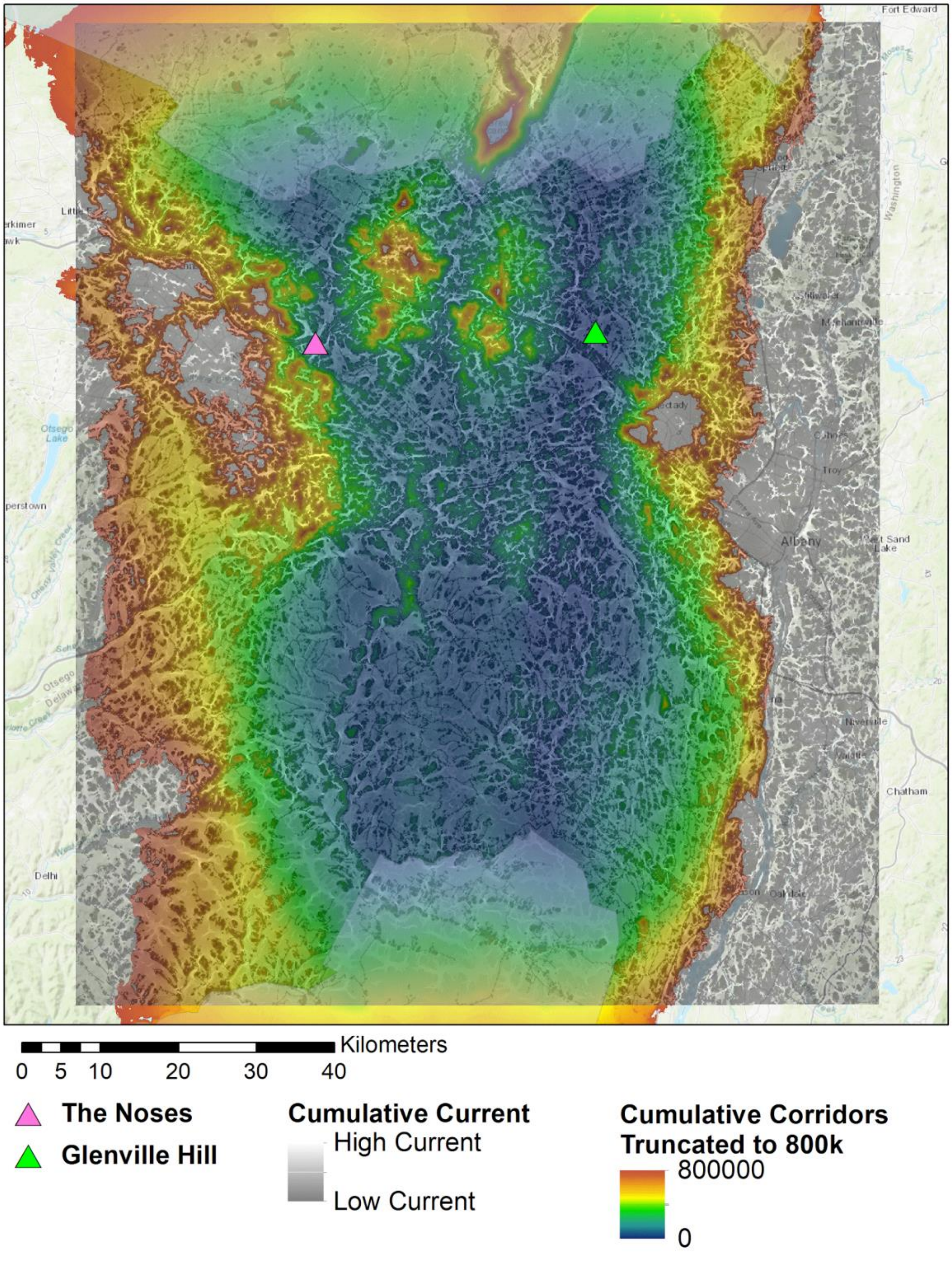


Figure 4. Linkage Mapper and Omniscape outputs for all three focal species were combined to visualize proposed linkage area boundaries. Cumulative least cost corridors are truncated to a travel cost of 800,000.