Assessing Urban Habitat Connectivity: Using Circuit Theory to Model Blanding's Turtle Movement

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Senior Comprehensive Exercise

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Environmental Studies

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March 9, 2016

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Abstract

With the burgeoning growth of urbanization, urban landscapes have become more heterogeneous and less suitable for nonhuman organisms. This translates into isolated patches of suitable habitat interrupted by anthropogenic infrastructure. The loss of continuous habitats has created a myriad of negative ecological effects, including loss of genetic diversity, overexploitation of local resources, and local extinction. In response to these concerns, ecologists have begun modeling habitat connectivity in order to connect isolated habitat patches and facilitate animal movement throughout highly fragmented urban areas. Although this modeling is critical, there is no standard model used. One model, based on circuit theory, has shown promise over the last ten years. In this model, animals are treated as 'current' flowing through the 'resistors' of the landscape. We selected a highly fragmented area - the Twin Cities Metro Region - in order to test the applicability of circuit theory to our target species: the Blanding's Turtle. We concluded that the model is highly effective at incorporating several different resistance layers based on existing landscape features while accurately predicting high-movement pathways. Our final output models contain important insight on dispersal patterns for the species, and have the potential to aid in future conservation efforts.

Acknowledgments

We would like to extend our most sincere thanks to those who have helped us with this project. This includes our two advisors, Melissa Eblen-Zaya and Tsegaye Nega, as well as additional Carleton faculty and staff Wei-Hsin Fu, Dan Hernandez, Kim Smith, and Doug Foxgrover. We would also like to thank the Minnesota Department of Natural Resources, particularly Lisa Joyal, for providing us with the turtle sightings data from which we based our model.*

**Due to the sensitive nature of our data, we are not be able to publish any location-specific sighting data. Our model displays only the most likely dispersal patterns.*

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I. Introduction

In light of the rapid and continuous growth of urbanization worldwide and its attendant ecological effects, habitat connectivity has emerged as one of the most important approaches to biodiversity conservation (Baguette and Van Dyke 2007; Bailey 2007; Pressey et al. 2007; Kindlmann and Burel 2008; Rayfield et al. 2011; Luque et al. 2012; LaPoint et al. 2015). Habitat connectivity aims to connect isolated habitat patches with corridors in order to facilitate animal movement throughout highly fragmented urban areas (Beier and Noss 1998; Pascual-Hortal and Saura 2006; Hodgson et al. 2009; Fagan et al. 2016). This movement allows animals to access habitat-related resources -- such as sustenance, predator avoidance, and genetic diversity -- thereby ensuring the survival of the species (Forman and Alexander 1998; Kindlmann and Burel 2008). Connectivity, at its most fundamental level, is the degree of movement of an organism or other ecological process (e.g. gene flow) throughout the landscape (Kindlmann and Burel 2008). This is particularly important in areas where urban land cover is the dominant matrix, as urban infrastructure such as roads and fences represents significant barriers to wildlife mobility (Forman and Alexander 1998; With and King 1999; Johst et al. 2011; Rayfield et al. 2011). In highly fragmented areas, the importance of a strong connectivity model is necessary in order to create a successful representation of dispersal patterns.

Although connectivity is one of the top priorities for biodiversity conservationists, there is disagreement over the best way to quantify or apply connectivity measures (Baguette and Van Dyke 2007; Luque et al. 2012; Rayfield et al. 2012; Fagan et al. 2016). This is because any measurement of connectivity is not only scale-dependent -- both spatial and temporal -- but also a function of the organism and/or ecological process of interest. Because connectivity must incorporate both spatial and temporal factors, an extremely complicated model is necessary in order to achieve any level of accuracy. Only recently have animal physiology and features such as dispersal rates been incorporated into connectivity models to make them more robust (Calabrese and Fagan 2004; Kindlmann and Burel 2008; Dutta et al. 2015). Though other models, such as least cost modeling, have dominated the literature on connectivity, a new model based on electronic circuit theory has recently been introduced (McRae 2007; McRae and Beier 2008; McRae et al. 2008; Dutta et al. 2016). In this model, animal movements are treated as 'current,' while the landscape features are 'resistors.' It assumes an animal will move in a random pattern into the areas that offer the least resistance. In a well-suited habitat the resistance of the landscape is effectively zero, whereas highly hostile areas have a large resistance and may completely stop current (McRae and Shah 2009). This creation of unique landscape resistances based on certain characteristics allows highly heterogeneous landscapes to be effectively modeled.

The purpose of this project is to identify potential connectivity corridors for the Blanding's Turtle in the Twin Cities Metro Region using software-based circuit theory. The rationale for our approach is two-fold. First, as previously mentioned, circuit theory is likely a better model for identifying areas of high movement in highly fragmented landscapes than other connectivity models. Second, to the best of our knowledge, circuit theory has not yet been applied to the Blanding's Turtle, even though it is a threatened species. Circuit theory is particularly adept at highlighting areas that necessitate greater attention to connectivity in order to ensure Blanding's Turtles are able to cross urban infrastructure without risking their lives. We will also be able to compare Blanding's Turtles' preferred movement patterns against existing animal corridors, informing city administrators where potential areas requiring more attention lie.

Objectives

The aim of this project is to test the applicability of circuit theory in highly fragmented landscapes, helping to understand the benefits and drawbacks of this method and to identify potential connectivity corridors for Blanding's Turtles throughout the Twin Cities Metro Region. We plan to create a comprehensive connectivity model that assesses available corridors and highlights areas in need of additional focus. If this model is adequately robust, the variables and resistance layers may be applied to other highly fragmented urban environments across the US that suffer from similar anthropogenic infrastructure disruptions.

This study will focus on the following five objectives:

1. Gather and review the literature on the Blanding's Turtles movement tendencies, effective barriers, habitat requirements, and past connectivity models used
2. Acquire and preprocess data relevant to the Blanding's Turtle in the Twin Cities Metro Region, including potential resistance layers and DNR sightings
3. Determine the proper resistance scale and assign resistance values based on the literature
4. Assess the movement patterns using Circuitscape, with focus on influences by the resistance layers
5. Compare the output with existing animal corridors in the study area

II. Analytical Framework

The Importance of Habitat Connectivity

Species preservation is incredibly dependent on the ability of individuals to access habitats and resources necessary for survival. One measurement of species health that is particularly recognized in the study of preservation is that of ecological connectivity, which incorporates the ability of a habitat to support animal movement, dispersal and gene flow, population persistence, maintenance of biodiversity, and other evolutionary processes that are essential to species survival (Beier and Noss 1998; McRae et al. 2008; Zeller, McGarigal, and Whiteley 2012). For species that rely on movement-dependent processes for survival, such as foraging, migration, and dispersal, connectivity is of particular concern (Spear et al. 2010).

Maintaining species movement is a central concern in conservation biology, as inadequate movement may lead to inbreeding, declining populations, and exploitation of local resources (Bowne, Bowers, and Hines 2005).

Animal species that have a large home range and rely on a variety of habitats for survival are particularly dependent upon ecological connectivity (Pascual-Hortal and Saura 2006; Saura and Pascual-Hortal 2007). This need is especially apparent in species that depend on–the availability of both terrestrial and aquatic habitats. The need for terrestrial habitat is recognized as a critical component of conservation and management for these semiaquatic species (Gibbons 1970). Therefore, conservation efforts need to address both landscape composition and connectivity, especially in an-increasingly urban environment that replaces viable habitats with inhospitable, developed landscapes. The decline in populations of these semi-aquatic organisms is primarily attributed to habitat loss and fragmentation, but other anthropogenic activities such as agricultural practices that alter land use and composition have also been found to have a negative impact on wetland habitats (Refsnider and Linck 2012). Proper mitigation techniques that devote special attention to habitat restoration and connectivity can help prevent further habitat and population degradation (Heller and Zavaleta 2009).

Connectivity and Turtles

The turtle is a semi-aquatic animal that has had difficulty escaping local extinction in human-dominated environments. The repercussions of anthropogenic activities have made it difficult for turtle populations to find suitable habitats, leading to a sharp decline in their populations across the globe. Approximately 40% of the world's turtle species are currently listed as globally threatened by the International Union for Conservation of Nature (Refsnider and Linck 2012). The recent decline in turtle populations is a strong indicator of deteriorating habitat quality, both globally and across the U.S. Because turtles are only able to survive in environments with clean water, ample foliage, and abundant prey, they serve as an excellent gauge of habitat quality (Bodie 2001; Refsnider and Linck 2012). Turtle populations cannot thrive in habitats that lack these environmental factors, so their presence in cities directly correlates to a healthy local ecosystem that contains all of their required features.

Blanding's Turtles (*Emydoidea blandingii*) are particularly sensitive to anthropogenic habitat fragmentation; the species is listed as Endangered, Threatened, or of Special Concern in 15 of the 18 states and provinces in which it currently resides (Refsider and Linck 2012). Though previously found across the Eastern and Central regions of the U.S., Blanding's Turtle populations are now restricted to a small number of states and provinces in the upper Midwest, New England, and southern Canada (Minnesota Department of Natural Resources 2008). Much of the decline in population numbers is due to human-induced land use change (Bodie 2001). The Blanding's Turtle is of particular interest for habitat fragmentation due to its highly mobile lifestyle. Individuals move continuously throughout the year, utilizing several distinct terrestrial and aquatic habitats throughout the life cycle. This necessitates adequate ecological corridors to facilitate movement (Bodie and Semlitsch 2000; Bodie 2001).

As noted by Rizkalla and Swihart (2006), most animals found in the Midwest today have developed a tolerance to human activity, as the region has experienced widespread habitat alteration and increased urbanization since the 1800s. However, species like the Blanding's Turtle still continue to experience changes in both behavior and movement patterns due to land conversion; urbanization decreases the amount of original habitat available while also altering the ability of an organism to move between remaining patches of natural habitat (Bowne, Bowers, and Hines 2005). Blanding's Turtles are also particularly sensitive to habitat quality, and have experienced population declines due to changes in water hydrology, temperature, and particulate loads (Bodie 2001). Habitat quality affects both movement and growth rates, and is particularly important for adult female turtles, whose survival is necessary for the species to continue (Smith and Peacock 1990; Verhulst, Perrins, and Riddington 1997; Bowne, Bowers, and Hines 2005).

Habitat connectivity and quality is of particular importance during the nesting season, as this is when mature females travel away from wetlands and into more urbanized areas. Historically, nesting turtles prefer open, sandy, elevated areas for laying eggs (Minnesota Department of Natural Resources 2008; Bodie 2001). However as these favored nesting habitats become increasingly unavailable as a result of urbanization, turtles are forced to seek alternative artificial habitats such as road shoulders, levees, gardens, and agricultural fields (Bodie 2001; Lang 2001; Minnesota Department of Natural Resources 2008; Refsnider and Linck 2012). Though it is possible for Blanding's Turtles to nest in these highly modified areas, Refsnider and Linck (2012) found that successful nesting required multiple attempts, and levels of both failed hatching and predation were higher in more heavily trafficked areas. Increased urbanization and proximity of roads to turtle habitats has led to extremely high road mortality rates, particularly for mature females during the annual nesting migrations (Piepgras and Lang 2000; Steen and Gibbs 2004).

Beyond external factors, Blanding's Turtles are also vulnerable to changing habitat availability due to their unique life cycles. Their life histories are characterized by low annual recruitment rates, high adult survival rates, and delayed sexual maturity (Bishop et al. 1991; Congdon, Dunham, and Van Lobel Sels 1993**;** Steen and Gibbs 2004). The Blanding's Turtle does not reach maturity until around 12 years of age, which is only realized by a small percentage of the population due to high mortality rates. Furthermore, the species is typically unable to reproduce until age 16 or 17, leading to low population recruitment rates due to high likelihood of dying before reaching reproductive age (Hamernick 2000). Population growth is further limited by the high rates of adult female mortality, as mature females are more susceptible to vehicle-induced mortality due to their increased terrestrial movement during nesting migrations (Steen and Gibbs 2004). However, the Blanding's Turtle has a potential lifespan of almost 80 years, giving this species the unique opportunity to rebound as long as the small remaining populations are able to survive and mate.

Since Blanding's Turtles are so sensitive to environmental disturbances, they are highly relevant to conservation initiatives that respond to these interruptions. However, the response of the species to fragmentation through their movement patterns has not been adequately studied, indicating the need for further research in fragmented, urbanized areas (Hamernick 2000; Rizkalla and Swihart 2006). In response to this increasing need, there has been a growing body of science that has focused on modeling habitat connectivity. Though much research is yet to be done, these models are the beginning of new mitigation efforts.

Connectivity Model Theory

Connectivity, in an ecological framework, can be broadly interpreted as the way in which the landscape facilitates or impedes an organism's movement among resource patches (Taylor et al. 1993; Kindlmann and Burel 2008). With the recent consensus that connectivity is a critical factor for species survival, two prominent measures have been developed and are organized into distinct groups: structural and functional (Tischendorf and Fahrig 2000; Kindlmann and Burel 2008). **Structural connectivity** is the spatial arrangement of habitat patches, and is measured by analyzing landscape structure without any reference to the movement of ecological processes (e.g organisms or gene flow) across the landscape (Meiklejohn et al. 2010). **Functional connectivity**, on the other hand, requires not only information about the spatial arrangement of habitat patches, but also some insight into the movement of ecological process through the landscape. Functional connectivity is therefore considered a better measure of connectivity, as it incorporates a more complete model of species movement (Kindlmann and Burel 2008; Sawyer et al. 2011).

Any effort to model functional connectivity must take into consideration the following three factors: (i) the phenotypical traits of the mover, (ii) the behavior of the moving object, and (iii) the characteristics of the medium that affect movement (Calabrese and Fagan 2004). In this context, the size of the mover is often related to the habitat fragmenting activities of humans. For example, a higher degree of urbanization pressures against larger animals; there is a higher chance of finding squirrels than moose in highly urbanized areas (Pardini 2005). The behavior of the moving object is simply the movement bias of an organism or other ecological process, also known as selection bias. While the characteristics of the medium that affect movement are dependent on the organism of interest, they often include differences in the land cover or land use types and their spatial arrangement, slope, and surface ruggedness. In sum, functional connectivity takes into account size of organisms, their behaviors, and landscape features. In order to model functional connectivity, it is necessary to choose an organism and determine its moving preferences, behaviors, and any landscape features it may encounter.

Since functional connectivity encompasses a wide variety of features, both biotic and abiotic, researchers have created several different measurements to properly weigh each feature and accurately model connectivity. Though all existing functional models attempt to incorporate biological, behavioral, and environmental factors, there are important differences in the extent to which these models are able to explicitly integrate these three characteristics. Previous functional connectivity models have used a variety of factors, such as emigration or dispersal success, search time, landscape permeability, and actual observations (see review by Kindlmann and Burel 2008).

Least-Cost Modeling

Least-cost modeling (LCM), which identifies the single best pathway between locations, is one of the methods most widely used to measure connectivity. In practice, LCM evaluates potential animal movements across a landscape based on the cumulative 'cost' of the movement (Howey 2011; Sawyer et al. 2011). After evaluating the cost of all possible routes between two points, the model outputs the single best path. In this model, the only inputs needed are the areas that are being connected and a 'cost' layer for the landscape in order to determine the lowest cost route. LCM is commonly utilized in connectivity modeling because of its relatively simple process. Because only two inputs are needed, the computational time for running LCM programs is extremely fast, even when studying large areas (Sawyer et al. 2011). Beyond a small computational time, LCM has the benefit of using a simple or complex 'cost' landscape as needed; it can incorporate only the most extreme barriers, or include very precise, small-scale costs (Burrough 1996, Sawyer et al. 2011). This allows several cost landscapes of varying detail to be compared in order to determine which 'cost' landscape is most reflective of the actual landscape.

However, LCM is not without its limitations. Several studies have found that using LCM fails to adequately model the movement of organisms of interest. One example is a study by Sawyer et al. (2011), which found that the relative coarseness of available cost data and problems of scale dulled the effectiveness of LCM on their research on Bighorn Sheep. Though LCM is a common, useful tool, it is not robust enough to stand alone, necessitating the use of newer models that incorporate additional factors.

Random Walk Theory

One type of functional connectivity modeling that has recently gained more interest is random walk theory. In this model, movement is completely independent of previous directions moved, meaning that there is no preferred direction; movement is completely random (Codling et al. 2008). An extension of this model incorporates the influence of selection bias into the walker's random movement (Bartumeus et al. 2005). In ecology, this random walk with selection bias reflects the movements of organisms in a heterogenous landscape without complete knowledge of the landscape or specific targets (i.e resource patches, shelter, mates, etc.). This moves away from direct-route models such as LCM, allowing for multiple pathways to be assessed rather than a best-fit line (McRae et al. 2008).

Random walk theory's ability to use selection bias is now being incorporated into ecological modeling techniques because it models the movement behavior of an organism based on barriers in the existing environment (McRae et al. 2008; Dutta et al. 2015). For example, when an animal encounters a location it wants to avoid (e.g. an urban environment), it can accomplish this in several ways, including (i) avoiding crossing the boundary into an urban area, (ii) immediately leaving the urban area if it has been entered, (iii) decreasing the time in the area by moving more often or at a greater rate, or (iv) some combination of the above (McRae 2006). Random walk that incorporates selection bias allows organisms to travel through less suitable areas (as would happen in reality), with movement patterns based on both preferences and the surrounding landscape.

Because random walk models are able to assess multiple pathways at once, they can identify important landscape features and resulting dispersal patterns whose logic is often unclear in data (Codling et al. 2008). Several studies have found random walk to be a better model of animal movement than other existing models (e.g. Chardon et al. 2003; McRae and Beier 2007; Sawyer et al. 2011). For example, McRae and Beier (2007) found random walk modeling to more accurately predict animal and gene dispersal rates because it uses multiple pathways rather than a single optimal pathway. Though still being developed, random walk theory that incorporates selection bias is an important contributor to more accurately modeling animal movement patterns and habitat connectivity.

Circuit Theory

One connectivity model that utilizes random walk theory is circuit theory (Chandra et al. 1997; McRae 2006; McRae et al. 2008). Circuit theory represents the movement behavior of a specific organism or ecological process by conceptualizing movement as an electrical current, influenced by the levels of resistance it encounters. Though there are several circuit theory-ecology crossovers, the four most important concepts taken from circuit theory are nodes, voltage, current, and resistance. Figure 1 represents the key elements of a circuit.

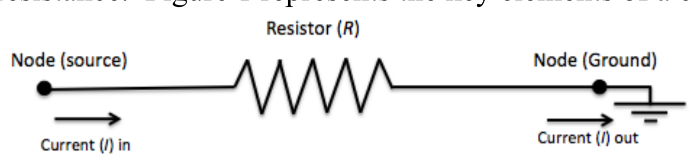


Figure 1. In a basic circuit, current (*I*) flows from the source node to the ground node, with the resistor (*R*) impeding the flow. Voltage (*V*) is the difference in potential energy between the source and ground node.

Nodes are the points where elements of a circuit meet. In the most simple circuit, one node acts as the source and the other the termination or ground. In an ecological sense, nodes represent specific points on a landscape, such as the actual location of an organism or the center of a habitat patch. The source node is usually designated the starting location of an organism while the ground node is its destination.

Voltage (*V*) is the difference in electrical potential energy between two nodes in an electrical circuit. In Figure 1, the source node is at a higher potential than the ground node, which is designated as zero. In an ecological sense, voltages give the probability that an individual organism leaving from any point will reach a given destination.

Current (*I*) is the flow of charge through a node-to-node connection. In Figure 1, current flows from left to right - higher to lower voltage - with the resistor impeding the current. In ecological terms, current would be the total movement of the ecological processes from source node to ground node, with higher current corresponding to an organism's freer movement through a landscape.

Resistance (*R*) determines how much current will flow between two nodes for a particular voltage difference. For every node-to-node connection, there is an inverse relationship between resistance and current for a fixed voltage difference, so as the resistance increases, the current will decrease. In an environment, resistance represents barriers to animal dispersal. Different landscape features have different resistance values, which will influence the target organism's movement through that area.

Voltage, current and resistance are the three major elements that circuit theory is based upon. Voltage is proportional to current, with resistance as the constant of proportionality. This proportionality is known as Ohm's Law, given by:

$$I = V / R$$

Equation 1. Ohm's Law. The relationship between current (*I*), voltage (*V*) and resistance (*R*)

Ohm's Law (Equation 1) can be applied to circuits that include multiple pathways. For a circuit that has two parallel pathways of equal resistance, as shown in Figure 2, current from the source will move towards ground. Since the resistance of each path is the same, current can flow equally easily down each path. The total current will split evenly between the two paths. Therefore, the current through each pathway is $I_{total} / 2$.

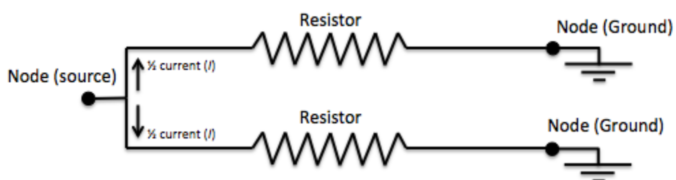


Figure 2. A Parallel circuit with two pathways of equal resistance. Because they are equally resistant to flow, the current splits equally.

Ohm's Law is also applicable to multiple pathways that do not have equal resistance (such as a landscape with varying land cover). For the circuit shown in Figure 3, the bottom pathway has twice the resistance as the top pathway, or $R_{bottom} = 2R_{top}$. Due to the inverse relationship, it is twice as difficult for the current to travel through the bottom pathway than the top, or $I_{bottom} = ½\ I_{top}$. Because the top pathway has half the resistance, it will receive twice the total amount of current. Thus, I_{top} is taking ⅔ of the total current while I_{bottom} will take the remaining ⅓.

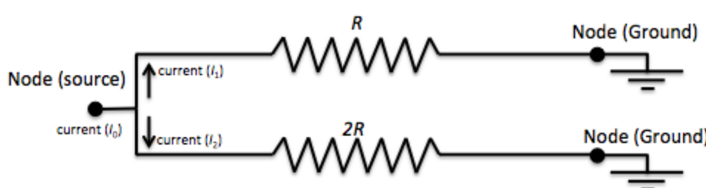


Figure 3. A parallel circuit with two different resistance pathways. According to Ohm's Law, the top pathway will have twice the total current flow than the bottom pathway.

Ohm's Law can be applied to movement in ecology. In a basic sense, this example states that it is twice as difficult for an ecological process to move through the bottom landscape as the top one. We therefore expect the ecological process to take the top pathway twice as frequently. Ohm's Law can be expanded to multiple pathways of varying resistances and predict the probability of flow through that pathway (McRae 2006). It allows for every pathway to be traveled, but less resistant pathways will be traveled more often.

Another important feature of circuit theory is the effective resistance. **Effective resistance** is the consideration of the overall resistance of the total pathways in a circuit. Essentially, the more parallel pathways, the lower the effective resistance because current can travel more pathways to ground. Conversely, the more resistors in series, the more impediments there are to current, creating a higher effective resistance. Figure 4 shows effective resistance.

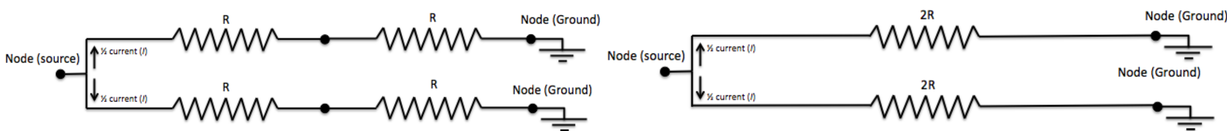


Figure 4. Effective Resistance. The upper and lower paths have two resistors in series that add to the effective resistance, while having two multiple pathways in parallel lowers the effective resistance between source and ground

Circuit Theory in Ecology

As briefly explained above, circuit theory is particularly adept at modeling random movement throughout a heterogeneous environment. In our case, animal movements are treated as current, while the features of the surrounding landscape are resistors. In well-suited habitats, the resistance of the landscape can be effectively zero while highly hostile areas can completely inhibit current. In practice, it is possible to use circuit theory to incorporate multiple resistance layers of a heterogeneous landscape -- such as water quality, roads, and land cover -- and model the dispersal of a species (McRae and Shah 2009). Circuit theory can model animals as they move randomly throughout the landscape, preferentially choosing areas of lower resistance and avoiding ones of higher resistance.

Unlike earlier, more simple ecological models, circuit theory is able to identify multiple pathways at once. The ability to run current through a resistance layer allows circuit theory to move beyond the common 'suitable' or 'unsuitable' dichotomy in favor of a more robust, accurate landscape assessment. The current is able to flow through all possible paths, but will follow the least resistive path. Thus, the output will show dispersal patterns in multiple directions and of varying strengths due to the influence of the resistance layer, unlike least-cost models (McRae and Beier 2007; Howey 2011; Dutta et al. 2015). This output more accurately reflects the dispersal patterns of an organism, demonstrating that random walk is a better model than one that only identifies a single, least-cost path (McRae and Beier 2007; Sawyer et al. 2011).

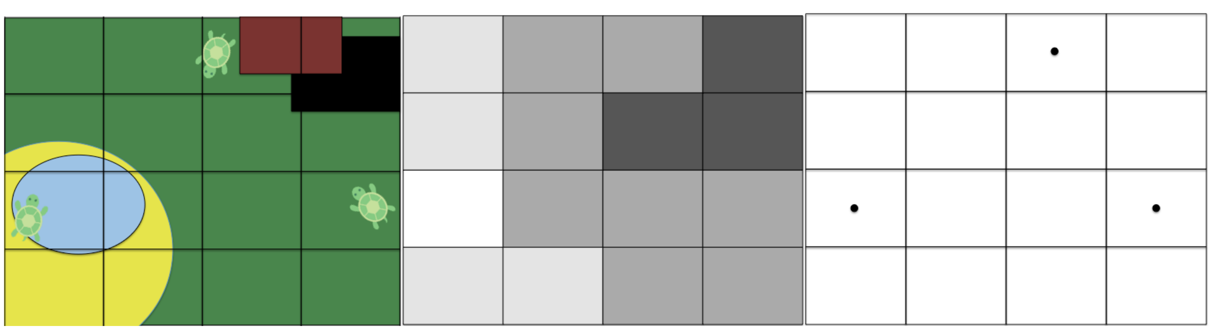
Finally, circuit theory is particularly useful for identifying areas of high importance. Because current is influenced by resistance, it is possible that there will be areas that have high current, but very few pathways with low resistance. These high-current, low-resistance areas have been termed '**pinch points**,' or places that experience high movement despite the existence of a hostile environment (Brakker et al. 2014). These areas are particularly interesting because they allow researchers to identify areas of special concern for an organism's dispersal. These small paths in highly resistive landscapes pose great danger to the traveler, potentially leading to lower dispersal success and higher mortality rates (McRae et al. 2008). Circuit theory is unique in its ability to identify such areas due to the use of current to model movement patterns.

Utilizing circuit theory, it is possible to transform landscapes, distances, and other barriers into resistors and model ecological processes. There have been several recent studies that incorporate circuit theory into ecological modeling (e.g. McRae and Beier 2007; Howey 2011; Braaker et al. 2014; Dutta et al. 2015). However, these models focus on a variety of ecological processes and organisms unrelated to Blanding's Turtles; there have been very few published papers on habitat connectivity for the species, and none that utilize circuit theory. It is our aim to apply circuit theory to the Blanding's Turtle to see if this model can accurately represent the species' dispersal patterns.

III. Methodology

Circuitscape

For our study, we used Circuitscape, the GIS-based circuit theory program, to calculate the probability of movement for a particular ecological process based on landscape resistances (McRae et al. 2014). By assigning different resistance values to multiple landscape features, the software is able to create a raster - a GIS grid - dataset, that is then used to determine dispersal probabilities (McRae 2006). Figure 5a and 5b show the translation of landscape features into a resistance layer. It is possible to integrate different GIS layers (i.e. land cover, water quality, roads, etc.) into a final resistance layer, thus allowing the model to be more robust than when only using a simple vegetation layer.



Figures 5 a-c. Landscape features to output layers. a) The original raster is shown at left. This is transformed into b) a landscape resistance layer (shown center) and c) a focal-point layer (shown right) based on landscape-based resistance values (e.g water/sand low resistance, house/driveway high resistance) and observed sightings

In Figure 5c, three focal points were chosen based on the 'sightings' in Figure 5a. Once both the focal node and resistance layers are established, Circuitscape is able to run the circuitry analysis. There are two different raster analysis options in Circuitscape: one-to-all and all-to-one. In the one-to-all option, a single node will be connected to a source while the remaining nodes will be grounded. In the all-to-one option, it is the exact opposite, grounding a single node while the remaining nodes are connected to a source. Because we are interested in the dispersal pattern from a specific node of origin, we used only the one-to-all mode to run our analysis.

Circuitscape, using circuit theory, runs a circuitry analysis on each node, determining the flow of the current through the resistance layer. This process is then repeated, allowing every node in turn to become the source while all others are held grounded; this means that for *n* nodes, Circuitscape will have *n* calculations. Figure 6 is a visualization of this process.

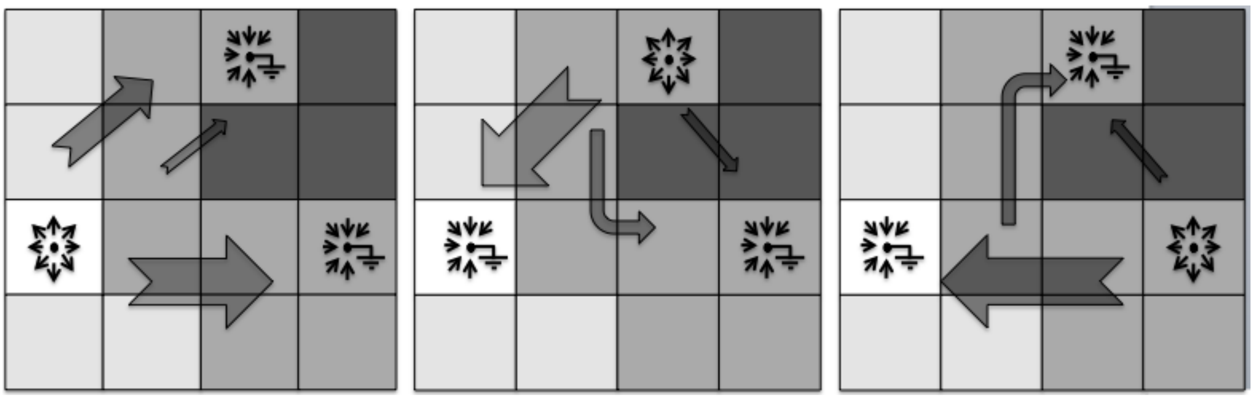


Figure 6. Visualization of Circuitscape's process. Each calculation has a different source node while the other two are grounded. Arrows show a general movement of current from source to ground due to the resistance layer

Circuitscape then creates an output file for each calculation that demonstrates the dispersal of current from a particular source node. The output is visual, with areas of high connectivity more brightly colored than those of lower connectivity. Since current and movement are synonymous in this model, each output file shows the probability of movement through the surrounding landscape. This dispersal information allows us to visually represent pathways with the highest current, helping to predict an organism's movement.

Study Area

We chose to narrow our study to the northern part of the Minneapolis-St. Paul Metro Area and its surrounding landscape. The area primarily contains Anoka, Washington, and Northern Ramsey counties, but also features parts of Eastern Hennepin, Southern Chisago, Southern Isanti, and South-Eastern Sherburne. This study area was chosen for several reasons: (i) most of the sightings were contained within this region, (ii) the landscape incorporates several different land classes including urban regions, suburbs, farmlands, and wetlands, and (iii) using a smaller area limits the computational time required. These three factors allow for a wide range of potential dispersal patterns while minimizing the necessary computational time, at roughly seven and a half hours per Circuitscape run.

Data Collection

We began our data collection by working with the Minnesota Department of Natural Resources (MnDNR) to obtain data on actual Blanding's Turtle sightings. Though MnDNR provided us with the data we needed, we were given strict instructions not to release any location-specific sighting data, as the Blanding's Turtle is listed under the Minnesota endangered species list. However, we were able to use the data to determine areas requiring specific attention. Due to the turtle's long potential lifespan of 80 years and the changing urban landscape, we decided to use sightings from the last twenty years. We opted not to include any sightings above twenty years old, as these could potentially negatively impact our model by not accurately representing modern areas still accessible to turtles. A twenty year time frame also provides us with 200 sightings, an adequate amount of data to run the model. All turtle points -- even those found dead or on the road -- were included, because they represent areas that an individual has at one point been able to access. Within these spatial and temporal constraints, we believed there was enough sighting information to run a robust model.

The landscape GIS layers we used were collected from the Minnesota Geospatial Commons. The chosen GIS feature layers were ones that could potentially affect the movement of the Blanding's Turtle. This included the National Land Cover Data (NLCD) 2011, Minnesota Roads, Minnesota Assessed Lakes and Streams, and Minnesota DNR Water Bodies. Each layer had to be clipped to our study area before any assessment could begin. These four landscape features were able to account for the major landscape resistors a Blanding's Turtle is likely to encounter. Other factors, such as slope, were considered, but we decided not to incorporate this into our analysis because the relatively flat nature of the Twin Cities landscape is not likely to represent a significant barrier to dispersal. However, this could be included as an additional layer in future studies. Another layer that was excluded was building footprints, because they are incorporated into the land cover layer, which identifies developed areas.

All layers were carefully chosen to ensure that the data was of the highest quality available for our intended purpose. Once we determined which layers were the best to use, these were selected and transformed into raster format so that resistance values could be assigned. Table 1 provides a brief overview of each layer and its function in our analysis.

Variable	Layer	Function
Turtle Sightings	MnDNR	Used for source node layer
Land Cover	National Land Cover Data 2011	Most extensive land cover data available
Roads	Minnesota Roads	Large barrier to turtle movement
Assessed Lakes & Streams	Minnesota Assessed Lakes; Minnesota Assessed Streams	Water quality affects quality of habitat
All Water Bodies	MnDNR Water Bodies	Distance from water affects habitat size

Table 1. The different variables, associated layer, and reason for the resistance layer. Each one contributes to the cumulative resistance of the landscape.

Assigning Resistance

For our Circuitscape model, we assigned resistance values to four features relevant to Blanding's Turtle movement patterns: (i) land cover; (ii) road type and location; (iii) water quality; and (iv) distance from bodies of water. We assigned resistance values based on a 0-1000 scale for each feature: 0, 250, 500, 750, and 1000. '0' represented an area with theoretically nonexistent resistance, while 1000 represented an area that was essentially impassable for individual turtles. Initial models that used a smaller scale (e.g. 0-10 or 0-100) did not yield a large enough range in cumulative resistance values to provide a conclusive output. Once resistance values were assigned to each of the four features, we combined each layer to get a cumulative resistance value for our entire study area. In order for Circuitscape to run properly, we needed a non-zero cumulative resistance. We achieved this by assigning a non-zero value (by replacing all 0 resistances with 1) to the land cover layer, as this layer covered the entirety of our study area and ensured that no areas had a 0 value. It is important to note that resistance values are relative for each layer; thus, resistance values can be compared against other features within the layer, but not across layers. For example, a value of 250 does not represent equivalent resistance for a land cover type and a road type. This was an assumption of our model that could be addressed in future studies.

Layer 1: Land Cover

Blanding's Turtles require distinct habitat types for different parts of the year. During their active season (April-October), the turtles can be found in aquatic land cover types of various types and sizes (Lang 2001; Refsnider and Linck 2012). During the winter months (generally November-March), the turtles select specific wetlands for overwintering, where they are protected from winter temperatures and predators (Lang 2001). During the June nesting season, female turtles venture upland to exposed, dry lands, up to a mile away (Lang 2001). Throughout the activity season, Blanding's Turtles are generally found in calm, shallow water bodies with mud bottoms and abundant aquatic vegetation, such as wetlands, lakes, ponds, marshes, swamps, bogs, ditches, and streams (Hamernick 2000; Rizkalla and Swihart 2006; Minnesota Department of Natural Resources 2008).

As the turtles progress into the overwintering season, they tend to move to warmer, shallower parts of water near the shoreline, or muddy bottoms of deeper bodies of water where they're protected from freezing (Minnesota Department of Natural Resources 2008; Refsnider and Linck 2012). Unlike during the active season, individuals do not move between wetlands during the winter months (Refsnider and Linck 2012). Because so much of Blanding's Turtle movement patterns are based on the available landscape, the main focus of our connectivity analysis was related to land cover classes throughout the region. Figure 7 demonstrates the land cover of our study area. Table 2 includes descriptions of all land cover classes, as well as the resistance values we assigned to each.

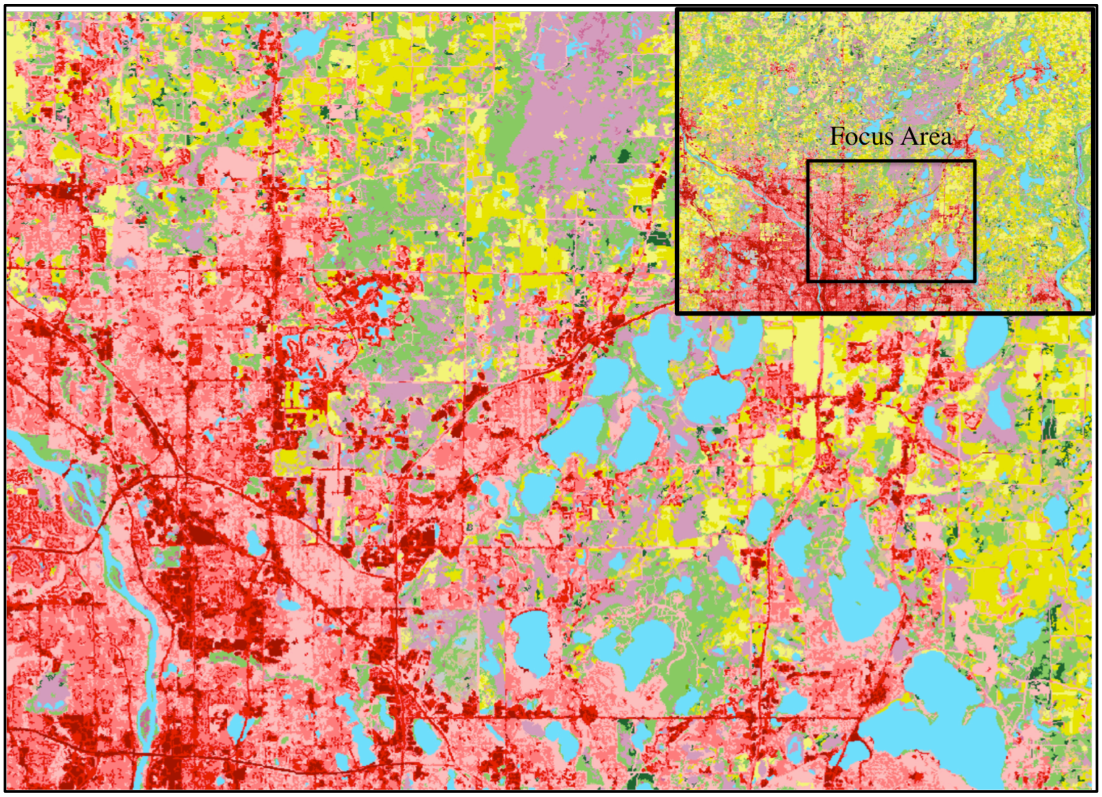


Figure 7. A closer view of the study area land cover classes. Focus area shows most of the land cover types.

Land Cover Type	Definition	Resistance	Color
Open Water	All areas of open water	1	
Developed- Open Space	Mostly vegetation in the form of lawn grasses; <20% impervious surfaces	1	
Woody Wetlands	Forest or shrub accounts for some of vegetative cover; soil is periodically saturated or covered with water	1	
Emergent Herbaceous Wetlands	Primary vegetative cover consists of perennial herbaceous vegetation; soil is periodically saturated or covered with water	1	
Developed- Low Intensity	Mixture of constructed materials and vegetation; 20-49% impervious surfaces	250	
Barren Land	Barren areas of rock, sand, clay, and other accumulations of earthen material	250	
Grassland/Herbaceous	Dominated by grasses or herbaceous vegetation	250	
Pasture/Hay	Grasses or legumes planted for livestock grazing or the production of crops	250	
Cultivated Crops	Used for the production of annual and perennial woody crops; includes all land being actively tilled	250	
Shrub/Scrub	Dominated by shrubs, young trees, or trees stunted from environmental conditions	500	

Deciduous Forest	Dominated by tall trees; majority of tree species shed foliage seasonally	750	
Evergreen Forest	Dominated by tall trees; majority of tree species maintain leaves all year	750	
Mixed Forest	Dominated by tall trees; neither deciduous nor evergreen tree species are most prominent	750	
Developed- Medium Intensity	Mixture of constructed materials and vegetation; 50-79% impervious surfaces	750	
Developed- High Intensity	Highly developed areas where people reside or work in high numbers; >80% impervious surfaces	1000	

Table 2. Land cover classes and their definitions. Adapted from the metadata provided by the MnDNR National Land Cover Database 2011

We obtained land cover data from the Minnesota Department of Natural Resources (MnDNR) National Land Cover Database 2011. Within our study area, there are 15 identified land cover classes: Open Water, Developed- Open Space, Developed- Low Intensity, Developed- Medium Intensity, Developed- High Intensity, Barren Land, Grassland/Herbaceous, Deciduous Forest, Evergreen Forest, Mixed Forest, Pasture/Hay, Cultivated Crops, Shrub/Scrub, Woody Wetlands, and Emergent Herbaceous Wetlands. We classified all land cover types with resistance values of 1, 250, 500, 750, and 1000. As previously mentioned, a resistance value of "1" signifies an effectively zero resistance.

We assigned resistance values based on the degree to which habitats were hospitable to the Blanding's Turtle. We gave the highest possible resistance (1000) to "Developed- High Intensity," assuming that these areas would feature urban infrastructure impeding turtle movement. We also assigned relatively high resistance values (750) to "Developed- Medium Intensity," as well as all three forest types, because the lack of warm, exposed areas under forest cover is not an ideal habitat for the Blanding's Turtle (Bodie 2001; Lang 2001). Similarly, areas of "Shrub/Scrub" feature barriers of shrubs and small trees, leading to a resistance value of 500. "Developed- Low Intensity," "Barren Land," "Grassland/Herbaceous," "Pasture/Hay," and "Cultivated Crop" were all given relatively low resistance values of 250, as Blanding's Turtles have been known to move throughout and even nest in these areas (Hamernick 2000; Bodie 2001; Minnesota Department of Natural Resources 2008; Refsnider and Linck 2012). "Open Water," "Developed- Open Space," and both types of wetlands were given resistance values of 1, as these land cover types do not represent a significant barrier to turtle movement (Hamernick 2000; Lang 2001; Refsnider and Linck 2012). Figure 8 represents the land cover layer when reclassified using the assigned resistance values.

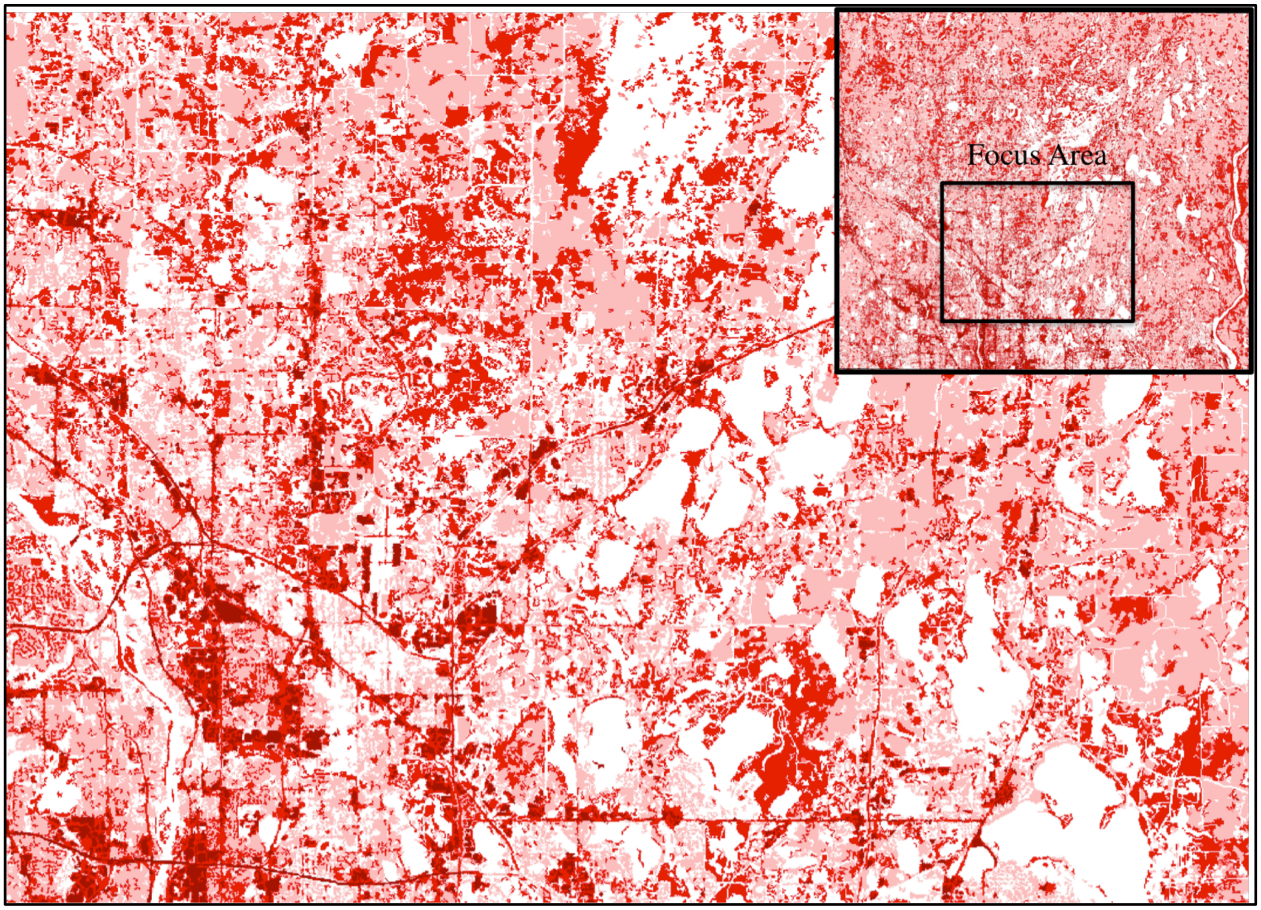


Figure 8. Land cover class translated into resistance values. Light colors represent low resistance while dark red represents high resistance.

Layer 2: Road Type

In urban areas, roads represent a considerable barrier to Blanding's Turtles habitat connectivity (Temple 1987; Sajwaj, Piepgras, and Lang 1998). Road networks throughout the US are continuously undergoing a steady expansion, further fragmenting already reduced habitat areas and making road crossings inevitable during species movement (Steen and Gibbs 2004). While roads directly decrease physical connectivity, they also subtly influence behavioral changes in individuals (Bowne, Bowers, and Hines 2005). Mature females are particularly vulnerable to road disturbance and mortality during the nesting season, as road crossing is necessary to get to viable nesting sites (Steen and Gibbs 2004; Refsnider and Linck 2012).

Furthermore, peak nesting movement occurs during the hours surrounding dawn and dusk, which are times that correspond to periods of peak traffic volume (Steen and Gibbs 2004; Minnesota Department of Natural Resources 2008). Refsnider and Linck (2012) found that 57 percent of turtles encountered during their study crossed paved roads during nesting migrations, and almost all crossed these roads at least once in each direction. With this significant infrastructure barrier in mind, we chose to incorporate existing road infrastructure within the study area into our model. Table 3 includes descriptions of all road type in the area, as well as the resistance values we assigned to each.

Road Type	Definition	Resistance
County Road	Locally maintained by county highway departments; spans a wide variety of road types	250
Township Road	Any road established, constructed, or improved under the authority of the town or county	250
Residential Road	Minor road which runs through urban residential areas	250
Private Road-Public Access	Road on privately-owned property; not maintained by local or national government	250
State Park Road	Provides access to public parks and recreational facilities	500
Municipal State Aid Street	Designated municipal street that is not already on the state highway or CSAH systems	500
County State Aid Highway	Specialized form of county road that is part of the state aid system	750
Interstate	Limited access divided road of at least four lanes designated by the Federal Highway Administration as part of the Interstate System	1000
US Highway	Roadway important to the nation's economy, defense, and mobility; developed by the Department of Transportation in cooperation with local municipalities	1000
MN Highway	Highway owned and maintained by the State of Minnesota or state-created authorities	1000
Ramp/Connector	Highway that connects hubs and corridors	1000

Table 3. Road types and assigned resistance values. Definitions adapted from MnDOT and other sources

We acquired late 2012 road type data from MnDOT. We classified road types based on relative travel speed and number of vehicles likely to be on the road, recognizing that both faster speeds and higher density of cars represent higher mortality rates for turtles (Temple 1987; Steen and Gibbs 2004). Because road crossing of any kind puts turtles at increased risk of mortality, the minimum resistance value we assigned for any road type was 250 to represent the clear barrier to individual movement.

We assigned the minimum resistance value (250) to roads that likely had slower traffic speeds and fewer vehicles traveling on them. These were County Roads, Township Roads, Residential Roads, and Private Roads. State Park Roads were given a resistance value of 500, recognizing that they are likely well-traveled by both automobiles and individual turtles. Municipal State Aid Streets were also given a value of 500 due to higher perceived travel. We gave County State Aid Highways a relatively high resistance value of 750, assuming that they are well-traveled and have higher traffic speeds. Interstates, Highways, and Ramps/Connectors are all likely to have very fast moving cars, particularly during peak travel times for both vehicles and turtles, necessitating an effectively impassible resistance value of 1000. Figure 9 represents our roads layer when resistance values are assigned to different road types.

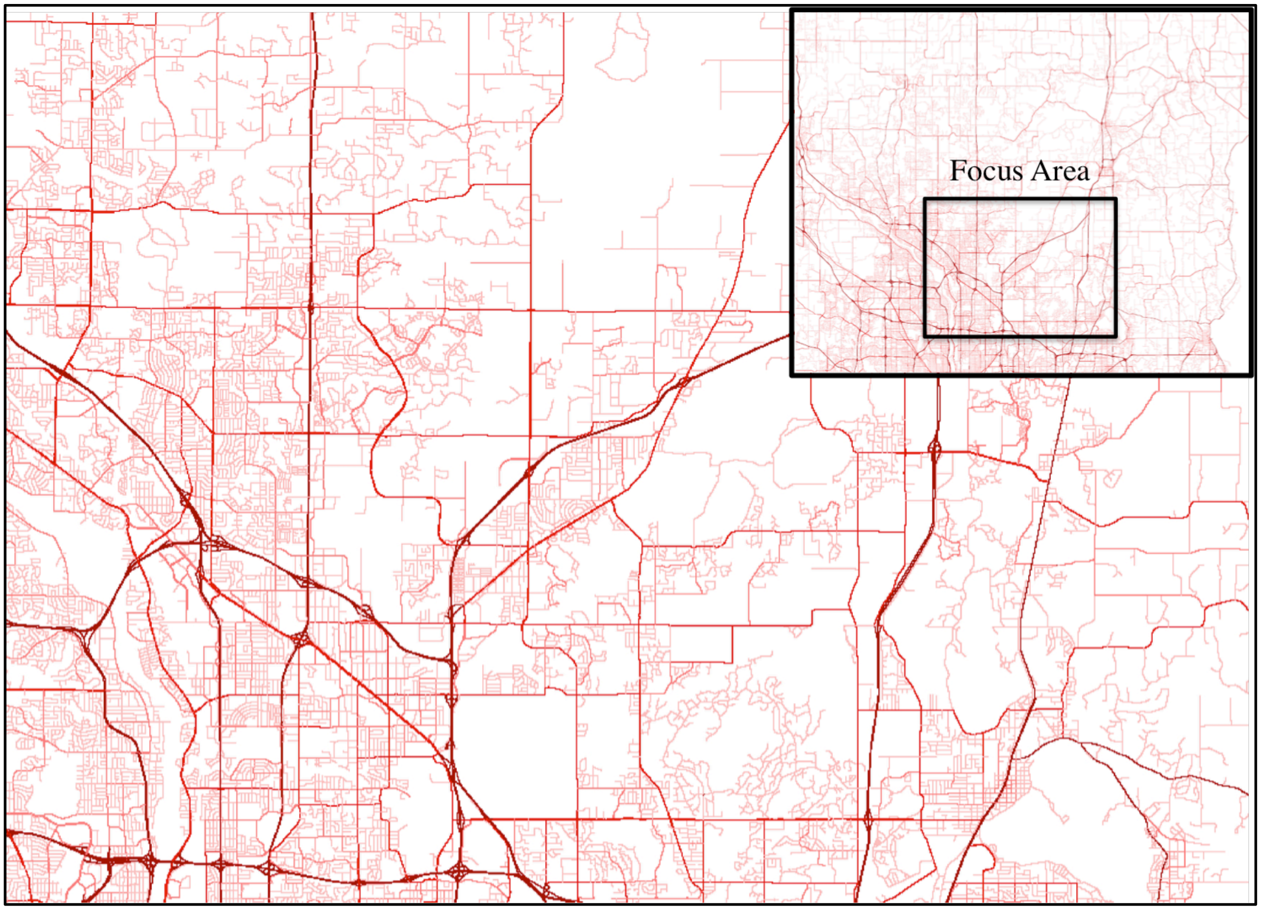


Figure 9. Roads layer translated into resistances. Darker colors represent higher resistances.

Layer 3: Water Quality

Another important factor affecting the ability of Blanding's Turtles to find suitable habitats is water quality, as individuals spend the majority of their life cycle in aquatic regions (Lang 2001; Steen and Gibbs 2004; Refsnider and Linck 2012). Adult female turtles, in particular, value water quality; they have been found to be willing to move greater distances in order to reach higher quality ponds. This puts them at higher risk of mortality due to vehicles and other urban factors (Bowne, Bowers, and Hines 2005). Because turtles prioritize higher quality bodies of water, we incorporated water quality data into our model. Table 4 shows the way we categorized quality, as well as the assigned resistance values.

Water Quality	Resistance
Not Specified	0
Impaired	250

Table 4**.** Water quality categories and assigned resistances

We acquired the water quality data for our third layer from the Minnesota Pollution Control Agency. In 2011, the MPCA completed assessments on a number of wetlands, lakes, and streams within the state for a report to the EPA. The datasets acquired did not include all bodies of water within the region, only a small subset of assessed ones. The MPCA uses a variety of classification levels to indicate the status of impaired bodies of water, but for uniformity we simplified the classification to either “impaired” or “not specified.” A water body was deemed “impaired” if it was found to contain any number of pollutants.

All bodies of water identified as “not specified” were deemed such in the original data file. Because there was insufficient data to determine whether the water was impaired or not, we assigned a resistance value of 0, rather than assigning a non-zero value that implied the water was tainted. We assumed that there was a certain threshold the water quality needed to reach in order to be deemed “impaired,” so insufficient data likely means the water quality did not reach this threshold. The data available for wetlands was much more limited than for lakes and streams, so only one wetland was identified as impaired within our study area, while everything else had insufficient data. Because of this, we decided not to include wetlands in our analysis, only incorporating impaired lakes and streams.

We assigned a resistance value of 250 to all “impaired” bodies of water, recognizing that low-quality water must still be used when no other water is available. Any bodies of water that were deemed “not specified” or were not included in the assessment were given a resistance value of 0. Figure 10 represents bodies of water that were identified as “impaired” and assigned a resistance value accordingly.

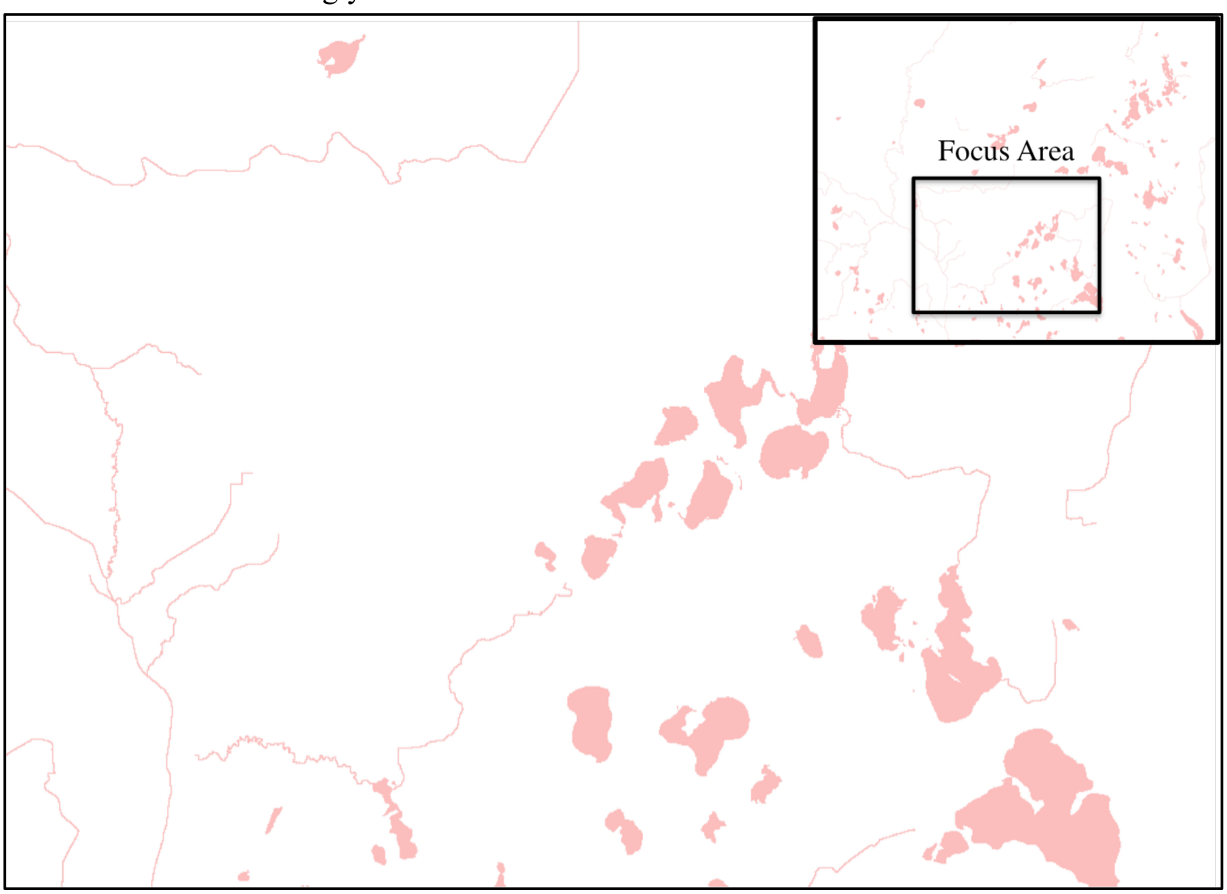


Figure 10. Impaired bodies of water with resistance values

Layer 4: Distance from Water Bodies

Another important factor affecting habitat suitability for Blanding's Turtles is the proximity of nearby terrestrial and aquatic regions. Blanding's Turtles rely on rivers, streams, channels, and ditches as movement corridors, necessitating the availability of water nearby to facilitate the movement of individuals (Lang 2001). Contrary to common perceptions of turtles, this particular species is actually highly mobile for its size, particularly during nesting seasons. Studies have shown that the species travel extensively between wetlands and upland regions (e.g. Piepgras and Lang 2000). Nesting forays generally take mature females up to a kilometer away from their wetland of origin, demonstrating that any habitats beyond this range are unlikely to be utilized (Piepgras and Lang 2000; Refsnider and Linck 2012). To incorporate the limited travel range and speed of Blanding's Turtles into our model, we assigned resistance values based on distance from bodies of water (the likely starting location of individuals). Table 5 demonstrates the classification system we used for assigning resistance values based on distance.

Distance from Water	**Resistance**
0-.5 km	0
.5-1 km	250
>1 km	750

Table 5. Distance from water bodies and assigned resistances

For our final water proximity layer, we used location data from MnDNR on Minnesota Hydrography. This included all bodies of water, both those assessed previously by the MPCA and those not. We assigned our resistance values based on the assumption that habitats farther away from bodies of water are likely to be increasingly difficult to reach. With this in mind, we assigned anything within .5 km of a water body a resistance of 0, indicating that travel to these regions is very easy. We assigned anything from .5 to 1 km away a resistance of 250, recognizing that these habitats are somewhat more difficult to reach. Lastly, we assigned anything greater than 1 km from any bodies of water a resistance of 750, as Blanding's Turtles are unlikely to travel this far away in search of suitable habitat. Figure 11 identifies areas that have varied resistances based on distance from water.

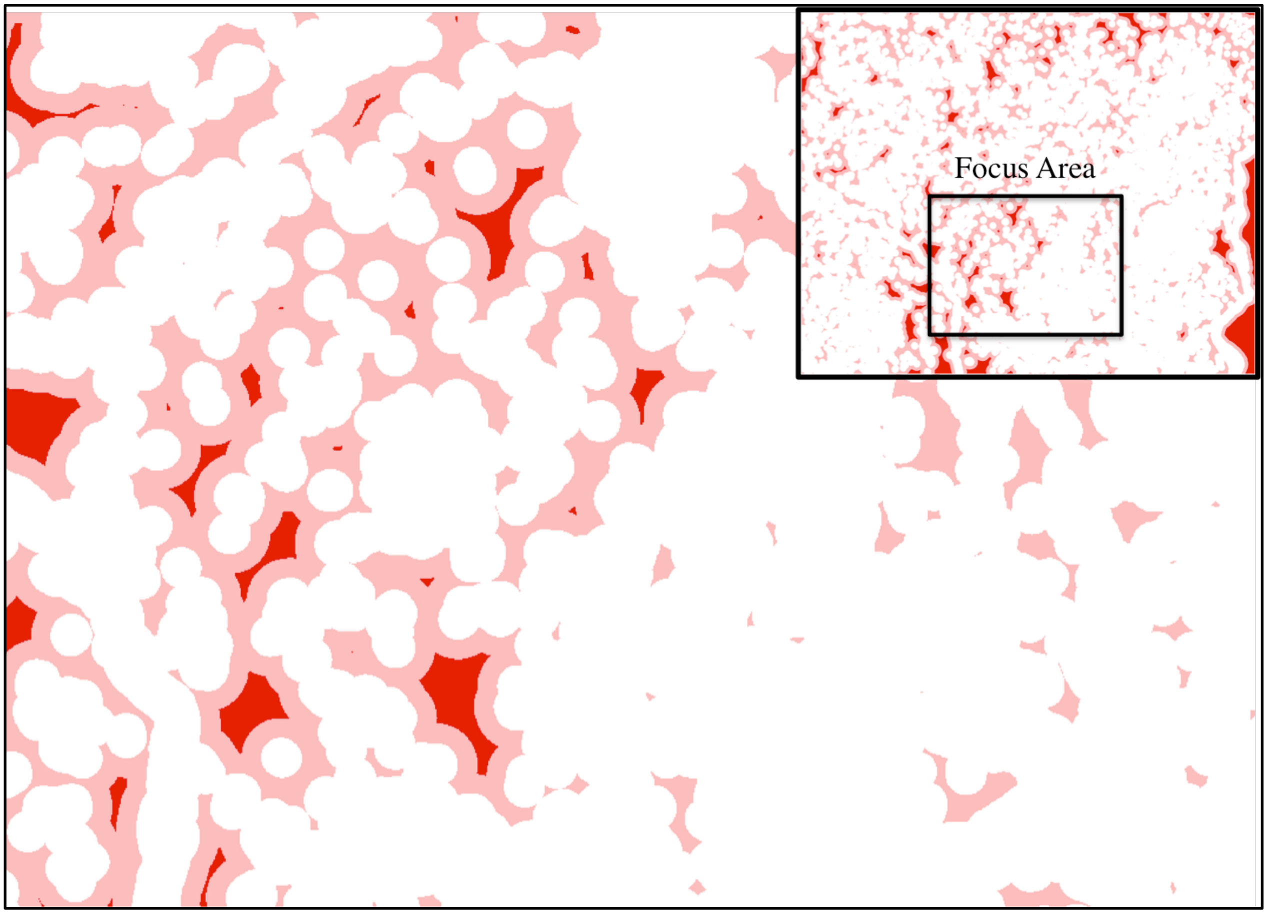


Figure 11. Distance from water with resistance values

Cumulative Resistance Layer

Once we classified and identified resistance values for each of our four model layers, we were able to identify areas of cumulative high and low resistance. Areas of high resistance represent large barriers to turtle movement, where individuals are unlikely to travel throughout. Areas of low resistance represent very little impediment to movement, and are likely to feature a lot of turtle movement.

The lowest possible cumulative resistance value we identified was 1. This was given to areas that featured unimpaired wetlands without roads. The highest cumulative resistance value we found was 2,750. This was given to highly urbanized areas, with a "Developed-High Intensity" classification featuring an interstate, highway, or ramp/connector at a distance greater than 1 km from any bodies of water. All other resistance values fell within this range, with areas of low resistance concentrated away from urban areas and around bodies of water. Figure 12 represents our cumulative resistance layer for the study area.

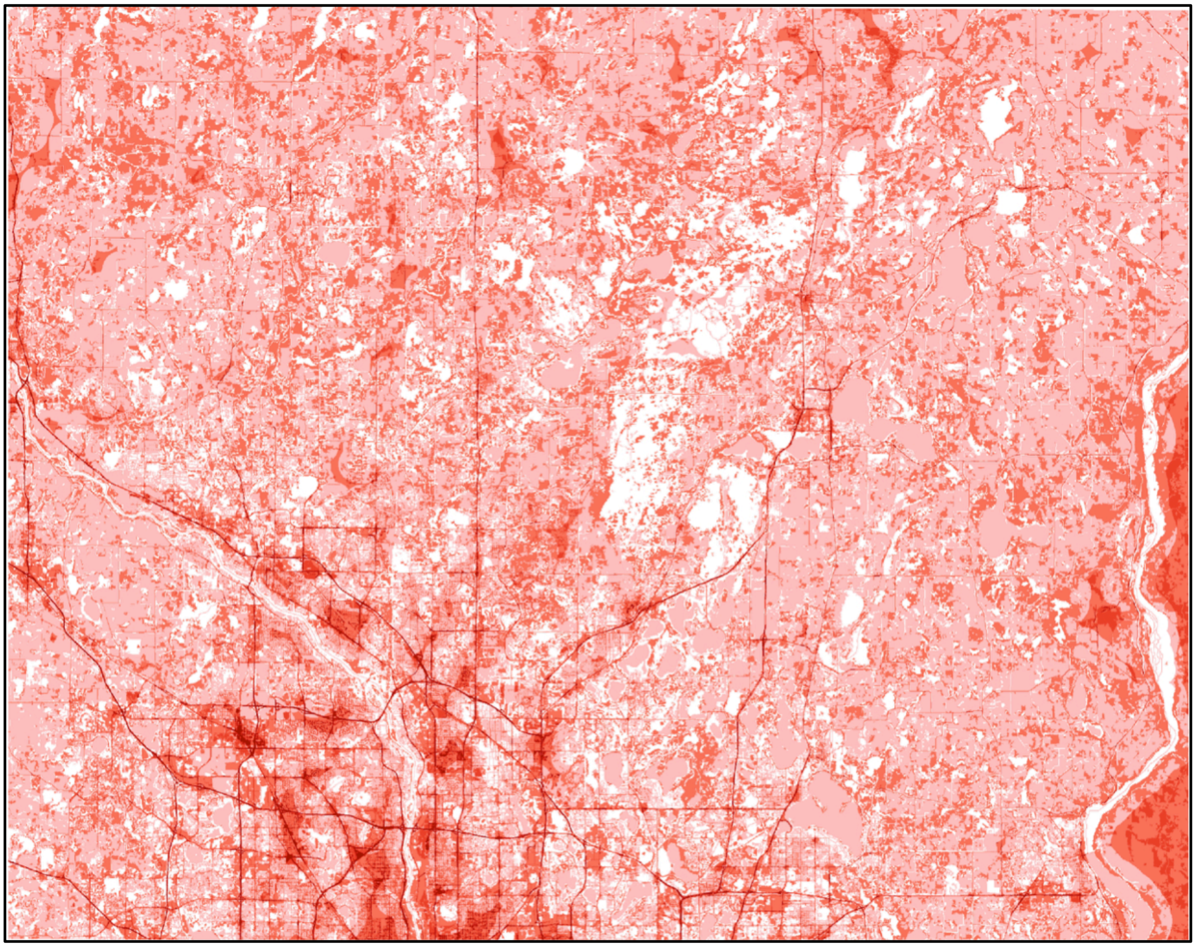


Figure 12. Cumulative resistance map. All individual resistance maps were added together to create the map shown. Areas of higher resistance are represented by darker colors.

Running Circuitscape

Once our focal points were identified and resistance layers were created, we had all the components necessary to run Circuitscape. As explained in the analytical framework section on Circuitscape, we opted to use the one-to-all option in our analysis. In this feature, a single node (or turtle sighting) is connected to a source while the remaining nodes (sightings) are grounded. The model calculates and creates an output layer that shows the flow of the current through the resistance layer, or landscape. This process is then repeated for every node (sighting), allowing each one to become the source while all others are held grounded. In our model, we chose 197 focal nodes based on actual Blanding's Turtle sightings reported to the MnDNR. With these 197 different nodes, Circuitscape created both an individual current map for each as well as a cumulative current map, giving us a total of 198 different output maps.

Data Analysis

Because there are few studies that have used Circuitscape, and we could not find any published paper that modeled any turtles (though a few masters theses exist), there were very few studies with which to compare our results. Beyond this, studies that have used Circuitscape also incorporated extensive statistical analyses or combined them with other modeling techniques, making them either too technical or unsuitable for comparison (e.g. McRae and Beier 2007; Braaker et al. 2014, Dutta et al. 2015). In light of this, we created our own qualitative criteria for exploring the robustness of our results.

As stated in our methods section, we had an input of 197 different source nodes. Due to time constraints and general overlap between certain nodes, we chose not to examine every individual node's dispersal pattern. Rather, we chose source nodes with different local characteristics to interpret how these differences in landscape influenced current. Three different nodes would allow for cross-comparison and examining general dispersal movements, while not creating too much repetition for our results.

In choosing our different nodes, we created criteria to ensure that each study node would be different. First, we wanted to get nodes from a variety of different landscapes. We chose nodes from urban, suburban, and rural areas in order to explore differences in landscape resistances. We also chose nodes that were either directly or near water bodies to examine how water bodies influence dispersal. Lastly, unique dispersal patterns were purposely chosen to exemplify the differences across landscapes and allow for the best comparisons.

Each individual current map was visually examined against its resistance layers (land cover, roads, water quality and distance from water) in order to determine if the resulting dispersal pattern reflected the patterns expected from the literature on Blanding's Turtles. After comparing the current maps to the resistance layers, we then contrasted each node against the other two to determine how current changes between local landscape resistances. Juxtaposing all three resulting dispersal patterns allowed us to get a better sense of how the current and resulting movement patterns are influenced by the base resistance layers. The results for all three nodes highlight the unique abilities that circuit theory is able to bring to ecology to enhance research on habitat suitability and connectivity.

For the cumulative current map, we visually examined the output against the resistance layers as well. However, since the cumulative result is simply an integration of every individual current map, it is not possible to determine the specific influencing factors on a suitable scale. However, we examined the areas of high current, in order to determine what factors led to high traffic in those areas. Finally, we compared the cumulative map to the existing conservation corridors as identified by the MnDNR, in order to determine if the existing corridors of focus are adequately addressing barriers to turtle movement.

III. Results

Individual Current Maps

In line with our methods, we determined three different focus areas. We selected areas with varying landscape types in order to model how Blanding's Turtles move through varying landscapes. In Area 1, the area is predominately wetlands, with little urban development. In Area 2, the area is mostly residential, near the Mississippi River. In Area 3, the area is most urbanized, as it is part of the Twin Cities suburbs. Figure 13 gives a depiction of the three chosen areas of focus.

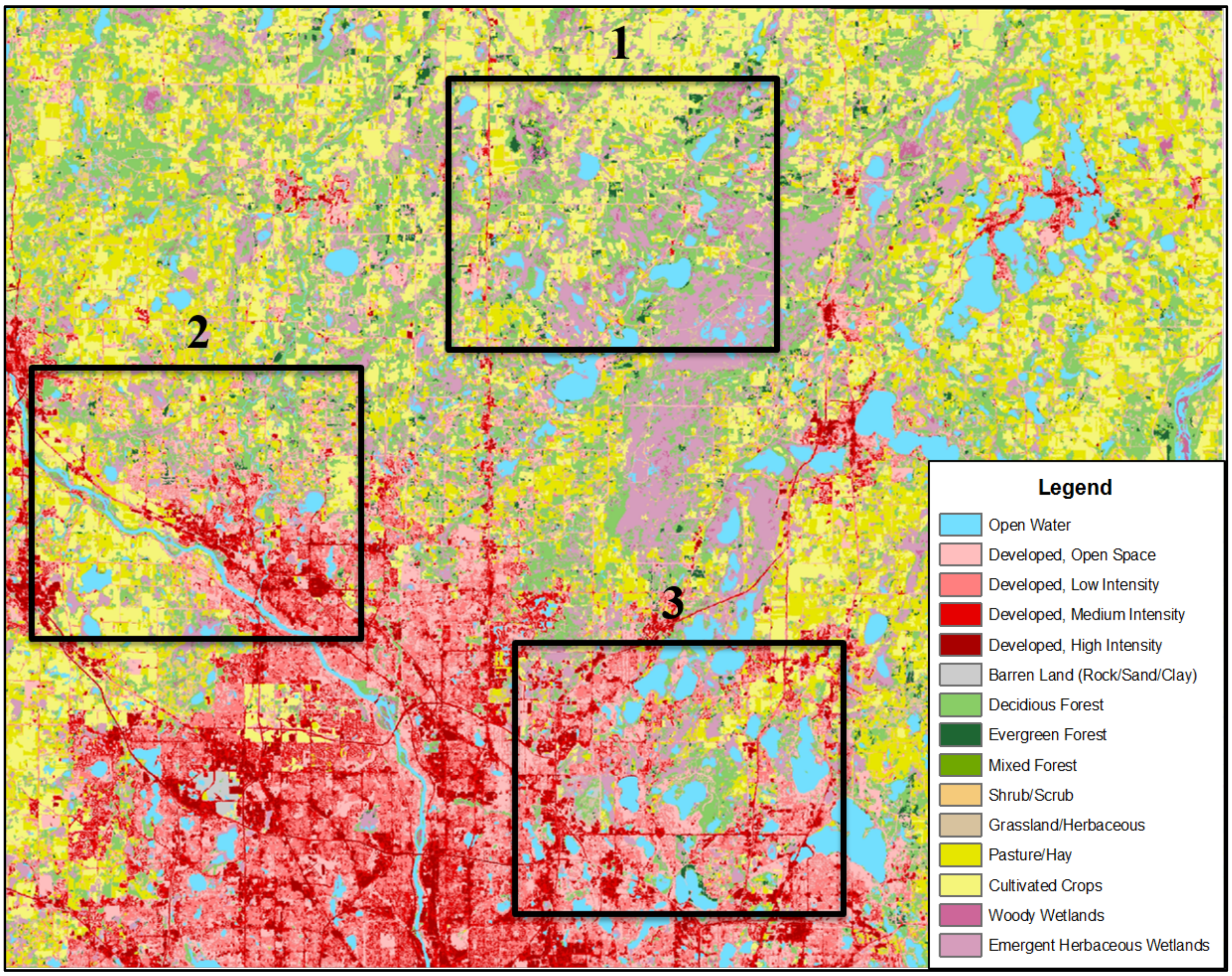


Figure 13. Focus areas for our three nodes. Area 1 is mostly rural and cropland. Area 2 is semi-developed and Area 3 is mostly residential, allowing for differences in land cover, road types and water quality.

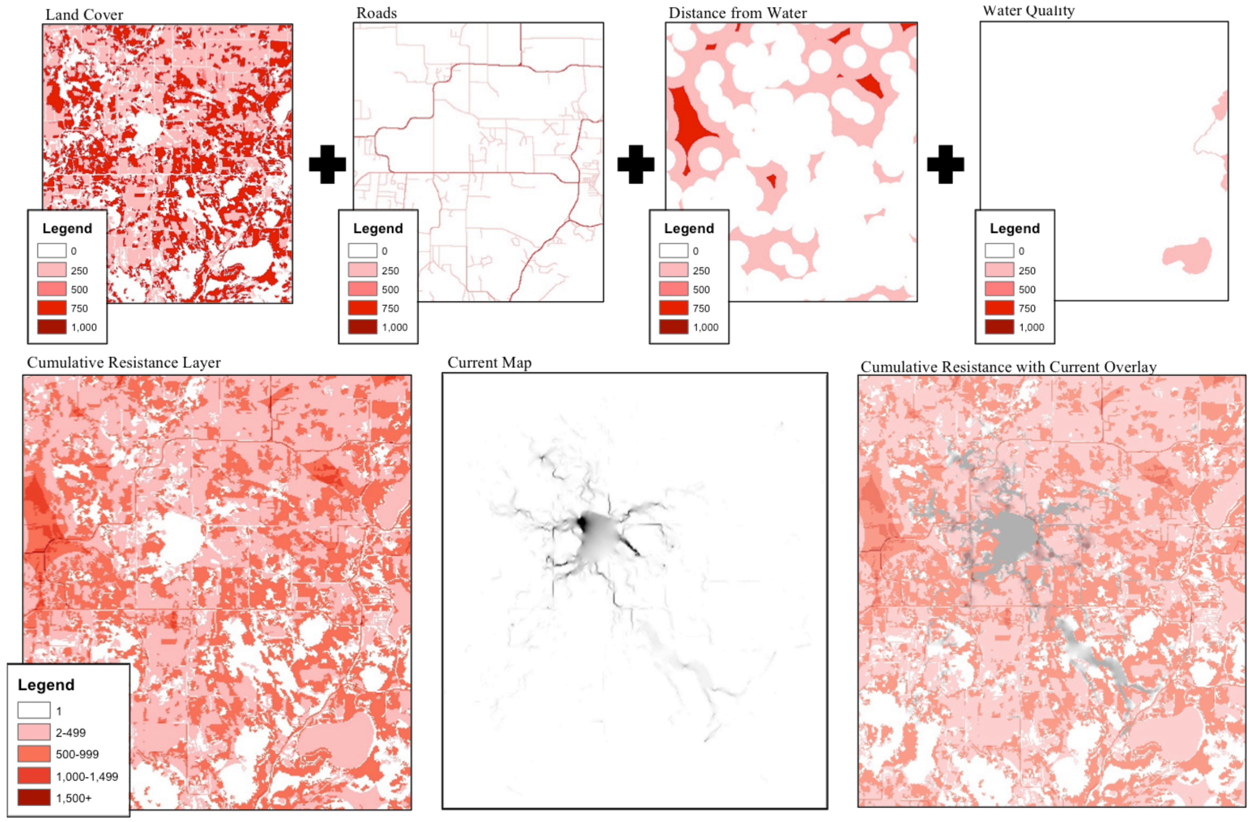


Figure 14. Focus Area 1 and its individual resistance layers (top row), cumulative resistance layer (bottom left) and the Circuitscape analysis (bottom middle). The current map and resistance map are overlaid (bottom right) to highlight dispersal patterns.

In each area, differences in the flow of current are apparent. In the first area (Figure 14), the current disperses evenly near its focus. This is partly because it is next to an unimpaired lake, leaving little resistance. However, once it moves past the lake, there are very specific paths that the current takes. To the south is an emergent herbaceous wetland. Just as hypothesized, the current follows this path because it is the area that offers the lowest resistance. Once the wetland stops, the current becomes condensed into one solitary path until it meets a road. Beyond the road, the current becomes less condensed as it finds another low-resistance landscape. Beyond the path to the south, other paths extend through different wetland streams and slowly dissipate as those streams end. Once outside the wetlands, the resistance values are low (all under 1000; most under 500), which allows the current to travel mostly unrestricted. This is to be expected, as Area 1 is in a highly rural area with high quality wetlands and water, allowing dispersal to occur in most directions.

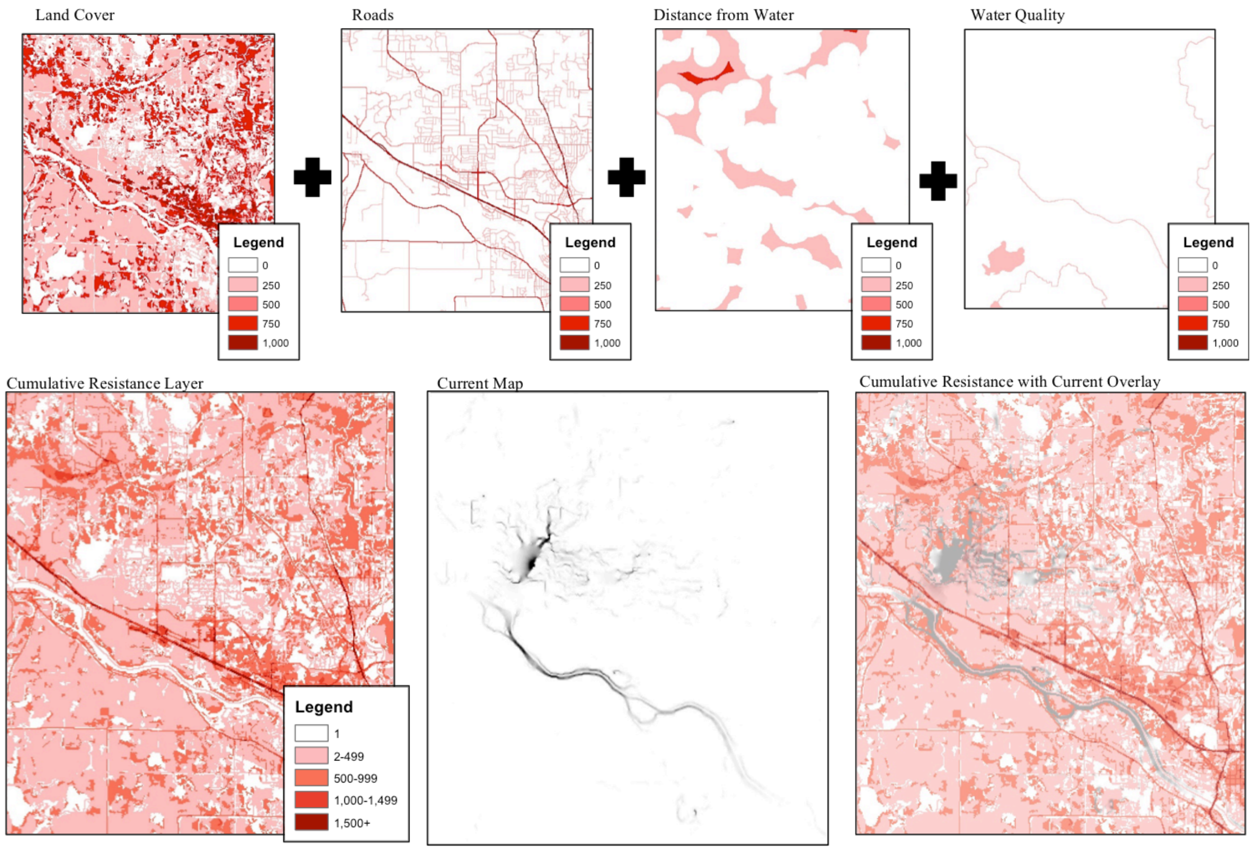


Figure 15. Focus Area 2 and its individual resistance layers (top row), cumulative resistance layer (bottom left) and the Circuitscape analysis (bottom middle). The current map and resistance map are overlaid (bottom right) to highlight dispersal patterns.

In the more residential Area 2 (Figure 15), dispersal patterns are quite different. Similar to the first area, this node is adjacent an unimpaired lake which allows the current to flow freely near the node. However, beyond the lake, the area is slightly more developed with the majority of the area to the east being open space or low development. To the south, the land cover is hay/pasture, offering little resistance to the current until it meets the Mississippi River, a surface with very low resistance. The current then follows the river south. An important note is that there is an apparent break in current between the lake and river. This is because there is a road separating the two, creating a high-resistance barrier. This makes the passage from the lake to the Mississippi treacherous, with no best-dispersal path. Another interesting point is that once in the river, the current stays within this area. This could be translated into a turtle's movement. Once in the river, the resistance on either side will likely keep the turtle from leaving the area.

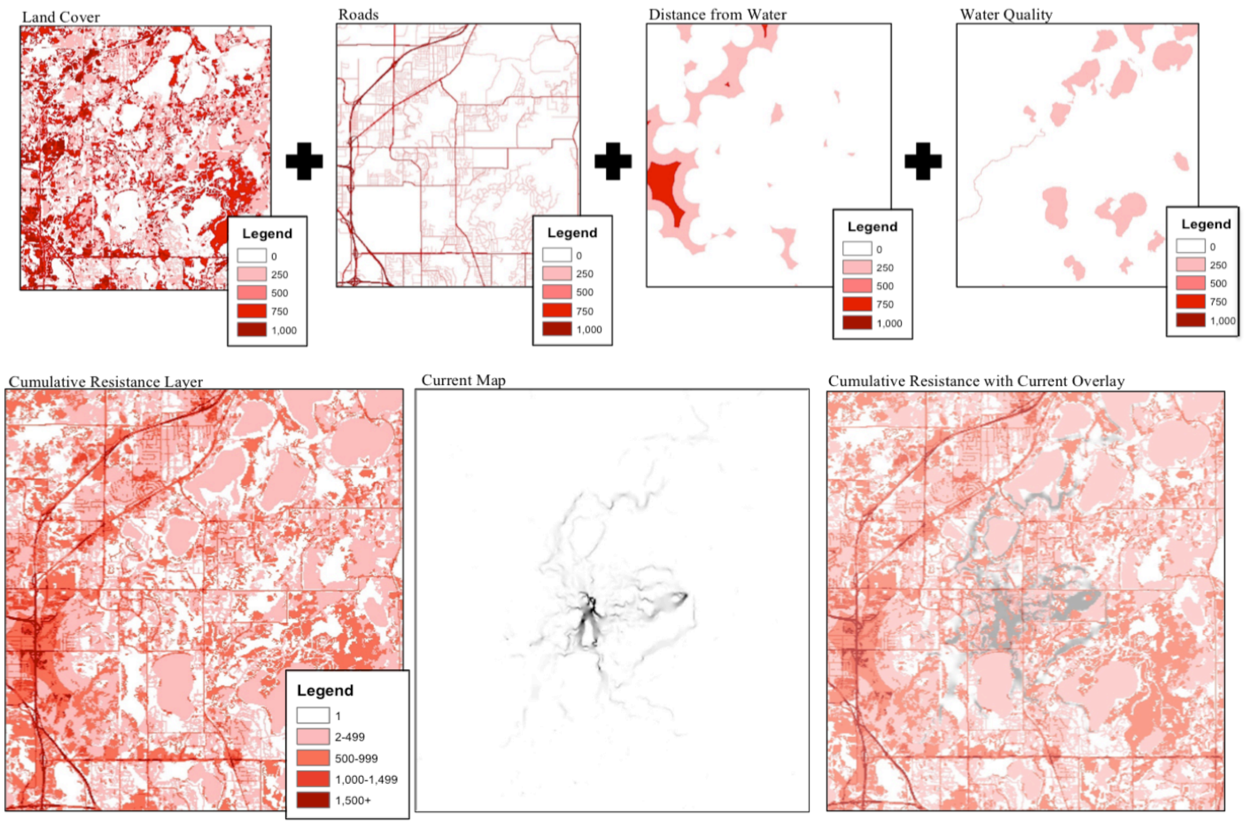


Figure 16. Focus Area 3 and its individual resistance layers (top row), cumulative resistance layer (bottom left) and the Circuitscape analysis (bottom middle). The current map and resistance map are overlaid (bottom right) to highlight dispersal patterns.

In Area 3 (Figure 16), the area is much more urbanized than the other two regions, as it is mostly comprised of residential neighborhoods. In this area, most of the land cover has low and medium developmental intensity, with the exception of a wetland to the south. This translates into a resistance layer that is mostly between 250 and 2000, except where the wetland lies. Just as expected, most of the current stays inside the wetland area with a few streaks moving out into the higher resistance areas. One area where current ventures out from the wetland is to the east. The current utilizes open, undeveloped space and snakes around areas of higher resistance until it runs into another wetland (depicted by the lighter area to the east). Although it may be difficult to see through the picture, the urban area creates a maze, forcing the current to weave through more developed or resistive areas. This can easily translate into turtle movement: the turtle mostly stays within the adjacent wetland, but once it begins to leave it will use open spaces to move until it can find another low-resistance area.

Cumulative Current Map

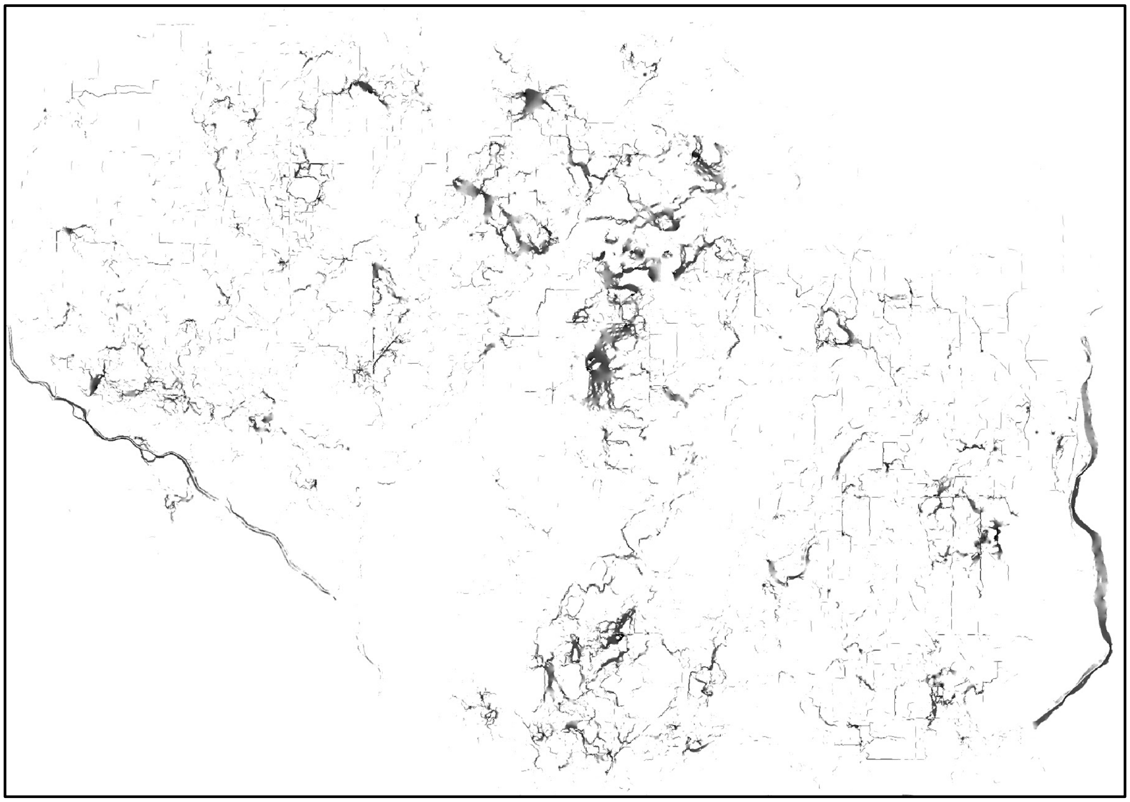


Figure 17. Cumulative resistance map. Low-current areas are exaggerated in order to make the movement patterns more visible. See Appendix 1 for non-exaggerated cumulative current.

The cumulative current map produced by Circuitscape (Figure 17) yields some interesting conclusions. First, the area that has the highest current (the darkest areas depicted) lay directly in the center of our study area. This is because the area mostly consists of rural wetlands and unimpaired lakes. In this area, the resistance layer is low (between 1 and 500) allowing current to flow fairly uninhibited. Of note, however, are the slivers of black that indicate areas of high current or movement without many alternative routes. In this central area, there are several spots that function as 'pinch points,' or areas with only a few available paths. Patches of deciduous forests created non-urban 'pinch points,' which we did not predict.

Another note is the apparent break between the northern-western cluster and the southern-eastern cluster. Though difficult to tell on the map, these two areas are divided by Highway 35, a major, virtually impassable highway. This model predicts that connectivity across this major highway is all but nonexistent and effectively breaks the habitat into two larger pieces. Though there may be no way to reconcile the ecological effects the highway has created, the model highlights the significance of major urban infrastructure as barriers to turtle movement.

Cumulative Current Map against Existing Corridors

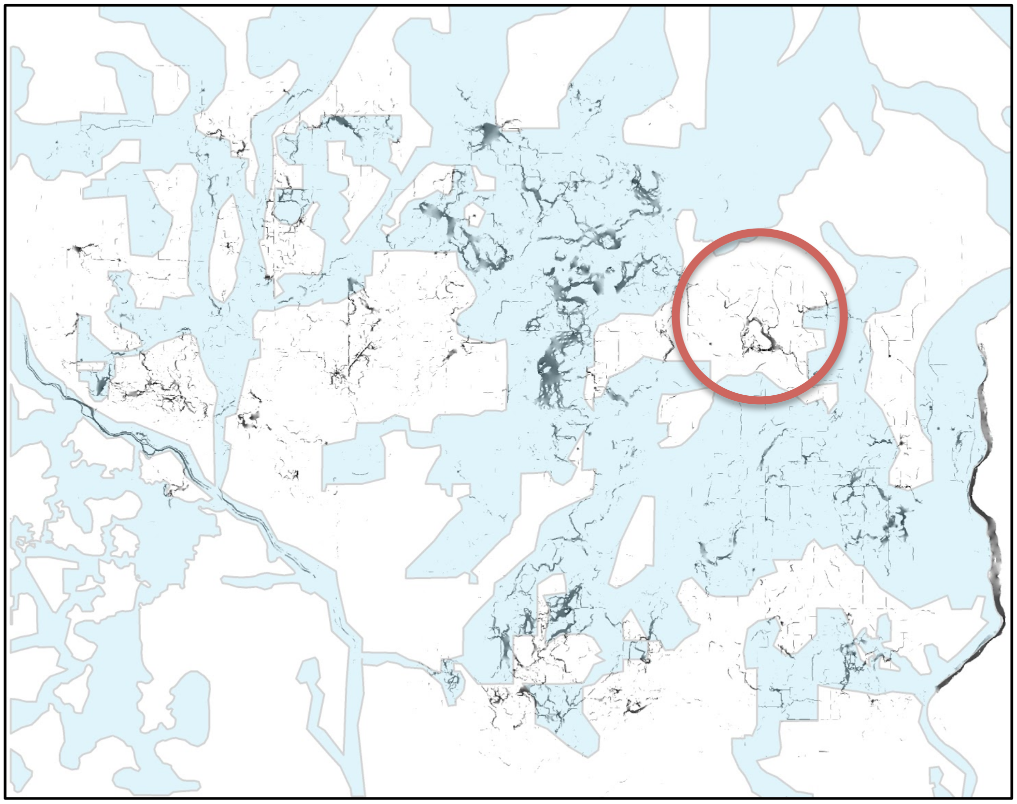


Figure 18. Identified Corridors. Low-current areas are exaggerated for visibility. See Appendix 2 for a non-exaggerated current map overlaid with the conservation corridors.

In Figure 18, the Metro Conservation Corridors are superimposed on our cumulative current map. The Corridors are key areas identified by the MnDNR whose protection and preservation helps maintain the quality of life in the region. These are areas of greatest regional importance for improving the health of local vegetation, fish, and wildlife species (Minnesota Department of Natural Resources 2016). The majority of current (predicted movement) identified by Circuitscape falls within the corridor area. This result could occur for two reasons: either the corridors are saving turtles and promoting movement, or these are the only areas where turtles have a chance of survival, and the MnDNR is correctly identifying these as areas of concern. Whatever the reason, our findings do conclude that there are very few additional areas where corridors could be created in order to promote connectivity.

That being said, there are a few areas outside of the corridors. Over to the east, (highlighted in the figure) there is a clear and bright area that signifies high current flow. This area is actually on an impaired lake across from an urbanized area. This area has a lot of high resistors around the pathways in the form of open space and deciduous forests to the east, and high development to the west. This is why the current is high: there are very few low-resistance pathways left. This may become the next area for local extinction, because of the few opportunities for dispersal.

Least-Cost Map v. Circuitscape

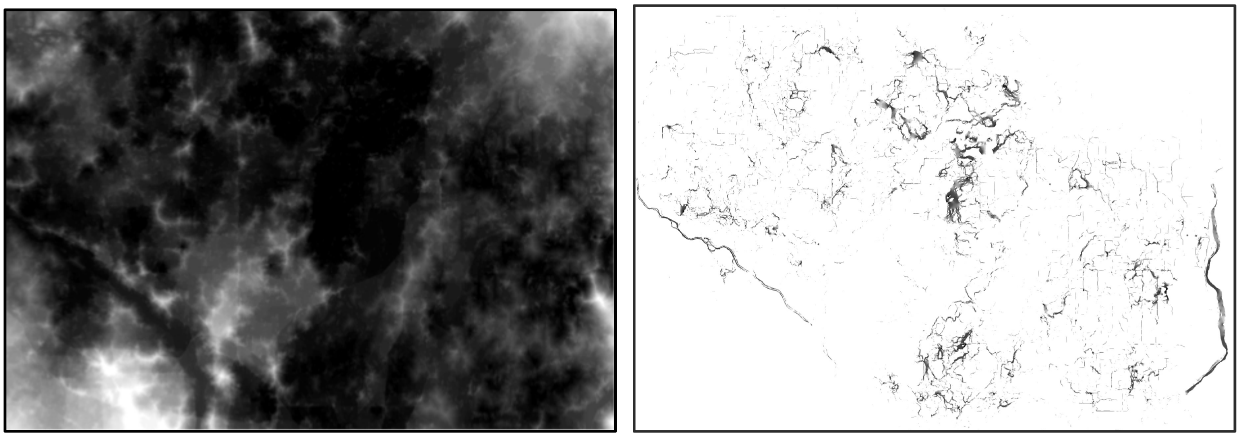


Figure 19. Least-cost map next (left) to Circuitscape output (right). The light areas for the least-cost map are areas of lower costs while the dark areas for the Circuitscape output show most-likely dispersal patterns.

There is a clear difference between the least-cost map and our Circuitscape output, as seen above. As explained in the least-cost modeling section, least-cost software runs an algorithm to determine the 'cost' between any two points. Since we are using almost 200 points, instead of getting a least-cost path, we had the software create a 'cost' landscape output using the same cumulative resistance layer. The lighter areas represent areas of higher cost between points while dark areas represent areas of low cost. We have added the least-cost map only to show how it compares to the Circuitscape output. In general, the two are very similar: Both depict areas of high cost/low movement in similar areas (i.e. the bottom left and top right) as well as areas of low cost/high movement (i.e center). We did not run any analysis between the two outputs, but adding the least-cost map helps highlight the differences between the two outputs.

IV. Discussion

Relevance

Without a consensus on a standard for connectivity modeling, habitat connectivity may always be an unrealized goal. However, with the rise of functional connectivity modeling, specifically Circuitscape, highly heterogeneous landscapes can be accurately modeled. We have shown that circuit theory via Circuitscape can predict movement patterns in a manner that seems consistent with the literature on turtle movement. Circuitscape is also able to take hundreds of nodes and map the movement between all of them at once, a feature that is not possible using only least cost models. We believe that more circuit theory modeling should be implemented into conservation efforts, even if it is only supplemental. As this technique becomes more established, it will only become more robust.

As for more concrete relevance, our results will directly help the conservation goals of the MnDNR. In our contractual agreement with the MnDNR, we offered to share our results with them to help inform future decisions regarding habitat protection and corridor identification. We will now be able to inform them that our model concludes that, for the most part, the metro corridors are in the right place to promote habitat connectivity. Our results will be one part of a multifaceted strategy to continue to promote the continuation of nonhuman animal species.

Limitations

Our model predicts animal dispersal patterns that match our expectations: high resistance areas are often avoided in favor of lower resistance ones. However, our model has limitations that should be addressed in future revisions.

First, additional studies should revisit the resistance values we assigned. Our model included only five different resistances: 1, 250, 500, 750, 1000. This was done in light of the fact that the literature did not have precise measures of the difficulty of habitat traversal (i.e no author explicitly stated that a highway is exactly four times as difficult to traverse as a township road). We thoroughly analyzed the existing literature in assigning resistances, but our values were purely based on best guesses informed by the literature. Other studies have also recognized this problem and have used circuit theory in conjunction with other strategies to create a more robust model (Chardon et al. 2003; Sawyer et al. 2011). Without GPS tracking, resistance assignments will always be a challenge.

Another issue with our model is the observation location for the turtles. Few resources are allocated to tracking and maintaining the Blanding's Turtle, as evident in the sighting data acquired from the MnDNR. Without radio tracking or marking the turtles, it is impossible to know if the sightings represent different turtles, or whether some of the sightings were simply the same individual. However, the sighting data do demonstrate areas that are hospitable to Blanding's Turtles, regardless of whether they represent one turtle over several years or different turtles every year. Additional sighting data would only serve to further reinforce our model.

Further Study

Though our model incorporated a variety of landscape features affecting Blanding's Turtle mobility, there are still opportunities to make it even more robust. For example, one important factor when it comes to ecological conservation possibilities is the tradeoffs associated with a project. MARXAN, a widely used form of conservation planning software, helps to incorporate the benefits and costs associated with a project in order to achieve an optimum outcome. By incorporating the costs associated with connectivity corridor preservation, such as mitigation requirements and loss of usable land, MARXAN is able to reach a target conservation goal while minimizing costs at the same time. This is particularly useful in an increasingly urbanizing setting such as the Greater Twin Cities Metro Region, where administrators and planners must balance competing priorities regarding ecological and anthropogenic land uses.

V. Conclusion

Though Blanding's Turtles are recognized as a species highly vulnerable to anthropogenic land use changes and urbanization, studies seeking to address habitat connectivity issues in urban areas are lacking (Baguette and Van Dyke 2007; Rayfield et al. 2012; Fagan et al. 2016). By utilizing circuit theory to model the movement patterns of Blanding's Turtle throughout the greater Twin Cities Metro Region, we sought to add to the existing literature and enhance knowledge relating to Blanding's movement patterns and habitat requirements. Our Circuitscape model incorporates resistance values for varying landscape characteristics in order to predict dispersal patterns in highly heterogeneous urban landscapes (McRae 2006; McRae et al. 2008). Through modeling dispersal patterns based on individual nodes (based on actual sightings), it was possible to create a model that depicts current, or the movement of an individual, throughout our entire study area. Our resulting model shows not only where 'pinch points,' or areas of high current with few pathways, exist, but is also able to reflect the effect that highly resistant landscapes (such as Highway 35) have on movement patterns.

By identifying dispersal probabilities for the species throughout the Twin Cities Metro Region, our model is able to conclude that the Metro Conservation Corridors as identified by the MnDNR are in fact in areas determined to serve as high dispersal areas for the Blanding's Turtle. This demonstrates that the existing corridors are already existing in the right areas to continue promoting turtle movement and survival. However, our model was also able to highlight areas of concern previously overlooked by the MnDNR, indicating the promise of Circuitscape as an additional connectivity model used by conservation organizations.

Our results demonstrate that the use of Circuitscape is very promising for future ecological research. The program allows large, highly heterogeneous landscapes to be modeled on both an individual and cumulative level, leading to an in-depth analysis of potential movement patterns and existing barriers to movement. With future studies, the use of circuit theory in modeling animal behavior and movement patterns will only continue to grow and become even more valuable.

VI. Bibliography

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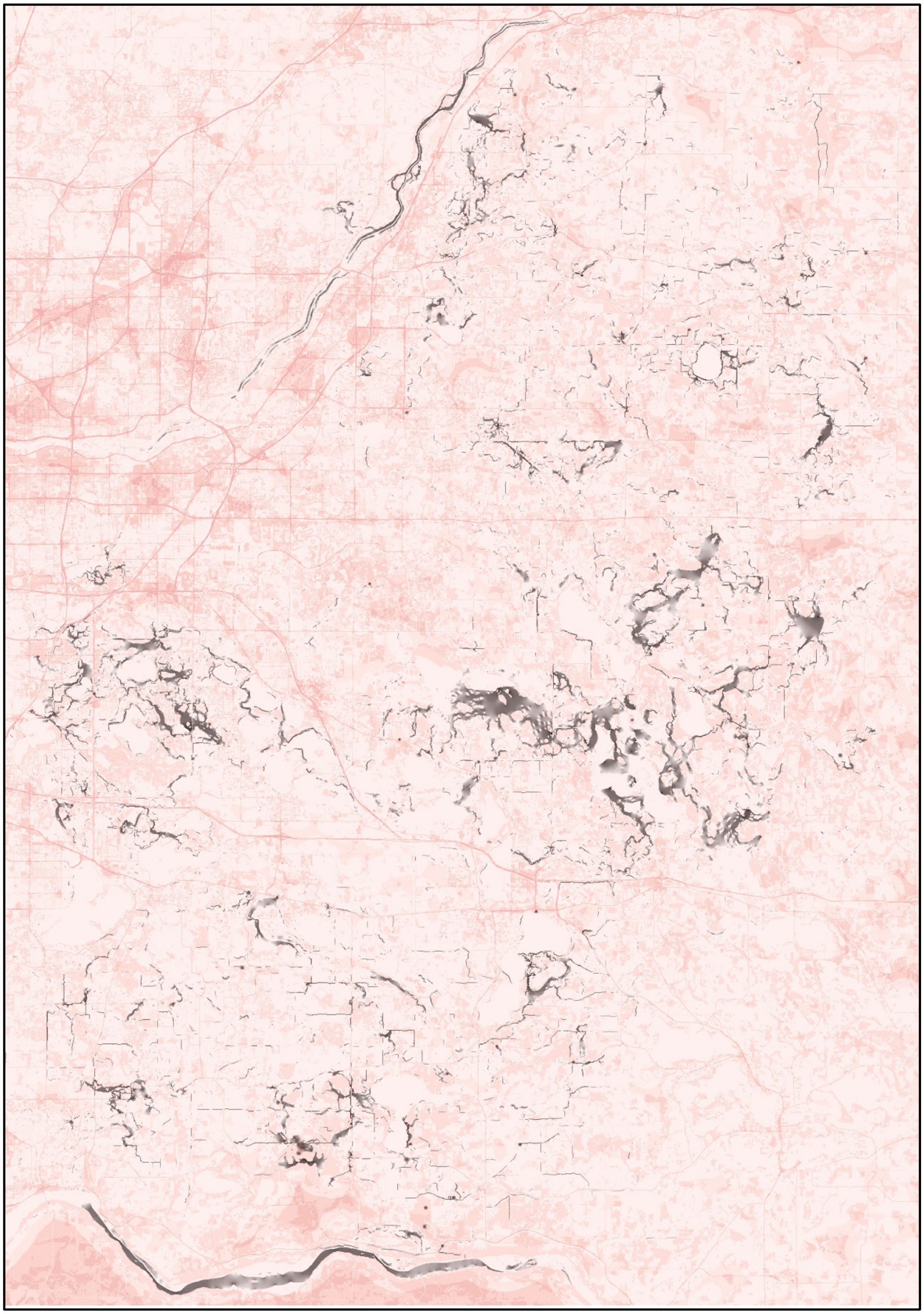
Appendix 1. Non-exaggerated Cumulative Current Map

Appendix 2. Exaggerated Cumulative Current Map Overlaid with Resistance Map



Appendix 3. Non-exaggerated Cumulative Current Map Overlaid with Corridors