Analysis of functional ecological connectivity across selected landscapes in Prince Edward Island, Canada

By

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Abstract

Habitat fragmentation and habitat loss are two of the largest threats to biodiversity in the modern age. Because of this, the study of how animals move between patches of fragmented habitats is crucial to being able to plan for the protection and conservation of species and habitats. I conducted a functional connectivity analysis of barriers to movement for three species with different movement types and habitat requirements- northern flying squirrel (*Glaucomys sabrinus*), pickerel frog (*Lithobates palustris*), and smooth green snake (*Opheodrys vernalis*) - in four different regions across the eastern Canadian province of Prince Edward Island, which has seen a significant reduction in natural areas since the 19th century. Resistance maps were created for each species using critical habitat components and the open-source toolbox Linkage Mapper was used to find the least-cost paths, barriers, and pinchpoints between core habitat areas in each region. I used the Linkage Pathways tool to find least-cost pathways between core habitat areas, Barrier Mapper tool to find areas where restoration could occur, and Pinchpoint Mapper tool to locate where movement could occur between core habitat areas outside of the least-cost path. I also compared this functional connectivity analysis to previous structural methods used on the island. I found that the cost-weighted distance and effective resistance for movement for the species varied by study region, and that *O. vernalis* was the least aligned with structural connectivity flow outputs. This analysis can assist landscape planners and environmental managers in making future conservation decisions.

May 27, 2021

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1. Introduction

One of the most significant issues facing the world's biodiversity today is habitat fragmentation, the process in which large areas of nature are broken up, either by natural or human impacts into smaller sections, resulting in only "fragments" of the habitat being left (Fahrig, 2003). Anthropogenic causes include the construction of roads or cities in formerly forested areas, or the deforestation of patches of forest (Salaria, 2013). When habitats become fragmented, corridors of habitat between patches are needed in order for animals to move freely between the patches. Because of this, the study of ecological connectivity, or the movement through an ecosystem or landscape by animals, genes, etc., is necessary. The corridors can be in the form of highway underpasses, green belts, or other green engineering and landscape planning methods.

The process of habitat fragmentation has major impacts on species biodiversity (Fahrig, 2003). Although almost all species around the world are being impacted by habitat fragmentation, or overall loss of habitat, the impacts differ with the species. Amphibians and reptiles, collectively known as herpetofauna, are heavily impacted by road activity. The mating calls of anuran species (including frogs and toads) can be disrupted by traffic noise (Eigenbrod, Hecnar, & Fahrig, 2009). Snakes are known to sunbathe on warm asphalt, leading to large numbers of casualties from being run over by vehicles (Brown, 2003). Small mammals have a harder time moving through corridors between fragmented landscape patches (Silva, Hartling, and Opps, 2005).

Prince Edward Island is a province in Eastern Canada, located on the Gulf of St. Lawrence. Because it is an island less than 6000 square kilometres in size, with a large proportion of the land devoted to agriculture rather than natural forest, it is therefore a particularly interesting setting to study ecological connectivity and the effects of landscape fragmentation on island species. Some structural connectivity analysis was previously completed on the island (see Fulton & Bush, 2020), and there has been a species-specific study on small mammals in 2005 (Silva, Hartling, & Opps, 2005). However, a full functional analysis examining the connectivity of the island and the impacts on different types of species has not yet taken place.

1.1. Habitat Fragmentation

Habitat fragmentation, habitat loss, and habitat degradation are major threats to species biodiversity around the world (Taylor et al., 1993). Habitat fragmentation occurs when a large expanse of habitat is transformed into a number of smaller patches of smaller total area, which are isolated from each other by a barrier (Fahrig, 2003). Habitat fragmentation generally occurs on the landscape scale and involves both the loss of habitat and the separation of habitat (Fahrig, 2003). Fragmentation can be caused by various means, both natural and anthropogenic. An example of natural habitat fragmentation is the destruction of a forested area through fire or flooding. Anthropogenic habitat fragmentation involves the removal of the flora of natural areas as a result of forestry activity or for agriculture, roads, and urban landscapes (Salaria, 2013). In Canada, it has been estimated that 84% of endangered plant and animal species identified by COSEWIC (the Committee on the Status of Endangered Wildlife in Canada) are primarily threatened by habitat loss (Venter et al., 2006), which can lead to fragmented habitats. One of the major reasons why species biodiversity is negatively impacted by habitat fragmentation is because it results in an increased rate of local extinction (Fahrig & Merriam, 1985). Habitat loss, especially on a large scale (for example, the clear-cutting of a forest patch or a large agricultural area), leads to increased distances between habitat patches as well as smaller patch sizes (Saunders et al., 1993). This means that individuals must travel further to migrate between populations in order to diversify the gene pool. Furthermore, competition for limited resources will increase inside of the smaller patches (Saunders et al., 1993). Because of the increased likelihood of local extinction from fragmented habitats, patches need to be connected to help ensure the survival of species living in fragmented landscapes.

1.2. Landscape Connectivity

The ability of a population to move between habitats is crucial for the survival of the population, which is why the connectivity of different habitats in an ecosystem and across a landscape is an important topic for research. Landscape connectivity is defined as “the extent to which movements of genes, propagules (pollen and seeds), individuals, and populations are facilitated by the structure and composition of the landscape” (Rudnick et al., 2012). Landscape connectivity can be viewed at fine or broad scales depending on the habitats and movements of the species being studied (Goodwin and Fahrig, 2002), and understanding how fine scale connectivity impacts broad scale ecosystem dynamics is essential for effective conservation of endangered species and critical habitats (Peters et al., 2008).

Landscape connectivity can be broken into two components. The first component is the structural connectivity of an ecosystem, which is the physical relationship between patches of habitat (e.g., the Euclidean distance). Structural connectivity allows researchers to better understand the structural makeup of the landscape, and the distances and barriers between habitat patches (Mühlner et al., 2010). The second component is functional connectivity, which is the effect that the structure of the landscape has on an organism's movement through the landscape (Mühlner et al., 2010). Functional connectivity allows for a more species-oriented approach and involves studying the movement and behaviours of specific species of concern. Many studies focus on either the structural connectivity of a landscape (e.g., Cunningham, 2020; Fulton & Bush, 2020, etc.) or on the influence of landscape connectivity on a specific species or multiple species (Churko, 2016; Salaria, 2013; etc.). Connectivity is either species-specific or landscape-specific or both (Tischendorf & Fahrig, 2000), and therefore these aspects of landscape connectivity are interconnected and inform each other.

1.3. Connectivity Analysis Methods

Least-cost path analysis is one of the most common techniques for modelling ecosystem connectivity (Alexander et al., 2016), and has been used in ecology since the early 2000s (Marrotte & Bowman, 2017). The basic premise of least-cost path analysis is that every movement in a landscape, whether human or animal, has a "cost" in the form of time (seconds per metre), energy (Joules per metre), or money (dollars per metre), etc. (Etherington, 2016). When using least-cost for ecological purposes, the cost tends to be unitless and weighed on a scale, as there are generally multiple factors that increase the cost of movement through the landscape. For example, if mapping the least-cost path for a bear to get from one habitat patch to another, an urban settlement might have a cost of 10 to travel through it, whereas a forested area next to a stream would have a cost of 1. Least-cost modelling was originally developed to aid in the transportation sector and reduce monetary shipping costs in the United States. However, ecologists discovered it was also highly applicable to landscape ecology and was more effective than Euclidean distance (the straight line distance from one point to another) for explaining human or animal movements from one habitat patch to another (Etherington, 2016). It is calculated by adding together all barriers to movement (e.g., slope, waterways, roads) and drawing a path cell by cell from one point on a map to another (in the case of landscape connectivity, two habitat patches) that has the lowest resistance.

Circuitscape is an open-source software created by Brad McRae, Viral Shah, Tanmay Mohapatra, and Ranjan Anantharaman (McRae, 2012). It is an emerging method of studying ecosystem connectivity which utilizes electrical circuit theory in order to measure a study areas' resistance to currents of electrical flow passing through the cells (Shah & McRae, 2008). This can predict how the connectivity of a landscape is impacted by different features in the environment, such as roads or water (Shah & McRae, 2008). The aim is to find pinchpoints in the landscape, or areas critical for conservation because there is a high likelihood of movement through the area (McRae et al., 2008). It is an extremely useful tool for analyzing functional connectivity as it can model both animal movement and population gene flow (McRae et al., 2008).

A key difference between least-cost modelling and circuit theory is their assumptions about animal movement. Where circuit theory assumes all pathways enhance connectivity, least-cost path analysis assumes that individuals choose the optimal path between patches (McRae, Shah, & Mohapatra, 2014). Linkage Mapper, another GIS tool created by the Circuitscape team, can bridge the gap between Circuitscape and least-cost path analysis; Linkage Mapper starts by mapping the least-cost corridors and then applies circuit theory to them in order to identify pinchpoints in a corridor or compare alternative designs (McRae, Shah, & Mohapatra, 2014). Laliberte and St-Laurent used both Linkage Mapper and Circuitscape to model connectivity for moose and deer in the Bas-St-Laurent region of southeastern Québec during a road enlargement and compared validation methods for both models (Laliberte & St-Laurent, 2020). Circuitscape tended to produce sparser, more dispersed, and more convoluted corridors and performed better at identifying corridors of functional connectivity for moose than deer, and Linkage Mapper corridors were more linear but were much more generalized than Circuitscape corridors. This was due to the mathematical algorithms, as Linkage Mapper assumes that animals can see the entire distance between patches and make the best decision as to a path, whereas Circuitscape algorithms assume that animals can only see one cell at a time and make a decision at each cell (Laliberte & St-Laurent, 2020).

1.4. Prince Edward Island

1.4.1. Land Use

Prince Edward Island, located in the Gulf of St. Lawrence in Eastern Canada, is a large island with an area of about 569,290 ha (PEI Agriculture and Forestry, 2010). Originally, Prince Edward Island was covered in Acadian forest (Silva, Hartling & Opps, 2005). Since European settlement of the island, most of the forest has been cleared, either for timber or to make space for agricultural land, which is one of the island's largest industries (Silva, Hartling & Opps, 2005). In 2013, it was estimated that 36% of land on the island was natural forest, with 44% being natural forest and plantations (PEI Agriculture and Forestry, 2010), making it the province with the lowest percentage of forested area in Canada (McAlpine, Harding, & Curley, 2013). Agricultural land use was estimated as 38% of total land on the island as of 2010 (PEI Agriculture and Forestry, 2010). The fragmentation of forested landscapes by agriculture results in losses of habitat and biodiversity on Prince Edward Island which prevents the flow of genes through animal populations in species such as the northern flying squirrel (*Glaucomys sabrinus*) and the eastern chipmunk (*Tamias striatus*) by preventing the movement of individuals between patches of forest (Silva, Hartling & Opps, 2005). In addition to forested and agricultural land use, 5% of the land is developed (urban or suburban), 2% is transportation (roads), 7% is wetlands and sand dunes, and 4% is abandoned agricultural lands which may either be used for agriculture or be naturally transitioning to a forest (PEI Agriculture and Forestry, 2010).

Wetlands are also areas of concern in Prince Edward Island. Covering 29,597 hectares, or about 5% of the province, they provide critical ecosystem services such as providing habitat for fish and wildlife species, aiding in the flow of the hydrologic cycle, and acting as water purification systems and carbon sinks. Of that 5%, it is estimated that 80% is freshwater wetlands (Government of PEI, 2021). Since European settlement, unknown numbers of freshwater wetlands have been lost through the processes of drainage and infilling in order to create usable land for agriculture (PEI Fisheries, Aquaculture and Environment, 2003). Current threats to freshwater wetlands on the island include large-scale farming operations as well as terrestrial erosion and sedimentation (PEI Fisheries, Aquaculture and Environment, 2003).

Roads also have a large impact on landscape connectivity in Prince Edward Island. It was determined in a 2010 meta-analysis of 49 studies on 234 mammal and bird species globally that the effects of species by roads can extend up to 17 km on either side of the road for mammals, although most effects occur within 5 km from the edge of the road (Benítez-López, Alkemade, & Verweij, 2010). On Prince Edward Island, the maximum distance from a road is 6.3 km and the median distance from one road to another is 0.3 km (Fulton & Bush, 2020) which suggests that almost all species on the island are affected by roads.

1.4.2. Connectivity Analysis in Prince Edward Island

To date, very few analyses on connectivity have been completed for Prince Edward Island. Circuitscape has been used on Prince Edward Island previously in large-scale regional analyses, including an analysis by the Nature Conservancy which focused on the entirety of eastern North America (Anderson et al., 2016), and another by the Nature Conservancy of Canada which focused on connectivity threats in Southern Canada (NCC, 2018), as well as a provincial scale Circuitscape analysis completed by Fulton & Bush (2020). A Circuitscape analysis was also completed on the entire country of Canada, including Prince Edward Island (Pelletier et al., 2017). Previously, specific areas significant for further connectivity study have been identified, due to their ability to act as pinch-points; in particular, the Portage region, northwestern Prince County, the Savage Harbour region, and St. Peter’s Bay are all known to be possible barriers for connectivity on the island (Fulton & Bush, 2020). Only one study has investigated the effects of habitat fragmentation on amphibian species on Prince Edward Island, which found a significant nonlinear relationship between amphibian species abundance and the perimeter length of forest patches on the island, indicating that amphibian abundance decreases with increased forest edges (Silva et al., 2003). The study also found that there was a scarcity of amphibian species on the island but that there was little evidence to suggest a decline in species abundance in the thirty years prior to the study (Silva et al., 2003). A functional connectivity study on small mammal species on Prince Edward Island found forest patches of 8-10 ha within 400m of another area of forest cover were essential for native species such as *Glaucomys sabrinus* (Silva, Hartling, and Opps, 2005). Hedgerows, which are rows of shrubs and trees bordering roads or agricultural fields, are also important for the movement of small mammals through a fragmented landscape (Silva, Hartling, and Opps, 2005).

1.5. Research Objectives

The purpose of this thesis is to analyze the functional ecological connectivity across selected regions of Prince Edward Island for various species. The objectives are to evaluate which regions have more resistance to movement than others and where restoration and connectivity conservation efforts can occur. It also aims to analyse how spatial patterns can identify different pinchpoints and barriers for selected species, and to compare the results obtained with prior structural connectivity studies completed on the island (Fulton & Bush, 2020). In order to assess landscape functional connectivity, three different focal species have been selected for analysis by the province of Prince Edward Island as species of interest which may be at risk due to a lack of habitat connectivity: the northern flying squirrel (*Glaucomys sabrinus*), the pickerel frog (*Lithobates palustris*), and the smooth green snake (*Opheodrys vernalis*). Four regions across the island have been identified from prior Circuitscape analysis in Fulton and Bush (2020) as areas of concern in regards to connectivity. These locations are the Portage region, St. Peter's Bay, Savage Harbour, and northwestern Prince county. It is hypothesized that the region south of Savage Harbour in eastern Kings County (study region C), will have the highest costs to travel between cores for all species as the region is geographically quite constricted by water on both sides of the island. Finally, it is hypothesized that *O. vernalis* is most likely to be overlooked in structural connectivity analysis in the province, due to a focus on wetland and forest connectivity. This research will be of use to ecologists and planners in both Prince Edward Island and the Canadian government to help in the conservation of these species by identifying places which may require the creation of wildlife underpasses, selecting and purchasing land for protection and restoration, and managing provincial and federal lands.

2. Methods

2.1. Study Locations

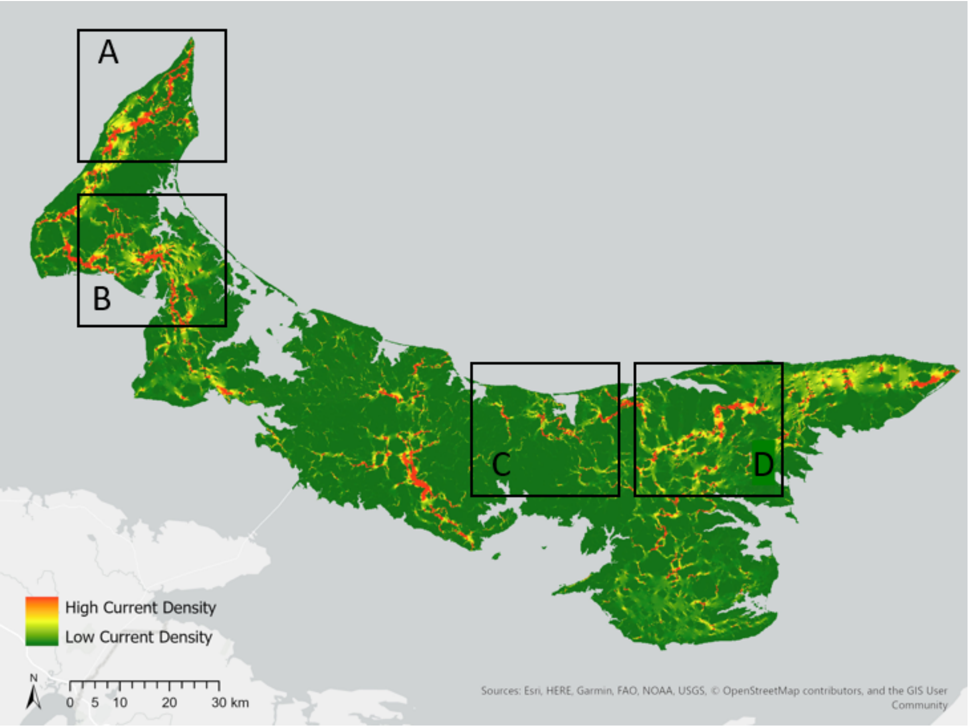


Figure 1. Map from Fulton & Bush (2020) showing pinchpoints for natural areas across the province of Prince Edward Island, modified to show the study regions chosen for this analysis.

The Canadian province of Prince Edward Island is located in the Gulf of St. Lawrence and is a large island with an area of about 569,290 ha. For this connectivity analysis, four study locations were selected based on a Circuitscape analysis of natural areas (consisting of natural and harvested forest, wetlands, and abandoned agricultural areas) by Fulton and Bush (2020), which found that north-western Prince county (study region A), southern Prince county around Portage (study region B), Kings county around Savage Harbour (study region C), and Kings county south of St. Peter's Bay (study region D) were all areas of significant pinchpoints that may restrict the movement of animals through the regions without conservation (Figure 1). Two core habitat areas were created in each region with a minimum area of 7.5 ha using the Corporate Land Use Inventory for 2010 (CLUI), from critical habitat components for each species in the selected regions. These were created to estimate where significant areas of habitat may be for each species in the study regions, as well as where species populations may be located. They were created from the largest adjacent polygons in the region matching the habitat criteria (see Section 2.3). The CLUI uses a combination of aerial photography, interpretation, and ground plots in order to map land use across the island (PEI Agriculture and Forestry, 2010).

2.2. Species Identification

Three species were identified for analysis by the PEI Forests, Fish and Wildlife Division to be used in this study as they are species which are of concern for connectivity. The species have different habitat requirements and represent different types of species on

Prince Edward Island: the northern flying squirrel (*Glaucomys sabrinus*), which inhabits and moves through old growth or mature coniferous or mixed wood forest (Canadian Wildlife Federation, 2021), the pickerel frog (*Lithobates palustris*), which inhabits wetlands and wet forests, and the smooth green snake (*Opheodrys vernalis*), which prefers flat grassy areas such as abandoned agricultural lands. As different species have different requirements for movement through the landscape, the key attributes required for travel were chosen for each species based on their critical habitat components. It is important to note that little is known about the distributions of these focal species on Prince Edward Island. For this analysis, the habitat suitability of the species was used to identify large contiguous patches of suitable habitat. These large contiguous patches of habitat can support metapopulations of the respective species, however, no actual species population data was available to support this assumption.

2.3. Spatial Analysis

ESRI ArcGIS 10.6 for Desktop with an ArcInfo license and Spatial Analyst extension was used for spatial analysis (ESRI, 2011). Linkage Mapper, which is a toolbox by McRae et al. (2010) for ArcGIS Desktop which utilizes circuit theory and least-cost analysis, was the primary tool used to analyze connectivity. The tool requires a polygon vector dataset of core habitats in the ESRI shapefile format, and a raster dataset of resistance (how difficult it is for the species to travel through the cell) in a GRID format. A shapefile with two core habitat polygons was created for each study area and each species for a total of 12 datasets. Resistance rasters were created on the provincial scale based on each species' critical habitat components.

The core habitat polygons represent the larger swathes of habitat in which species would live, feed, and reproduce. Habitats for each species were defined by habitat preferences found in the literature. For *Glaucomys sabrinus*, the core habitats were forested land use with a development stage of “mature” or “old” and a primary or secondary cover type of softwood or mixedwood species (Lehmkuhl et al., 2006, and Canadian Wildlife Federation, 2021). For *Lithobates palustris*, the core habitats had a “wetland” or “forest wetland” land use (McAlpine, Harding, and Curley, 2006), and for *Opheodrys vernalis*, land with “abandoned agriculture” and “meadow” use types were selected (Canadian Wildlife Federation, 2021b, and Ontario Nature, 2021). To find representative core habitat areas for this analysis, the “Select By Attributes” tool was used to select the critical habitat components for each species in the CLUI. Adjacent polygons in the dataset which matched the habitat criteria were then exported into a new dataset and merged into a single polygon using the “Dissolve” tool in the Data Management toolbox. A new short integer field was then created in the attribute table called “Core_ID” which numbered the cores. The core habitat areas each had a minimum area of 7.5 ha.

For the creation of the resistance layers, the “Select By Attributes” tool was used to select the critical habitat components for each species in the CLUI. The Reclassify tool in the Spatial Analyst toolbox was used to reclassify cells based on how they fit the habitat components from 1 to 10, with 1 perfectly matching the critical habitat components and 10 being a barrier to movement. A 2 m lidar elevation contour dataset was also obtained from the Government of PEI (PEI Department of Environment, Energy & Forestry, 2008). The “Topo to Raster” tool was used to create an elevation raster layer as part of habitat suitability for *L. palustris* and *O. vernalis*. Elevation was not considered for *G. sabrinus* as the species does not move on the ground. Once all reclassified layers were created and transformed into raster datasets using the “Polygon to Raster” tool with a cell size of 50 m and the cell value being the reclassified movement value, or “cost”, the Weighted Sum tool was used to add all layers together with their respective weights based on the significance of each factor to the species’ movement.

A project directory was created for each location-species combination. The “Build Network and Map Linkages” tool from the Linkage Mapper toolbox was used to create a cost-weighted distance raster and a least-cost path between the cores. The “Pinchpoint Mapper” tool, which also utilizes Circuitscape, was then used to find the main pinchpoints along and around the path, in order to help determine where restoration should take place in the study areas. Pinchpoint Mapper was run at a buffer zone of 1000 m around the least-cost paths in order to find other pathways between the cores. Finally, the “Barrier Mapper” tool was used to find key barriers to movement along the path. The appendix provides a visualization of the geoprocessing model for this analysis using ModelBuilder in ArcGIS. The least-cost path outputs from the Linkage Pathways tool were compared with prior Circuitscape analysis completed by Fulton & Bush (2020) to find where least-cost paths for various species matched flow outputs for natural areas and where they differed. To do this, the structural connectivity raster was reclassified into either “flow” (greater than 0), or “no flow” (0), with flow given a value of 1 and no flow given a value of 0. The least-cost paths for each species were then rasterized and the “Extract by Mask” tool was then used to clip the structural flow to the least-cost path, in order to find the percentage of cells along the least-cost path that matched Circuitscape flows from the structural analysis.

The main values taken from this analysis were cost-weighted distance (CWD), effective resistance (R̂), CWD to path length ratios, and CWD/R̂ ratios. CWD is the cost to move through a landscape cell by cell with each cell having a specific cost associated with it (McRae, 2012). It has been used in previous functional connectivity analysis as a measure of analysing movement routes for functional connectivity between habitat patches (see Dutta et. al., 2015, Marrotte & Bowman, 2017, Singleton & Lehmkuhl, 2001, etc.). CWD to path length ratios allow for comparisons between study regions as it accounts for changing distances between core habitat areas. R̂ is a measure of connectivity that takes into account the corridor width and the number and quality of alternative pathways available within a corridor. The effective resistance of a corridor decreases (and the cost-weighted distance/effective resistance ratio increases) when corridors are wider or provide high-quality alternatives to the least-cost path. When R̂ is high, there is a high resistance to movement between the habitat areas, and when R̂ is low there is a low resistance to movement (McRae et al., 2008, and Marrotte & Bowman, 2017). CWD/R̂ ratios are useful because they explain the quality and number of pathways and indicate redundancy (McRae et al., 2008).

3. Results

3.1. *Glaucomys sabrinus*

For *Glaucomys sabrinus*, the linkage pathways analysis provided the least-cost path between the core habitat areas for each region (Table 1). Study region B had the highest cost-weighted distance along the linkage pathway, even when accounting for path length. Study region D had the lowest R̂ and the highest CWD/R̂ ratio, meaning it had the greatest quality and number of paths (Figure 2). Study region A had the highest R̂ and the lowest CWD/R̂, meaning that it had the lowest quality pathways and flow was most constricted in this region. Barrier mapper provided areas where restoration would lower the cost-weighted distance of the least-cost path (Figure 3). All regions had many areas where restoration could occur, but Study region D has one large area east of Savage Harbour which is of particular significance. Comparisons with Circuitscape analysis (Figure 6) show that across all study regions, least cost paths created through the Linkage Pathways tool for Linkage Mapper follow along the calculated flows and pinchpoints for natural areas found in Fulton & Bush (2020) (Table 2).

Figure 2. Resistance map depicting difficulty travelling through the landscape for *Glaucomys sabrinus*.

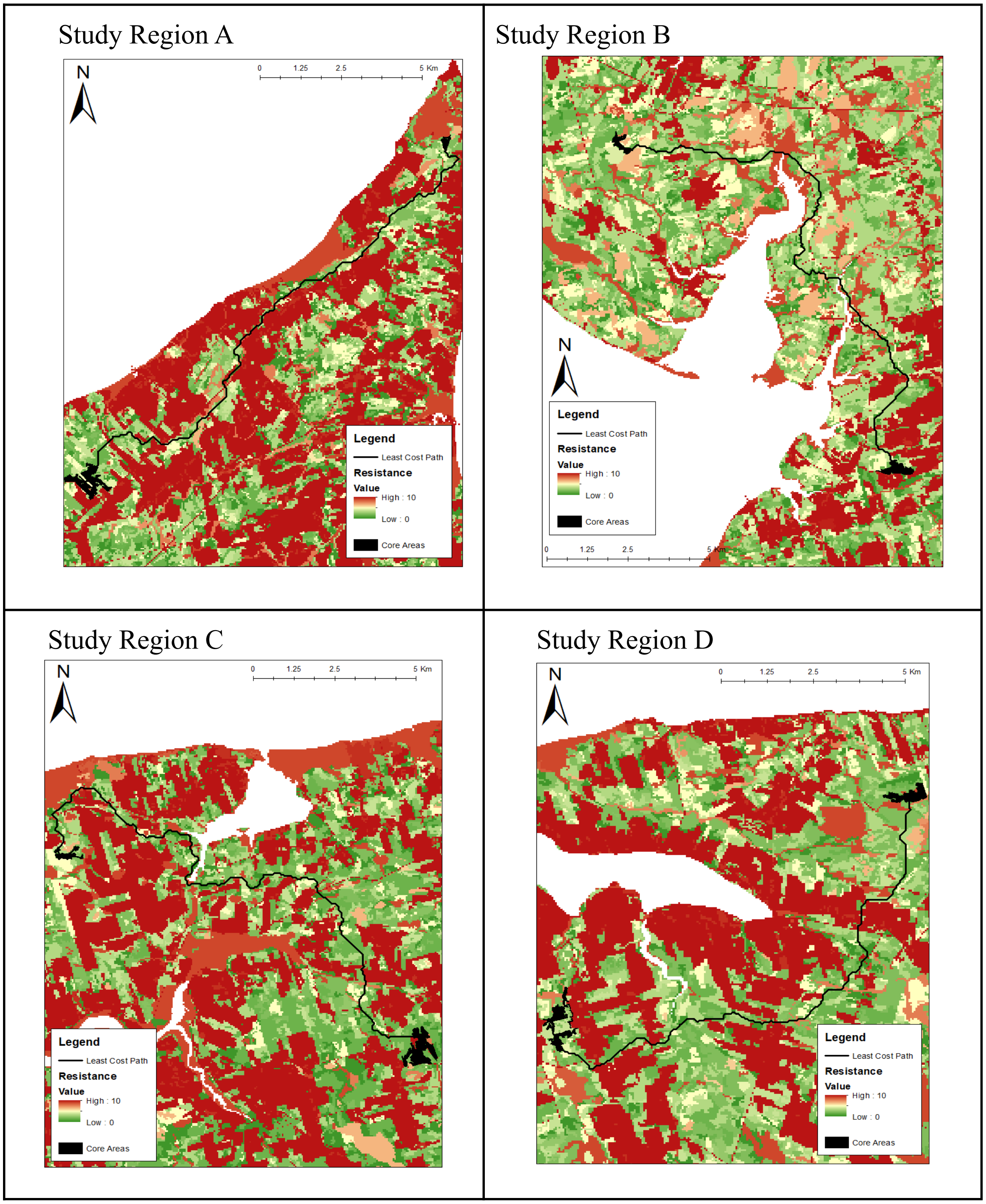


Figure 3. Least cost paths between selected core habitat areas for *Glaucomys sabrinus* in a) North-west Prince County, b) Portage area, c) south of Savage Harbour, and d) south of Saint Peter's Bay.

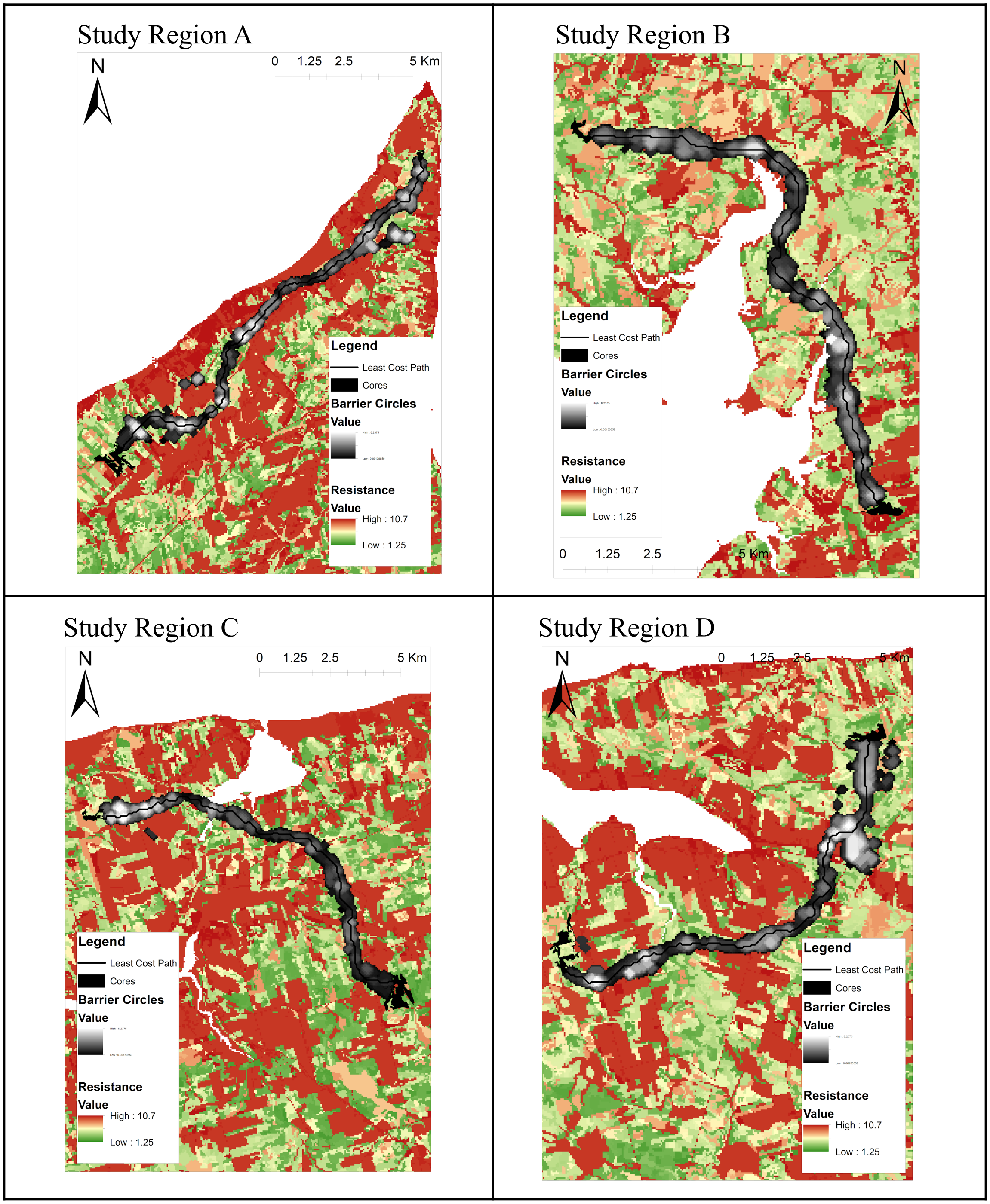
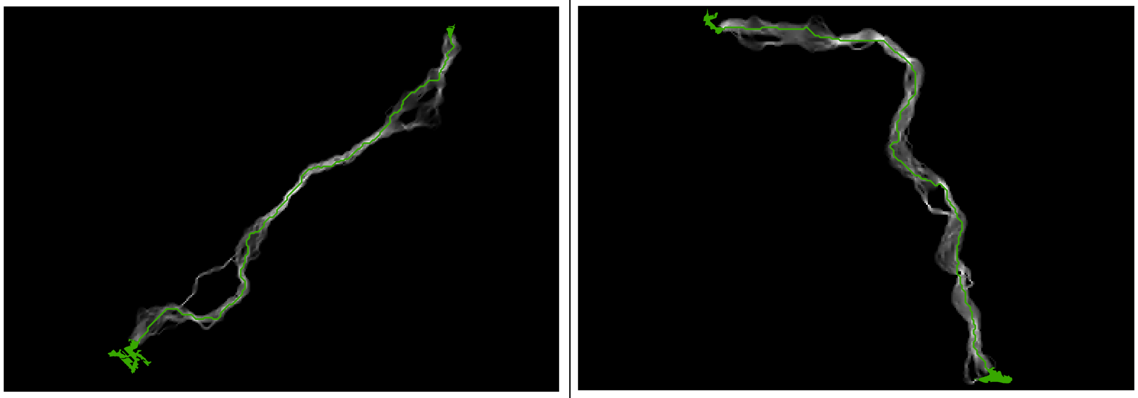
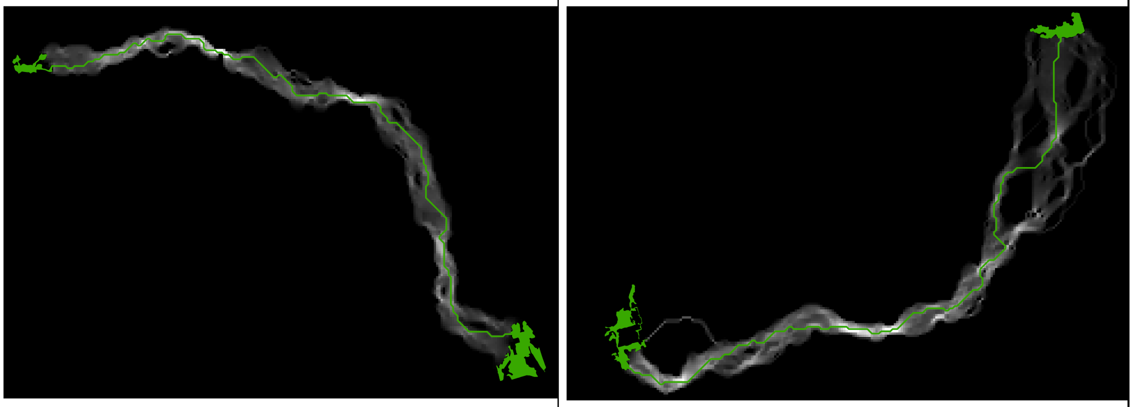


Figure 4. Barriers between selected core habitat areas for *Glaucomys sabrinus* in a) North-west Prince County, b) Portage area, c) south of Savage Harbour, and d) south of Saint Peter's Bay.



a) Study Region A

b) Study Region B



c) Study Region C

d) Study Region D

Figure 5. Pinchpoints between selected core habitat areas for *Glaucomys sabrinus* in a) North-west Prince County, b) Portage area, c) south of Savage Harbour, and d) south of Saint Peter's Bay.

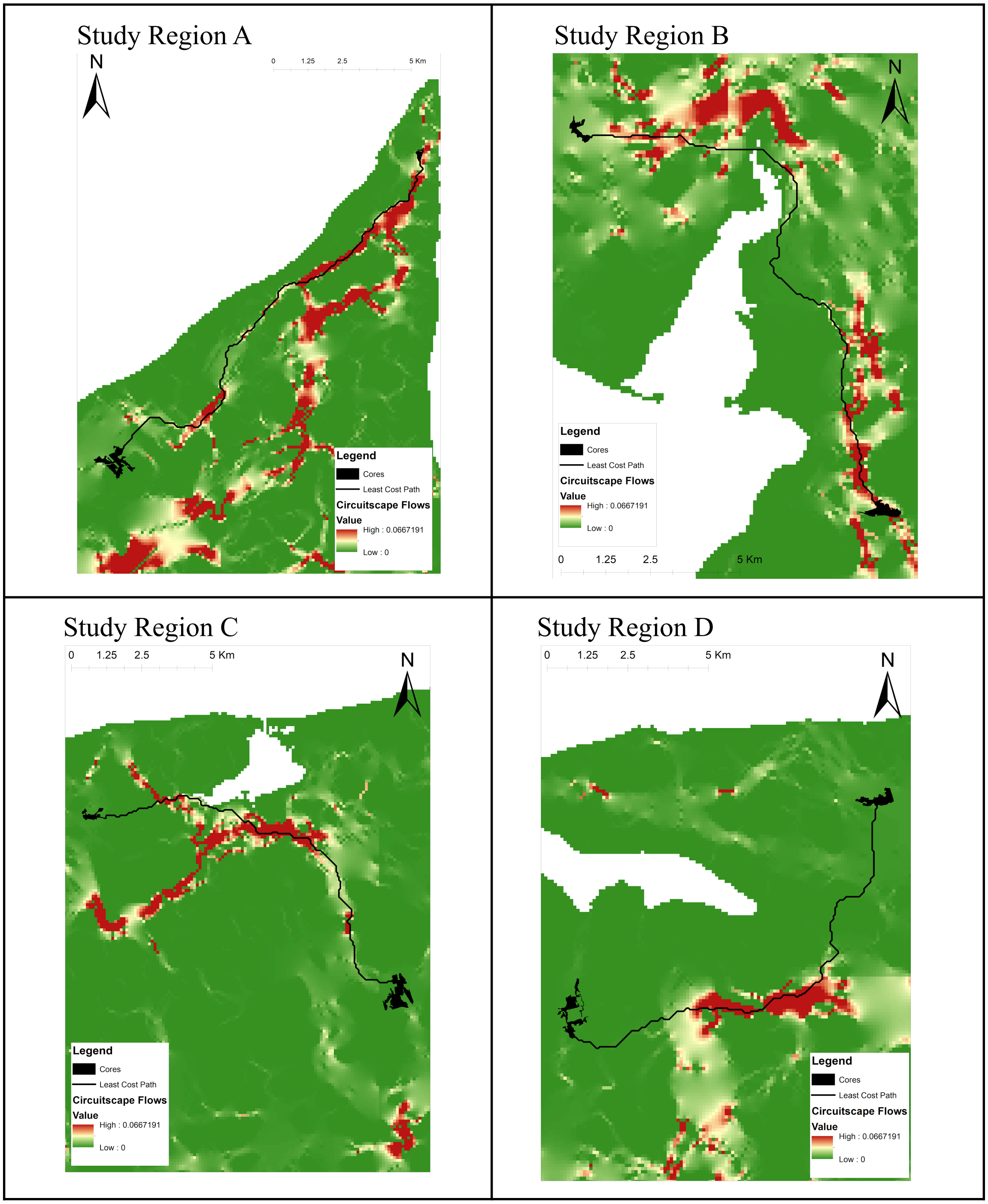


Figure 6. Least-cost paths overlaid on natural areas Circuitscape analysis (Fulton & Bush, 2020) for selected core habitat areas for *Glaucomys sabrinus* in a) North-west Prince County, b) Portage area, c) south of Savage Harbour, and d) south of Saint Peter's Bay.

Table 1. Linkage Mapper and Pinchpoint Mapper metrics for *Glaucomys sabrinus*.

Study Region	CWD	CWD/Path Length Ratio	R̂	CWD/R̂
A	60419.5	3.3	4267.7	14.2
B	63251.5	3.6	3631.9	17.4
C	48542.0	3.1	3267.6	14.9
D	51077.9	3.2	2440.2	20.9

Table 2. Percent overlap (%) between least-cost paths and structural analysis for *G. sabrinus*.

Study Region	Percent Overlap (%)
A	98.0
B	96.3
C	94.2
D	97.1

3.2. ***Lithobates palustris***

For *Lithobates palustris*, the linkage pathways analysis provided the least cost path between the core habitat areas for each region (Table 2). Study region C had the highest CWD along the linkage pathway, even when accounting for path length. Study region B had the lowest CWD and CWD to path length ratio. Study region A had the lowest R̂ but also the lowest CWD/R̂, meaning that although it had the least resistance to movement, it also had the lowest quality pathways and flow was most constricted in this region. Barrier mapper provided areas where restoration would lower the CWD of the least-cost path (Figure 9). Similarly to *G. sabrinus,* while all regions had many areas where restoration could occur, Study region D has one large area east of Savage Harbour which is of significance, the same patch as *G. sabrinus*. Comparisons with Circuitscape analysis show that for the most part, with the exception of some sections of the pathway in Region A, the least cost paths created by the Linkage Pathways tool in Linkage Mapper do not follow the corridor flows for natural areas from Circuitscape.

Figure 7. Resistance map depicting difficulty travelling through the landscape for *Lithobates palustris*.

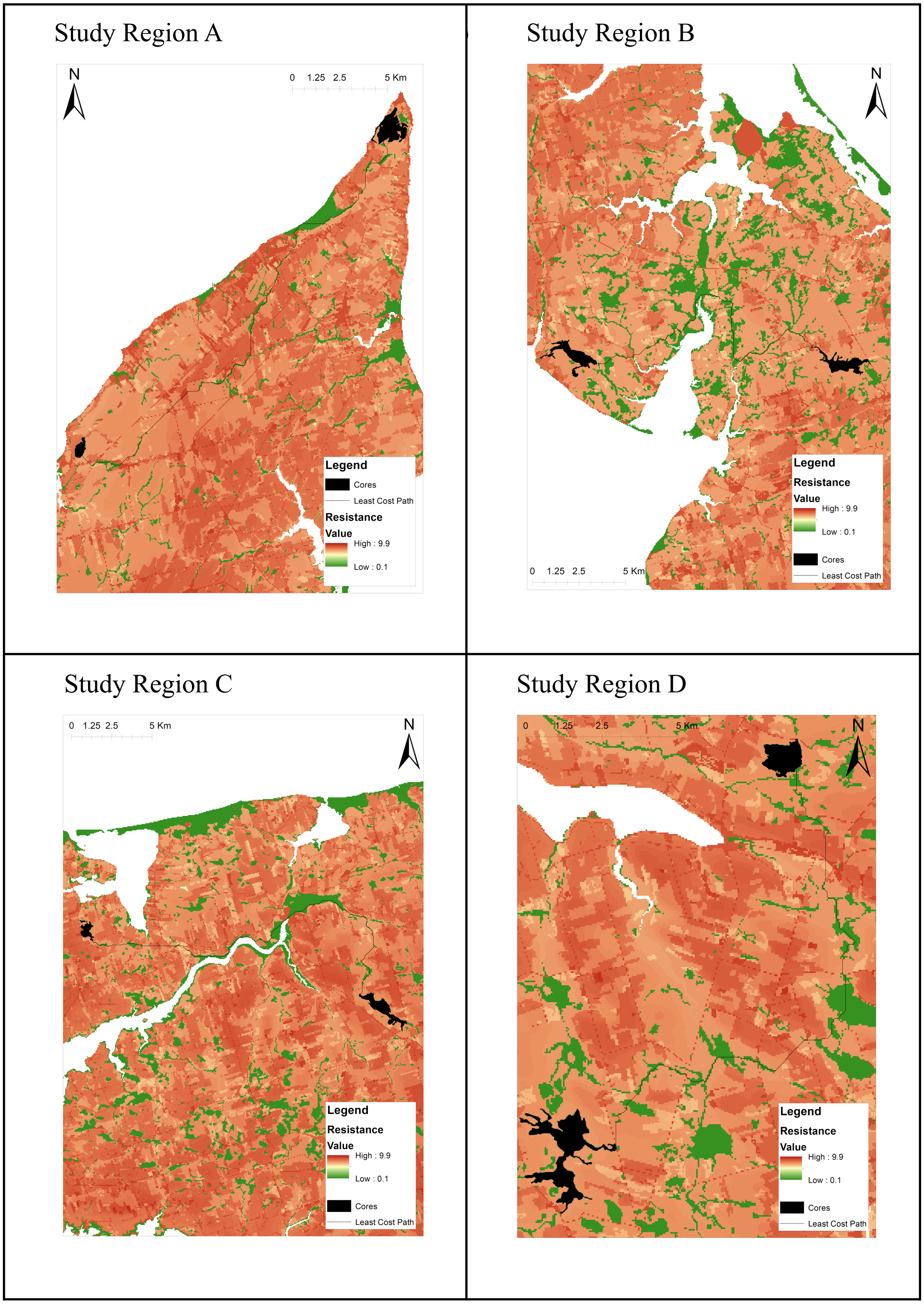


Figure 8. Least cost paths between selected core habitat areas for *Lithobates palustris* in a) North-west Prince County, b) Portage area, c) south of Savage Harbour, and d) south of Saint Peter's Bay.

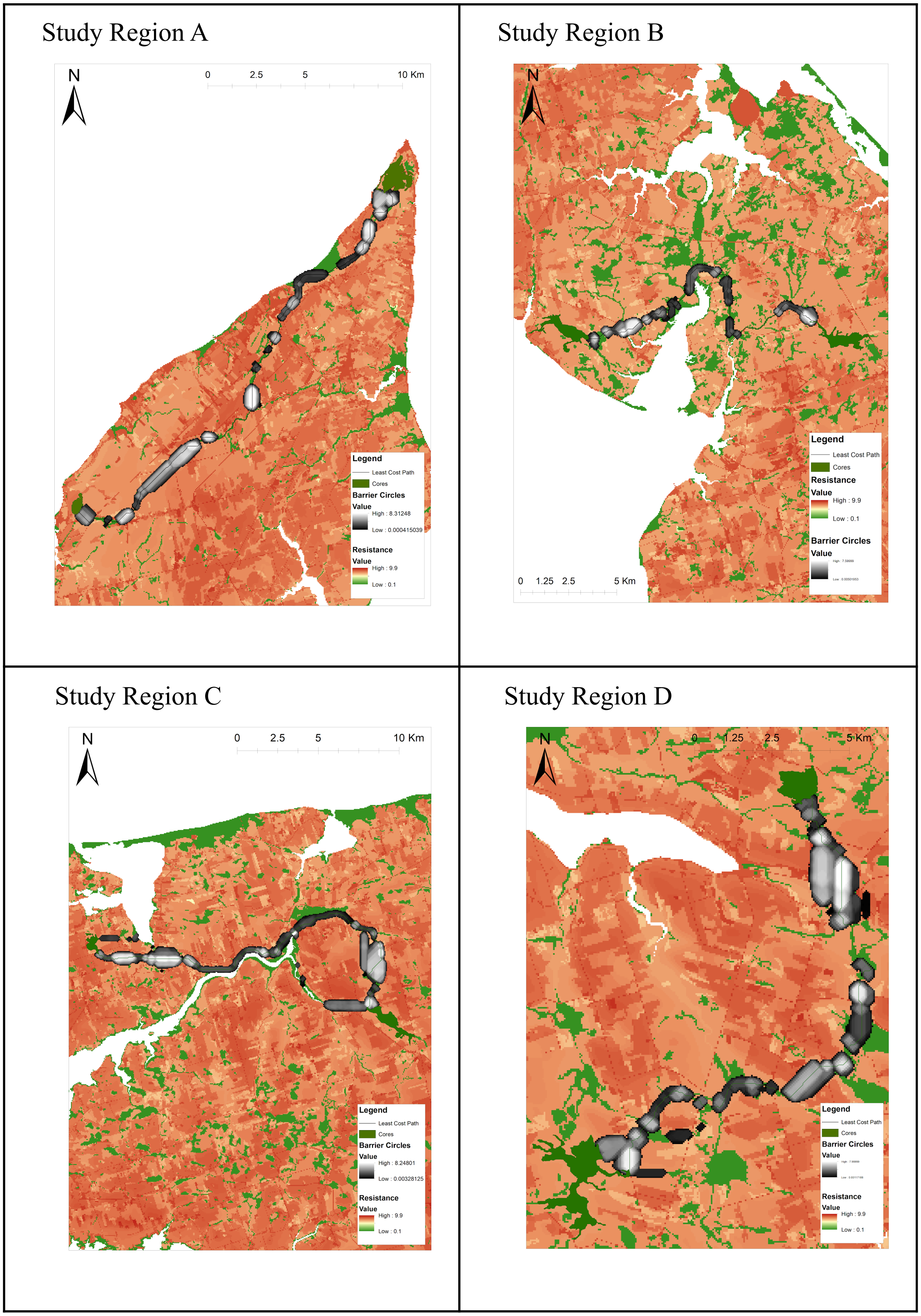


Figure 9. Barriers between selected core habitat areas for *Lithobates palustris* in a) North-west Prince County, b) Portage area, c) south of Savage Harbour, and d) south of Saint Peter's Bay.

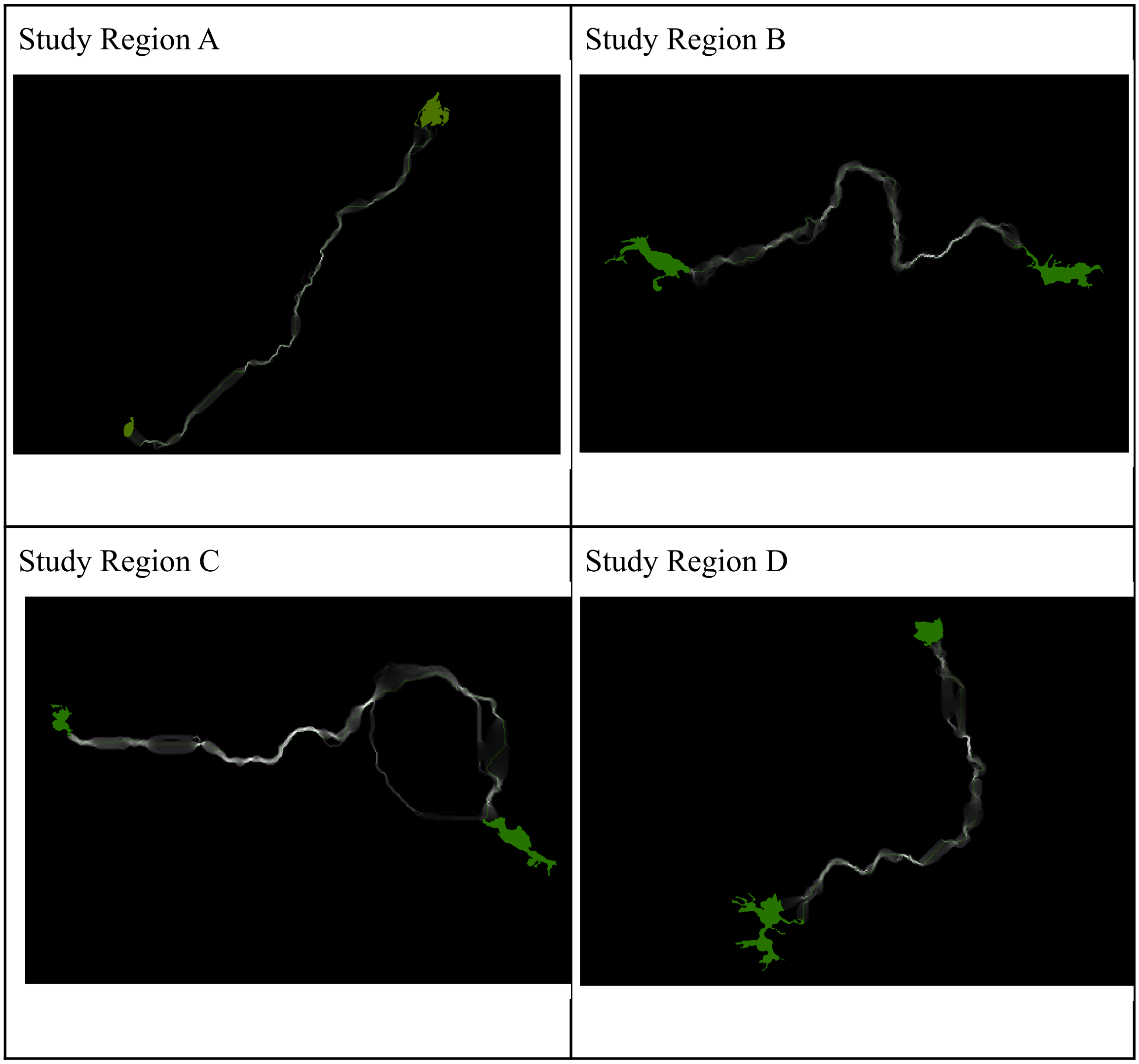


Figure 10. Pinchpoints between selected core habitat areas for *Lithobates palustris* in a) North-west Prince County, b) Portage area, c) south of Savage Harbour, and d) south of Saint Peter's Bay.

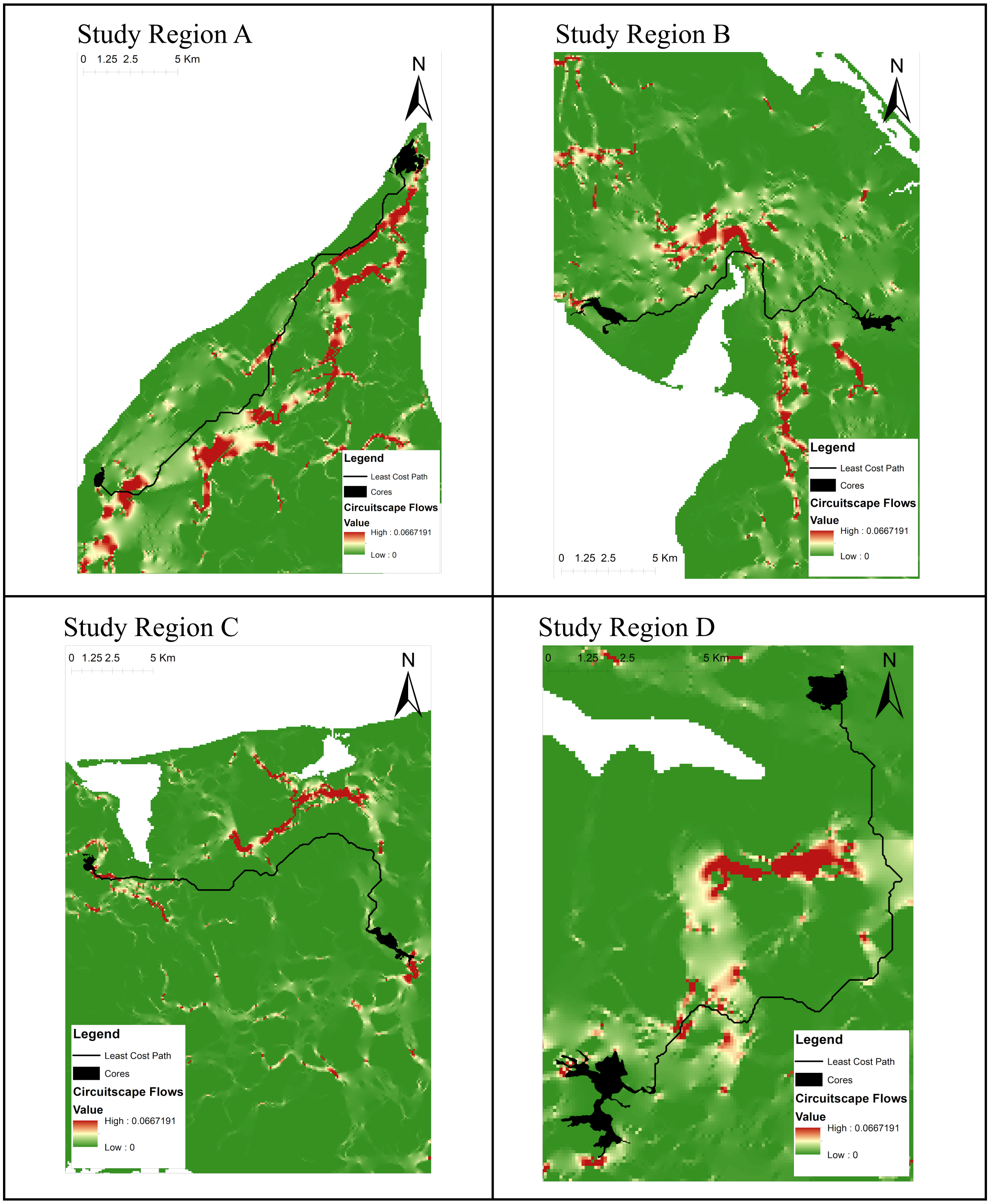


Figure 11. Least cost paths overlaid on natural areas Circuitscape analysis (Fulton & Bush, 2020) for selected core habitat areas for *Lithobates palustris* in a) North-west Prince County, b) Portage area, c) south of Savage Harbour, and d) south of Saint Peter's Bay.

Table 3. Linkage Mapper and Pinchpoint Mapper metrics for *L. palustris*

Study Region	CWD	CWD/Path Length	R̂	CWD/R̂
A	109432.2	3.8	3683.8	3.0
B	54494.6	2.9	5017.1	10.9
C	117167.1	4.4	8464.8	13.8
D	81138.7	3.9	4916.0	16.5

Table 4. Percent overlap (%) between least-cost paths and structural analysis for *L. palustris*.

Study Region	Percent Overlap (%)
A	73.2
B	62.9
C	50.2
D	72.6

3.3. *Opheodrys vernalis*

For *Opheodrys vernalis*, the linkage pathways analysis provided the least cost path between the core habitat areas for each region (Table 3). Study region A had the highest CWD by a wide margin along the linkage pathway, even when accounting for path length. Study region C had the lowest CWD and CWD/path length ratio, although regions B and D were also relatively low. Study region C had the highest R̂ value and the lowest CWD/R̂ ratio, meaning that it had the most resistance to movement and the lowest quality and number of paths. In contrast, Study region A had the lowest R̂ and the highest

CWD/R̂, meaning that it had the highest quality pathways and flow was least constricted in this region. Barrier mapper provided areas where restoration would lower the CWD of the least-cost path (Figure 14). Similarly to the other species, Study region D has one large area east of Savage Harbour which is of significance for restoration, although all regions had many areas where restoration could occur. Comparisons with Circuitscape analysis show that for Study Region B, the least cost path followed the flow patterns from Circuitscape relatively, however regions A, C, and D all differ greatly from the flow patterns for natural areas.

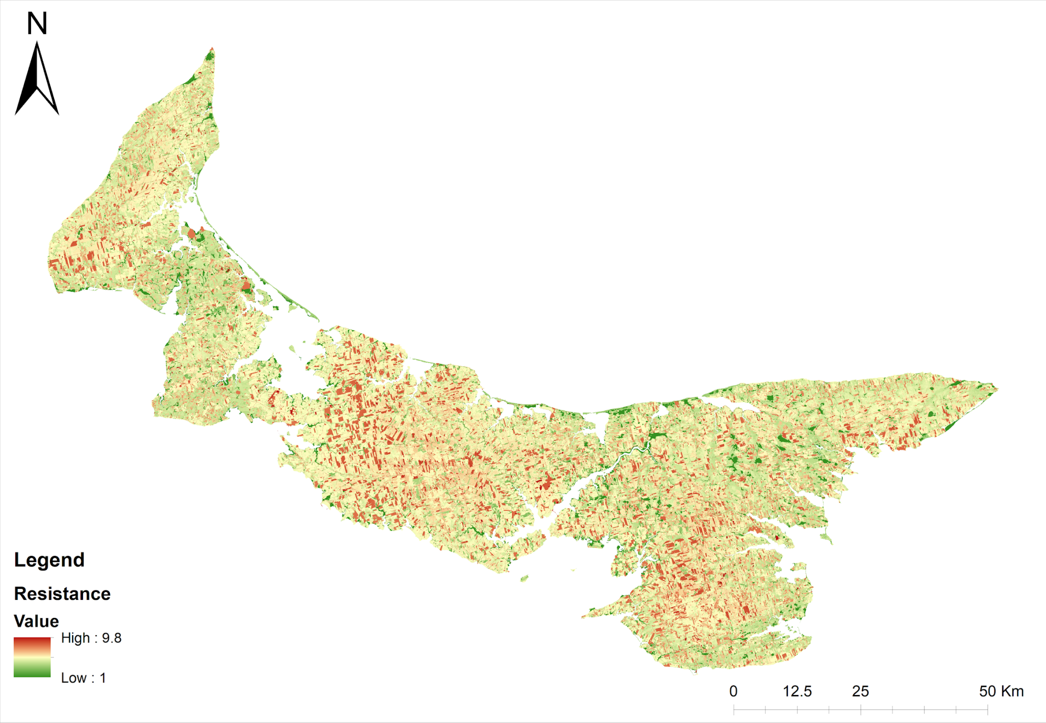
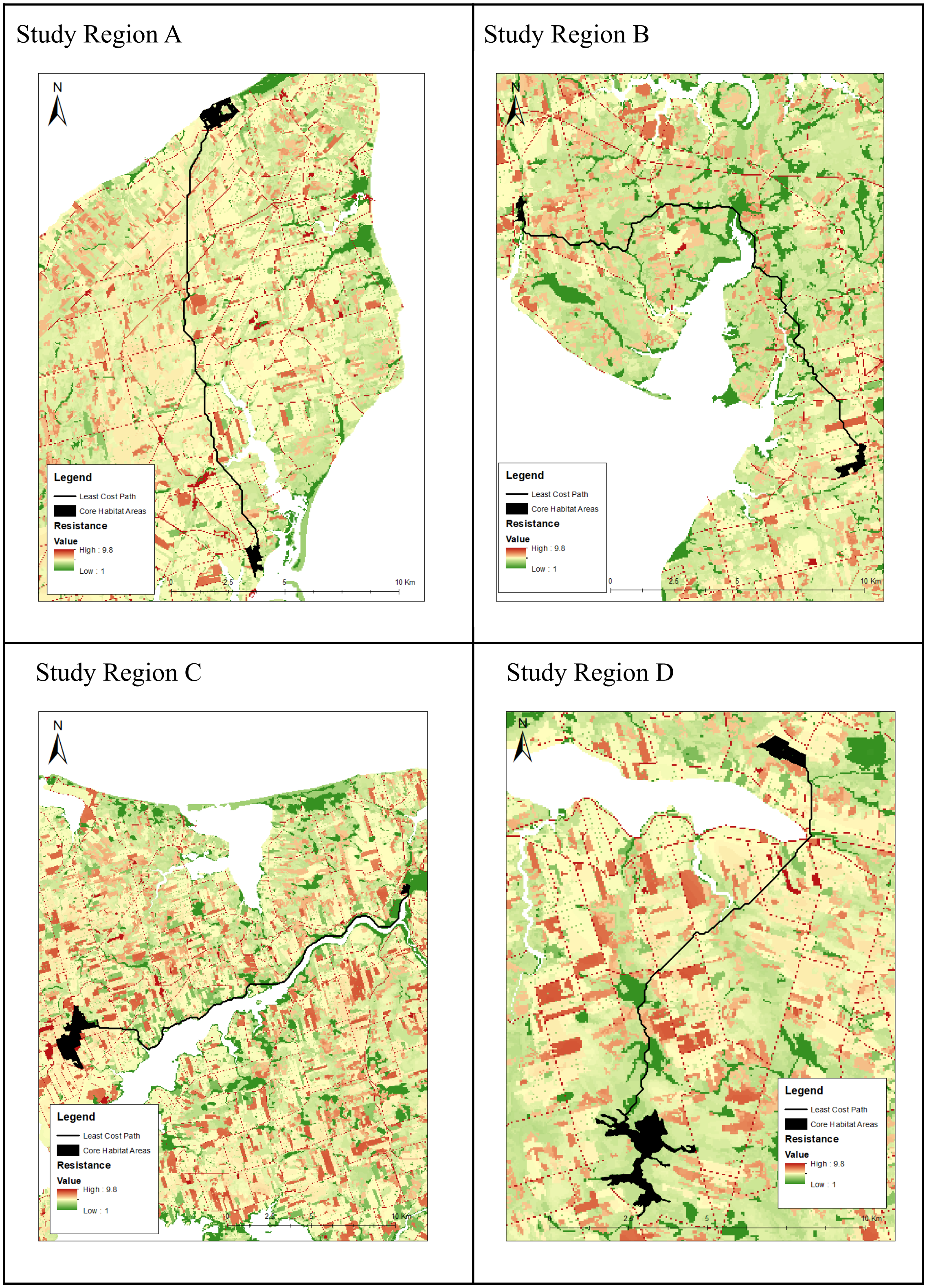


Figure 12. Resistance map depicting difficulty travelling through the landscape for *Opheodrys vernalis*.


Study Region A

Study Region B

Study Region C

Study Region D

Figure 13. Least-cost paths between selected core habitat areas for *Opheodrys vernalis* in a) North-west Prince County, b) Portage area, c) south of Savage Harbour, and d) south of Saint Peter's Bay.

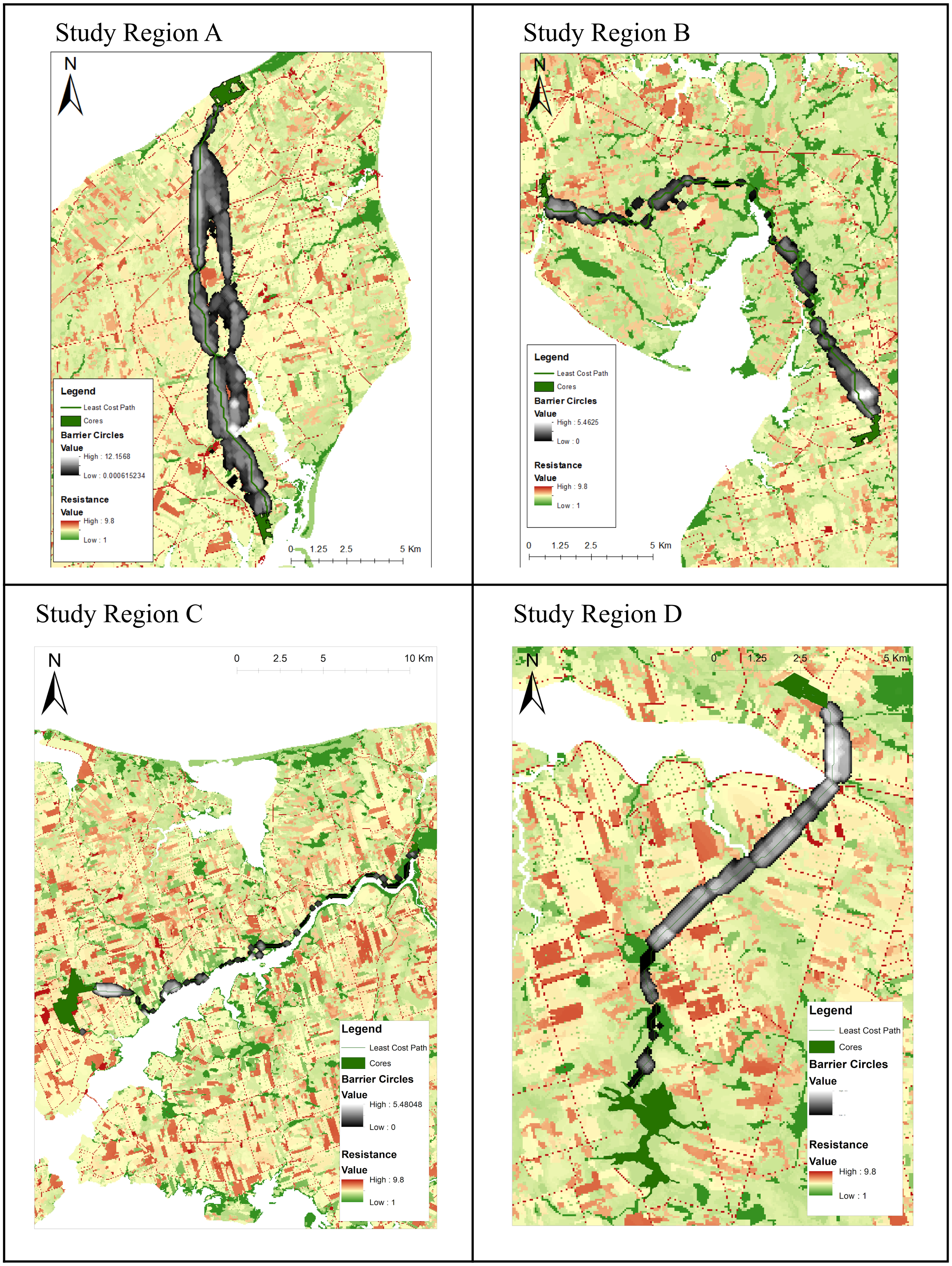
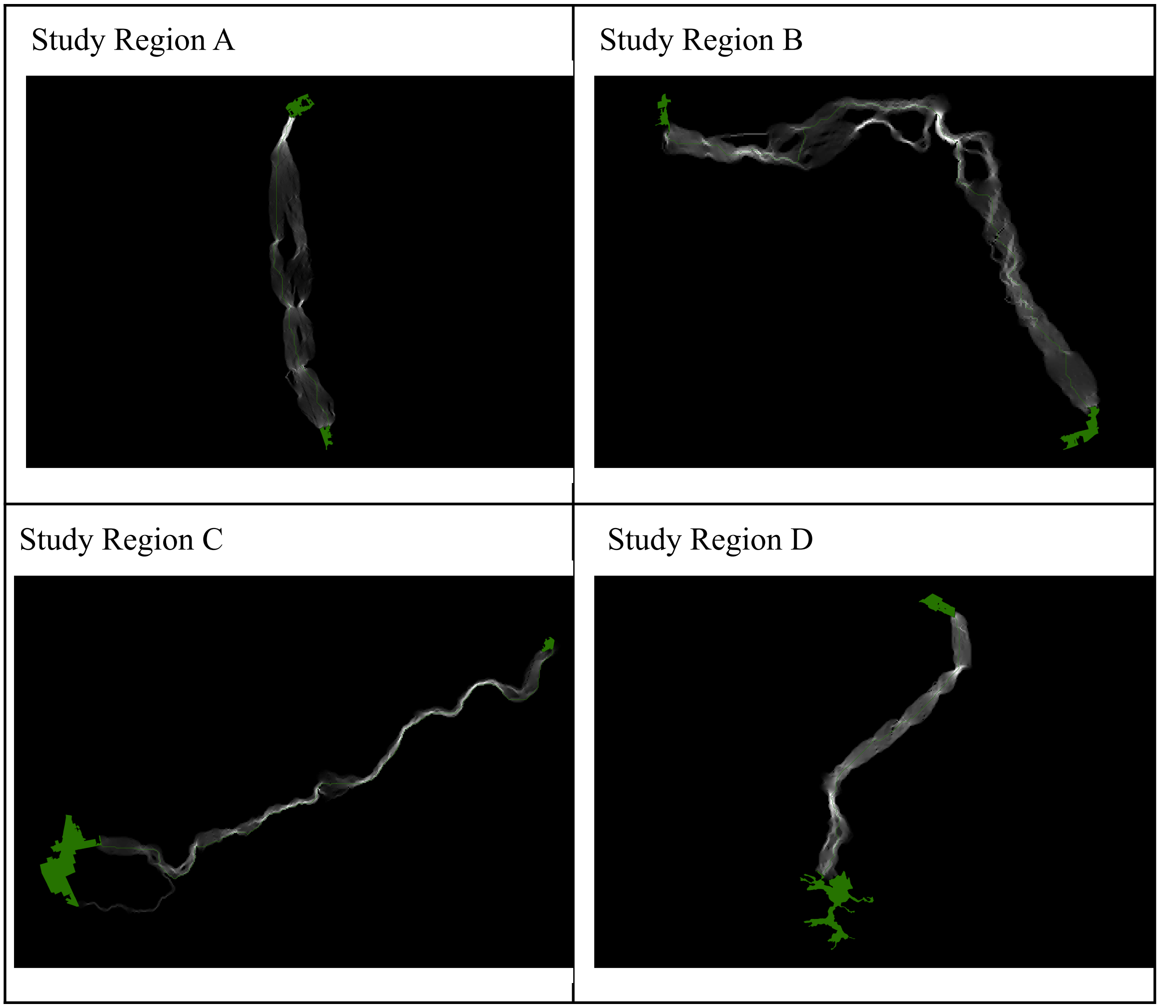


Figure 14. Barriers between selected core habitat areas for *Opheodrys vernalis* in a) North-west Prince County, b) Portage area, c) south of Savage Harbour, and d) south of Saint Peter's Bay.


Study Region A

Study Region B

Study Region C

Study Region D

Figure 15. Pinchpoints between selected core habitat areas for *Opheodrys vernalis* in a) North-west Prince County, b) Portage area, c) south of Savage Harbour, and d) south of Saint Peter's Bay.

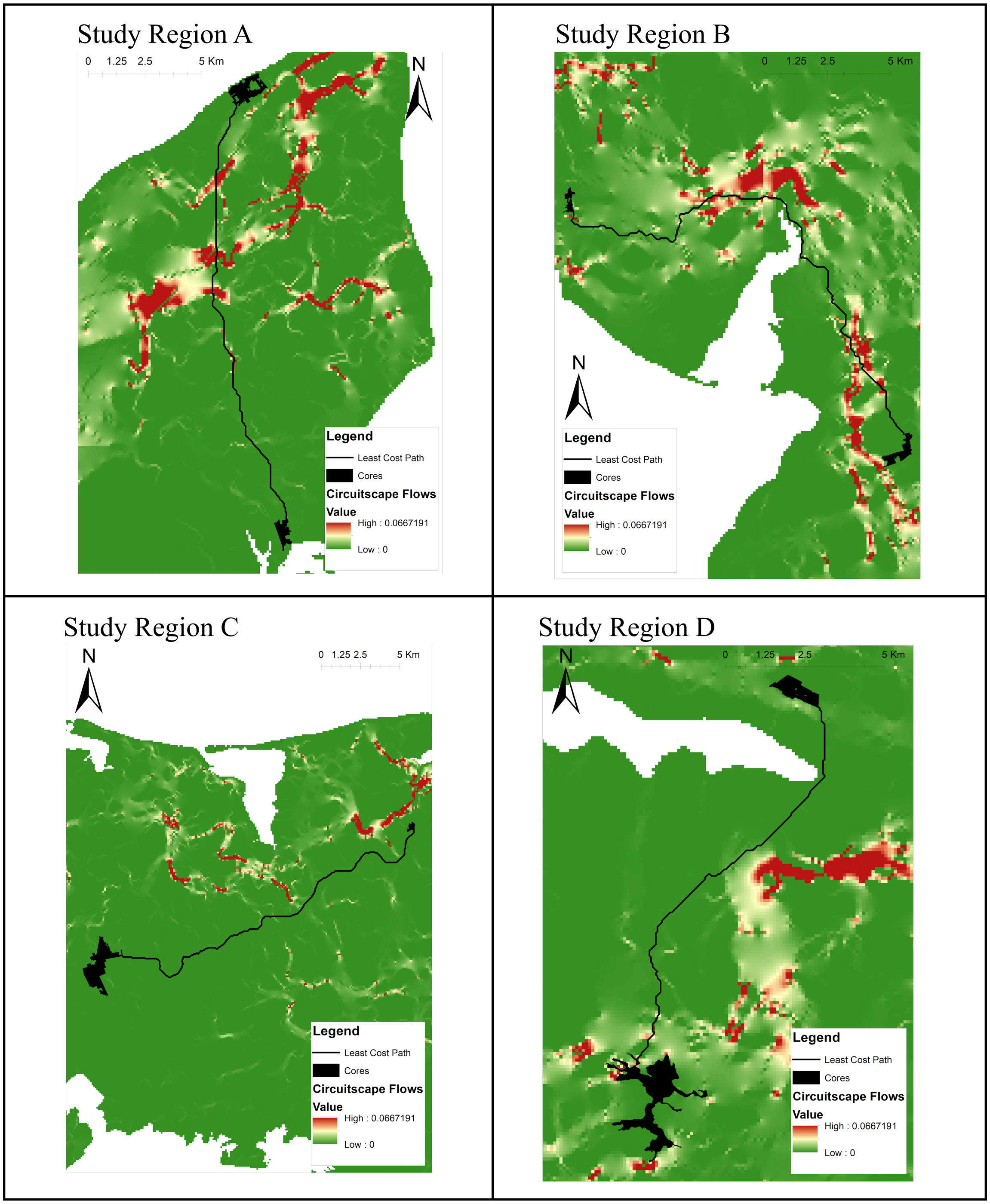


Figure 16. Least cost paths overlaid on natural areas Circuitscape analysis (Fulton & Bush, 2020) for selected core habitat areas for *Opheodrys vernalis* in a) North-west Prince County, b) Portage area, c) south of Savage Harbour, and d) south of Saint Peter's Bay.

Table 5. Linkage Mapper and Pinchpoint Mapper metrics for *O. vernalis*.

Study Region	CWD	CWD/Path Length	$\hat{R}$	CWD/$\hat{R}$
A	71264	3.5	1445	49.3
B	47427	2.1	1896	25.0
C	40376	1.5	4053	10.0
D	42914	2.9	1815	23.6

Table 6. Percent overlap (%) between least-cost paths and structural analysis for *O. vernalis.*

Study Region	Percent Overlap (%)
A	72.1
B	52.8
C	44.2
D	47.4

3.4. Comparisons

Comparing least-cost paths for all species against natural areas structural connectivity Circuitscape flow analysis found that *G. sabrinus* primarily followed movement flows across all study regions, with the highest percent overlap being 98.0% in Study Region A and the lowest being 94.2% in Study Region C (Table 2). *L. palustris* followed the Circuitscape flows more closely for regions A (73.2%), B (62.9%), and D (72.6%) than for region C (50.2%) (Table 4). The least-cost path for *O. vernalis* did not follow natural areas flow patterns for any region with the exception of region A (72.1%, see Table 6). *Lithobates palustris* had the highest CWD/Path Length ratios in Regions C and D. *Opheodrys vernalis* had a much higher CWD/Path Length ratio value in study region A than in any other study region, with a low CWD/Path Length ratio in study region C. However, *G. sabrinus* had relatively similar values in all four study regions.

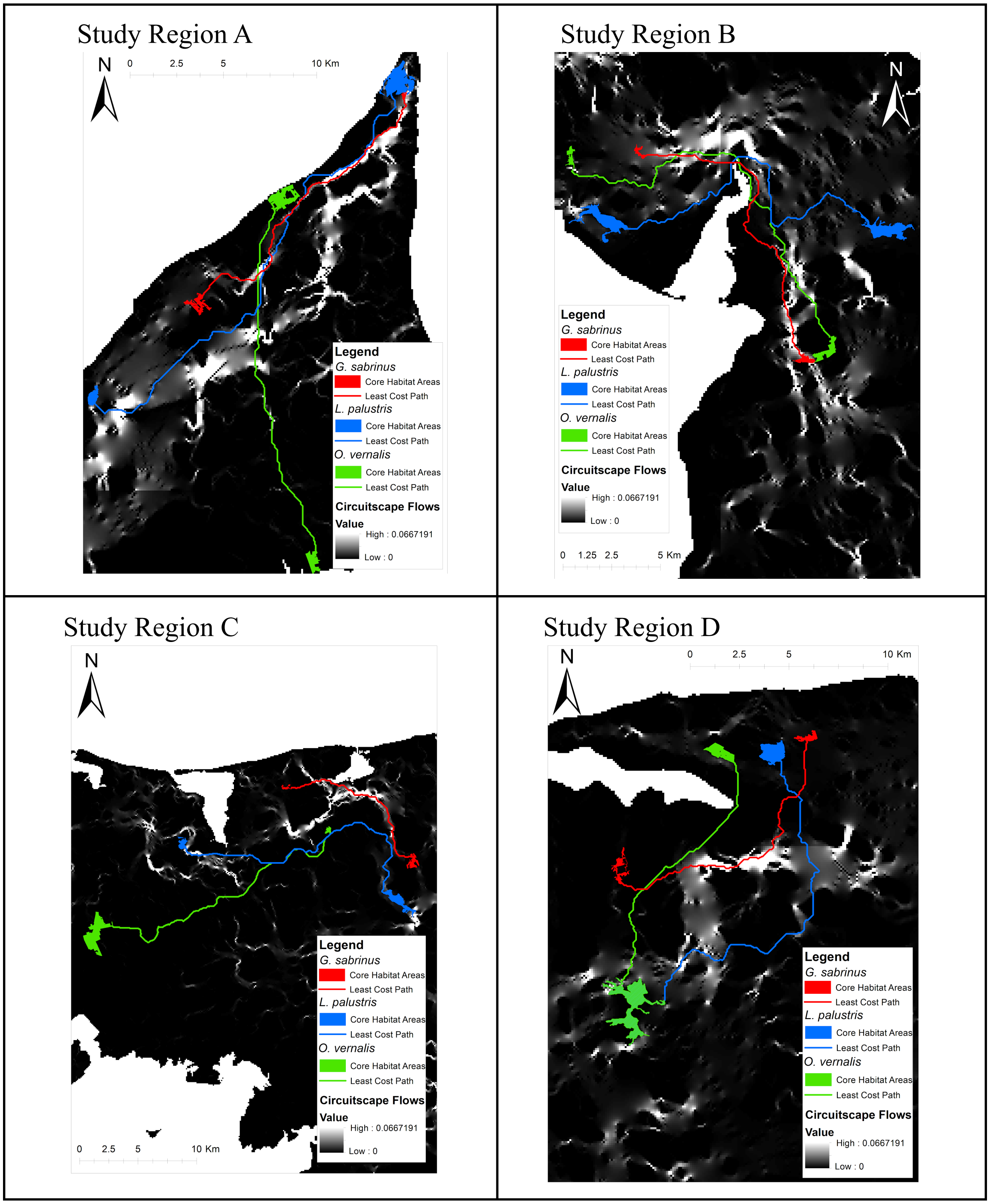


Figure 17. Least cost paths overlaid on natural areas Circuitscape analysis (Fulton & Bush, 2020) for a) North-west Prince County, b) Portage area, c) south of Savage Harbour, and d) south of Saint Peter's Bay.

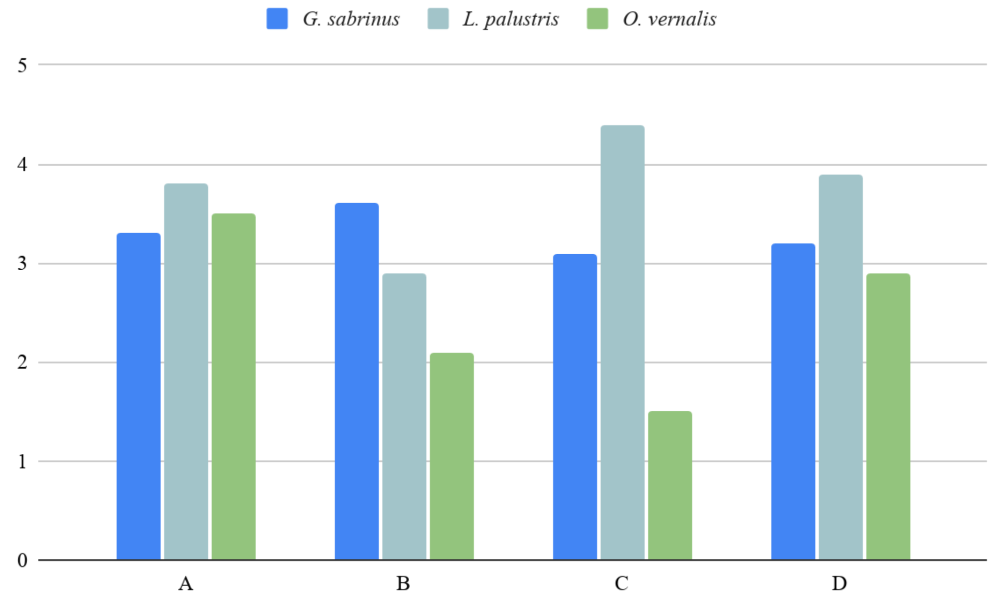


Figure 18. Bar chart comparing CWD/Path Length Ratios for the three species across Study Regions A, B, C, and D.

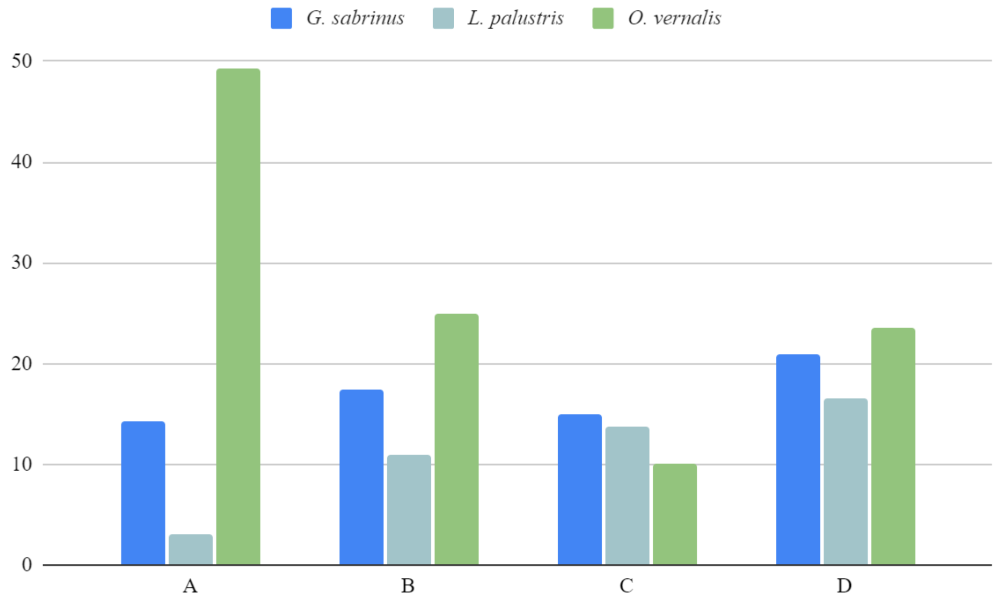


Figure 19. Bar chart comparing CWD/R̂ Ratios for the three species across Study Regions A, B, C, and D.

4. Discussion

4.1. Linkage Pathways

Overall, *L. palustris* had the most resistance to movement through the landscape, due to a lack of wetlands and wet forested areas. Linkage Pathways used the inputs of the core habitat areas and the resistance raster to find the path of least resistance (or the least-cost path) between the two core areas. This provided an output of the CWD/path length ratio, which is the ratio of the CWD to the non-weighted least-cost path length. This is equivalent to the average resistance per cell encountered moving along the least-cost route between the two core areas and can help understand which species have the highest resistance when moving through the landscape. *Glaucomys sabrinus* had a relatively high resistance to movement between habitat patches for all four study regions, suggesting that mature forest habitat is lacking all across the island. In contrast, *O. vernalis* had a relatively low resistance to movement throughout the landscape, with the exception of Study Region A, which had a cost weighted distance to path length ratio of 3.5, closer to the values of *G. sabrinus* and *L. palustris*. This suggests that Study Region A is lacking in open areas such as abandoned agricultural land and meadows, which are important for the connectivity of habitats for *O. vernalis*.

4.2. Pinchpoint Mapper

The analysis using Pinchpoint Mapper found that $\hat{R}$ differed across the study regions and between species. Pinchpoint Mapper used Circuitscape and electrical circuit theory to send a model of an electrical flow through the pathways highlighted in the Linkage Pathways tool in order to find where “pinchpoints”, or areas where flow is highest and movement may be restricted if land-use changes occur along or around the path between core habitat areas (McRae 2012). The Pinchpoint Mapper tool complemented the Linkage Pathways tool by taking all pathways between core habitats into account (not just the least-cost path). It also provided the effective resistance (R̂) between the core areas, which takes into account the corridor width and the number and quality of alternative pathways available within a corridor, as well as the CWD/R̂ ratio, which is the ratio of the CWD found through Linkage Pathways to the R̂ and serves as a measure of "linkage robustness" (Jones, 2015). Pinchpoint Mapper was run at a buffer zone of 1000 m around the least-cost paths in order to find other pathways between the cores. For *G. sabrinus*, Study Region D had the highest CWD/R̂ value across the regions with a value of 20.93 (Figure 4), suggesting that this region requires greater connectivity protection of mature forests. For *L. palustris*, Study Region D had the highest CWD/R̂ value across the regions with a value of 16.50 for this species as well (Figure 8), suggesting that this region also requires greater connectivity protection of wetland areas. For *O. vernalis*, Study Region A had the highest CWD/R̂ value across the regions with a value of 49.30 (Figure 12), which is much higher than ratios for the other species and for *O. vernalis* in other regions across the map, which suggests that this region has little connectivity in the way of abandoned agricultural lands, meadows, etc. and that more should be done to enable connectivity.

4.3. Barrier Mapper

The Barrier mapper tool was used to find where there may be barriers to movement along the least-cost path, and where restoration would create "shortcuts" that would most reduce the least-cost distance between patches. For *G. sabrinus*, Study region

D had a large area just east of St. Peter’s Bay which the tool highlighted as significant for restoration in order to shorten the least-cost path distance between the cores (Figure 3). *L. palustris* had a few areas for which restoration would reduce the least-cost distance between habitat patches (Figure 7). Study region D had the most areas where restoration was suggested, which makes sense given the results of the Linkage Pathways and Pinchpoint Mapper tools. For *O. vernalis*, one particular area was identified in the south-west of Study region B where restoration could occur in order to shorten the least-cost distance (Figure 11).

4.4. Comparisons Between Functional and Structural Connectivity Analysis

Functional connectivity is the effect that the structure of a landscape has on an organism’s movement through the landscape (Mühlner et al., 2010). One of the objectives of this research was to compare the functional connectivity analysis completed here to the structural connectivity analysis completed by Fulton and Bush in 2020, which used various structural connectivity analysis methods such as Circuitscape, Effective Mesh Size (m_{Eff}), and Fragmentation Statistics to map the connectivity of forests, mature forests, and natural areas across the province of Prince Edward Island. The analysis undertaken by Fulton and Bush (2020) was also completed on a much larger scale, at the provincial level with a 25 km cell size as opposed to the regional level (with a cell size of 50 m) undertaken in this analysis. Previous comparative studies have found that for organism groups where species richness and diversity are known in detail, structural metrics such as Euclidean distance (i.e. the straight line distance between two patches, or, “as the crow flies”) explained more variance at the finer scale whereas functional metrics explained more variance at the landscape scale (Mülner et al., 2010).

For *O. vernalis* specifically, the least cost paths created through the functional analysis for Regions C and D both had little overlap with the structural analysis of natural areas. This is significant, as there are only three species of snake on Prince Edward Island (Ross, 2019), so the protection and conservation of these species are crucial to functioning ecosystems as well as to the agriculture industry on Prince Edward Island, as snakes largely feed on mice and other small rodents which could damage crops (Holm & Kirk, 2013). The least-cost paths for L. palustris also differed from the structural analysis of natural areas in Study Regions B and C (Table 4). This suggests that both abandoned agricultural lands and wetlands were not fully taken into account when analyzing the connectivity of all natural areas, which can lead to gaps in conservation of corridors for species who inhabit those areas.

Circuitscape was used in both analyses as it can be a useful tool for both structural and functional connectivity studies. Although it was used at a larger scale in Fulton & Bush (2020), the larger more general pinchpoints can still be compared to the finer scale pinchpoints and the linkage pathways for each individual species in this analysis. For example, when comparing the natural areas Circuitscape analysis by Fulton and Bush (2020) with the linkage pathways analysis for *G. sabrinus* in study region A, we can see that the path follows the Circuitscape flow very closely, because very little else in the area has flow at all due to agricultural lands (see Figure 1, Figure 2a).

This comparison highlights the need for both structural and functional connectivity analysis when studying the ecological connectivity of a region. Structural connectivity can be of more use for general conservation and land use management as it allows the user to look at broad groups of organisms to find the best areas for conservation for many species. Functional connectivity can aid in the protection of keystone and endangered species, but it can overlook some of the broader analysis that can aid more species, and can run into the issue of failing to see the forest through the trees.

4.5. Management & Conservation Opportunities

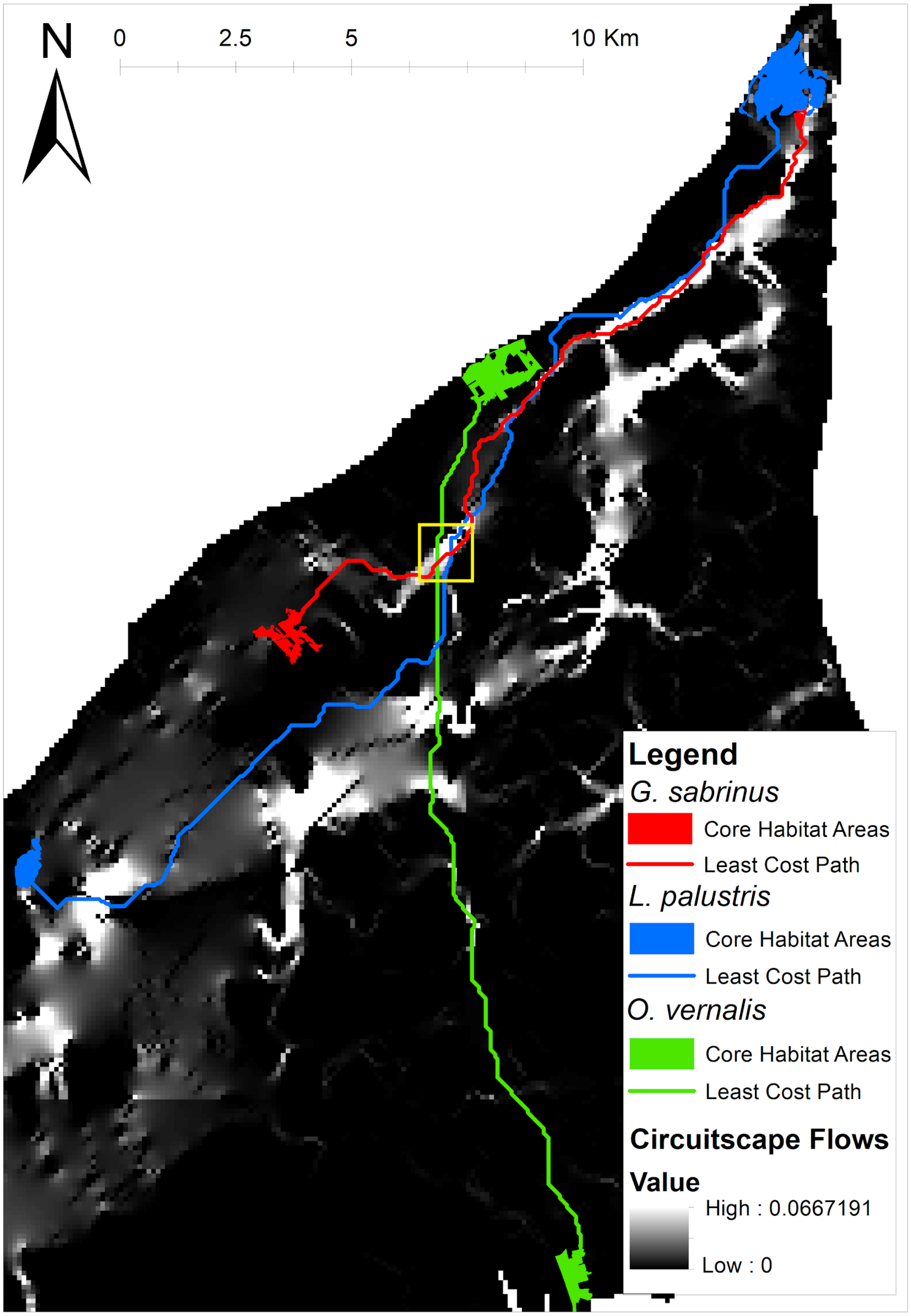


Figure 20. Map of species' least-cost paths for Study Region A over natural areas Circuitscape analysis (Fulton & Bush, 2020), with a yellow square highlighting the area of overlap.

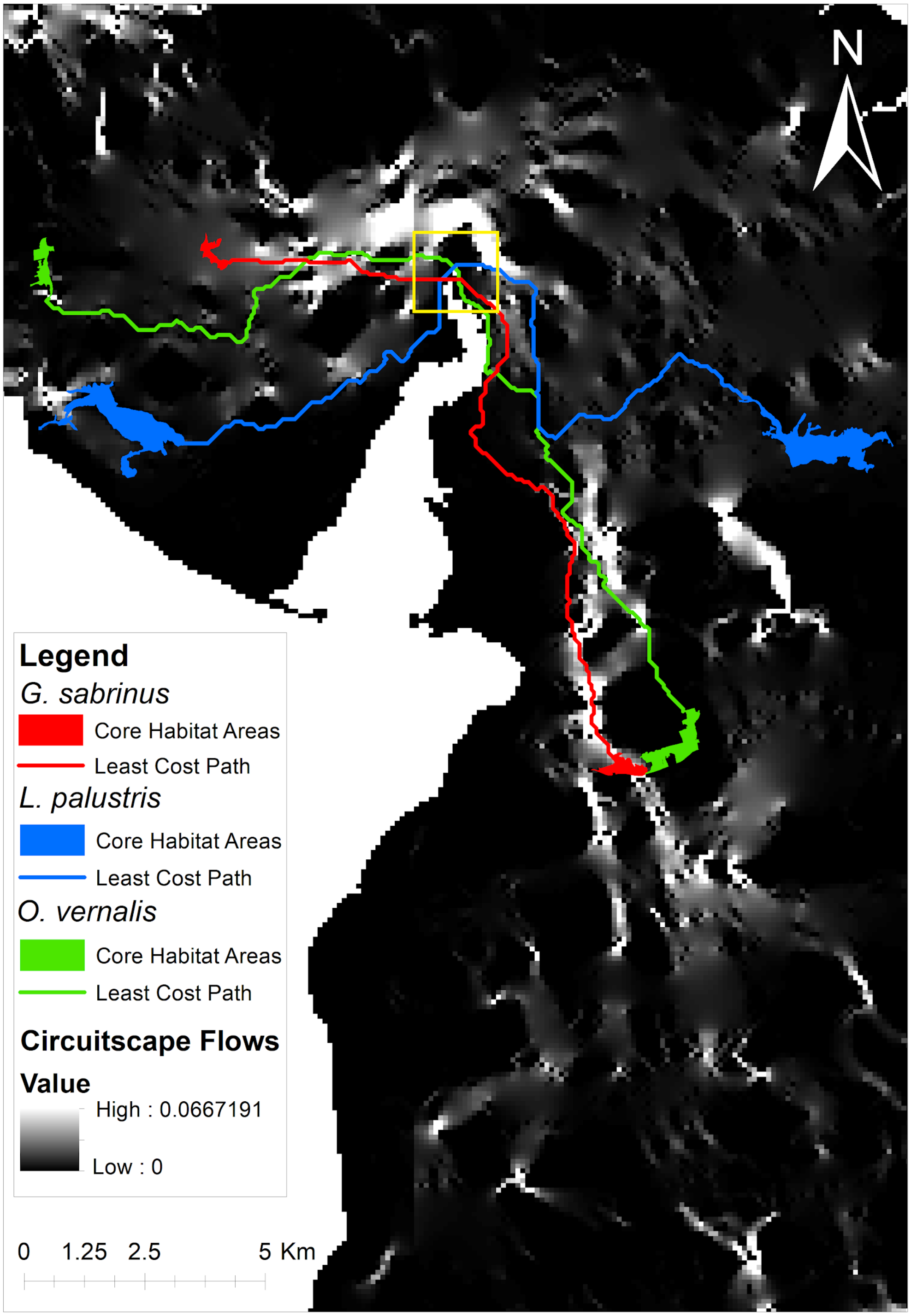


Figure 21. Map of species' least-cost paths for Study Region B over natural areas Circuitscape analysis (Fulton & Bush, 2020), with a yellow square highlighting the area of overlap.

Figures 19 and 20 provide a closer look at where least-cost paths and Circuitscape flows overlap in Study Regions A and B. The areas highlighted in yellow are areas where conservation and protection are of utmost importance as these are areas where all three species may travel between habitat patches and where the Circuitscape tool had a high flow through the landscape.

Study Region D, in the area of Kings county surrounding St. Peter's Bay, saw the greatest need for habitat conservation and restoration, for both wetland and mature forest habitats. For mature forest areas potentially inhabited by *G. sabrinus*, the priority should be to maintain the stands of mature forest still in the region, and ensure that harvesting activities taking place prioritize non-clearcutting methods such as an irregular shelterwood system. This is necessary to ensure that *G. sabrinus* can still move between trees through the landscape, as they can glide for upwards of 20 metres (Canada Wildlife Federation, 2021). Between 2001 and 2010, more than 33,000 hectares of forest were clear cut, the majority of which were softwood stands (PEI Agriculture & Forestry, 2013). As Prince Edward Island is the least forested province in Canada (McAlpine, Harding, & Curley, 2006), focus should be on restoring natural habitats and conserving and protecting mature forest stands that are still intact.

The analysis highlights the need for extensive wetland conservation around the province of Prince Edward Island. Study region D, in particular, had the highest ratio of cost weighted distance to effective resistance for *L. palustris*, meaning that the region around St. Peter's Bay should be prioritized for wetland conservation and restoration. One potential factor is that since the region is near a large bay, saltwater intrusion due to long term sea level rise may result in the degradation of freshwater wetland habitat in the area in the years to come.

The fact that *O. vernalis* had more difficulty moving through the landscape in region A than the other species despite having a greater ease of movement throughout the other study areas suggests that the inclusion of abandoned agricultural land and meadows in conservation efforts, especially in northwestern Prince county, may be beneficial for the movement of snake species including *O. vernalis*. This is significant, as the province only has three species of snake (Ross, 2019) which need to be protected to ensure their conservation even though their large range of habitats and ease of movement through many landscapes may make them less of a priority for corridor management.

4.6. Future Research and Limitations

This analysis only begins to brush the surface of functional connectivity on Prince Edward Island. Future research should be undertaken in other areas of Prince Edward Island, especially in Queens County, as the areas surrounding Charlottetown, PEI are especially susceptible to habitat loss and fragmentation from urbanization. From 2000 to 2010, 992 ha of forested land was converted to urban or residential areas across the island from 2000 to 2010 (PEI Agriculture & Fores6try, 2013). Research should also be done on other taxa such as avian species and larger mammals, who may be impacted differently by roads and agricultural land use.

Restoration of natural areas is important for habitat conservation on Prince Edward Island as it is the least forested province in Canada (McAlpine, Harding, & Curley, 2006). Barrier Mapper has not previously been used as a tool for the identification of areas for potential restoration on Prince Edward Island, and this study only begins to scratch the surface of this. Future studies should be completed on areas identified with the Barrier Mapper tool in this analysis in order to look further into the current land use of the areas identified as potential restoration areas and the feasibility of restoration of that land.

One limitation to this analysis is the lack of data on the spatial patterns of the species. The core habitat areas used in the analysis are pieces of land which meet the core habitat criteria for each species, and not where the species are actually located. Due to the nature of COVID-19 and the difficulty doing fieldwork during these times, I had to rely on the land use database without being able to visit the lands to ground-truth the data. The most recent land use database for Prince Edward Island was used for this analysis, but it was from 2010 and there have probably been changes to the landscape in the eleven years since the creation of the database.

Another limitation to this analysis is that the processing of data introduces errors in the analysis. The cell size for the land use rasters for this analysis was 50 m, which was selected to limit the processing time required for the mapping. Although this is still a relatively small scale, some smaller parcels of land and roads may be underrepresented. Also, this analysis did not account for the road effect zone or edge effect in its analysis. However, all species cells with a land use of "Transportation" (i.e. roads, highways, etc.) were given the highest resistance value of 10, so adjacent cells that met core habitat criteria would not be affected by their adjacency to roads.

5. Conclusions

This project was undertaken with the goal of analysing the finer scale functional connectivity of Prince Edward Island and comparing it to prior broad scale structural connectivity studies completed previously across the province. Based on previous studies by Fulton and Bush (2020), it was predicted that *O. vernalis* would be most overlooked by traditional structural connectivity analysis, which was correct when qualitatively comparing the least-cost paths for all three species in all four study areas against the natural areas Circuitscape flows. It was also hypothesized that study region C would have the highest resistances for the three species, however this was only true for *L. palustris*, where *G. sabrinus* had the most difficulty in region D and *O. vernalis* in region A, suggesting that the different areas all require more habitat restoration and corridor conservation. Suggestions for areas of concern for land conservation management were also provided, including where pinchpoints may be located for the movement of *G. sabrinus, L. palustris,* and *O. vernalis* in regions across Prince Edward Island. Although urban areas were considered in this study, areas where urbanization and development are most affecting connectivity such as Charlottetown and Summerside were not in our study regions and as such future research should focus on these regions.

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Appendix A: Attribute tables used in the creation of resistance rasters

G. sabrinus

LAND USE	VALUE
FOREST	1
WETLAND	8
RESIDENTIAL	9
RECREATIONAL	9
AGRICULTURAL	10
INDUSTRIAL	10
NON-USE	10
TRANSPORTATION	10
COMMERCIAL	10
INSTITUTIONAL	10
URBAN	10

COVER	VALUE
BS	1
RS	1
WS	1
CE	1
WP	1
BF	1
RP	1
LA	1
NS	1

EL	1
HE	1
JL	1
JP	1
SP	1
AP	1
LX	1
LP	1
CP	1
HS	1
YP	1
HP	1
AL	5
RM	5
WB	5
PC	5
PO	5
YB	5
RO	5
SM	5
DF	5
LI	5
BA	5
WI	5
GB	5
MA	5
EM	5

EB	5
TREE	5
AS	5
HAY	10
BARN	10
GRAIN	10
POTATO	10
SHRUB	10
GRASS	10
SOY	10
PAVED	10
OTHER	10
PASTURE	10
BUILDING	10
CORN	10
CLEARCUT	10
BLUEBERRY	10
SAND DUNE	10

DEVELOPMENT STAGE	**VALUE**
OLD	1
MATURE	2
YOUNG	8
REGENERATING	9
S/N/C/W/0/T/B	10

CROWN (%)	VALUE
0-10	10
10-20	9
20-30	8
30-40	7
40-50	6
50-60	5
60-70	4
70-80	3
80-90	2
90-100	1

HEIGHT (m)	VALUE
0-2.7	10
2.7-5.4	9
5.4-8.1	8
8.1-10.8	7
10.8-13.5	6
13.5-16.2	5
16.2-18.9	4
18.9-21.6	3
21.6-24.3	2
24.3-27	1

L. palustris

LAND USE	**VALUE**
WETLAND	1
FOREST	5
AGRICULTURE	9
RESIDENTIAL	9
RECREATIONAL	9
INDUSTRIAL	10
NON-USE	10
TRANSPORTATION	10
COMMERCIAL	10
INSTITUTIONAL	10
URBAN	10

SUB USE	**VALUE**
FOREST	1
RESERVOIR	2
ABANDONED LAND	5
PLANTATION	9
ALL OTHER NON FOREST/NON WETLAND SUB USES	10

CLASS	**VALUE**
BOG	8
OPEN WATER	10
MEADOW	5
DEEP MARSH	2

SHALLOW MARSH	2
SALT MARSH	10
SAND DUNE	10
SEASONALLY FLOODED FLAT	10
BRACKISH MARSH	10
SHRUB SWAMP	2
WOODED SWAMP	1

JUXTAPOSITION	**VALUE**
1 – Connected to a different dominant class within 1.6km	5
2 – Connected to a same dominant class within 0.4km	1
3 – Equal to or larger than 20.1 Ha with 3 classes	1
4 – Connected to a different dominant class within 1.6-5.0km	5
5 – Connected to a same dominant class within 0.4-0.8km	3
6 – Unconnected to any other wetland but has a wetland of a different dominant class within 0.8km	8
7 – Other	10

ELEVATION	**VALUE**
-2.97138 - 11.182432	1
11.182432 - 25.336244	2
25.336244 - 39.490056	3
39.490056 - 53.643869	4
53.643869 - 67.797681	5
67.797681 - 81.951493	6
81.951493 - 96.105305	7
96.105305 - 110.259118	8
110.259118 - 124.41293	9

124.41293 - 138.566742	10

O. vernalis

LAND USE	**VALUE**
WETLAND	2
FOREST	2
AGRICULTURE	3
RESIDENTIAL	5
RECREATIONAL	5
INDUSTRIAL	10
NON-USE	1
TRANSPORTATION	10
COMMERCIAL	10
INSTITUTIONAL	10
URBAN	10

SUB USE	**VALUE**
FOREST	2
RESERVOIR	5
ABANDONED LAND	1
PLANTATION	5
ALL OTHER NON FOREST/NON WETLAND SUB USES	10

COVER	**VALUE**
BS	3
RS	3
WS	3
CE	3
WP	3
BF	3
RP	3
LA	3
NS	3
EL	3
HE	3
JL	3
JP	3
SP	3
AP	3
LX	3
LP	3
CP	3
HS	3
YP	3
HP	3
AL	3
RM	3
WB	3
PC	3

PO	3
YB	3
RO	3
SM	3
DF	3
LI	3
BA	3
WI	3
GB	3
MA	3
EM	3
EB	3
TREE	3
AS	3
HAY	8
BARN	10
GRAIN	8
POTATO	8
SHRUB	1
GRASS	1
SOY	8
PAVED	10
OTHER	10
PASTURE	1
BUILDING	10
CORN	8
CLEARCUT	8

BLUEBERRY	8
SAND DUNE	**10**

CLASS	**VALUE**
BOG	5
OPEN WATER	10
MEADOW	1
DEEP MARSH	1
SHALLOW MARSH	1
SALT MARSH	10
SAND DUNE	10
SEASONALLY FLOODED FLAT	10
BRACKISH MARSH	10
SHRUB SWAMP	5
WOODED SWAMP	5

ELEVATION	**VALUE**
-2.97138 - 11.182432	1
11.182432 - 25.336244	2
25.336244 - 39.490056	3
39.490056 - 53.643869	4
53.643869 - 67.797681	5
67.797681 - 81.951493	6
81.951493 - 96.105305	7
96.105305 - 110.259118	8
110.259118 - 124.41293	9
124.41293 - 138.566742	10

Appendix B : ModelBuilder visualization of geoprocessing workflow of analysis