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Modeling Landscape Permeability

A description of two methods to model Landscape Permeability

Landscape permeability is a multidimensional characteristic. As part of The Nature Conservancy's Terrestrial Resilience project, we developed two separate analytical models to assess different aspects of its local and regional nature. The first, local connectedness started with a focal cell and looked at the resistance to flows outward in all directions through the cell's local neighborhood. The second, regional flow patterns, looked at broad east-west and north-south flow patterns across the entire region and measures how flow patterns become slowed, redirected, or channeled into concentration areas, due to the spatial arrangements of cities, towns, farms, roads, and natural land.

This data documentation is taken from a larger report, "Resilient Sites for Terrestrial Conservation in the Northeast and Mid-Atlantic Region" which can be downloaded from:

http://conserveonline.org/workspaces/ecs/documents/resilient-sites-for-terrestrial-conservation

These datasets would not have been possible without the expertise contributed by Brad McRae of The Nature Conservancy and Brad Compton of University of Massachusetts both who have created powerful new tools for measuring permeability. They were always willing to listen to our questions, provide guidance in using the tools correctly, and, in some cases, run the analysis for us.

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1/24/2012

PROJECT BACKGROUND

The natural world constantly rearranges, but climate change is expected to accelerate natural dynamics, shifting seasonal temperature and precipitation patterns and altering disturbance cycles of fire, wind, drought, and flood. Rapid periods of climate change in the Quaternary, when the landscape was comprised of continuous natural cover, saw shifts in species distributions, but few extinctions (Botkin et al. 2007). Now, however, pervasive landscape fragmentation disrupts ecological processes and impedes the ability of many species to respond, move, or adapt to changes. The concern is that broad-scale degradation will result from the impaired ability of nature to adjust to rapid change, creating a world dominated by depleted environments and weedy generalist species. Fragmentation then, in combination with habitat loss, poses one of the greatest challenges to conserving biodiversity in a changing climate. Not surprisingly, the need to maintain **connectivity** has emerged as a point of agreement among scientists (Heller and Zavaleta 2009, Krosby et al. 2010). In theory, maintaining a permeable landscape, when done in conjunction with protecting and restoring sufficient areas of high quality habitat, should facilitate the expected range shifts and community reorganization.

We use the term '**permeability**' instead of 'connectivity' because the conservation literature commonly defines 'connectivity' as the capacity of individual species to move between areas of habitat via corridors and linkage zones (Lindenmayer and Fischer 2006). Accordingly, the analysis of landscape connectivity typically entails identifying linkages between specific places, usually patches of good habitat or natural landscape blocks, with respect to a particular species (Beier et al. 2011). In contrast, facilitating the large-scale ecological reorganization expected from climate change - many types of organisms, over many years, in all directions – requires a broader and more inclusive analysis, one appropriate to thinking about the transformation of whole landscapes.

Landscape permeability, as used here, is not based on individual species movements, but is a measure of landscape structure: the hardness of barriers, the connectedness of natural cover, and the arrangement of land uses. It is defined as *the degree to which regional landscapes, encompassing a variety of natural, semi-natural and developed land cover types, will sustain ecological processes and are conducive to the movement of many types of organisms* (Definition modified from Meiklejohn et al. 2010). To measure landscape permeability, we developed methods that map permeability as a continuous surface, not as a set of discrete cores and linkages typical of connectivity models. In line with our definition, we aimed for an analysis that quantified the physical arrangement of natural and modified habitats, the potential connections between areas of similar habitat within the landscape, and the quality of the converted lands separating these fragments. Essentially, we wanted to create a surface that revealed the implications of the physical landscape structure with respect to the continuous flow of natural processes, including not only the dispersal and recruitment of plants and animals, but the rearrangement of existing communities. Hence we use the term "ecological flows" or just "flows" to refer to both species movements and ecological processes.

Because permeability is a multidimensional characteristic, we developed two separate analytical models to assess different aspects of its local and regional nature. The first, **local connectedness,** started with a focal cell and looked at the resistance to flows outward in all directions through the cell's local neighborhood. The second, **regional flow patterns**, looked at broad east-west and north-south flow patterns across the entire region and measures how flow patterns become slowed, redirected, or channeled into concentration areas, due to the spatial arrangements of cities, towns, farms, roads, and natural land. Regional flow patterns are discussed in Chapter 4 because the results were not used as an estimate of site resilience, but rather for connections linking sites into resilient networks.

Our basic assumption in both models was that the permeability of two adjacent cells increases with the similarity of those cells and decreases with their contrast. If adjacent landscape elements are identical (e.g. developed next to developed, or natural next to natural), then there is no disruption in permeability. Contrasting elements are presumed less permeable because of differences in structure, surface texture, chemistry, or temperature, which alters flow patterns (e.g. developed land adjacent to natural land). Our premise was that organisms and processes can, and do, move from one landscape element to another, but that sharp contrasts alter the natural patterns, either by slowing down, restricting, or rechanneling flow, depending on the species or process. We expect the details of this to be complex and that in many cases, such as with impervious surfaces, some processes may speed up (overland flow) while others (infiltration) slow down.

Both of the models discussed below are based on land cover / land use maps consisting of three basic landscape elements subdivided into finer land cover types, and we used these categories in the weighting schemes described below.

Natural lands: landscape elements where natural processes are unconstrained and unmodified by human intervention such as forest, wetlands, or natural grasslands. Human influences are common, but are mostly indirect, unintentional, and not the dominant process.

Agricultural or modified lands: landscape elements where natural processes are modified by direct, sustained, and intentional human intervention. This usually involves modifications to both the structure (e.g. clearing and mowing), and ecological processes (e.g. flood and fire suppression, predator regulation, nutrient enrichment).

Developed lands: landscape elements dominated by the direct conversion of physical habitat to buildings, roads, parking lots, or other infrastructure associated with human habitation and commerce. Natural processes are highly disrupted, channelled or suppressed. Vegetation is highly tended, manicured and controlled.

Our analyses were intentionally focused on natural lands, but we recognize that there are species that thrive in both developed and modified lands.

LOCAL CONNECTEDNESS

The **local connectedness** dataset measures how impaired the structural connections are between natural ecosystems within a local landscape. Roads, development, noise, exposed areas, dams, and other structures all directly alter processes and create resistance to species movement by increasing the risk (or perceived risk) of harm. This dataset is an important component of resilience because it indicates whether a process is likely to be disrupted or how much access a species has to the microclimates within its given neighborhood.

The method used to map local connectedness for the region was resistant kernel analysis, developed and run by Brad Compton using software developed by the UMASS CAPS program (Compton et al. 2007, http://www.umasscaps.org). Connectedness refers to the connectivity of a focal cell to its ecological neighborhood when it is viewed as a source; in other words, it asks the question: to what extent are ecological flows outward from that cell impeded or facilitated by the surrounding landscape? Specifically, each cell is coded with a resistance value base on land cover and roads, which are in turn assigned resistance weights by the user. The theoretical spread of a species or process outward from a focal cell is a function of the resistance values of the neighboring cells and their distance from the focal cell out to a maximum distance of three kilometers (Figure 1).

To calculate this metric, **resistance weights** were assigned to the elements of a land cover/road map. A variety of methods have been developed for determining resistance weights, in particular metrics of ecological similarity in community types (e.g. oak forest to oak forest assumed to be more connected than oak forest to spruce forest) have been used to good effect (B. Compton personal communication 2009, Compton et al. 2007). However, our weighting scheme was intentionally more generalized, such that any natural cover adjacent to other natural cover was scored as highly connected. We did not differentiate between forest types, and only slightly between open wetland and upland habitats (Table 1). Our assumption was that the requirements for movement and flows through natural landscape were less specific than the requirements for breeding, and that physical landscapes are naturally composed of an interacting mosaic of different ecosystems. Our goal was to locate areas where these arrays occur in such a way as to maintain their natural relationships and the connections between all types of flows, both material processes and species movements, not to maximize permeability for a single species (Hunter and Sulzer 2002, Ferrari and Ferrarini 2008, Forman and Godron 1986).

The resistance grid we created was based on a 90-meter classified land use map with roads embedded in the grid. The source data was the 2001 NLCD for United States and NALC 2005 for Canada that identify each grid cell as one of 16 classes of land cover (NALCMS 2005). We used 90-meter grid cells to make a reasonable processing time because the CAPS software program is computationally intense. Weights assigned to the land cover grid are shown in Table 1.

The final result was a grid of 90-meter cells for the entire region where each cell was scored with a local connectivity value from 0 (least connected) to 100 (most connected). Actual scores had a mean of 31.8 and standard deviation of 30.6 for the region (Map 1, Figure 2, 3, and 4).

Table 1: Land Cover classes and the assigned resistance weights.

Land Cover Class	Land Element Category	Weight
Developed Medium Intensity/Minor Roads	Developed: Medium/High Intensity	100
Developed High Intensity/Major Roads	Developed: Medium/High Intensity	100
Developed Open Space	Developed: Low Intensity	90
Developed Low Intensity	Developed: Low Intensity	90
Pasture/Hay	Agriculture	80
Cultivated Crops	Agriculture	80
Barren Land (Rock/Sand/Clay)	Barren Land (Rock/Sand/Clay)	50
Open Water Natural	Water	50
Deciduous Forest	Natural	10
Evergreen Forest	Natural	10
Mixed Forest	Natural	10
Shrub/Scrub	Natural	10
Grassland/Herbaceous	Natural	10
Woody Wetlands	Natural	10
Emergent Herbaceous Wetlands	Natural	10

Figure 1: Examples of four resistant kernel cells shown against the land cover and roads map. The focal cell is the central point of each kernel and the spread, or size, of the kernel is the amount of constraints, so the score for the focal cell reflects the area around the cell. Kernel A is the most constrained; D is the least constrained.

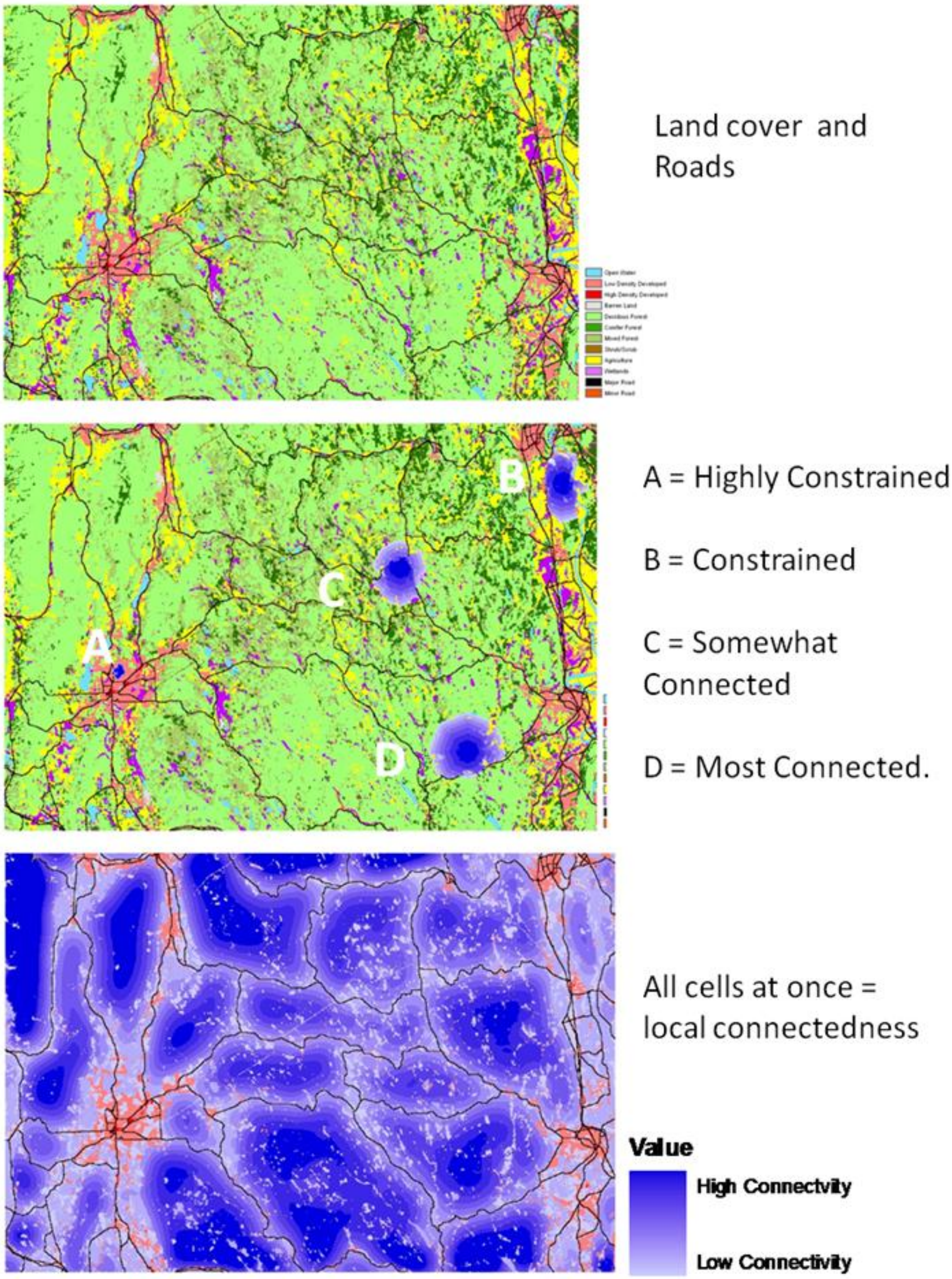


Figure 2: Detailed look at Kernel B in Figure 1. The top left image shows the topographic map for a rough location. The top right shows detail of the land use grid. The bottom left shows the aerial and the 3km circular resistant kernel distance. The bottom right shows the kernel spread. Kernel B is constrained on the west by roads and railroads and on the east by water. The kernel can flow well through the natural landscape in the north and south direction.

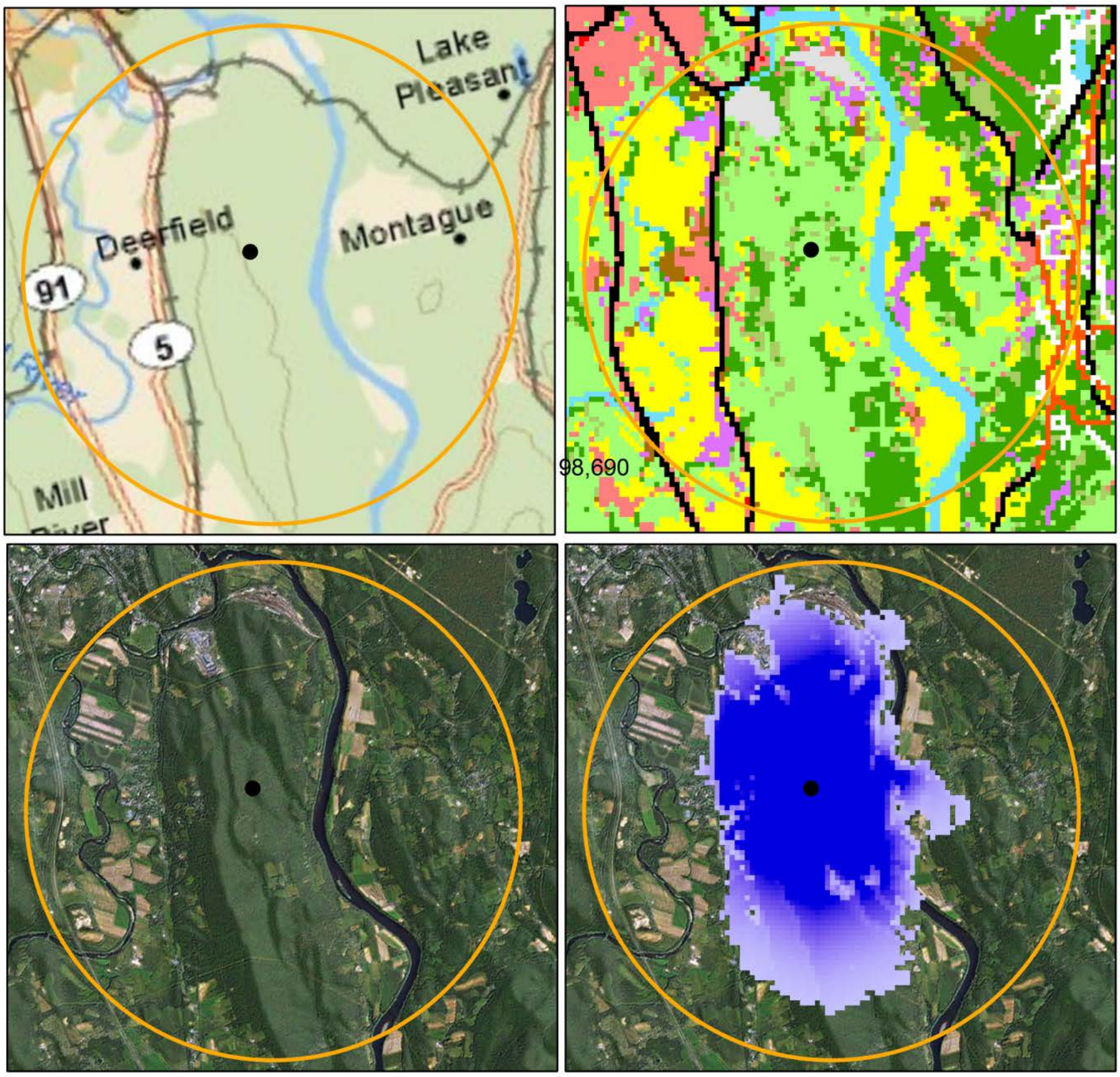
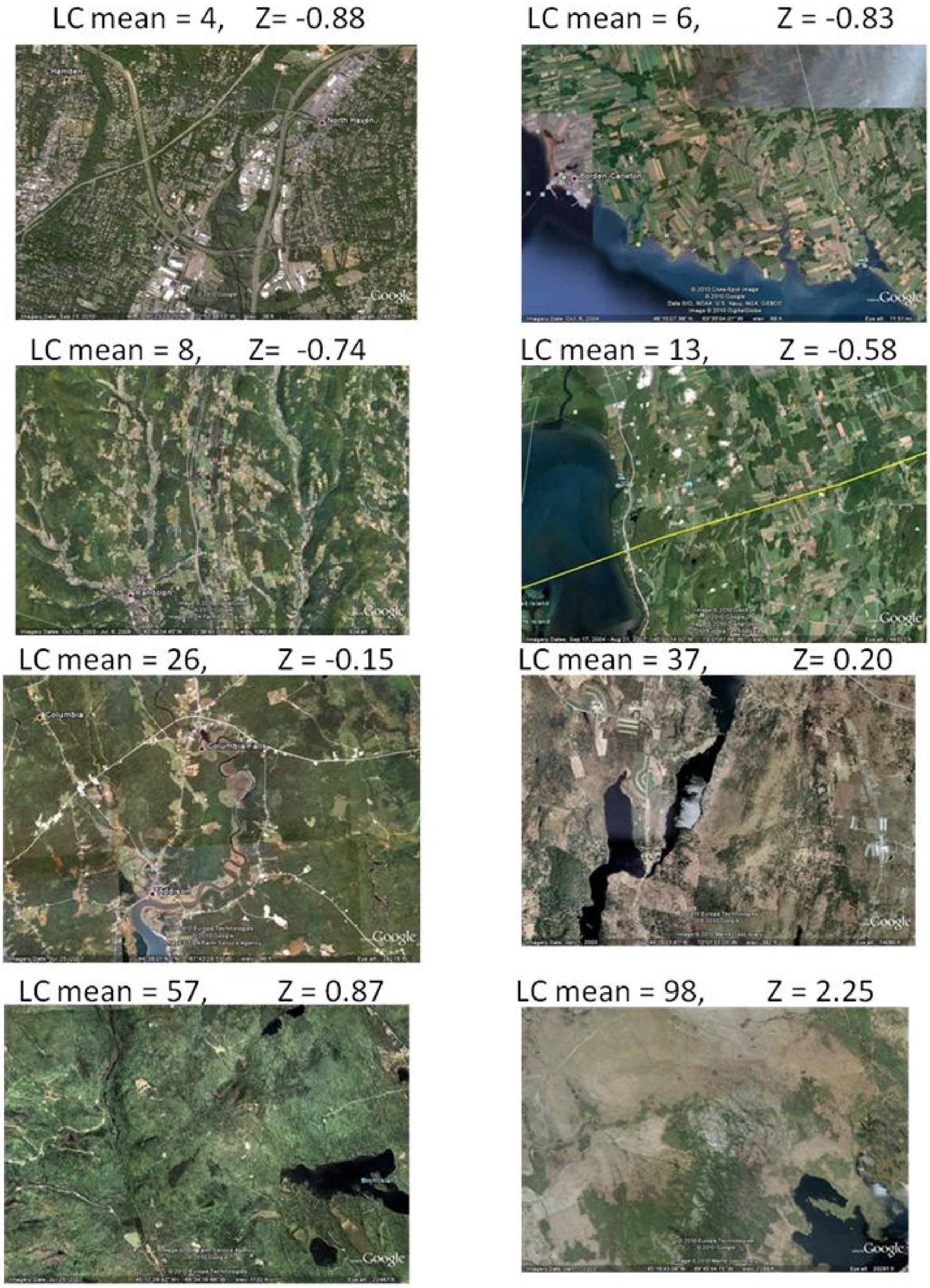


Figure 3: A gallery of satellite images and their corresponding local connectedness (lc) scores. The mean scores are based on a roughly circular site positioned at the center of each image (not shown). Z is units of standard deviation from the regional mean.



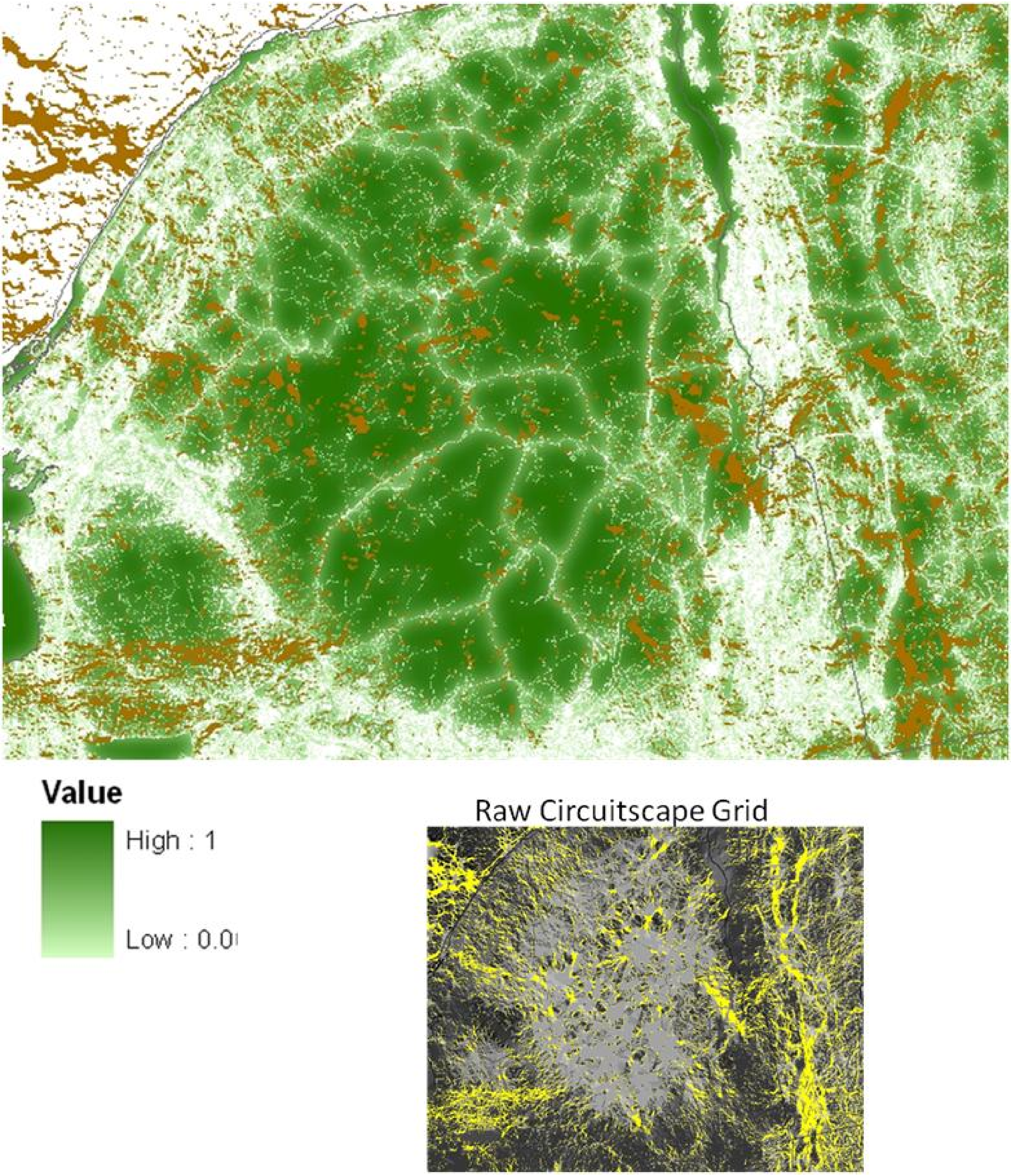
Map 1: Local connectedness. This map estimates the degree of connectedness of a cell with its surroundings within a three kilometer radius.

Regional Flow Patterns

The previously described "local connectedness" dataset quantified the permeability of the landscape based on the local neighborhood surrounding every 90 m cell in the region, but the local connectedness dataset did not account for broader scale movements such as directional range shifts, north-south migrations, or upslope dispersal patterns. The **regional flow patterns** dataset was designed to identify potential larger-scale directional movements and pinpoint the areas where they are likely to become concentrated, diffused, or rerouted, due to the structure of the landscape. We used the software tool Circuitscape (McRae and Shah 2009, http://www.circuitscape.org/) based on electric circuit theory, to model these larger flow patterns for the region. Like the local connectedness analysis, the underlying data for this analysis was land-cover and road data converted to a resistance grid by assigning weights to the cell types based on their similarity to cells of natural cover. However, instead of quantifying local neighborhoods, the Circuitscape program calculates a surface of effective resistance to current moving across the whole landscape. The output of the program, an effective resistance surface, shows the behavior of directional flows. Analogous to electric current or flowing water, the physical landscape structure creates areas of high and low concentrations similar to the diffuse flow, braided channels, and concentrated channels one associates with a river system. Three basic patterns can be seen in the output, as the current flow will: 1) *avoid* areas of low permeability, 2) *diffuse* in highly intact/highly permeable areas, or 3) *concentrate* in key linkages where flow accumulates or is channeled through a pinch point. Concentration areas are recognized by their high *current density*, and the program's ability to highlight concentration areas and pinch-points made it particularly useful for identifying the linkage areas that may be important to maintaining a base level of permeability across the whole region.

Before applying the model to the entire region we calibrated it by focusing on a few well-studied places that served as linkages between conservation areas, such as the region surrounding the Adirondacks. Our aim was to experiment with a variety of scales and parameters, until the model systematically identified these known linkages. The results in Figure 4.4 show where the Circuitscape analysis, overlaid on the local connectedness map, revealed directional flow concentration areas that are distinctly different from, and complementary to, the local connectedness analysis. In this figure, the highest flow concentration areas are mapped in brown on top of the local connectedness grid mapped in green. The figure illustrates where east-west ecological flows disperse and become diffuse in the highly intact central region of the Adirondacks (where local connectedness is very high), and how the flows concentrate in the broad linkages in and out of the Adirondacks, that are highlighted in several places and correspond well with key linkage areas identified through local studies. This was the scale of flow concentrations that we wanted to identify across the region, and the parameters described below reflect this scale.

Figure 4: Flow concentration areas. This figure shows the flow concentration areas in brown overlaid on the resistant kernel analysis (green) for the Adirondack region. In this figure the flow concentration areas are regions where east-west flows become concentrated because the structure of the landscape provides limited options for movement. Areas within the center of the region have moderate scores because the flow is dispersed across a highly intact landscape.



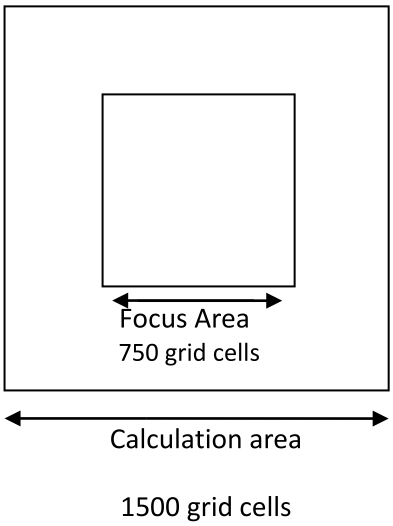
Details on Running the Circuitscape Program

The Circuitscape program "sees" the landscape as made up of individual cells. For this analysis we used a 270 meters cell size and each cell was coded with a resistance score derived by assigning it a value based on land cover and roads, with a proportional weight. We used the same land cover maps supplemented with major and minor roads, and the same weighting scheme as for the local connectedness analysis (Table 1). In this weighting scheme, natural lands have the least resistance, agriculture or modified lands have more resistance and developed lands have the highest resistance. In the Circuitscape program, the landscape is converted into a graph, with every cell in the landscape represented by a node (or a vertex) in the graph and connections between cells represented as edges in the graph with edge weights based on the average resistance of the two cells being connected (Shah and McRae 2008). The program performs a series of combinatorial and numerical operations to compute resistance-based connectivity metrics, calculating net passage probabilities for random walkers passing through nodes or across edges. Unlike a least cost path approach, Circuitscape incorporates multiple pathways, which can be helpful in identifying corridors (McRae and Beier 2007). More detail about the model, its parameterization, and potential applications in ecology, evolution, and conservation planning can be found in McRae and Brier (2007) and McRae and Shah (2009).

Circuitscape was originally designed to run resistance-based connectivity metrics from one focal area (habitat patch) to another. To get at overall landscape permeability, however, we measured current accumulation using continuous equal inputs across the entire landscape instead of providing a set of points/patches to connect. After many trials, test runs, and conversations with the software developer, we developed a method to get complete wall-to-wall coverage by running the model in gridded landscape squares where one whole side was assigned to be source and the other side the ground, repeating the run for each of four directions: east-west, west-east, north-south, south-north, and then summing the results. This method gave stable and repeatable results for the central region of each square (the focus area) but was subject to edge effect around the perimeter. Thus, to create a continuous surface we clipped out the central area of each square and tiled them together.

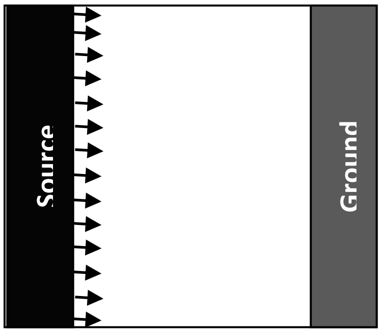
Our final methods were as follows:

First, the study area was divided into 53 tiles – or calculation areas – comprised of 1500 cells by 1500 cells (~ 405 kilometers). Each tile was intersected with a land cover and road map coded for resistance using the weighting scheme in Table 4.1. (The analysis was run for all tiles with complete land cover information, but tiles that were solely water were ignored).



Second, within each tile we identified a focus area that was one quarter the size of the total calculation area. In the final results we used only the results from the central focus area because the results in this region stayed consistent even as the calculation area is increased. This eliminated the margin of the calculation area, which appeared, based on many trials to have considerable noise created by the starting points.

Third, we ran Circuitscape for each of the 53 calculation areas. To calculate the resistant surface, we set one side of the square to be



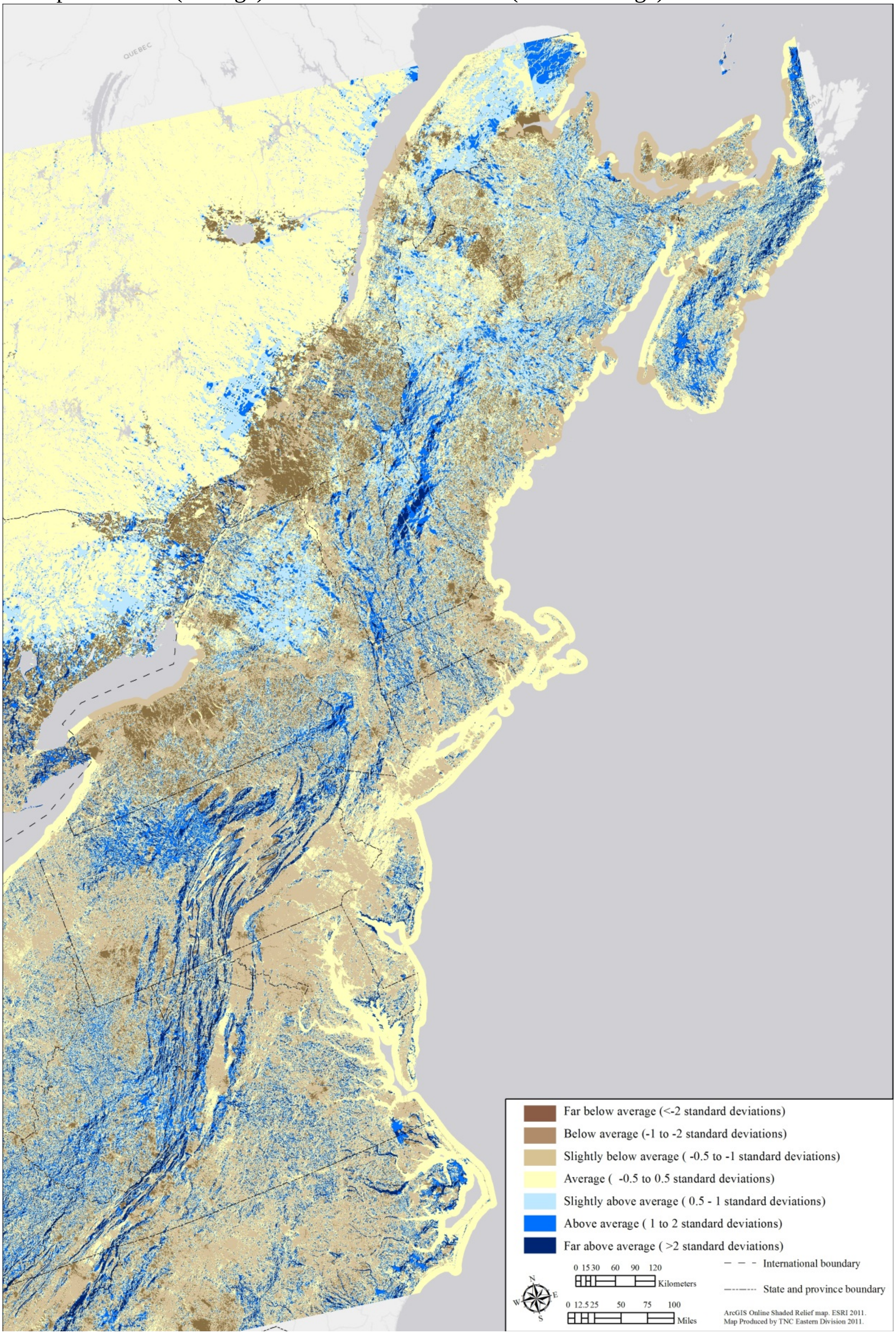
the source and the other side area to be the ground. Current was injected into the system from each grid cell on the source side of the square. Because current seeks the path of least resistance from the source cells to any grid cell on the ground side, a square run with the west edge as source and the east side as ground will not produce the same current map as a square run with the east edge as source and west edge as ground. To account for these differences, we ran the program for all four of the direction possibilities - west to east, east to west, north to south, south to north, and summed the results.

Lastly, the focus area was clipped out of each calculation area and joined together to create a continuous coverage of results for the region (Map 2). The square focus areas had scores that were normalized to their calculation area, and we also created a surface where all scores were normalized to the whole region. When we compared these two results we found that the former map, normalized to each calculation area, was more effective at highlighting local concentration areas and pinch points while still revealing regional scale patterns as well. Thus, the results we used in the analysis and shown here, were normalized to the calculation area.

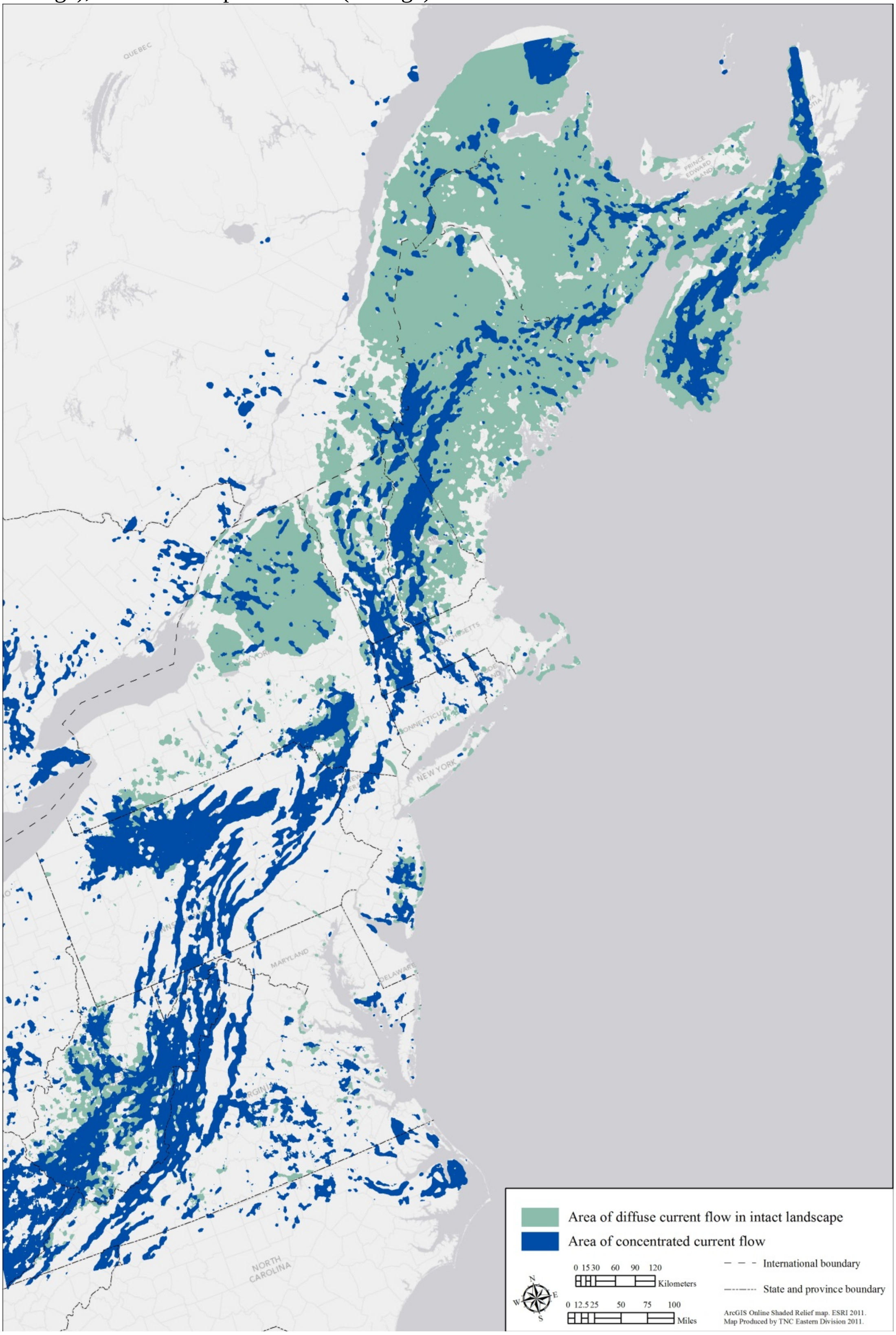
To add in analysis we created a Regional Patterns Polygon dataset takes the regional flow patterns grid and groups it into regional scale patterns (Map 3). To do this we extracted all grid cells that scored above average (>1000) for the concentrated flow and all average grid cells (between -500 and 1000) and then converted these grids into points. Next, we ran a point density analysis using a 10,000 acre circular neighborhood at 90 meter resolution. The smaller polygons (less than 1000 acres) were filtered out in order to produce a clean map.

Notes on the use of Circuitscape: As suggested by McRae we did try using the source side as focal region. This allowed the current to flow not from every point on the source side, but to flow from the optimum point on the source side to the ground side. This did show the most direct flow of current from the source to the ground, but did not represent how current would flow through the landscape as a whole. Additionally, the primary reason for using the 270 m grid cell was that Circuitscape is a memory intensive program and we ran the program for a very large area. This also had the nice property of highlighting meaningful groups of cell at the scale of interest to us. At the 30-meter scale, more individual grid cells are highlighted making the patterns more dispersed. To change the spatial resolution from 90-meters eastern region dataset to 270 meters the aggregate function was used. When aggregating, the maximum value of the 9 smaller 90-meter grid cells was used. This insured that the barriers (roads, developed areas) were not averaged out. Cell size is important, but as long as it remains fine enough to capture relevant landscape elements, such as narrow corridors and barriers, the program has great flexibility to get similar results with varying cell size (McRae et al 2008). The developers note that it is particularly important to capture absolute barriers (such as roads and railroads) to movement that may not be detectable at larger cell sizes (McRae et al 2008). A 270 meter grid cell size is much smaller than was used in published case studies. For a landscape genetic example using wolverine, McRae and Beier (2007) used a grid cell size of 5 kilometers, which they thought was course enough for computation on a desktop computer, but allowed them to capture major landscape features and minimizing categorization errors.

Map 2: Regional flow patterns. This map shows areas of concentrated flow (above average), diffuse or dispersed flow (average) and low or blocked flow (below average).



Map 3: Grouped regional flow patterns. This map shows areas of concentrated flow (above average), diffuse or dispersed flow (average).



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