Identifying and Prioritizing Key Habitat Connectivity Areas for the South Atlantic Region

Final Report for the South Atlantic Landscape Conservation Cooperative

Ron Sutherland, Wildlands Network
Paul Leonard, Clemson University
Derek Fedak, Colorado State University
Rachael Carnes, California Wolf Center
Alison Montgomery, Wildlands Network
Rob Baldwin, Clemson University

June 24, 2015
We thank the South Atlantic Landscape Conservation Cooperative for providing primary funding for this work under Cooperative Agreement #20111509. The South Atlantic LCC staff, particularly Rua Mordecai and Amy Keister, was very helpful and remarkably patient during the entire project.

Private donors to Wildlands Network also contributed to making this much needed project a reality, and we greatly appreciate their enthusiasm for our connectivity work.


The project simply would not have happened without these generous individuals who shared their accumulated expertise with us, completed the surveys and answered our follow-on questions.

Jen Costanza and her colleagues at NC State University supplied us with the urbanization projections, and our South Atlantic LCC project also benefited from numerous discussions with Nick Haddad, James Watling, Heather Lessig, Jen Costanza, and Stephanie Romañach, as part of a separate ongoing connectivity investigation for the broader Southeast.

Brad McCrae and Carlos Carroll were quick to respond to our numerous questions about their respective connectivity modeling software packages.

Edward Duffy and the Cyberinfrastructure Technology Integration Group at Clemson invested many hours assisting us with the supercomputing aspects of this research.
Fragmentation of critical wildlife habitats by suburban growth threatens many areas within the South Atlantic region.
Using corridors to reconnect fragments of natural habitat is widely recognized as an essential tool for promoting the survival of many species. Likewise, the present threats to biodiversity such as climate change, urbanization, sea level rise and the demographic vulnerability of small, isolated populations are leading more and more conservationists to see the increasingly urgent need to protect and restore networks of connected habitats.

**The Goal**

This report summarizes the results of a three-year investigation of terrestrial habitat connectivity priorities for the South Atlantic Landscape Conservation Cooperative (South Atlantic LCC). Our primary objective was to generate results that could be used to drive fine-scale conservation planning for the enhancement of habitat connectivity across the region.

**Approach**

The project focused on seven target species, including large mammals (black bear, red wolf, Florida panther/eastern cougar) and a group of terrestrial reptiles (eastern diamondback rattlesnake, timber rattlesnake, pine snake, and box turtle). We used two modeling approaches: one to identify areas with high predicted flow of a given species (Circuitscape), the other to identify areas with greater importance to the overall habitat network for a given species (Connectivity Analysis Toolkit). We parameterized our models with a combination of expert opinion, land cover data, and traffic information. We also projected the same models into the future (year 2100) using predictions of urbanization and sea level rise.

**Results**

Our results highlight a number of high-priority connectivity areas across the South Atlantic LCC region. While intact coastal river floodplains figure prominently for many species, we also identify potential routes for overland corridors connecting longleaf pine ecosystems and other priority upland habitats. At present and for many species, the southern half of the South Atlantic LCC region seems to retain greater permeability for wildlife movement. However, future urbanization and sea level rise appear to threaten habitat connectivity across the region, especially around pinch-points such as coastal cities, in low-lying areas such as the Albemarle Peninsula in NC, and within the expanding Piedmont megalopolis from Atlanta, GA to Raleigh, NC.

**Research Utility and Next Steps**

Conservationists will be able to put our results to immediate use, helping to steer major investments in land acquisition, habitat restoration, private landowner outreach, and wildlife road crossing structures across the South Atlantic LCC.

Additional research is needed to empirically calibrate our predictions (which are made in relative and not absolute terms) so that they can be directly related to animal movement trends. There also is a strong need for connectivity research focused on longleaf pine ecosystems range-wide across the southeastern U.S. Such research would help direct the substantial investments being made in longleaf restoration toward facilitating a functioning, climate-robust habitat network for many terrestrial species associated with longleaf forests.

If substantial new sources of funding were found for protecting habitat corridors across the South Atlantic LCC, this task would be more feasible. The report concludes with a range of policy options for connectivity funding, many of which involve boosting existing conservation funding sources and then targeting the funds more specifically towards connectivity conservation.
Introduction to the Project
This report summarizes the results of three years of research to complete the modeling of terrestrial habitat connectivity priorities for the South Atlantic Landscape Conservation Cooperative (South Atlantic LCC) by the authors.

PROJECT OBJECTIVES
We began the project with the following key objectives:

➤ to map current and future levels of habitat connectivity in the South Atlantic region, from the standpoint of multiple groups of terrestrial wildlife species;

➤ to prioritize key corridors and linkage areas based on their relative importance and centrality within the overall habitat network, and their relative influence on the viability of target wildlife populations; and

➤ to publish data layers representing the outcomes from the first two objectives, in such a way as to significantly improve conservation decision-making across the South Atlantic LCC region.

To understand why these objectives are critically important for the South Atlantic LCC and all of the conservation partners working within the region, the following background narrative has been provided.

BACKGROUND NARRATIVE
Habitat loss and fragmentation have long been recognized as some of the most urgent threats to the incredibly rich biodiversity found in the southeastern U.S. Despite impressive gains in the amount of protected areas across the region by various land trusts and conservation agencies as well as the lingering economic downturn, rapid human population growth and urbanization continue to drive the loss and degradation of remaining fragments of natural habitats that once supported diverse natural communities. In recent years, climate change and its various indirect impacts, such as sea level rise have also been identified as critical challenges to the persistence of native plants and animals.

Although various conservation groups have begun promoting myriad techniques for helping species adapt to climate change, the most logical, straightforward and time-tested solution for preventing climate-induced extinctions is simply to provide organisms with networks of connected habitats so they can successfully migrate to keep up with their preferred environmental conditions (Chetkiewicz et al. 2006, Heller and Zavaleta 2009). Indeed, migration is precisely the mechanism that has allowed many species to quickly adjust to constantly fluctuating climate and sea level conditions over past millennia. Restoring and protecting robust connections between existing fragments of natural habitat will not only allow species to move across environmental gradients and adapt to climate change, it also will create networks of habitat that are large and interconnected enough for species to maintain viable populations. In turn, this will help overcome the current and future negative consequences of outright habitat loss.

From the perspective of the South Atlantic LCC, identifying regional-scale priorities for preserving and enhancing habitat connectivity must, therefore, be considered one of the core applied-science missions of the partnership. Providing imperiled species with sufficient room to roam is an exercise that must cross geographic, political and bureaucratic boundaries. Habitat network design must consider future conditions, and it must be an adaptive process capable of responding to changes in data availability and landscape change. Furthermore, climate change and habitat loss are factors that affect all...
species; thus, efforts to improve habitat connectivity in the Southeast must consider the dispersal requirements and movement capabilities of multiple types of organisms.

The one group of animals that clearly would benefit from additional habitat connectivity at the scale of the entire South Atlantic LCC is the top mammalian carnivores, such as the red wolf and Florida panther. These animals once ranged across the entire region, irrespective of state or project boundaries, and scientists estimate they need large networks of usable habitat to maintain viable populations. Top predators play essential ecological roles in regulating the trophic structure of ecosystems (Estes et al. 2011), and their absence over much of the nation has led to profound alterations in the health of our natural resources, as lamented by Aldo Leopold and other well-known ecologists. Restoring these animals to large blocks of habitat where they are now absent, and buffering the existing populations where they still occur or have been reintroduced, will require conservationists to pay close attention to habitat connectivity levels at the South Atlantic LCC broad scale. The black bear—an omnivore which has already recovered to a widespread (yet still incomplete) distribution in the Southeast—also will certainly benefit from a network of interconnected habitats in the region.

Of course, the large mammalian carnivores and omnivores are highly mobile animals with fairly generalized habitat requirements. Therefore, a connectivity plan that focuses on bear, wolves and panther may fail to meet the needs of less mobile, more specialized wildlife species. Reptiles, amphibians, and certain small mammals and birds fit this description; they are vertebrate species whose connectivity needs may not be adequately met by a system of core reserves and corridors sufficient to maintain the top predators. The smaller vertebrates also may not be able to cross even low-traffic roads and other barriers that do not pose major obstacles for the larger mammals.

In response to the LCC’s request for “integrative projects that meet all aspects of the South Atlantic LCC niche,” we have attempted to map and prioritize key areas for terrestrial habitat connectivity across the South Atlantic region, from the perspective of both the wide-ranging top carnivores and a group of traffic-sensitive and habitat-specific reptiles. The resulting geospatial data layers, which will consider both current and future landscape and climate conditions, will provide essential guidelines for improving conservation decision-making throughout the region, for years to come. Our results will update and improve upon those of the only comparable attempt at connectivity analysis done at such a large scale in the Southeast: the U.S. EPA-funded Southeastern Ecological Framework (SEF). The SEF was completed in 2001 using 1990-era land cover data, and emphasized primarily riparian corridors identified using basic least cost path analysis (Hoctor et al. 2008).

Methodology

OVERVIEW OF METHODS

We employed the following basic steps to complete the habitat connectivity models:

1. We chose a set of target species and established a study area expansive enough to minimize edge effects within the South Atlantic LCC region itself (= South Atlantic LCC region + 100km buffer).
2. We asked experts (for each species) to quantify different factors related to the degree of “resistance” posed by different land cover types, roads with varying levels of traffic, and other factors. An example of the expert survey form we employed is available upon request.
3. We used the expert-derived parameters to translate the 2006 National Land Cover Database (NLCD) data into a map of land cover resistance for each species, at a 90m x 90m resolution (Figure 1, page 26).
4. We adjusted the land cover resistance values using different scores for open water/distance to shore, and also a reduction in resistance for existing protected areas (Figures 2–3, pages 27–28).
5. We calculated a separate resistance layer based only on traffic values, using the expert data to assign resistance values to roads with different levels of vehicle traffic (Figure 4, page 29).
6. We adjusted the traffic resistance layer by reducing the resistance value for certain large bridges that may allow wildlife to cross underneath (Figure 4, page 29).
7. We added the adjusted traffic and land cover resistance values to each other, and then calculated a “landscape resistance” value representing the average (land cover resistance + traffic resistance) values across a moving window (Figure 5, page 30). The landscape resistance metric helped account for the possibility that species may perceive the landscape at a greater scale than 90m pixels.
8. We added the landscape resistance to the land cover and traffic resistance sum, to create a final resistance layer for each species (contemporary 2006 values) at the 90m resolution.
9. We identified the parts of the South Atlantic LCC region with the lowest resistance values and then broke
those areas up into smaller "ecoblocks" using higher traffic roads as dividers (Figure 6, page 31).

10. Within each resulting ecoblock, we found the point of lowest resistance, and those points defined the nodes used in our Circuitscape Analysis (Figure 6, page 31).

11. We ran Circuitscape models using the Clemson University supercomputer ("Palmetto Cluster"), summing up cumulative current density between each pair of nodes that were within a species-specific threshold distance of one another. We adjusted the cumulative current density summations by weighting the pairwise outputs by the relative size of the ecoblocks represented by the nodes within each pair, to avoid overvaluing fragmented landscapes with undue amounts of cumulative current flow.

12. We converted the resistance layer for each species into its inverse value, conductance, and ran Connectivity Analysis Toolkit (CAT) models (shortest path betweenness centrality) on each conductance layer, using a hexagon size of 200ha.

13. We relativized the centrality results from the CAT models by dividing the observed centrality values by the expected centrality values we observed in a null model in which the study area landscape was devoid of variation in conductance values (Figures 7–8, pages 32–33).

14. We created future resistance layers, incorporating projections of urbanization (to the year 2100) and sea level rise (2.5 meter bathtub model) to update the land cover resistance layer. These future resistance layers also were used to define future node locations.

15. We re-ran Circuitscape models on the future resistance layers and nodes, and CAT models on the future conductance values.

16. We standardized the results for visualization purposes by reclassifying the Circuitscape and CAT model outputs according to their quantile score. We also created several index values by summing Circuitscape results across groups of species and time periods.

**STUDY AREA**

The South Atlantic Landscape Conservation Cooperative (South Atlantic LCC) region encompasses portions of Florida (FL), Georgia (GA), Alabama (AL), South Carolina (SC), North Carolina (NC) and Virginia (VA). We applied a 100 km buffer to the original South Atlantic LCC region border to remove the deep indentation that existed in its southwest side in GA, which has since been revised by South Atlantic LCC staff in order to suppress the influence of boundary effects in the computer models. The results from the connectivity models were pruned after analysis to focus on the revised South Atlantic LCC boundary (Blueprint 2.0 edition).

Although our raw results stretched well into the mountain landscapes of the Southern Appalachians, the possible influence of boundary effects is much higher along that western edge of our models. We can provide the raw results for the entire study region upon request.

**TARGET SPECIES**

Seven animal species were chosen to model habitat connectivity potential at multiple scales across the study area. Analyses were applied to the eastern cougar/Florida Panther (*Puma concolor*), red wolf (*Canis rufus*), black bear (*Ursus americanus*), eastern diamondback rattlesnake (*Crotalus adamanteus*), pine snake (*Pituophis melanoleucus*), timber rattlesnake (*Crotalus horridus*) and box turtle (*Terrapene carolina*). These particular species were strategically chosen in order to characterize a wide range of animal mobility, while still focusing on species for which on-the-ground habitat connectivity was a particular conservation concern.
TARGET SPECIES, CLOCKWISE FROM UPPER LEFT

Eastern cougar/Florida Panther (*Puma concolor*), red wolf (*Canis rufus*), eastern diamondback rattlesnake (*Crotalus adamanteus*), timber rattlesnake (*Crotalus horridus*), box turtle (*Terrapene carolina*), pine snake (*Pituophis melanoleucus*), and black bear (*Ursus americanus*)
For example, while the Florida panther may utilize a home range as large as 400 square kilometers, a timber rattlesnake may only use 40 hectares, and a box turtle only 1–2 hectares. Hence the large mammals and the reptiles likely experience the human-altered landscape in the southeastern U.S. very differently at different scales. This is particularly true at the larger scales, where connections that might represent daily or monthly movement patterns for the large mammals might require intergenerational migrations for reptiles to achieve. At the smaller scales, however, the species may use many of the same structural habitat features for connectivity. It is important to capture these different perspectives in order to provide a comprehensive multi-scale look at the region’s habitat connectivity priorities. At the same time, we also wanted to examine the extent to which the connectivity priorities for the different species might overlap, indicating complementary needs that would be useful to highlight for conservation planning.

We chose not to focus on birds, in part because high conservation priority bird species such as the red cockaded woodpecker have already been the targets of so much research in the southeast region. Also, although variation certainly exists looking across the full range of bird species, many birds can presumably fly over a variety of terrestrial obstacles (such as roads and houses), and are thus likely to be less in need of habitat corridor protection. Any habitat corridor sufficient to allow the movement of non-flying reptiles, for example, may be expected to be sufficient to facilitate dispersal of most birds that use the same basic habitat types.

We did not include any fully aquatic species, reasoning that the threats to habitat connectivity for aquatic species (e.g. dams) are so different from those facing the terrestrial mammals and reptiles that the aquatic species require a completely different approach. We also did not include any terrestrial amphibians, as the life cycles of most amphibians are closely linked to aquatic breeding habitat availability, and there was not sufficient data available to model breeding habitat occurrence across the South Atlantic LCC landscape when we began the project. This is particularly true for the rarest species of amphibians that rely on ephemeral wetlands for breeding—such wetlands are difficult to map out using remote sensing alone.

Two of the species, the eastern diamondback rattlesnake and the pine snake, may be regarded as habitat specialists within the region, as they show greater affinity for longleaf pine ecosystems. The large mammals, timber rattlesnake, and box turtle were considered to be more general in their habitat requirements.

The pine snake and the box turtle contain recognized subspecies within the South Atlantic LCC region, but we did not attempt to distinguish between the subspecies in our expert opinion questionnaires, nor in the models that followed. We expect our results should be highly applicable to each subspecies in the region, and our data may also be informative for additional subspecies or related taxa that occur elsewhere.

OCCUPIED VERSUS POTENTIAL HABITAT

One interesting dilemma presented itself early on in the project: Should we model habitat connectivity for each species only where it is currently known to occur, or should we model habitat connectivity across all potentially suitable habitats within our study area? We chose the latter approach, for three reasons:

1. Accurate, up-to-date occurrence maps were available only for the red wolf and Florida panther (in part because those two species are so constrained in their current wild range).
2. We wanted to facilitate conservation work promoting the recovery of these species by highlighting corridors that may be critical to range expansion.
3. Since we were going to incorporate future projections of land cover and sea level rise into our future models, it didn’t make sense to restrict each species to its current known range.

As noted, the Florida panther and the red wolf are currently absent from nearly all of their historically occupied habitats in the region. The black bear was extirpated from many areas of the Southeast, but is now rapidly recolonizing certain areas (such as parts of NC and SC). The timber rattlesnake has been driven to extinction in many parts of the Piedmont, but remains widespread in the coastal plain and mountains. The eastern diamondback rattlesnake and pine snake are very patchily distributed in the coastal plain of NC and SC, but continue to be widespread in coastal GA and north FL. Our smallest species, the box turtle, remains abundant across much of the South Atlantic LCC region, but is rapidly losing local habitat fragments due to urbanization.

For the pine snake and eastern diamondback rattlesnake, we did restrict the contemporary models of habitat connectivity to the rough boundary of suitable longleaf pine/coastal forest habitats. With climate change, the amount of suitable habitat for these two species could change in unpredictable ways, so we included more of the study region in those future models.
In order to model habitat connectivity for each species in the absence of detailed empirical data, we relied heavily on expert opinion to parameterize our resistance surfaces. For each species, we identified a set of experts (based on published work and our own personal contacts in the region) and then sent these experts a questionnaire. Table 1 summarizes the responses received:

<table>
<thead>
<tr>
<th>Species name</th>
<th>Surveys sent out</th>
<th>Surveys returned</th>
<th>% return</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>P. concolor</em></td>
<td>12</td>
<td>7</td>
<td>58</td>
</tr>
<tr>
<td><em>C. rufus</em></td>
<td>7</td>
<td>7</td>
<td>100</td>
</tr>
<tr>
<td><em>U. americanus</em></td>
<td>35</td>
<td>15</td>
<td>43</td>
</tr>
<tr>
<td><em>C. adamanteus</em></td>
<td>27</td>
<td>11</td>
<td>41</td>
</tr>
<tr>
<td><em>C. horridus</em></td>
<td>27</td>
<td>12</td>
<td>44</td>
</tr>
<tr>
<td><em>P. melanoleucus</em></td>
<td>16</td>
<td>13</td>
<td>81</td>
</tr>
<tr>
<td><em>T. carolina</em></td>
<td>33</td>
<td>12</td>
<td>36</td>
</tr>
</tbody>
</table>

Table 1. Summary of expert survey return rates by species.

The four-page questionnaires had two major components:

1. We asked respondents to quantify the resistance value of each National Land Cover Database (NCLD 2006) land cover type, on a scale of 1–100, with 100 being the highest possible obstruction to species movement.
2. We asked the experts to quantify the resistance posed by different levels of vehicle traffic, again on a scale of 1–100.

Higher resistance equates to a lower likelihood that a species will move through a given area.

Using the expert data described above, we created a basic layer representing the degree of resistance posed by land cover conditions across the study area by reclassifying the available National Land Cover Database (2006) data set according to the average values received from the experts. We modified this land cover resistance with correction factors for open water, bridge locations and protected area status, to yield a final version.

We created a second resistance layer based on traffic values in the same fashion, using expert opinion to rescale available data on road traffic levels to create an index of traffic-induced resistance across the region. The traffic and land cover resistance values were then combined, and a landscape resistance metric was calculated as the average of the traffic+landcover resistance across a broader moving window around each unit of the landscape. Then we added landscape, land cover and traffic resistance together into a single resistance layer for each species, which we used as the basic input into the connectivity models we detail below.

We created resistance models for both contemporary and future conditions, with the future models incorporating urbanization projections, out to the year 2100, and a simplified model of sea level rise impacting the coastline. The resistance models were then used to define nodes of interest for each species, with each node representing a potential subpopulation of the species that was worth evaluating for connectivity with other nodes. A comprehensive description of our GIS methods used to create the resistance layers and node points is available upon request.

The first connectivity model we used was Circuitscape (McCrae et al. 2008). Circuitscape works in a similar fashion to ordinary least cost path analysis, but instead of returning...
a single least cost path or corridor for a given pair of nodes, Circuitscape calculates the expected flow of the target species across all of the different pathways from one node to the other. The method is analogous to electrical circuit theory, treating the habitat nodes as electrodes and the landscape as a circuit board matrix with varying levels of resistance. Pathways that are expected to receive many dispersing animals are scored with high current-density values, whereas cities, major roads and out-of-the-way routes between the nodes tend to get low current-density values.

We modified the Circuitscape program to run on Clemson University’s supercomputer, which enabled fine-scale analysis of connectivity between large numbers of pairs of nodes across the study region for each species. Importantly, the supercomputing approach allowed us to run the analyses simultaneously across the entire model extent. This eliminated the risk of boundary effects that would have occurred had we used a tiling approach to divide the study area into smaller modeling units. After calculating current density flow between each pair of nodes, we summed the results together using a weighted average approach, with weights derived from the relative size of the nodes in each pair.

**CONNECTIVITY ANALYSIS TOOLKIT MODELS**

We used the Connectivity Analysis Toolkit program (CAT; Carroll et al. 2011) to generate a second set of habitat connectivity models for each of the seven focal species. Of the options presented by the CAT software package, we chose the shortest path betweenness centrality method, as it was less computationally intensive and easier to interpret. Betweenness centrality has become a popular way to represent habitat connectivity across a landscape. It is based on graph theory (e.g. Urban et al. 2009) and considers the degree to which any single point on a graph contributes to paths or flows between all other points. The idea behind shortest path betweenness centrality, specifically, is to identify the one shortest (in terms of conductance) path that connects each pair of points on a graph representing the study area (with each point representing a grid cell pixel). The program essentially counts the number of shortest paths in which a specific grid cell is involved and assigns a centrality score to that grid cell based on that number. Hence, hexagon cells that are involved in many least cost paths receive much higher centrality scores in the output.

We converted our resistance values from the Circuitscape models to conductance (the inverse of resistance), and the CAT software generated centrality scores for a hexagonal grid covering the study area (each hexagon = 200ha). The raw centrality scores were relativized by dividing them by a null model of centrality that we created for a uniform-resistance landscape of the same size and scope as our study area.

**FUTURE LANDSCAPE ANALYSIS**

A secondary goal of this project was to compare connectivity potential across our study area under contemporary versus hypothetical future conditions, incorporating sea level rise and increased urbanization and development. We created a projected land cover dataset for the year 2100 by utilizing a bathtub model representing a relatively extreme 2.5m sea level rise, and an urbanization projection layer that was available prepublication from the authors of Terando et al. (2014). To reflect expected habitat loss under such future conditions, we used the node-size thresholds derived from the contemporary landscapes to define future nodes. This resulted in fewer (and smaller) nodes being used for each species in the future model runs for Circuitscape. The future CAT models were run as for the contemporary models, with adjustments for the expanding potential range of certain species.

**Connectivity Results**

**CIRCUITSCAPE MODELS**

We generated Circuitscape models at a 90m output resolution for 6 out of 7 species. The box turtle, due to its local-scale habitat requirements, ended up with far too many nodes to analyze, even with the Clemson Supercomputer (Figures 9–22, pages 34–47).

In this section, we present some general observations about the contemporary and future Circuitscape results obtained for the remaining six species. The fine scale and wide geographic extent of our models prevent us from describing every noteworthy aspect of the results. Potential users of the data are encouraged to examine the maps showing our model outputs, and to download the actual data sets themselves to peruse in much greater detail.

Also, the data we report here are the weighted current density sums across all pairs of nodes that were included in each species model. This is appropriate for evaluating big-picture connectivity issues at a wide scale, such as looking across the South Atlantic LCC boundaries. However, for local-scale analyses concerning the potential corridors between any two nodes or core areas, we can provide the single pair results upon request.
Two observations about Circuitscape current density results worth noting are:

1. Current density should be high when large numbers of the given target species (and hence their genes) are expected to flow through a relatively small area. In some situations of generally suitable habitat, the current flow between nodes may spread out, and the resulting sheet flow may not appear as significant in terms of density as other areas where the current flow is much more restricted. On the other hand, areas where the current density appears robust may actually represent places where the surrounding landscape has generally high resistance, channeling the species to move along narrow corridors and through tight, high-density pinch points.

2. All of these model results are expressed in terms of relative current density. Two core areas that appear to have relatively high current flows between them may, nonetheless, be too far apart from each other, or cross too challenging of terrain, to actually enable the target species to ever make that journey. Likewise, in some situations, areas that appear to have relatively lower current density values may, in fact, still be well connected in terms of dispersing animals. It is important to remember that our models indicate potential connectivity between nodes that may or may not currently contain the target species.

Also, the results presented in Figures 9–22 are shown relative only to the current density values observed inside of the South Atlantic LCC boundaries. Higher current density values were often observed in the 100-km buffer of our study area in the Southern Appalachian Mountains, most likely due to the greater amount of public forest in that region. We do not focus on those results here, as they fall outside of the conservation planning concerns of the South Atlantic LCC, and because the risk of substantial boundary effects becomes higher in the buffer zone regions. We can provide model results for areas in the buffer zone upon request.

**Black Bear.** The contemporary results for black bear show a distinct pattern of significantly less current density in the northern half of the South Atlantic LCC. There are major concentrations of predicted flow of bears in coastal GA, the Gulf Coast of FL, and west-central GA. Moving northward, the current density values become patchier in SC and NC. Several river corridors stand out with high current density values, such as the Altamaha (GA), Great Pee Dee, and Little Pee Dee (SC). Very little current is projected to flow out of NC’s Albemarle Peninsula, despite the large number of bears that reside in that region (Figure 9, page 34).

The future Circuitscape results for black bear suggest a great loss of current flow in the Piedmont region, from central NC to central GA. At the same time, there is a greater relative current density in the coastal plain, particularly in coastal NC. Southern VA along the NC border is also predicted to have high potential flow of black bears in 2100, at least relative to the remainder of the region (Figure 10, page 35).

**Eastern Cougar/Florida Panther.** The lack of nodes in eastern NC and southeast VA leads to a result in which high potential cougar flow is only predicted to occur in the southern half of the South Atlantic LCC, to an even greater extent than observed for the black bear. The Uwharries in NC and a few nodes in south-central VA are exceptions to this pattern (Figure 11, page 36).

The future Circuitscape results show even greater concentration of cougar flow further south in the region, as the NC nodes are lost due to urban encroachment. There is not much current density differentiation in GA, except for lower flow predicted around the major city of Atlanta (Figure 12, page 37).

**Red Wolf.** The red wolf contemporary model looks quite different from the bear and cougar results. The current density patterns are much more diffuse, with circular “holes” representing cities being the most notable features. There is generally high potential flow predicted across eastern NC, southern GA and northwest FL, with an unexplained gap occurring in central SC from the coast to the mountains (Figure 13, page 38).

The future Circuitscape output for red wolves departs considerably from the contemporary model, as a result of the loss of nodes outside of the Southern Appalachians. Eastern NC and Okefenokee National Wildlife Refuge stand out with high current densities, but otherwise the high flow areas are restricted to the edge of the South Atlantic LCC along the mountain border (Figure 14, page 39).

**Eastern Diamondback Rattlesnake.** In contrast to the large mammal results, the current density maps for the eastern diamondback rattlesnake show a fine-grained pattern of localized connections. The high-current density areas are predicted to occur in clusters such as: southeast NC, the Onslow Bight region around Camp Lejeune in NC, Francis Marion National Forest, the ACE Basin and
surrounding coastal plain in coastal SC, the inner coastal plain of GA, southwest GA, and essentially all of northern FL (Figure 15, page 40).

Generally, there is only a small shift in relative current density patterns throughout our future models for the diamondback. There is a general inland movement of high density areas, a loss of flow in northeast FL that is likely associated with projected urban development, and increased relative current density in southeast NC and the Onslow Bight region (Figure 16, page 41).

**Pine Snake.** The pine snake contemporary results show very patchy current flow patterns centered on the Sandhills region of NC and SC. Other focal areas of high density show up in Brunswick County, NC Francis Marion National Forest and the Savanna River site in SC. However, much more generalized potential flow of pine snakes is predicted by our models for the piedmont and mountains of GA and Alabama (AL) Apalachicola National Forest in Florida, and the area west of Osceola National Forest in FL (Figure 17, page 42).

Future pine snake current flows are predicted to be largely similar to those in the contemporary models, with exceptions being a collapse in current density in north-central GA and northeast FL. The future model does show high-predicted flow of pine snakes along the GA/AL border (Figure 18, page 43).

**Timber Rattlesnake.** More so than for the other species, the Circuitscape results for timber rattlesnake resemble the theoretical “hub and spoke” design of habitat connectivity networks. There are large core areas of high flow, representing major blocks of forest, that are joined by riverine corridors such as the Great Pee Dee, Little Pee Dee and Altamaha. Concentrations of timber rattlesnake connectivity occur along the coastal plain, the Piedmont fall line forest region and along the edge of the South Atlantic LCC’s border with the Southern Appalachian Mountains (Figure 19, page 44).

Our future models predict timber rattlesnake current density will condense in many areas, including a collapse in a large core area of rattlesnake flow that was predicted by the contemporary model for the GA Piedmont. Timber rattlesnake current densities decline around the outskirts of Atlanta, GA and Charlotte, NC. The Great Pee Dee River continues to stand out, connecting coastal SC to the Sandhills and Uwharries of NC (Figure 20, page 45).

**Combined Results Across Species.** We combined the quantile scores from the different species models into several indices of connectivity importance for the region. First, we created a generalized forest combination (GFC), incorporating black bear, red wolf, Florida panther and timber rattlesnake current densities across the South Atlantic LCC. The resulting index remained heavily weighted in terms of higher current densities to GA and north FL. The GFC model also avoids Atlanta, the Piedmont and NC inner coastal plain, and is generally spotty along the NC outer coastal plain (Figure 23, page 48).

The future GFC model scores (same species, but combining future model results) were no longer weighted towards the southern part of the South Atlantic LCC. Instead, a much more diffuse pattern was observed, visually dominated by Okefenokee National Wildlife Refuge, and major river corridors in SC and southeast NC. (Figure 24, page 49).

Adding in the two longleaf-associated species (pine snake and diamondback rattlesnake) yields an “all species” model that is not too different from the GFC outputs. The exception is that the all-species current densities are higher in southeast and south-central NC (Figure 25, page 50).

Looking ahead to 2100, our future all-species index suggests that current density patterns will essentially be shredded across the South Atlantic, especially in the urbanizing piedmont of GA and NC (Figure 26, page 51).

### CONNECTIVITY ANALYSIS TOOLKIT MODELS

Many of the same caveats apply to the Connectivity Analysis Toolkit (CAT) results as were noted above for Circuitscape. The centrality values are relative, and lines of high centrality may cross areas of unsuitable habitat that would pose insurmountable barriers to successful dispersal by the target species. They also depict potential centrality levels assuming the species in question could be found by the target species. They also depict potential centrality levels assuming the species in question could be found across the entire region represented in each model. In addition, the CAT model algorithms incorporated potential connections between all pairs of hexagonal cells across the landscape, no matter how far apart such hexagons were.

For visual clarity, we present the CAT results pared down to only the hexagons representing the top 5% and top 10% of the South Atlantic LCC region. The resulting patterns show “lines” of the highest centrality values tending to intertwine across the landscape. As with Circuitscape, however, if a broad area were generally suitable for a species, the CAT centrality results would be diffuse as well, resulting in centrality scores that were lower than in restricted areas where many least cost paths would necessarily converge. Such areas may not show up in the top 10% of the hexagons; therefore, we suggest users directly download the hexagonal CAT result shapefiles to better evaluate connectivity patterns in their area of interest.
For all of the models, the spidery vein-like patterns that emerge in the CAT centrality results can be characterized as visually appealing (as they form networks across the LCC) but also quite challenging to interpret (given their complexity). See Figures 27–40 for maps showing the CAT-model outputs for each species and time period.

Despite our attempts to minimize erroneous connectivity patterns in coastal situations where estuaries should pose major barriers to species movement, our CAT results show lines of high centrality across certain water bodies as well as some rather bizarre striations of small fragments of centrality in the same areas. These open water striations can be safely disregarded, as they are not relevant to terrestrial habitat connectivity patterns.

**Black Bear.** The contemporary CAT results for black bear show lines of high centrality that are well-distributed across the entire South Atlantic LCC. The centrality lines fan out more extensively in the north and south, possibly an artifact of our relativization process. There are numerous areas of convergence (where two or more high centrality lines come together), too many to list here for black bears or for the species that follow. We do note that there are a few areas where high centrality lines run parallel and close together, suggesting high importance for connectivity. These include Hofmann Forest in North Carolina, the Little Pee Dee River at the NC/SC border, the Carolina Sandhills National Wildlife Refuge and parts of coastal GA (Figure 27, page 52).

The only major change in the future black bear CAT results is a generalized shift inland away from the NC and SC coastlines (Figure 28, page 53).

**Eastern Diamondback Rattlesnake.** We restricted the eastern diamondback contemporary model away from the mountains and VA, reflecting range limits for the species. Within the smaller area covered by the CAT model for this species, high centrality lines stretched through the Sandhills in NC and SC, and along the coastal plain from NC to GA. In southern GA and northern FL, the lines spread out into a very diffuse pattern (Figure 33, page 58). We allowed the future diamondback CAT models to consider the mountains and southern VA as well. Apart from that, no major shifts are discernable (Figure 34, page 59).

**Pine Snake.** More so than the other species, the pine snake centrality lines in the contemporary results appeared to be very fragmented, perhaps indicating patchy habitat availability. As with Circuitscape, the NC and SC Sandhills figure prominently in the pine snake CAT results (Figure 35, page 60). The future centrality scores for pine snake show an interesting and hard-to-explain expansion towards the coastline with numerous fragments of high values appearing next to the ocean (Figure 36, page 61).

**Timber Rattlesnake.** Major convergence areas for timber rattlesnake high centrality lines were observed in southeast NC, the Uwharries region of NC, and the coastal plain of GA and SC. The centrality lines became more diffuse in southwest GA and northern FL (Figure 37, page 62). The major shift shown in the future CAT models for timber rattlesnakes was an inland shift away from Wilmington, NC (Figure 38, page 63).

**Box Turtle.** Major convergence areas were noted for the box turtle contemporary centrality values in the Uwharries region of NC, and the GA/SC border within the coastal plain (Figure 39, page 64). The future centrality scores tended to collapse inward from the coast, and there was a greater degree of convergence and consolidation in the piedmont region of the different states (Figure 40, page 65).

**FOCAL AREA RESULTS**

To illustrate the potential use of our newly produced connectivity datasets for the South Atlantic LCC, in this section we present details on the connectivity patterns observed for a series of focal areas. We believe these focal areas will be of interest to many different conservation groups working in the Southeast. Additional maps can be prepared upon request for other area/species combinations. For each focal area map, we include connectivity results (CAT centrality scores and Circuitscape current density...
values) for one or more species that we considered most relevant to conservation planning in that area. For focal areas expected to undergo major changes due to urbanization and/or sea level rise, we include the corresponding future model results as well in a separate map for comparison purposes.

**Albemarle Peninsula to Roanoke NWR/Dismal Swamp.** The red wolf is currently found only on the Albemarle Peninsula, so it seems a logical choice for examining connectivity issues in this area. However, red wolf current density patterns from the contemporary models show very diffuse flow from the peninsula inland to the Roanoke River area, suggesting few barriers to wolf dispersal are present. There was a potential red wolf node highlighted west of the Roanoke River National Wildlife Refuge/Gamelands area, which could be deserving of consideration for conservation efforts. The CAT model centrality lines for the wolf travel off the peninsula and then south, primarily, and there also are lines of high centrality connecting the Dismal Swamp to the Roanoke and Chowan River areas (Figure 41, page 66).

In our future scenario, the red wolf Circuitscape results show a drastic shift inland, driven by sea level rise across this very low-lying peninsula. However, the area westward of the sea level rise remains very diffuse in terms of current density for the wolves. There continues to be a major centrality line from the Dismal Swamp to the Chowan and Roanoke River regions. Some strange CAT centrality patterns are apparent in the estuaries around this region, which have little bearing on red wolf conservation planning (Figure 42, page 67).

**Onslow Bight—NC.** When we examine black bear model results for the Onslow Bight region in coastal NC, one very interesting feature stands out: the presence of three parallel lines of top 5% centrality running through the Hofmann Forest property owned by NC State University. A secondary line runs closer to the coastline from Croatan to Camp Lejeune and Holly Shelter. Circuitscape data for the bear in the same area indicate high potential flow of bears between Hofmann Forest and Croatan, between Camp Lejeune and Holly Shelter and in the triangle area between Hofmann, Lejeune, and Croatan (Figure 43, page 68).

The eastern diamondback rattlesnake is another priority species for the Onslow Bight, since Camp Lejeune is essentially the only place in NC where this state-endangered species continues to be regularly found. Centrality lines for the diamondback rattlesnake run along the coast through Camp Lejeune, and on a parallel track further inland through Hofmann Forest to Croatan. There is a convergence point along the U.S. 17 highway between Hofmann and Croatan. The diamondback rattlesnake current density patterns suggest high potential flow between Hofmann and Camp Lejeune, including a currently unprotected node just south of Hofmann Forest. There also is high flow between Holly Shelter Gamelands and Camp Lejeune (Figure 44, page 69).

**Southeast NC/Cape Fear Arch.** Contemporary black bear CAT results for the Cape Fear Arch region reveal relatively straight and direct centrality lines running from Holly Shelter Gamelands to the Green Swamp Preserve owned by The Nature Conservancy, and also from Angola Bay Gamelands to Bladen Lakes State Forest. There is a large unprotected area of high current density centered around an unprotected node east of Bladen Lakes, and also west of Juniper Creek Gamelands. The current flow between Holly Shelter and the Green Swamp is relatively diffuse, other than avoiding the city of Wilmington (Figure 45, page 70).

The future black bear models reveal this region to have relatively higher levels of current density for black bears, when compared to the rest of the South Atlantic LCC (but not when compared to the contemporary models). The bear current density flows seem to avoid the large unprotected tract along the NE Cape Fear River (where the river turns south to join the main stem Cape Fear), possibly due to sea level rise inundating this floodplain area. Centrality lines for the black bear shift far inland in the future models (Figure 46, page 71).

When we look at timber rattlesnake connectivity for the same region, the most striking difference is that one of the high centrality lines in the contemporary model closely follows the NE Cape Fear river. An additional parallel track further inland suggests there are two good options at present for connecting Holly Shelter to the Green Swamp for the rattlesnakes (Figure 47, page 72). The future timber rattlesnake results, however, show the centrality lines moving inland, with greater emphasis on the Holly Shelter to Bladen Lakes State Forest connection (Figure 48, page 73).

In both the bear and rattlesnake models, there also is a corridor of high current density running from Bladen Lake State Forest south to the region below Lake Waccamaw.

**Sandhills—NC & SC.** The Sandhills region is a hotspot for conservation of the pine snake. Our CAT centrality results for pine snakes show possible corridor routes for connecting Ft. Bragg to the southern block of NC’s Sandhills Gamelands. From there, the corridors continue to unprotected pine snake nodes just south of the border.
with SC, and onward to the SC Sandhills National Wildlife Refuge. Circuitscape results for the same region reveal widespread areas of high potential flow within the Sandhills, with one major exception southwest of the Sandhills Gamelands, which corresponds with the City of Rockingham, NC. Better potential current flows are observed northward and southward of the urban area (Figure 49, page 74).

**Myrtle Beach & Winyah Bay, SC.** Our results show a relatively direct line of high centrality for black bears running from the Green Swamp in NC to Frances Marion National Forest in SC, bypassing the urban areas of Myrtle Beach as it goes. There are also high bear centrality areas further inland along the Great Pee Dee and Little Pee Dee River corridors. High current density flow for the bears also was observed along the rivers and around an unprotected potential bear node north of Frances Marion National Forest. The potential flow of bears becomes very sparse and broken up in the area directly inland from Myrtle Beach, all the way to Conway. This suggests this area is already very difficult to traverse, with the exception of the Waccamaw River itself, which flows right through Conway (Figure 50, page 75).

The future black bear models for this region show a shift inland to focus on the rivers. The Circuitscape current density flow around Myrtle Beach remains tenuous, and the high centrality line along the Waccamaw disappears. The Green Swamp to Little Pee Dee River connection is highlighted in the future bear centrality model (Figure 51, page 76).

**SC Piedmont Fall Line Forests—Sumter to Oconee.** We explored connectivity patterns in the Oconee to Sumter region in the piedmont of SC using both timber rattlesnakes and black bears. The timber rattlesnake centrality lines (contemporary) are widely spaced in the region. Circuitscape current density flows are very patchy and suggest a low degree of connectivity between the two units of Sumter National Forest. Higher flow was predicted for the Oconee to Sumter connection further south. There are many potential timber rattlesnake nodes in the region that are unprotected (Figure 53, page 78).

The black bear models were similar, but with fewer nodes that were concentrated in the major protected areas. Lake Greenwood appears to block most of the potential connection between the two Sumter National Forest districts, for the bear and the rattlesnake (Figure 52, page 77).

**ACE Basin to Frances Marion—the Charleston Linkage.** Centrality lines and relatively discrete current density flows from the contemporary timber rattlesnake models suggest potential corridor routes between Frances Marion National Forest and the ACE Basin (formed by the confluence of the Ashepoo, Combahee and Edisto Rivers) conservation complex in SC. The corridor options appear constricted around the outskirts of Charleston, where there is not much open space before running into the large lakes further inland (Figure 54, page 79). There is a large unprotected area of high current density and nodes north and inland from the ACE Basin. (Some of this land may have been recently protected in a transaction with Mead Westvaco.)

Our future models indicate that the innermost line of high centrality for timber rattlesnakes disappears from the outer limits of Charleston, suggesting this connection may be vulnerable to future urbanization. A larger zone of low current density shows up in the same area as well. Current flows in much of the ACE Basin area are removed by rising sea levels (Figure 55, page 80).

**Ft. Stewart to Okefenokee.** In coastal GA, our eastern diamondback rattlesnake models highlight several relatively direct pathways for connecting the Army’s Ft. Stewart base to Okefenokee National Wildlife Refuge. Numerous unprotected diamondback nodes dot this landscape (Figure 56, page 81).

**Apalachicola to Okefenokee.** The Apalachicola to Okefenokee connection was explored from the perspective of both Florida panthers and eastern diamondback rattlesnakes. For the cougar, our results show a direct network of high centrality lines connecting the protected areas in this region. There is an unprotected cougar node west of Okefenokee that deserves conservation attention. The Circuitscape model results show relatively high current density flow across the entire region, especially along the Gulf Coast of FL, and between the Red Hills area of southern GA to Okefenokee (Figure 57, page 82).

The eastern diamondback rattlesnake centrality lines also highlight the Red Hills to Okefenokee corridor as being important, along with a separate corridor between the Red Hills and Apalachicola National Forest to the south. As for the cougar models, there was not much differentiation shown in the Circuitscape results for diamondbacks in this region (Figure 58, page 83).

**DISCUSSION—SCIENTIFIC IMPORTANCE Accomplishing our Project Goals.** We have fully accomplished two of our project goals (#1 and #3), and partially accomplished the remaining goal (#2). In this
project, we were able to successfully map contemporary and future levels of habitat connectivity in the South Atlantic region, from the standpoint of multiple groups of terrestrial wildlife species (reptiles and large mammals). We have also published our data layers online via the South Atlantic LCC’s Conservation Blueprint portal. We expect to take additional steps to make sure our connectivity results are easily accessible to all potential users across this region.

While we were not able to undertake population viability assessments of the target species within the project’s available time frame and budget, we have generated centrality data layers that can be used to help prioritize corridors across the South Atlantic LCC in terms of their importance for a given species. Connectivity areas with both high current density (equivalent to predicted flow of dispersing animals) and high centrality (more important for achieving the overall habitat network for the species) should be considered as the highest priority sites for efforts to conserve and restore corridors in the region.

Novelty And Scientific Significance. In this report, there are seven innovative aspects of our work that deserve mention because of their novelty and scientific significance. These include:

1. We used a supercomputer to achieve fine-scale connectivity results across a very broad region (entire multi-state LCC plus 100km buffer). This important development will lead to additional projects in other areas and should prove beneficial to conservation efforts by providing plenty of detail for parcel-level planning by land trusts and government agencies. Previous connectivity projects have tended to be fine scale and local or coarse scale and regional. One previous usage of a supercomputing approach to connectivity (PATH, Hargrove and Westervelt 2012) focused on a much smaller area (gopher tortoises in Ft. Benning, GA), but it will be interesting to compare the utilities and outputs for PATH and Circuitscape in future work.

2. Our work represents the first attempt in the southeastern U.S. to combine connectivity models for a range of very different species, focusing simultaneously on large mammals and large terrestrial reptiles. Previous work in the region has been dominated by a focus on red-cockaded woodpeckers, when in fact, they may not even need corridors to successfully disperse across wide gaps in their preferred habitat. Our longleaf specialist models (pine snake and eastern diamondback rattlesnake) should provide a perfect complement to connectivity plans that have been formulated with woodpeckers in mind. Also, our results should greatly facilitate connectivity planning at multiple scales in the region.

3. We made several key improvements to the Circuitscape methodology. These include:
   A. dividing up the pairwise calculations to make the models suitable for parallel processing;
   B. weighting the pairwise results by node size, to prevent areas with numerous small nodes from dominating the cumulative current density maps; and
   C. adding in a very useful distance threshold approach to eliminate the consideration of unrealistic pairs of nodes in the Circuitscape analysis, thereby allowing us to work with species that had otherwise intractable numbers of potential node pairs to evaluate.

4. We also made a crucial improvement to the Connectivity Analysis Toolkit centrality modeling techniques. By using a null model to derive relativized centrality values, we were able to discern those areas that are more important to the overall habitat network than would be expected by geographic position alone.

5. We used a comprehensive approach to create our resistance layers for each species, involving expert opinion, land cover maps, traffic data, landscape effects, bridges, open water correction factors and protected area adjustments. This approach, while time-consuming, yielded what we think is a more realistic surface for each species.

6. When faced with a shortage of empirical data on population centers for our target species, we created an innovative approach to determine node locations for Circuitscape that relied on the base resistance layers we had derived from expert opinion. This approach makes logical sense, as areas with very low resistance should be expected to provide the largest numbers of dispersing animals. An alternative approach would have been to rely on occurrence-based habitat suitability models, but such models can be heavily influenced by the available location data for a given species.

7. We took the creative approach of examining potential connectivity across the entire available landscape for each species, rather than only focusing on existing population locations. This was an appropriate method given our interest in promoting the recovery of wildlife populations. Black bears, for example, are still expanding in some areas of the Southeast, and our models will be useful for designing corridors to promote their recovery. Red wolves and Florida
Methods—comparison of CAT and Circuitscape. Now that we have considerable experience working with both Circuitscape and Connectivity Analysis Toolkit (CAT), we are able to compare the two methods in terms of their utility for conservation planning. Each approach has its own strengths; however, at the moment, neither are perfect solutions for connectivity analysis at the LCC-scale.

Circuitscape is well suited for parallel processing, which allows for application to broad areas while still yielding fine scale results. However, we found our Circuitscape cumulative current density maps to be, oftentimes, very diffuse, yielding less differentiation than we might have otherwise hoped (see timber rattlesnake models). Such a result may be realistic, if indeed many options are still available for achieving connectivity in a given area. We did find that our single pair results (which were stacked together to form the cumulative maps shown in this report) provided clearer, more articulated results than the cumulative maps. We will investigate the best ways of sharing the single pair outputs given the sheer number of these layers that were produced.

The shortest path betweenness centrality data generated by the CAT software, while not as fine scale as the Circuitscape results, did yield a ready-made map of a potential habitat network for the entire region for each species. By focusing on the lines of highest centrality, the priority corridor routes were identified quite discretely in comparison to the diffuse results from Circuitscape. The other chief advantage of the CAT centrality approach was the lack of need to develop nodes for the target species. In contrast, our Circuitscape results were highly dependent on the size, location, and numbers of nodes we employed, particularly, so given our modification of the approach to incorporate node size more explicitly in the calculations. However, the lack of discrete nodes for CAT could be a disadvantage in situations where conservation planning guidance is needed for connecting specific areas of the landscape. And, subject to further empirical testing, the CAT results could be found to be over-precise, especially in areas where many connectivity conservation options still remain.

We found the CAT models to suffer from some minor issues when it came to dealing with large water bodies. It was not clear to us how to properly deter centrality lines from crossing what should have been unsuitably broad gaps created by estuaries and the ocean itself.

Both CAT and Circuitscape yielded what we predict will be found to be more realistic results than we would have expected using a simpler least cost path approach alone (e.g. if we had simply run pairwise LCP’s between each pair of target nodes in the South Atlantic LCC). These more complex algorithms generate multiple corridor options for conservationists to consider, which is useful in real-world situations where optimal corridor routes may not always be feasible. Of course, the complexity of the results is also a curse, as they may prove to be overwhelming to conservationists looking for more simplified guidance.

Methods—other lessons learned. We found the information gleaned from our expert surveys to be very useful for connectivity model development. However, designing and distributing the expert surveys, and then collating the results, was a very time-consuming process.

We also found that ArcGIS software from ESRI remains somewhat cumbersome when dealing with large raster data sets. We spent months trying to find solutions to our raster classification issues, which was very frustrating. We hope that the soon-to-be released ArcGIS Pro version of the software will solve some of these problems.

Comparison with other Southeast work. The two most comparable projects that have been completed in the South Atlantic LCC region include the Southeast Ecological Framework assessment (Hoctor et al. 2008) and the more recent Southeast Resilience Analysis conducted by TNC (Anderson et al. 2014). We have not yet attempted a test of the correlation of our results with these other studies—a priority that is included in our list of future research directions. What follows are some general thoughts comparing our connectivity modeling approach to the other studies.

The Southeastern Ecological Framework (SEF) relied heavily on a least cost path approach to connect significant natural areas, and in general terms, ended up highlighting river corridors across the region. Our models help shift the focus to terrestrial connectivity priorities, particularly for longleaf pine species such as pine snakes and eastern diamondbacks. Such connections will be the hardest and most expensive to secure, unfortunately, given their inherently higher suitability for urban development. Still, our results do highlight river corridors as well, which makes sense given that these corridors should be heavily used by a number of terrestrial species due to the seasonal nature of water depth in the river floodplains. The high frequency of hurricanes impacting the South Atlantic LCC coastal...
plain region serves to protect the river corridors from being developed, due to the threat of flooding.

The SEF was based off the same methodology used to generate the Florida Ecological Greenways Network (FEGN) plan (Hoctor et al. 2000), but unlike the SEF, the FEGN plan continues to be refined and implemented. Our results for the South Atlantic LCC only intersect with the Florida plan in the northern part of that state, but we soon hope to more directly compare our results in that area. We also hope that our South Atlantic LCC results can be used to guide similar corridor planning efforts in other states, mirroring the excellent work that has been achieved in Florida.

The resilience models developed by The Nature Conservancy have a different focus than our South Atlantic LCC connectivity modeling project, even though the TNC resilience project employed some of the same tools (such as Circuitscape, see Pelletier et al. 2014). Anderson et al. (2014)’s resilience models highlight areas of highest geologic and topographic complexity, and then within such areas, award higher resilience scores for sites that appear to be well connected to the surrounding landscape. In contrast, our intention was to facilitate the prioritization of corridor protection efforts across the South Atlantic LCC region, with an eye towards the development of local and regional habitat networks sufficient to promote the long-term viability of target species.

Our Circuitscape and CAT results lay the groundwork for such cohesive habitat networks, which are difficult to consider in piecemeal format. This is especially important from a resilience standpoint when considering the conservation needs of keystone species (such as top predators like wolves and cougar) whose presence in the landscape is believed to be very important for ecosystem health and function (Estes et al. 2011).

Other existing conservation plans by The Nature Conservancy, state wildlife agencies and others also serve to highlight specific corridors in the region. Our results lend better scientific precision to such maps, and we hope our data can be effectively incorporated into existing plans as they are revised.

Comparison with other regional and national connectivity projects. Expanding outside of the Southeast, we can draw a few comparisons to other major connectivity projects in other areas within the U.S. For example, our project was much more of a standalone research effort than the large collaborative projects undertaken in Washington State (WHCWG, 2010) and California (Spencer et al. 2010). Washington’s ongoing project, like ours, includes a focus on a number of different species. We look forward to expanding our approach to better involve a larger number of scientists and conservationists in the South Atlantic LCC and Southeast regions.

The flow accumulation models developed nationwide by Theobald et al. (2012) provide another opportunity for comparison with our work. Theobald et al. (2012)’s project relied on a non-species specific resistance layer, attempting to represent the degree of naturalness. Our species-specific models should do a better job of capturing the often- idiosyncratic response of wildlife to human influences, especially from the standpoint of dispersal of animals across the landscape. However, it will be interesting to measure the degree of convergence between the Theobald et al. (2012) data and our own in the South Atlantic LCC. We predict the CAT centrality results for generalist species like black bear and timber rattlesnake should be most similar, as Theobald’s approach also generated a metric of centrality for their generic naturalness index. The other key difference between our work and Theobald’s was the choice of nodes: We used the expert-derived resistance layers to delineate nodes, whereas the approximately 40 flow accumulation targets used by Theobald were chosen, more or less, at random. Again, this provides an important opportunity for testing and comparing outputs of different models.

Suggestions for Future Connectivity Research. The following are our best ideas for future research, building directly off our experiences in this modeling exercise for the South Atlantic LCC:

1. There is a strong need for range-wide connectivity mapping for longleaf species across the broader southeastern U.S. A more generalized approach to longleaf ecosystem connectivity could also be developed. Both approaches would be useful for prioritizing longleaf restoration efforts across the region, so that we don’t end up with a situation where too many restoration dollars are spent on unconnected small parcels of land. We already have some of this work underway on behalf of the USGS Southeast Climate Science Center. Range-wide connectivity mapping would be enhanced if range-wide maps of the current distribution of longleaf habitats could be developed.

2. Our basic approach could be easily employed on behalf of other LCC’s in the Southeast and across the country. Given the purpose of the LCC network, we feel strongly that connectivity research and planning should remain a high priority for the partners within each LCC, with
an eye towards guiding the investments in conservation infrastructure for years to come.

3. There is certainly room for evaluating and improving our methods. First, it will be very interesting to directly compare our output models to other datasets generated by the projects mentioned above. Second, we also look forward to employing some of the methods recently introduced by McCrae et al. (2012) to systematically assess the importance of different areas for corridor restoration. Such an approach could be used, for example, to guide the placement of wildlife road crossing structures, or to guide the restoration of key land parcels.

4. As part of any attempt to systematically investigate connectivity priorities across a region, we also see a need for more precise and interpretable metrics of the impacts of landscape changes on the connectivity levels of the entire focal area. Such metrics could be used not just in research, but also for monitoring yearly progress towards improving the levels of habitat connectivity in a given LCC.

5. Our results are definitely in need of empirical validation, beginning with bear, red wolves, and Florida panther, since those species are most amenable to existing GPS collar technologies for monitoring long-range dispersal. Empirical data for reptile movement patterns are also sorely needed, not just the movements of adult animals, but especially the migration and dispersal patterns of juveniles that may do the bulk of movements to new habitats. Scientifically, these questions can be phrased as “Do we observe relatively higher rates of animal movement through locations that are shown by models to have relatively higher levels of current density (Circuitscape) or centrality (CAT)?”

The ultimate goal should be empirical assessments that allow us to calibrate connectivity models to the point where we are able to translate from model results into actual #’s of dispersing animals per unit time period. This would include identifying connectivity gaps in the landscape where no dispersal is achieved.

Such research is complicated by the perceived rarity of dispersal events, and by the patchy existing nature of species distributions since connectivity model predictions are, of course, only valid if the species in question is present in a given area.

6. Our connectivity results, pending any empirical validation that can be quickly achieved, should also be immediately applied to the task of designing a network of wildlife road crossings across the South Atlantic LCC region. It is a relatively easy task to overlay our connectivity data layers on the existing (and planned future) road network to identify priority locations. Of course, as implied above with the McCrae et al. (2012) approach, the placement of a wildlife road crossing structure changes the connectivity situation across the landscape. Therefore, we need to evaluate different options for incorporating such changes dynamically into any plan for wildlife crossing placement in the region. An interesting question becomes: To what degree can wildlife crossings be placed for convenience, given that by punching holes in the resistance offered by highways, such structures change the connectivity situation in the landscape? It remains to be seen how flexible wildlife species are in locating such crossing structures, with respect to existing animal movement pathways.

7. Looking beyond centrality and other GIS-based metrics for prioritizing wildlife connectivity areas, we remain interested in employing a population viability approach to assessing the strategic importance of each important corridor identified by other methods. We intended to attempt this research in the current project, but came to realize fairly quickly that the population viability integration was deserving of a separate multi-year investigation. The challenge will be rendering the connectivity options to a fairly discrete set of corridors, so that the computationally intensive viability models can be run systematically in all of the different scenarios of corridor protection. Such an approach should yield a theoretical assessment of how important any major corridor is to a given species’ long-term survival.
A lone longleaf pine seedling
Our connectivity results are well suited for immediate use by conservationists across the South Atlantic LCC. Four primary roles are envisioned:

1. Using terrestrial habitat connectivity to guide new land and easement acquisition efforts and help place proposals for protection projects in a broader regional context
2. Guiding ecosystem restoration priorities, so that even small-scale restoration projects can serve to enhance the broader habitat network on behalf of terrestrial wildlife
3. Targeting the placement of new wildlife road crossing structures across the South Atlantic LCC.
4. Helping to steer inappropriate urban development and highway construction projects away from areas most critical to terrestrial habitat connectivity.

For all such uses, rather than relying on the maps contained in this report, users should download the data directly, either from the South Atlantic LCC’s online Conservation Planning Atlas, or via arrangements with Wildlands Network staff, who will be more than happy to share the data with any interested parties. We also think it will be very useful to explore other avenues for incorporating our data into state or local conservation decision frameworks, such as the “One NC Naturally” Conservation Planning Tool operated by the NC Dept. of Environment and Natural Resources.

In addition to using the data, we also hope conservation groups in the South Atlantic LCC will provide feedback to us concerning the accuracy and utility of the connectivity models, so that future iterations of this project can be enhanced. The combination of models with on-the-ground experience should prove very valuable to delineating the best ways to conserve and restore habitat connectivity across the region.

In particular, our Circuitscape results were highly dependent on the nodes used in the analysis, and we would like to work with wildlife conservationists familiar with each of our target species to refine those node locations based on what we know about the animals’ current and potential distributions. In some cases, our algorithm-derived nodes may provide unique insights into new population clusters for a given species that may deserve protection. In other cases, we may have included nodes in our models that are, for a variety of reasons, inappropriate or at least non-optimal habitat for the target species.

Refining the central nodes of interest will also get us much closer to the goal of crafting a true “Wildlands Network Design” for the South Atlantic LCC region (Noss, 2003), with core areas and corridors identified and carefully prioritized. Such a plan, similar to what has been achieved by the Florida Ecological Greenways Network plan, would encourage long-range planning and funding efforts needed to safeguard the future of many wildlife species in a region expected to continue to experience climate change, sea level rise and rapid urban growth in the future.

**General Findings From Our Results**

Some general observations from our results that should prove useful for conservationists in the region are:

First, river corridors are, indeed, very important for wildlife in the South Atlantic coastal plain, not only because of the places these corridors connect, but also because the river corridors happen to also be relatively intact compared to the rest of the coastal plain landscape. Such corridors need to be protected from any emerging land-use trends that could result in the river forests being converted to other uses, such as farming or aquaculture. The heavily fragmented Mississippi River floodplain provides a sobering example of what could happen to such forests if they become valuable for agricultural production.

Second, terrestrial movement corridors are just as important as the river corridors, but they often are in need of both restoration of habitat features, and provision with wildlife road crossing structures where the terrestrial corridors intersect highways, as they frequently do. We encourage giving special attention to the challenge of creating terrestrial corridors for longleaf pine ecosystems. The emphasis needs to shift from thinking only about the needs of red cockaded woodpeckers—known to disperse across fairly wide gaps—to also considering the connectivity requirements of reptile and amphibian species, many of which may be unable to disperse without intact corridors of...
suitable habitat and wildlife crossings where the corridors cross high-traffic roadways.

Looking at the big picture within the South Atlantic LCC region, two landscape bands of special importance for wildlife connectivity emerge:

1. the outer coastal plain forests and wildlife refuges from the Dismal Swamp down to Okefenokee; and
2. the extensive fall-line forests in the Sandhills and Piedmont geographies that stretch from Ft. Bragg down to southern GA.

These two regional pathways (which themselves contain multiple corridor routes), along with the existing connections in the Southern Appalachian mountains, provide needed habitat connectivity as a counterpoint to the urban megalopolis that continues to develop across much of the central piedmont of the South Atlantic LCC (Terando et al. 2014).

The South Atlantic LCC should also continue to coordinate with surrounding regions in protecting wildlife corridors that cross LCC boundaries. Our project included nodes to the north, west and south of the South Atlantic LCC, and so our buffer-zone results (available upon request) can be used to examine such priority areas in greater detail.

Specific High Priority Corridors

There are a number of specific high priority corridors that our models have highlighted and that we feel deserve special mention:

The Altamaha, Great Pee Dee, Little Pee Dee, Waccamaw and NE Cape Fear Rivers stand out as particularly important river corridors within the South Atlantic LCC, along with any other major coastal rivers with intact riparian forests.

The potential wildlife movement corridors around Wilmington, NC, Charleston and Myrtle Beach, SC (and likely Savannah, GA) seem to be at greatest risk of being permanently destroyed, as coastal urban development in these cities pushes inland. Given this threat, it is imperative that key land acquisition efforts be targeted now to the outskirts of these cities in order to protect modest wildlife linkages from being overwhelmed by suburban and commercial development projects as the economy rebounds.

The Albemarle Peninsula in NC and the ACE Basin in SC seem to be at highest risk of being subsumed by sea level rise, an unfortunate trend that cannot be directly mitigated in situ. However, by protecting and restoring corridors of natural vegetation heading inland from these locations while also protecting sufficient core area space at higher elevations, it may be possible to allow much of the rich biodiversity of these areas to migrate to higher ground.

Hofmann Forest stands out in our results, as it is a large tract of public land with high connectivity value for several species and because it faces the imminent threat of being sold for urban and agricultural development by its current owner, NC State University. Hofmann’s location is central to both the Onslow Bight region (connecting Camp Lejeune and Croatan National Forest) and also to the larger coastal plain habitat network across the South Atlantic LCC. It seems clear that any efforts to promote wildlife habitat connectivity across the South Atlantic region will ultimately fail if the core areas that form the anchors for the corridor network are allowed to fall out of protected status and be destroyed.

The Waccamaw River floodplain (below Lake Waccamaw in NC) and the large forested area west of Okefenokee National Wildlife Refuge in GA, stand out as other core areas that need to be protected to maintain the broader habitat network in the region, in addition to what we’ve listed above.

Funding Connectivity Conservation in the SE

Even assuming that the core areas in the South Atlantic region can be protected for now, there is still a substantial and urgent need for funding mechanisms to buy land from willing sellers along the corridors we’ve helped identify in this project, and to incentivize private landowners to voluntarily participate in restoring the wildlife habitat across these key routes. Such a funding mechanism needs to be established quickly, before urbanization and sea level rise interact to remove all potential for reconnecting the islands of wildlife habitat that now exist across much of the South Atlantic LCC (and across the remainder of the southeastern U.S. as well).

A few possible approaches to generating the required funds for promoting habitat connectivity would include:

1. Targeting USDA Farm Bill conservation funds to give greater prioritization to landowners whose properties fall within identified wildlife corridors. This approach is already in place for the Louisiana black bear in the Lower Mississippi River region, and it could be applied elsewhere with relative ease once crucial corridors are officially identified.
2. Fully funding the federal Land and Water Conservation Fund (LWCF), and dedicating a significant portion of its budget towards protecting and restoring wildlife corridors. This seems appropriate, given the fact that LWCF is funded by fossil fuel extraction royalties, and since fossil-fuel-driven climate change is one of the main reasons why species need corridor networks to move and adapt.

3. Likewise, the U.S. Forest Service’s Forest Legacy Program could, if it was better funded, contribute substantially to the development of a habitat network in the Southeast, by purchasing easements from key private timberland tracts in the region that fall along priority corridors.

4. The U.S. Military also has a vested interest in promoting corridors of compatible use land across the Southeast, principally to maintain flight paths encircling bases and connecting bases to bombing ranges and other offsite training areas. Such flight path corridors also could serve as wildlife corridors, if they are routed through priority areas and either maintained or restored to appropriate habitat conditions.

One key question emerges: Can military flight paths and priority wildlife corridor routes be simultaneously adjusted to provide the most mutual benefits to both concerns? Such an option seems likely to us. The possibility of securing substantial funding for flight path protection efforts should be encouraged, particularly since hundreds of millions of dollars of wildlife conservation funding per year pales in comparison to the broader Defense budget. From a military perspective, protecting wildlife corridors as flight paths serves an additional vital purpose: greatly enhancing the viability of rare species that are either currently federally listed or under threat of becoming federally listed in the near future. Furthermore, forested connections between military bases and adjacent core natural areas can also be used for on-the-ground training maneuvers by soldiers, simulating long-distance troop movements that may be necessary in conflicts in less-developed parts of the world.

5. The potential for private philanthropy contributing heavily to connectivity conservation in the southeastern U.S. should also be highlighted. There are certainly many individuals and families with the wealth needed to implement the protection of large-scale wildlife corridors across the region, at a scale and pace sufficient to respond to the challenges posed by urbanization, climate change and sea level rise.
Figure 1. Example of land cover resistance reclassification methods.
Figure 2. Example of distance-from-shore resistance classification methods.
Figure 3. Example of protected area resistance reduction methods.
Figure 4. Example of traffic resistance classification and bridge resistance reduction methods.
Figure 5. Example of landscape-scale resistance modification methods and final resistance layer.
Areas with low landscape-level resistance were divided by major roads and used as core habitat polygons.

Polygons were filtered by the amount of suitable land cover they contained. Those that met the requirement were called functional ecoblocks.

A point of minimum local resistance was identified within each functional ecoblock in order to create species-specific nodes.

Figure 6. Example of node identification process.
Figure 7. Example of original CAT results compared with the null model CAT results.
Figure 8. Example showing original top CAT centrality scores vs. top CAT centrality scores after being relativized.
Figure 9. Cumulative current density model for black bear (circa 2006). This map shows the output from Circuitscape connectivity software for black bear, with each of the black dots representing the nodes that were used in the analysis. Green areas have the highest current density, indicating they have a higher potential flow of the target species across that portion of the landscape.
Figure 10. Cumulative current density model for black bear (circa 2100). This map shows the output from Circuitscape connectivity software for black bear, with each of the black dots representing the nodes that were used in the analysis. Green areas have the highest current density, indicating they have a higher potential flow of the target species across that portion of the landscape.
Figure 11. Cumulative current density model for eastern cougar (circa 2006). This map shows the output from Circuitscape connectivity software for eastern cougar/Florida panther, with each of the black dots representing the nodes that were used in the analysis. Green areas have the highest current density, indicating they have a higher potential flow of the target species across that portion of the landscape.
Figure 12. Cumulative current density model for eastern cougar (circa 2100). This map shows the output from Circuitscape connectivity software for eastern cougar/Florida panther, with each of the black dots representing the nodes that were used in the analysis. Green areas have the highest current density, indicating they have a higher potential flow of the target species across that portion of the landscape.
Figure 13. Cumulative current density model for red wolf (circa 2006). This map shows the output from Circuitscape connectivity software for red wolves, with each of the black dots representing the nodes that were used in the analysis. Green areas have the highest current density, indicating they have a higher potential flow of the target species across that portion of the landscape.
Figure 14. Cumulative current density model for red wolf (circa 2100). This map shows the output from Circuitscape connectivity software for red wolves, with each of the black dots representing the nodes that were used in the analysis. Green areas have the highest current density, indicating they have a higher potential flow of the target species across that portion of the landscape.
Figure 15. Cumulative current density model for eastern diamondback rattlesnake (circa 2006). This map shows the output from Circuitscape connectivity software for the rattlesnake, with each of the black dots representing the nodes that were used in the analysis. Green areas have the highest current density, indicating they have a higher potential flow of the target species across that portion of the landscape.
Figure 16. Cumulative current density model for eastern diamondback rattlesnake (circa 2100). This map shows the output from Circuitscape connectivity software for the rattlesnake, with each of the black dots representing the nodes that were used in the analysis. Green areas have the highest current density, indicating they have a higher potential flow of the target species across that portion of the landscape.
Figure 17. Cumulative current density model for pine snake (circa 2006). This map shows the output from Circuitscape connectivity software for the pine snake, with each of the black dots representing the nodes that were used in the analysis. Green areas have the highest current density, indicating they have a higher potential flow of the target species across that portion of the landscape.
Figure 18. Cumulative current density model for pine snake (circa 2100). This map shows the output from Circuitscape connectivity software for the pine snake, with each of the black dots representing the nodes that were used in the analysis. Green areas have the highest current density, indicating they have a higher potential flow of the target species across that portion of the landscape.
Figure 19. Cumulative current density model for timber rattlesnake (circa 2006). This map shows the output from Circuitscape connectivity software for the rattlesnake, with each of the black dots representing the nodes that were used in the analysis. Green areas have the highest current density, indicating they have a higher potential flow of the target species across that portion of the landscape.
Figure 20. Cumulative current density model for timber rattlesnake (circa 2100). This map shows the output from Circuitscape connectivity software for the rattlesnake, with each of the black dots representing the nodes that were used in the analysis. Green areas have the highest current density, indicating they have a higher potential flow of the target species across that portion of the landscape.
Figure 21. Node locations that were generated for the box turtle (circa 2006). The large number of nodes prevented us from running Circuitscape models for this species.
Figure 22. Node locations that were generated for the box turtle (circa 2100). The large number of nodes prevented us from running Circuitscape models for this species.
Figure 23. Generalized Forest Combination (circa 2006). This map shows the sum of the Circuitscape cumulative current density results for black bear, eastern cougar, red wolf, and timber rattlesnake. Quantile scores (1-20) from each species layer were added together to form the index score shown here, with green areas indicating higher predicted current flow across all four species.
Figure 24. Generalized Forest Combination (circa 2100). This map shows the sum of the Circuitscape cumulative current density results for black bear, eastern cougar, red wolf, and timber rattlesnake. Quantile scores (1-20) from each species layer were added together to form the index score shown here, with green areas indicating higher predicted current flow across all four species.
Figure 25. All Species Combination (circa 2006). This map shows the sum of the Circuitscape cumulative current density results for black bear, eastern cougar, red wolf, timber rattlesnake, diamondback rattlesnake, and pine snake. Quantile scores (1-20) from each species layer were added together to form the index score shown here, with green areas indicating higher predicted current flow across all four species.
Figure 26. All Species Combination (circa 2100). This map shows the sum of the Circuitscape cumulative current density results for black bear, eastern cougar, red wolf, timber rattlesnake, diamondback rattlesnake, and pine snake. Quantile scores (1-20) from each species layer were added together to form the index score shown here, with green areas indicating higher predicted current flow across all four species.
Figure 27. Relativized shortest path betweenness centrality for black bear (circa 2006). This map shows the centrality output from the Connectivity Analysis Toolkit software, providing an index of how often each hexagonal unit of the landscape is used in a set of least cost paths connecting every pair of hexagons across the landscape. Highest centrality scores (top 5 & 10%) are shown in blue, protected areas in green.
Figure 28. Relativized shortest path betweenness centrality for black bear (circa 2100). This map shows the centrality output from the Connectivity Analysis Toolkit software, providing an index of how often each hexagonal unit of the landscape is used in a set of least cost paths connecting every pair of hexagons across the landscape. Highest centrality scores (top 5 & 10%) are shown in blue, protected areas in green.
Figure 29. Relativized shortest path betweenness centrality for eastern cougar/Florida panther (circa 2006). This map shows the centrality output from the Connectivity Analysis Toolkit software, providing an index of how often each hexagonal unit of the landscape is used in a set of least cost paths connecting every pair of hexagons across the landscape. Highest centrality scores (top 5 & 10%) are shown in blue, protected areas in green.
Figure 30. Relativized shortest path betweenness centrality for eastern cougar/Florida panther (circa 2100). This map shows the centrality output from the Connectivity Analysis Toolkit software, providing an index of how often each hexagonal unit of the landscape is used in a set of least cost paths connecting every pair of hexagons across the landscape. Highest centrality scores (top 5 & 10%) are shown in blue, protected areas in green.
Figure 31. Relativized shortest path betweenness centrality for red wolves (circa 2006). This map shows the centrality output from the Connectivity Analysis Toolkit software, providing an index of how often each hexagonal unit of the landscape is used in a set of least cost paths connecting every pair of hexagons across the landscape. Highest centrality scores (top 5 & 10%) are shown in blue, protected areas in green.
Figure 32. Relativized shortest path betweenness centrality for red wolves (circa 2100). This map shows the centrality output from the Connectivity Analysis Toolkit software, providing an index of how often each hexagonal unit of the landscape is used in a set of least cost paths connecting every pair of hexagons across the landscape. Highest centrality scores (top 5 & 10%) are shown in blue, protected areas in green.
Figure 33. Relativized shortest path betweenness centrality for eastern diamondback rattlesnakes (circa 2006). This map shows the centrality output from the Connectivity Analysis Toolkit software, providing an index of how often each hexagonal unit of the landscape is used in a set of least cost paths connecting every pair of hexagons across the landscape. Highest centrality scores (top 5 & 10%) are shown in blue, protected areas in green.
Figure 34. Relativized shortest path betweenness centrality for eastern diamondback rattlesnakes (circa 2100). This map shows the centrality output from the Connectivity Analysis Toolkit software, providing an index of how often each hexagonal unit of the landscape is used in a set of least cost paths connecting every pair of hexagons across the landscape. Highest centrality scores (top 5 & 10%) are shown in blue, protected areas in green.
Figure 35. Relativized shortest path betweenness centrality for pine snakes (circa 2006). This map shows the centrality output from the Connectivity Analysis Toolkit software, providing an index of how often each hexagonal unit of the landscape is used in a set of least cost paths connecting every pair of hexagons across the landscape. Highest centrality scores (top 5 & 10%) are shown in blue, protected areas in green.
Figure 36. Relativized shortest path betweenness centrality for pine snakes (circa 2100). This map shows the centrality output from the Connectivity Analysis Toolkit software, providing an index of how often each hexagonal unit of the landscape is used in a set of least cost paths connecting every pair of hexagons across the landscape. Highest centrality scores (top 5 & 10%) are shown in blue, protected areas in green.
Figure 37. Relativized shortest path betweenness centrality for timber rattlesnakes (circa 2006). This map shows the centrality output from the Connectivity Analysis Toolkit software, providing an index of how often each hexagonal unit of the landscape is used in a set of least cost paths connecting every pair of hexagons across the landscape. Highest centrality scores (top 5 & 10%) are shown in blue, protected areas in green.
Figure 38. Relativized shortest path betweenness centrality for timber rattlesnakes (circa 2100). This map shows the centrality output from the Connectivity Analysis Toolkit software, providing an index of how often each hexagonal unit of the landscape is used in a set of least cost paths connecting every pair of hexagons across the landscape. Highest centrality scores (top 5 & 10%) are shown in blue, protected areas in green.
Figure 39. Relativized shortest path betweenness centrality for box turtles (circa 2006). This map shows the centrality output from the Connectivity Analysis Toolkit software, providing an index of how often each hexagonal unit of the landscape is used in a set of least cost paths connecting every pair of hexagons across the landscape. Highest centrality scores (top 5 & 10%) are shown in blue, protected areas in green.
Figure 40. Relativized shortest path betweenness centrality for box turtles (circa 2100). This map shows the centrality output from the Connectivity Analysis Toolkit software, providing an index of how often each hexagonal unit of the landscape is used in a set of least cost paths connecting every pair of hexagons across the landscape. Highest centrality scores (top 5 & 10%) are shown in blue, protected areas in green.
Figure 41. Focal Area Connectivity Map for the Albemarle Peninsula to Dismal Swamp region, showing model results for red wolves (circa 2006). High predicted values of cumulative current density are shown in the background as shades of green, and the areas with highest shortest path betweenness centrality are shown in the foreground in shades of blue. Protected areas are labeled in dark green, and the nodes used in Circuitscape are shown as black stars.
Figure 42. Focal Area Connectivity Map for the Albemarle Peninsula to Dismal Swamp region, showing model results for red wolves (circa 2100). High predicted values of cumulative current density are shown in the background as shades of green, and the areas with highest shortest path betweenness centrality are shown in the foreground in shades of blue. Protected areas are labeled in dark green, and the nodes used in Circuitscape are shown as black stars.
Figure 43. Focal Area Connectivity Map for the Onslow Bight region, showing model results for black bear (circa 2006). High predicted values of cumulative current density are shown in the background as shades of green, and the areas with highest shortest path betweenness centrality are shown in the foreground in shades of blue. Protected areas are labeled in dark green, and the nodes used in Circuitscape are shown as black stars.
Figure 44. Focal Area Connectivity Map for the Onslow Bight region, showing model results for eastern diamondback rattlesnakes (circa 2006). High predicted values of cumulative current density are shown in the background as shades of green, and the areas with highest shortest path betweenness centrality are shown in the foreground in shades of blue. Protected areas are labeled in dark green, and the nodes used in Circuitscape are shown as black stars.
Figure 45. Focal Area Connectivity Map for the Holly Shelter to Green Swamp region, showing model results for black bear (circa 2006). High predicted values of cumulative current density are shown in the background as shades of green, and the areas with highest shortest path betweenness centrality are shown in the foreground in shades of blue. Protected areas are labeled in dark green, and the nodes used in Circuitscape are shown as black stars.
Figure 46. Focal Area Connectivity Map for the Holly Shelter to Green Swamp region, showing model results for black bear (circa 2100). High predicted values of cumulative current density are shown in the background as shades of green, and the areas with highest shortest path betweenness centrality are shown in the foreground in shades of blue. Protected areas are labeled in dark green, and the nodes used in Circuitscape are shown as black stars.
Figure 47. Focal Area Connectivity Map for the Holly Shelter to Green Swamp region, showing model results for timber rattlesnakes (circa 2006). High predicted values of cumulative current density are shown in the background as shades of green, and the areas with highest shortest path betweenness centrality are shown in the foreground in shades of blue. Protected areas are labeled in dark green, and the nodes used in Circuitscape are shown as black stars.
Figure 48. Focal Area Connectivity Map for the Holly Shelter to Green Swamp region, showing model results for timber rattlesnakes (circa 2100). High predicted values of cumulative current density are shown in the background as shades of green, and the areas with highest shortest path betweenness centrality are shown in the foreground in shades of blue. Protected areas are labeled in dark green, and the nodes used in Circuitscape are shown as black stars.
Figure 49. Focal Area Connectivity Map for the Sandhills region of NC and SC, showing model results for pine snakes (circa 2006). High predicted values of cumulative current density are shown in the background as shades of green, and the areas with highest shortest path betweenness centrality are shown in the foreground in shades of blue. Protected areas are labeled in dark green, and the nodes used in Circuitscape are shown as black stars.
Figure 50. Focal Area Connectivity Map for the Myrtle Beach/Winyah Bay region, showing model results for black bear (circa 2006). High predicted values of cumulative current density are shown in the background as shades of green, and the areas with highest shortest path betweenness centrality are shown in the foreground in shades of blue. Protected areas are labeled in dark green, and the nodes used in Circuitscape are shown as black stars.
Figure 51. Focal Area Connectivity Map for the Myrtle Beach/Winyah Bay region, showing model results for black bear (circa 2100). High predicted values of cumulative current density are shown in the background as shades of green, and the areas with highest shortest path betweenness centrality are shown in the foreground in shades of blue. Protected areas are labeled in dark green, and the nodes used in Circuitscape are shown as black stars.
Figure 52. Focal Area Connectivity Map for the Sumter to Oconee region, showing model results for black bear (circa 2006). High predicted values of cumulative current density are shown in the background as shades of green, and the areas with highest shortest path betweenness centrality are shown in the foreground in shades of blue. Protected areas are labeled in dark green, and the nodes used in Circuitscape are shown as black stars.
Figure 53. Focal Area Connectivity Map for the Sumter to Oconee region, showing model results for timber rattlesnake (circa 2006). High predicted values of cumulative current density are shown in the background as shades of green, and the areas with highest shortest path betweenness centrality are shown in the foreground in shades of blue. Protected areas are labeled in dark green, and the nodes used in Circuitscape are shown as black stars.
Figure 54. Focal Area Connectivity Map for the Frances Marion to ACE Basin region, showing model results for timber rattlesnake (circa 2006). High predicted values of cumulative current density are shown in the background as shades of green, and the areas with highest shortest path betweenness centrality are shown in the foreground in shades of blue. Protected areas are labeled in dark green, and the nodes used in Circuitscape are shown as black stars.
Figure 55. Focal Area Connectivity Map for the Frances Marion to ACE Basin region, showing model results for timber rattlesnake (circa 2100). High predicted values of cumulative current density are shown in the background as shades of green, and the areas with highest shortest path betweenness centrality are shown in the foreground in shades of blue. Protected areas are labeled in dark green, and the nodes used in Circuitscape are shown as black stars.
Figure 56. Focal Area Connectivity Map for the Ft. Stewart to Okefenokee region, showing model results for eastern diamondback rattlesnake (circa 2006). High predicted values of cumulative current density are shown in the background as shades of green, and the areas with highest shortest path betweenness centrality are shown in the foreground in shades of blue. Protected areas are labeled in dark green, and the nodes used in Circuitscape are shown as black stars.
Figure 57. Focal Area Connectivity Map for the Apalachicola to Okefenokee region, showing model results for eastern cougar/Florida panther (circa 2006). High predicted values of cumulative current density are shown in the background as shades of green, and the areas with highest shortest path betweenness centrality are shown in the foreground in shades of blue. Protected areas are labeled in dark green, and the nodes used in Circuitscape are shown as black stars.
Figure 58. Focal Area Connectivity Map for the Apalachicola to Okefenokee region, showing model results for eastern diamondback rattlesnake (circa 2006). High predicted values of cumulative current density are shown in the background as shades of green, and the areas with highest shortest path betweenness centrality are shown in the foreground in shades of blue. Protected areas are labeled in dark green, and the nodes used in Circuitscape are shown as black stars.


