Final Project Memorandum

SECSC Project 030:
Turning the Science of Connectivity into Action: Finding Model Consistency and Identifying Priority Habitats for Conservation

1. ADMINISTRATIVE

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Project title: Turning the science of connectivity into action: finding consensus models, key nodes, and priority parcels

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2. PUBLIC SUMMARY

Climate change is already affecting biodiversity, in particular shifting the ranges of species as they move to cooler places. One problem for wildlife as their ranges shift is that their path is often impeded by habitat fragmentation. Because of this, the most common recommended strategy to protect wildlife as climate changes is to connect their habitats, providing them safe passage. In partnership with South Atlantic LCC members, we previously assessed current and projected connectivity for three species (black bear [Ursus americanus], Rafinesque’s big-eared bat [Corynorhinus rafinesquii], timber rattlesnake [Crotalus horridus]) that inhabit bottomland hardwoods throughout the southeastern US. We observed large variation in connectivity across geographical areas, time periods, and species. These results raised new questions about which connections are most important for management actions. In this project, we extended our previous research through four different techniques that provide a more detailed analysis of connectivity in the region. We found low overlap between our connectivity maps and other related connectivity maps, and we generated additional detailed connectivity maps that provide suggestions for how to manage for the three focal species in the present compared to
future conditions under climate change and urbanization. We also identified key core habitats and links in longleaf pine habitat, and generated a practical application for assessing the trade-off between preserving connectivity and working within a limited budget. Our results allow managers and other stakeholders to make realistic decisions about key areas of connectivity in the southeastern US, and to more effectively conserve them in the face of challenges such as changing climate and limited resources.

3. TECHNICAL SUMMARY

The objective of this project was to extend our previous work identifying key linkages for wildlife in the southeastern United States by providing a greater understanding of high priority areas for connectivity to inform conservation planners in the region. In partnership with South Atlantic LCC members, we previously assessed current and projected connectivity for three species (black bear [Ursus americanus], Rafinesque’s big-eared bat [Corynorhinus rafinesquii], timber rattlesnake [Crotalus horridus]) that inhabit bottomland hardwoods throughout the southeastern US. Our focus was the region of the US within the SEAFWA (Southeastern Association of Fish and Wildlife Agencies) borders, which most effectively encompassed the region of interest to us and our partners. We observed large variation in connectivity across geographical areas, between both present and future climate scenarios, and among all three focal species. These results raised new questions about which connections are most important for management actions, necessitating a more in-depth analysis to provide more accurate recommendations.

This research achieved our goal of extending our assessment of regional connectivity with results that can be used by managers and regional landscape planners to determine where conservation efforts could be focused to maintain connectivity in the future. We found low overlap between our connectivity maps and three other related connectivity efforts, suggesting that ensemble modelling may be the best approach to determining key linkages in the landscape. We also successfully identified priorities for conservation and management of existing habitat connections based on their importance to each focal species’ overall habitat network, their current degree of protection, and projected future threats from climate change and urbanization. The analysis was extended to include identification of key nodes within longleaf pine ecosystems, which represent a critical ecosystem that remains fragmented across the southeastern US. Finally, we developed a practical application that determines the trade-offs required when planning for connectivity in the landscape while working within a constrained budget. These results will be important for local and regional conservation and land management, and provide a basis for future work examining connectivity in other habitats and with other species.
4. PURPOSE AND OBJECTIVES

Our objective was to extend our previous work identifying key linkages for wildlife in the southeastern United States by providing a greater understanding of high priority connectivity areas for conservation planners in the region. Connectivity has been identified as a focal element of conservation as climate changes by most state and federal agencies, conservation NGOs, and scientists. In identifying high-priority connections, we planned to advance Themes 1 (Climate and other appropriate projections to use for resource management), 2 (Land use and land-cover change projections) and 4 (Ecological research and modelling) of the SECSC Science Plan. Our research proposed to address the following four questions: 1. How much consistency is there between our previous work identifying key linkages in the southeastern US and other connectivity efforts? 2. What are the trade-offs between current and future connectivity in the southeast? 3. How can we extend our connectivity efforts to identify a set of key nodes in longleaf pine habitat that could then be used in subsequent analyses of connectivity across the former range of the ecosystem? 4. What is the best method to optimize site selection for conservation action at the local scale?

We were able to successfully meet our goals in answering all four questions. Due to the reduced time period of the project (completed in 6 months), although we met all our objectives we did not do so to the depth that we originally proposed. These changes resulted in less detailed analyses than previously expected, but still allowed us to take a step forward in identifying priority linkages throughout the Southeast that can be useful for resource managers.

5. ORGANIZATION AND APPROACH

We conducted this project in four steps as a response to each of the four questions we proposed. These steps were conducted independently and integrated here to address final implications and recommendations of the project.

*Step 1: Analyze consistency between our previous work identifying linkages in the Southeast and other connectivity efforts*

Our first objective was to use the 21 connectivity maps from our previous project (SECSC Project 009; Table 1) that mapped connections for three wildlife species (Rafinesque’s big-eared bat, black bear, and timber rattlesnake; hereafter, “bat,” “bear,” and “snake,”) and compare them to products from other regional connectivity modeling efforts.
Table 1. Key of meta-data for 21 landscape connectivity models for the SEAFWA region developed during previous phase of this project (SECSC Project 009).

<table>
<thead>
<tr>
<th>Model number</th>
<th>Species</th>
<th>Resistance source</th>
<th>Algorithm</th>
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<tbody>
<tr>
<td>1</td>
<td>Bat</td>
<td>Expert opinion</td>
<td>CAT</td>
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<tr>
<td>2</td>
<td>Bat</td>
<td>Expert opinion</td>
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<td>3</td>
<td>Bat</td>
<td>Expert opinion</td>
<td>LCP</td>
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<td>Niche models</td>
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<td>Snake</td>
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<td>CAT</td>
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<td>Snake</td>
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<tr>
<td>21</td>
<td>Snake</td>
<td>Niche models</td>
<td>LCP</td>
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Because of time constraints we focused on three comparable products, a national ecological integrity map (Theobald et al. 2012), The Nature Conservancy’s terrestrial resilience maps (Anderson et al. 2014), and the Florida Ecological Greenways Network (Hoctor et al. 2013). A brief synopsis of each of these products is included below:

**Ecological integrity:** This is a national product that identifies linear pathways of high connectivity throughout the continental United States. For our comparison, we buffered the pathways identified in the ecological integrity map by 2.5 km creating polygons 5 km wide from which we calculated overlap with our previous connectivity maps.

**TNC terrestrial resilience:** The TNC product places land in the eastern USA into one of nine categories based on estimates of ecological resiliency and possibility of serving as key climate corridors. For our comparisons, we used the TNC’s five-class ‘prioritized network’ layer, which includes 24.4% of the study area along the eastern seaboard.

**Florida Greenways:** This state-level product identifies priority areas for landscape connectivity based on a variety of criteria, including species-specific models, distribution of threatened habitats, and possible location of coastal-to-inland migration pathways. We compared our outputs with six Florida Greenways components: their overall map, high priority areas (1-3 of a six category system), three models for the bear based on the same algorithms we used (CAT, Circuitscape, and a least-cost path model), and a general landscape connectivity model. For the
bear models, we compared the Florida Greenways map to our three bear maps using the same algorithm, whereas for other comparisons we used all models.

We matched the extent of our maps to each of these external maps, rescaling the cell size of external maps to match the 1080 x 1080 m resolution used in our previous study. In all cases, we calculated the proportion of our map(s) that intersected the external layer. We calculated pairwise comparisons between each of the external maps and our 21 individual maps (with the exception of the Florida Greenways bear maps which we compared only with our bear models for the same algorithm). We also compared each external map to the composite of our 21 layers, and the ensemble map indicating areas where at least 10/21 of our maps intersected.

To contextualize the results for comparisons between our maps and external maps, we also calculated pairwise overlap between the three external maps.

**Step 2: Assessing trade-offs between current and future connectivity**

This portion of our project focused on identifying priorities for conservation and management of existing habitat connections based on their importance to each of the three focal species’ overall habitat network, their current degree of protection, and projected future threats from climate change and urbanization.

To measure the importance of each link to the overall network, we calculated the Integral Index of Connectivity (IIC) using Conefor software. The IIC index is a graph theory metric that ranges in value from 0 (no connectivity) to 1 (complete connectivity) and measures the proportion of the landscape that is occupied by connected habitat. The difference in IIC (dIIC) can be calculated for any connection or node in the landscape based on how much the IIC index decreases when the given link or node is removed from the network. The IIC metric characterizes habitat connections in terms of their ability to integrate resources across the habitat network, and has been shown to be well suited for landscape conservation planning. For each species’ network, we designated a connection as highly important if it had a dIIC score in the 90th percentile or above, or if it connected to a habitat node with a dIIC score in the 90th percentile or above.

Next, we assumed that the conservation option to best maintain connectivity for each important connection would depend on the degree to which the connection is currently under protected status. We extracted protected areas that are managed for conservation (GAP Status Codes I, II, or III) from the Protected Areas Database (PAD-US) version 1.3. We overlaid those areas onto the highly important connections to determine the proportion of each connection under conservation protection. To calculate the proportion of each connection that would be
converted to urban land use, we overlaid future urban growth from Terando et al. (2014) for 2050, then calculated the change in the proportion of each connection that would be urban land use between 2010 and 2050. Finally, from our previous work, each of the mapped connections had also been scored based on how much the habitat suitability in each connection would change due to climate change between 2010 and the middle of the 21st century.

We used thresholds to separate highly important connections with high vs. low protection status, as well as high and low climate and urbanization threats. For protected status, connections that fell above the regional average for all land of 9% protected were designated as having “high protection,” while those in the 50th percentile or below were designated as “low protection.” For the relative climate change threat, connections were designated as having “low climate change threat” if their overall habitat suitability was projected to show an increase in the future, or if their suitability decreased by less than 25% compared to today. A decrease in habitat suitability of 25% or more was designated “high climate change threat.” Connections were designated as having high urbanization threats if their projected change in urbanization was greater than the 50th percentile for all highly important connections. The result was a database of highly important connections along with information about the protection status, and threats from climate change and urbanization that could be used to compare the threats among species, and explore the appropriate conservation actions for each connection.

Step 3: Identifying nodes of connectivity for longleaf pine habitat

We used the 2014 Landfire Existing Vegetation Type (EVT) layer from USGS, which has vegetation codes very similar to commonly used Southeast GAP landcover data but is more continuous in coverage. We reclassified the EVT layer according to a table that we devised indicating which vegetation types were longleaf and which were not. This was a fairly straightforward process except for a few instances in South Florida, where very similar pine forests occur outside of the range of longleaf. We decided for the sake of continuity across Florida to include those longleaf-similar ecosystems. Longleaf and longleaf-similar vegetation types were given a code of 1, while all other vegetation types (including urban development) were given a 0.

We then ran focal statistics on that reclassified longleaf vegetation layer. This involved using a moving circular window with a 5km radius to calculate how much longleaf (by percentage of the circular window) was around each unit of the landscape. Scores ranged from 0% to 100%, and for visualization purposes we identified places with more than 25% and more than 50% longleaf at 5km radius. These areas formed discrete concentric clusters around the landscape,
with the 50% longleaf areas nested inside the broader 25% longleaf areas, which themselves formed discrete units around the southeast coastal plain.

We also took a complementary approach of analyzing longleaf content of existing protected areas around the region. The main challenge was assembling an appropriate and comprehensive set of protected area polygons. To do this, we merged several existing protected area GIS layers together, including the USGS PAD-US, the Conservation Biology Institute PAD-US, the National Conservation Easement Database, and one state-specific Managed Area file for North Carolina.

We next proceeded to download the latest federal Highway Performance Monitoring System (HPMS) traffic data for all of the longleaf-relevant SE states. The HPMS data includes all of the major highways around the country, and provides data for each road concerning the Annualized Average Daily Traffic (AADT). The HPMS state files were merged into one regional file, and then we pulled out highways that were >10,000 AADT into a new layer. We then buffered those roads a small distance to turn them into narrow polygons, and used the road buffer polygons to erase any overlapping portions of the protected areas file. This step ensured that any protected area clusters that were divided by busy roads would count as more than one unit, which we deemed important for connectivity analysis in the future (i.e. to identify places where wildlife road crossings might best be installed to reconnect adjacent protected areas that were separated by highways). After the road buffers were erased, we dissolved the resulting protected area blocks across jurisdictional/ownership boundaries so that adjacent protected areas merged into conglomerate protected area blocks (except where the busy roads intervened). We used these blocks and the reclassed Landfire longleaf file to calculate how much longleaf was in each protected area cluster.

We then pulled out the protected area clusters that had more than 500 hectares of longleaf into a new layer showing all of the protected areas around the region that had what we deemed to be a significant total amount of longleaf pine. However, these units varied considerably in terms of their density of longleaf. To help visualize these trends we also calculated the percent longleaf composition of each protected area cluster (longleaf area divided by total area).

Finally, we concentrated on the areas around the region that were >25% longleaf at the 5km radius. The raster focal stats data were converted to polygons, and then those polygons were cut with the same highway buffers as described above. We then used the protected area file to identify the longleaf focal nodes (>25% longleaf at 5km radius) that were more than 50% protected.
Step 4: Optimization of site selection for conservation action at the local scale

Connectivity analysis based on landscape resistance surfaces estimated for specific species provides a way to identify the ecologically most likely paths that individuals of a particular species will take when dispersing from one core habitat area to another. Given the present-day-conditions resistance layer for a species, we identified a collection of corridors that would connect the various protected core habitat areas using the Linkage Mapper toolbox in ArcMap. The corridors computed were the paths of least resistance between all adjacent protected areas, where adjacency is defined by the Euclidean distance between any two areas. The collection of protected areas and corridors form a network with the protected areas acting as the nodes, and the corridors as the links that connect the nodes.

Since it is unlikely that the full network of identified corridors can be protected, we developed a method to prioritize corridor conservation under varying budget criteria while maximizing the ecological benefit of the selected corridors. The ecological benefit of a selected set of corridors is measured by the Probability of Connectivity (PC) metric, given by equation 1:

\[ PC = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} a_i a_j p_{ij}^*}{A_L^2} \]

where, \( a_i \) and \( a_j \) are the areas of the nodes i and j, \( A_L \) is the total landscape area, \( p_{ij}^* \) is the maximum product probability across all corridor paths between nodes i and j. The product probability of a path is the product of the dispersal probabilities along each edge (i.e. corridor) along that path connecting i and j. This metric indicates the probability that two animals placed randomly within the landscape fall into habitat areas that are reachable from each other given a set of \( n \) habitat areas.

We considered the conservation planning problem where, given a budget expressed as total number of corridors or alternatively as maximum cost, we need to select a subset of the corridor links within that budget that still provide a path between every pair of core habitat areas while maximizing the Probability of Connectivity provided by the selected corridor subnetwork (The Maximum Connectivity Corridor Subnetwork Conservation Design Problem). We showed that selecting a set of corridors maximizing this metric is equivalent to selecting a set of corridors minimizing a metric based, pair-wise, area-weighted, least resistance paths. We implemented two different optimization techniques for this conservation planning problem: a greedy algorithm approach that gives an approximate solution, and an Integer Linear Programming (ILP) method that gives the exact most optimized solution. The greedy algorithm heuristically deletes one corridor at a time from the network, choosing the one that causes the least decrease in the connectivity metric until the remaining corridors are within the budget.
The order of deletion of the links in the network gives the prioritization of the corridors. The ILP solution finds the optimum subset of corridors within each given budget.

Given a resistance layer for a species based on current conditions, we identified what we call ‘present corridors’. Such corridors, however, might change in resistance under future climate conditions. Hence, given a resistance layer for the same species under future conditions, we can re-evaluate the total future resistance value of each ‘present corridor’. We extended our corridor subnetwork design methodologies to help conservation managers make decisions about which corridors to protect while incorporating both present-day considerations as well as future conditions in order to make more robust recommendations, based on a weighting parameter alpha in [0,1]:

\[
\alpha \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} a_{ij} d_{ij} p_{ij}}{A_{L}^2} + (1 - \alpha) \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} a_{ij} d_{ij} f_{ij}}{A_{L}^2}
\]

Where \(dp^*\) is the maximum product probability based on present resistances, and \(df^*\) is the maximum product probability based on future resistances.

In addition to ‘present’ corridors, we also considered ‘future’ corridors, which are the corridors identified by Linkage Mapper between adjacent core areas based on the future resistance layer for the species. Not surprisingly, the sets of present corridors differ from the set of future corridors, and furthermore each corridor provides differing level of connectivity in the present vs. future. We also extended the analysis to include selecting corridors among a larger set including both present and future corridor links.

In summary, we considered two different variants of this conservation problem where: 1) we considered present corridors and optimized for connectivity based on their present resistance as well as connectivity based on their future resistances; 2) we considered both present corridors as well as future corridors, and optimized for selecting a subnetwork of corridors among this expanded corridor set that maximizes connectivity both in the present and in the future.

6. PROJECT RESULTS

Consistency between connectivity projects

Pairwise overlap between our models and external maps was generally low (Table 2). Pairwise overlap values were relative high between our models and the ecological integrity map, with a
mean of about $50 \pm 5.6\%$ overlap. By comparison, mean pairwise overlap between our individual models and the TNC priorities was only about $19.7 \pm 8.2\%$. Pairwise overlap between our models and Florida Greenways high priorities was also relatively high, but much more variable than for the ecological integrity map ($\text{mean} = 53.6 \pm 15.6\%$ overlap). Pairwise comparisons for bear models and general landscape connectivity were very low, and the overall Florida Greenways map showed intermediate overlap with our maps. However, there was generally much more overlap between each external map and our ensemble map of areas where at least 10 of our models intersected than there was between any one of our individual maps. The mean pairwise overlap between external maps was $53.0 \pm 14.4\%$. 
Table 2. Proportional overlap between our previous landscape connectivity models and eight external maps from three other connectivity modeling projects (see text). Pairwise overlap was generally low between our outputs and comparison maps, although the areas identified in our ensemble layer showed much greater overlap with external maps than individual layers.

<table>
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<th>SEAFWA layers</th>
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<td></td>
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<td>TNC terrestrial resilience</td>
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<td>Florida Greenways all</td>
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<td>Florida Greenways Black bear least-cost paths</td>
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| Florida Greenways general land               | 0.03 0.02 0.02 0.02 0.03 0.01 0.01 0.03 0.01 0.02 0.03 0.02 0.03 0.03 0.03 0.0 0.08 0.02 0 | 0.02 | 0.02 | 0.02 | 0
Trade-offs between current and future connectivity

We identified the highly important habitat connections in each species’ habitat network, including links that themselves had high dIIC values, or that connected to nodes with high dIIC values. The snake and bat had the largest numbers of highly important connections identified, as well as the largest proportions of highly important connections compared with the total number of connections in the landscape. For the snake, 480 of 1282 total connections (37.4%) were highly important, and for the bat, 341 of 888 (38.4%) were highly important. For the bear, 74 of 258 (28.6%) were highly important. However, of those highly important connections, the bear had the largest proportion with a high level of current protection (37.8% of important links, cool colors in Figure 1 and Figure 2), followed closely by the snake (33.5%). The bat had a lower proportion of highly protected important links (19.1%).

The threats and level of protection for each species’ important connections can be used to suggest some conservation strategies for maintaining connectivity in the future. The bat had a high proportion of highly important links that were currently unprotected and highly threatened by climate change (dark red and orange in Figure 1 and Figure 2). For those connections, strategies like assisted migration or identifying alternate corridors that connect the same two habitat patches but with reduced threat from climate change may be appropriate. In addition, because the proportion of important connections that were highly protected was relatively low for the bat, aiming to increase the overall level of protection within important connections could be beneficial for the species.

The bear had a relatively large proportion of highly important connections with a low degree of climate change threat, whether with high levels of protection or low. That low threat, along with the relatively high degree of protection for the bear’s connections suggests that working to maintaining existing connectivity in those important connections could be a key strategy for the species. The snake’s highly important connections also had a relatively high degree of protection, but important connections with low protection were relatively evenly split among all types of threats. Therefore, a mixture of strategies including maintaining existing connectivity within protected areas, working with private land owners to maintain habitat connectivity, and identifying alternative connectivity routes where climate and urbanization threats are low may all be appropriate for the snake.
Figure 1. Proportion of highly important connections for each species according to their current protection status, projected climate change threat, and projected urbanization threat.
Figure 2. Maps of highly important connections for each species, colored by their current protection status, projected climate change threat, and projected urbanization threat.
Connectivity for longleaf pine habitat

We produced a consistent layer of potential nodes for longleaf pine connectivity analysis that span across the former range of the ecosystem and identified which of those nodes were already largely protected, and which were still unprotected (Figure 3).

This draft layer will allow us to conduct preliminary connectivity analyses on those nodes in order to investigate how well the node layer appears to function. Before any connectivity models are run (e.g. Circuitscape) we will also need to develop resistance layer for the intervening matrix areas, likely by developing an index of "similarity to/suitability for longleaf habitat." We will also go to the Longleaf Alliance, the America's Longleaf Coalition, and the various state-level longleaf coalitions, to seek their help in recruit expert volunteers to help inspect the draft nodes. Once we have completed the expert review, we'll complete a final longleaf node network that will set the stage for a comprehensive connectivity analysis of the longleaf region.

Figure 3. Protected areas with at least 500km of longleaf pine that are at least 50% longleaf with a 5km buffer.
Optimization of conservation site selection

We here focus on our connectivity models for black bear only. We evaluated how far from optimal the selections proposed by our greedy approach were by comparing the connectivity values obtained with the greedy approach to the connectivity values obtained by the ILP approach. Due to the computational challenge of finding optimal solutions for larger networks, we used a subset of the corridor network including only 60 of the original corridors as our set of corridors to choose among. We also optimized for present connectivity.

![Difference between Greedy and ILP for subgraph of size 60](image)

**Figure 4.** Difference between optimal ILP and greedy solutions for subgraph of size 60.

Our results showed that the greedy algorithm was nearly as accurate as the ILP algorithm, and that the scalability of the ILP algorithm was an issue with regard to the size of the network (Figure 4). We therefore used the greedy algorithm for the remainder of the analysis.

We first prioritized among the set of corridors based on present condition, and optimized for the connectivity they provide both for the present and for the future (Figure 5). The connectivity for present and for future was weighted equally (alpha=0.5).
Figure 5. Prioritization of present corridors based on optimizing present and future connectivity with alpha=0.5: (left) a map with order of removal going from red to green, red first (right) plot of tradeoff of budget vs connectivity.

We generated a map (Figure 5, left) reflecting the order of removal of corridors from the network using the greedy algorithm. The order of removal is represented using the color ramp from red to green, red being the link that is removed first, green being the ones removed latest. In the map, the corridors represented in black are the final (n-1) ‘backbone’ corridors that are essential to maintain connectivity. The black corridors should be protected first, and with a larger budget, one would first protect green links, and lastly the red links.

We also compared budgets vs. obtained connectivity (Figure 5, right). The budget is the number of corridors to preserve in the network. The x-axis represents the ‘Normalized Budget’, which is the number of links selected divided by (n-1) where n is the number of protected areas (nodes). The y-axis reports the connectivity metric in terms of total pair-wise area-weighted least cost resistances (‘ODweightedSp’). We determined that a small fraction of additional corridors beyond the minimum number of n-1 quickly improves the provided connectivity, and that protecting all corridors provides a small marginal benefit over smaller well-chosen subsets of corridors.

We also considered the trade-off of the present connectivity vs. the future connectivity at a given (normalized) budgets (of 1.5). We assigned different weights for the present and future resistances using the alpha value and found that significant tradeoffs occur when ignoring complete either future or present conditions (Figure 6). For alpha=0.3, we can dramatically improve future connectivity provided by the selected subnetwork by only slightly worsening/increasing the present resistance distances incurred.
We also considered the set of corridors between adjacent protected areas based on future least cost paths. This provided two sets of corridors, which we combined into a larger set of potential corridors and applied the same optimization analysis. We observed a similar trend of quickly diminishing returns in connectivity of protecting additional corridor (Figure 7).

We found that contrasting the ‘backbone’ set of (n-1) corridors selected in the two cases (present corridors only vs. both present and future corridors) showed that expanding the set of corridors with future ones provides better options when balancing present and future connectivity (Figure 8).
Figure 8. ‘Backbone’ set of (n-1) corridors based on optimizing present and future connectivity with alpha=0.5: (left) selecting among present corridors only (right) selecting among present and future corridors.

7. ANALYSIS AND FINDINGS

*Strategies for identifying key linkages in the landscape*

As seen by our four approaches to identifying critical connections in the Southeast, there is no one map or methodology that can address every conservation need for connectivity. When compared to other connectivity efforts, just as we reported relatively low overlap between pairwise combinations of our models in our initial study, here we continue to see overlap values that seldom exceed 50% for individual pairwise comparisons. This observation suggests that outcomes from alternative landscape connectivity projects are highly contingent on the individual decisions and approaches made in each case. The contingency of connectivity results is illustrated by the relatively low overlap between results from the external maps we used for our comparisons (about 53%), which was well within the range of variation in overlap we observed between our models and the external maps. However, our ensemble predictions generally showed much higher overlap with external maps than pairwise comparisons, reinforcing the utility of focusing on connectivity ensembles for conservation prioritization.

Creating conservation priorities can also be species-specific. For example, in our project we found that bats had a large number of unprotected, important links and were most likely to be affected by climate change. In comparison, bears and snakes had a large proportion of important links already under protection, but varied to the degree in which threats such as climate change and urbanization might affect them in the future. This suggests that
conservation planners should be aware of species-specific needs for the future in their areas of focus, and further supports the conclusion from our previous project that the use of “umbrella species” to advance connectivity goals may be limited.

We have successfully extended our methodology beyond bottomland hardwoods to include longleaf pine ecosystems, which represent one of the most biodiverse and yet endangered ecosystems in North America. They are highly fragmented compared to the original state of the ecosystem, making longleaf pine forests a high priority target for connectivity research. Our findings provide a key initial step to identifying core habitat in need of protection and can form the basis for conservation action in the future by key stakeholders.

Finally, regional resource managers can benefit from our methods to optimize which sites should be chosen as high priority for conservation given budget limitations. The greedy algorithm developed here gives a clear prioritization of corridors in a given network, depending on the budget constraints, taking the least resistance path between protected areas. This can be customized with various types of budget constraints as needed in a scenario, to identify key corridors and preserve connectivity studying systematically the tradeoffs between budget and connectivity, as well as between present and future benefits. This results in a practical tool that can be applied toward conservation decision-making.

Future research needs

Our analysis was limited to longleaf pine habitat and bottomland hardwoods with three focal species. By expanding to consider additional habitat types critical to the region, future research could determine how linkages in the landscape may overlap between habitats. Other habitat types, such as coastal lowlands or high elevation mountain ecosystems, would benefit from connectivity analysis. Other species, such as those listed as species of conservation concern, would also benefit from detailed analysis could inform future conservation strategies.

8. CONCLUSIONS AND RECOMMENDATIONS

The southeastern US is a mosaic of differing landscape uses and ownership, creating a great need to identify how species are linked throughout the landscape and whether these linkages are secure under threats such as climate change. We examined connectivity of one type of habitat representative of the region as a whole, and extended our methods to begin assessment of another imperiled habitat within the region. Our results make it clear that the most effective approach to preserving connectivity is to use ensemble modelling across multiple species that accounts for both current and future conditions and incorporates the realities of working with limited resources. We recommend that managers and others
examining linkages for a specific region take advantage of the multiple techniques presented here and elsewhere to gain a more accurate picture of how to conserve connectivity within the landscape.

One difficulty in conducting this project was the limited time frame in which we had to work. Given that we only had 6 months to complete the project, it was necessary to limit the amount of analyses we could perform to only the most critical and informative ones. This prevented us from providing the in-depth analysis we originally proposed, but still allowed us to generate useful management recommendations and tools.

9. MANAGEMENT APPLICATIONS AND PRODUCTS

By assessing connectivity across multiple species in the southeast more closely, we provide critical information to managers in making decisions about future land use. We provide multiple ways to address challenges such as the effects of climate change, the integration of multiple sources of information, and the difficulties in making informed decisions while working with a limited budget. In addition, we extend our connectivity analysis to longleaf pine, a fragmented ecosystem within the region that has been identified as critical by multiple private and governmental agencies. The information we provide can be beneficial in informing decisions about which land to prioritize for connectivity, where the highest conservation value lies in a region, and how managers can mitigate the effects of climate change through careful planning of linkages. These results allow local and regional managers to make better informed decisions on how to prioritize conservation and management actions throughout the Southeast and maintain connected landscapes in the long term.

10. OUTREACH

The following publications are in preparation as a result of this project:


In addition to our connectivity analysis, we also maintained a website (ConservationCorridor.org) that summarizes current research and news on connectivity and corridors, including in a changing climate. This website is aimed at providing information to
scientists and managers, as well as informing the general public about connectivity and corridors in general. Our aim has been to not only disseminate information but also provide a forum for individuals to interact and communicate on the latest news and ideas. We have been highly successful in drawing a global audience to the website, with average monthly use approximately 2,500 users. Our most popular features include summaries of recent scientific publications, a toolbox for use in designing corridors, and a strong presence in social media to ensure that there is easy access to recent information and updates.