Final Project Memorandum

SECSC Project 009:

Connectivity for Climate Change in the Southeastern United States

1. ADMINISTRATIVE

Project title: Connectivity for climate change in the Southeastern United States

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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. There are great challenges to implementing this strategy in the southeastern US, however, because most intervening lands between habitat patches are held in private

ownership. In partnership with South Atlantic LCC members, we 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. For each species, we measured connectivity using three different modeling approaches that incorporated three types of resistance layers. We found that there was not a high degree of overlap between connectivity models for each species, suggesting a limited capacity for "umbrella" estimates of connectivity. Incorporating climate change showed that on average under future climate conditions, linkages decreased in suitability compared to current conditions. These results suggest that, for these three species at least, connectivity modeling should focus on species-specific traits. Managers should be aware that outcomes of connectivity modeling may be specific to the type of model used, and potentially consider multiple species planning for connectivity in a region. Climate change is likely to decrease connectivity overall in a species-specific manner and may vary by geographic region.

3. TECHNICAL SUMMARY

The objective of this project was to identify key connections in the southeastern US that would provide a template for reconnecting landscapes in face of a changing climate. 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 chose three focal species inhabiting one habitat type, bottomland hardwoods, based on suggestions from LCC partners: black bear (*Ursus americanus*), Rafinesque's big-eared bat (*Corynorhinus rafinesquii*), and timber rattlesnake (*Crotalus horridus*). For each species, we measured connectivity using three types of resistance layers (niche models, expert opinion, empirical movement data) and three different algorithms (Linkage Mapper, Circuitscape, Connecivity Analysis Toolkit). Lack of available data for some factor levels resulted in 21 unique combinations of resistance estimate, algorithm, and species.

This research achieved our goal of assessing 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 that while we were able to successfully model connectivity for each individual species, there was not a high degree of overlap among combinations of models for each species. Ensemble estimates of landscape connectivity resulting from the intersection of all 21 models showed estimates of high connectivity were largely concentrated at mid elevations of the Appalachian Mountains in eastern Tennessee. Our data suggest limited capacity for "umbrella" resistance estimates, algorithms, or species to generalize the results of one connectivity model to other conditions.

Based on our observation that predictions from connectivity models are largely contingent on methodological considerations, managers may find that a suite of modeling approaches may provide the best means for estimating landscape connectivity. Incorporation of climate change predicted that on average under future conditions, the mean suitability of links will decrease compared to current conditions. Overall, modeled links for black bear showed the smallest decreases in suitability, while Rafinesque's big-eared bat and timber rattlesnake both showed similar, larger decreases in suitability under climate change. The geographic distribution of changes in suitability also varies by species. 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 create a map of landscape connectivity for the southeastern United States that identified key linkages for wildlife and key targets for conservation to facilitate range shifts as climate changes. 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 Theme 2 of the SECSC Science Plan, specifically Task 3: Biological responses to changing land use and climate and Task 4: Develop land cover and habitat projections for the southeastern US. Our research proposed to address the following questions: 1. When connecting landscapes, can we do better at conservation when we consider the potential effects of climate change? 2. How will connectivity after climate change differ for species that vary in their dispersal ability, habitat affinity, and home range sizes? 3. How can we connect landscapes in the face of rapid urbanization and climate change? 4. How will sea level rise affect the location of key connections?

We were able to successfully meet our goals in answering Questions 1, 2, and 3. Our project integrated climate change projections with our connectivity models for the three species we examined, and resulted in detailed maps that specifically outline areas of both current and future connectivity. We were ultimately unable to address Question 4, so that sea level rise was not integrated into our final results. The challenge of assessing connectivity for multiple species, with multiple resistance layers and multiple modeling techniques, was more complex than originally anticipated. We spent the majority of our project time focusing on improving the quality of connectivity output for three focal species, so that we could provide reliable and useful maps for a few species rather than force multiple other considerations into our analysis with lower quality results. These changes resulted in meeting fewer of our objectives, but provided critical information that could inform others in the future for incorporating sea level rise into our analysis.

5. ORGANIZATION AND APPROACH

We conducted this project in three steps. First, we consulted with South Atlantic LCC partners to determine which species and habitat type would be most useful for us to focus our analysis on. Once we chose one habitat type and three species to use, we collected data for use in the three different resistance layers, which were then analyzed for connectivity using three different algorithms. Finally, we integrated connectivity with climate change to determine how well our networks based on current conditions would do under climate change.

Step 1: Focal species and habitat type

In December 2012 we met with managers from the South Atlantic LCC for a two day workshop to elicit opinion on which species and habitat types would be most useful to them in assessing connectivity within their regions. This meeting resulted in our choice of bottomland hardwoods as a focal habitat type, which was seen as highly supportive of a diversity of species, and also highly vulnerable to climate change. We decided to focus on three species based on LCC member recommendations as representatives that covered a wide range of taxa and varied in their ability to disperse and adapt to other habitats: black bear (*Ursus americanus*), Rafinesque's big-eared bat (*Corynorhinus rafinesquii*), and timber rattlesnake (*Crotalus horridus*).

Step 2: Data collection and analysis

For each of the three species, we calculated resistance using each of the following three methods: niche models using species occurrence to estimate environmental suitability, collecting expert opinion on movement and resistance through surveys, and compiling empirical movement data from published literature.

To create species distribution models, we compiled occurrence data from a variety of sources, including online and as well as direct requests to natural heritage programs in the SEAFWA states. We also compiled maps of climate conditions in the US for the period 1971-2000 from the PRISM climate group. The 30 year climate 'normals' for monthly maximum temperature, monthly minimum temperature, and monthly precipitation were transformed to seven bioclimatic variables. Species distribution models included all seven bioclimatic variables, as well as land cover variables with an importance score at least as great as the least important bioclimatic variable. Background environmental conditions were sampled using 2000 randomly selected points located more than 100 km from any presence record. Models were then run using BIOMOD package in R using several modeling algorithms. We took the inverse of the estimate of suitability in each cell as an estimate of landscape resistance.

To collect expert opinion of movement data for each species, we identified scientists, managers, and other natural resource workers who we considered experts on each focal species. These individuals were sent a detailed survey that included questions on probability of movement though specific habitat types, questions on barriers to movement, and asked them to score their own resistance values for the species based on land cover classes from the 2006 NLCD (National Land Cover Database). We then calculated the resistance values for each land cover class by averaging the estimated resistance values provided by the group of experts for each particular species.

To compile empirical movement data, we performed an extensive literature search on each species identifying all publications concerning movement probabilities through all habitat types. Within these publications, we focused on research that published resistance values, identified preferred habitat, gave home and or/foraging ranges, or identified dispersal distances moved. For two of the three species (Rafinesque's big-eared bats and timber rattlesnakes), we were unable to find enough published data to generate resistance data. Therefore, resistance based on empirical movement data was restricted to black bears. For each habitat type used in analysis, for each publication used we identified the percent of that habitat available in the study area, the percent of that habitat actually used, and the ratio of the two. This value was then converted to a resistance value and averaged across all studies. We filled in missing land cover resistance values with our expert values. We also incorporated the presence of protected areas and the effects of traffic density on resistance. Ultimately we generated 7 resistance layers: 3 for black bears, 2 for Rafinesque's big-eared bats and 2 for timber rattlesnakes.

We next used each resistance layer as input for three different algorithms, represented by three connectivity programs: Linkage Mapper (http://www.circuitscape.org/linkagemapper), Circuitscape (www.circuitscape.org), and Connectivity Analysis Toolkit (CAT, http://www.klamathconservation.org/science_blog/software/).

Linkage Mapper uses the least-cost path framework to describe connectivity. The identification of least-cost paths is one of the most widely-used approaches to connectivity modeling because it is straightforward and intuitive: the route between two nodes that minimizes accumulated resistance across all pixels intersecting the route is the least-cost path for the two nodes. Linkage Mapper calculates least-cost paths within neighborhoods of adjacent nodes by identifying zones around each node. Each zone comprises the pixels closest to a particular node in Euclidian or least-cost space. Nodes are considered adjacent if their zones are juxtaposed, and non-adjacent if it is necessary to pass through an intermediate zone to achieve a connection. Linkage Mapper only calculates least-coast paths among adjacent nodes. We used Linkage Mapper to identify least-cost paths among adjacent nodes for all species by resistance combinations in our study.

Circuitscape is a software package that borrows algorithms from electronic circuit theory to predict connectivity in heterogeneous landscapes. The program requires nodes, or population source points, to run connectivity analyses. Accurate population data for any species is difficult to come by; we therefore developed a methodology for estimating node points for each species. This included pinpointing a pixel of minimum resistance within significant areas of predicted core habitat. The final node files and resistance layers for each species were converted to ASCII files and processed with Circuitscape. The program calculates connectivity between pairs of focal nodes, which we then summed for each species.

The CAT program uses the shortest-path betweenness centrality method to count the number of shortest paths in which a specific grid cell is involved and assigns a score to that grid cell based on that number. This output file provides a grid for the creation of a graph file, which represents pathways between every pair of delineated hexagons within the study area. The connectivity analysis is then applied to this graph file and produces a centrality assessment, which can be visually displayed in ArcGIS.

Ultimately we generated 21 output maps of connectivity (7 resistance layers into each of 3 algorithms). We reasoned that spatial overlap was an intuitive way to describe similarity among the 21 connectivity models. To calculate spatial overlap among all pairs of models, we first calculated the total network area from the Linkage Mapper outputs for each species by resistance combination using a two km wide buffer around the identified least-cost path. We used the total network area obtained from the Linkage Mapper outputs to extract a corresponding area from the Circuitscape and CAT models, extracting the number of most-connected pixels needed to create a network with the same area as the Linkage Mapper network. Once we had area-standardized networks for each of the 21 models, we calculated the proportion of overlapping cells for each pair of models. For each pairwise comparison, the network with lowest total resistance was used as the denominator in the calculation of proportional overlap.

Step 3: Integration of climate change

We compared modeled habitat suitability under current climate for our connectivity maps to future habitat suitability. First, we created niche models for each of the three species based on climate data projections under the IPCC AR4 A2 scenario, which represents relatively high emissions. We used a consensus approach for projected climate data by gathering projections of mean temperature and total annual precipitation produced by three sources: (1) La Florida (https://floridaclimateinstitute.org/resources/data-sets/regional-downscaling), (2) Katherine Hayhoe (http://cida.usgs.gov/gdp/ ; Eighth-degree CONUS Statistical Asynchronous Regional Regression), and (3) University of Wisconsin (http://ccr.aos.wisc.edu/resources/data_scripts/ipcc/index.php). At each pixel in the landscape, we averaged the 3 model values for each climate variable to create two raster data sets, one for mean temperature and one for precipitation, circa 2050. We input these rasters into MaxEnt to create a raster for each species with continuous values for suitability based on future climate, which were converted to binary values. We applied that same threshold to the niche models for current climate to produce a binary raster indicating suitable habitat for current conditions.

To create 21 connectivity networks with formats that were comparable to one another, we converted the raster outputs from the CAT and Circuitscape connectivity model algorithms to least cost paths. Each of those rasters was used as a resistance surface in the Linkage Mapper software, with the result being a set of links based on each of the CAT and Circuitscape models. That gave us a total of 21 sets of links: one for each species/resistance/algorithm combination.

Next, we calculated the current and future proportions suitable for each buffered link in the 21 networks. We overlaid each of the 21 networks on the current binary suitability raster for the corresponding species, and calculated the proportion suitable for each link in the network using the zonal mean function in ArcGIS. We repeated that process for future binary suitability rasters. To summarize the changes in suitability, we calculated the difference between the current and future proportions suitable for each individual link in each network. We also calculated a suitability difference z-score for the future portion suitability for each link, based on the distribution of habitat suitability under current conditions. We calculated the mean of these z-scores for each of the 21 networks.

6. PROJECT RESULTS

Species-specific connectivity analysis

We successfully created 21 model outputs for our 3 focal species (Figures 1-3). These outputs show a wide variety of linkages present in the landscape, and vary according to resistance layer and algorithm used for each species.

Proportional overlap among pairs of models was low, averaging 0.166 +/- 0.09 (SD) (Table 1). The low degree overlap among connectivity models suggests that results of connectivity modeling exercises for conservation planning may be contingent on the methods used in a particular study. If the results of connectivity models are indeed contingent on methods, we expect correspondingly large uncertainties in model predictions. The problem is analogous to the projection of species distributions as a function of climate change, in which alternative general circulation models describing future climate provide different estimates of climate conditions and ultimate species ranges. Ensembles of multiple species distribution models are routinely used to minimize uncertainty by identifying areas of common prediction from alternative general circulation models.

We used an ensemble modeling approach to reduce uncertainty in predictions from connectivity models by identifying areas where the greatest number of models predicted connections among nodes. Our ensemble model was constructed by intersecting a 5 km grid over the union of connections from all 21 models, and calculating the number of models with connections in each grid cell. The maximum number of models overlapping an individual grid cell was 14. The cells with the greatest number of overlapping models (N > 11) were concentrated in the Cumberland Plateau region of eastern Tennessee (Figure 4).

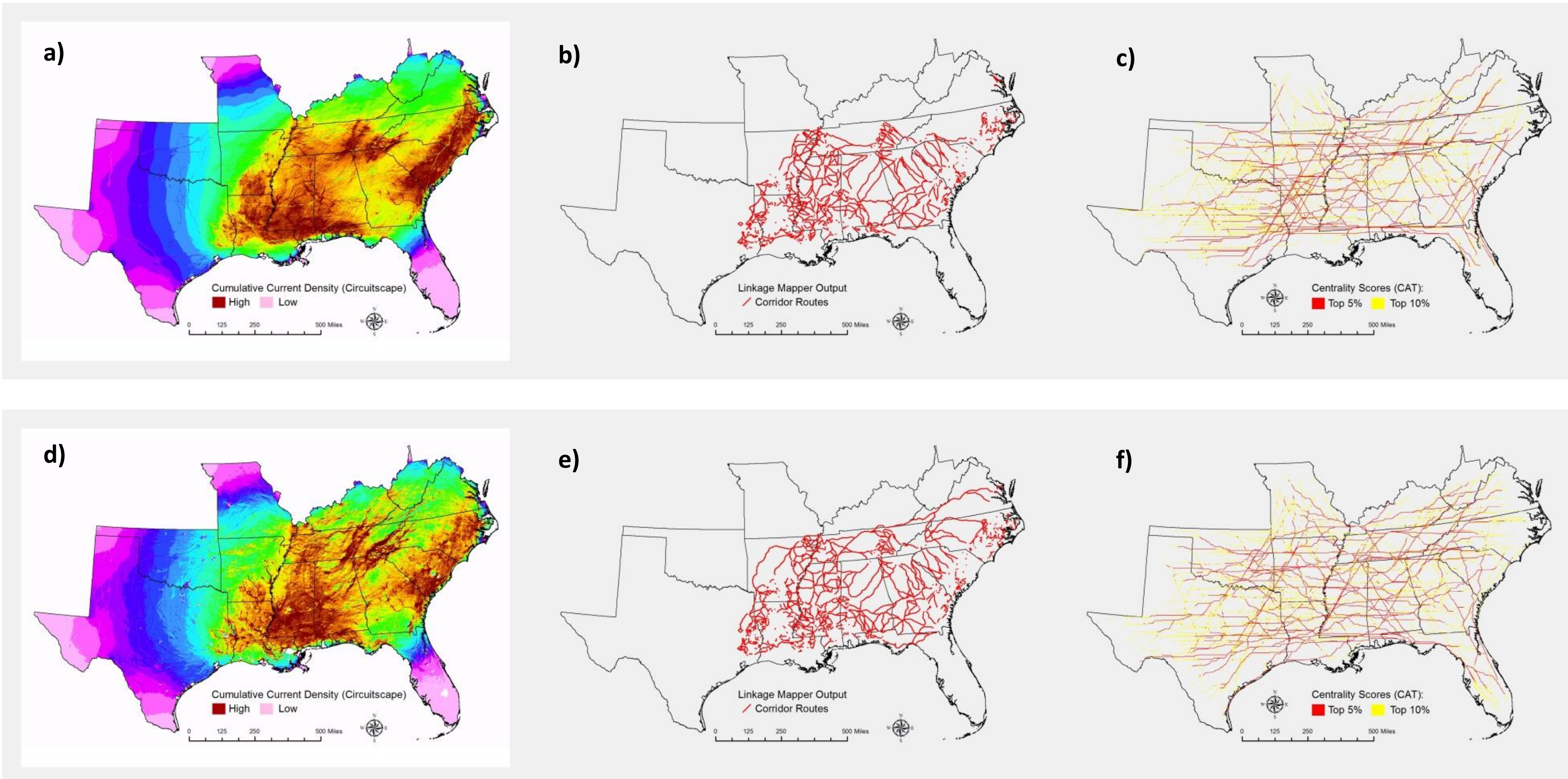

Figure 1. Connectivity analysis output for Rafinesque's big-eared bat. Maps vary according to resistance layer and algorithm used. a) Niche resistance layer, Circuitscape algorithm; b) Niche resistance layer, Linkage Mapper algorithm; c) Niche resistance layer, CAT algorithm; d) Expert resistance layer, Circuitscape algorithm; e) Expert resistance layer, Linkage Mapper algorithm; and f) Expert resistance layer, CAT algorithm. No maps are available using an empirical resistance layer due to lack of data.

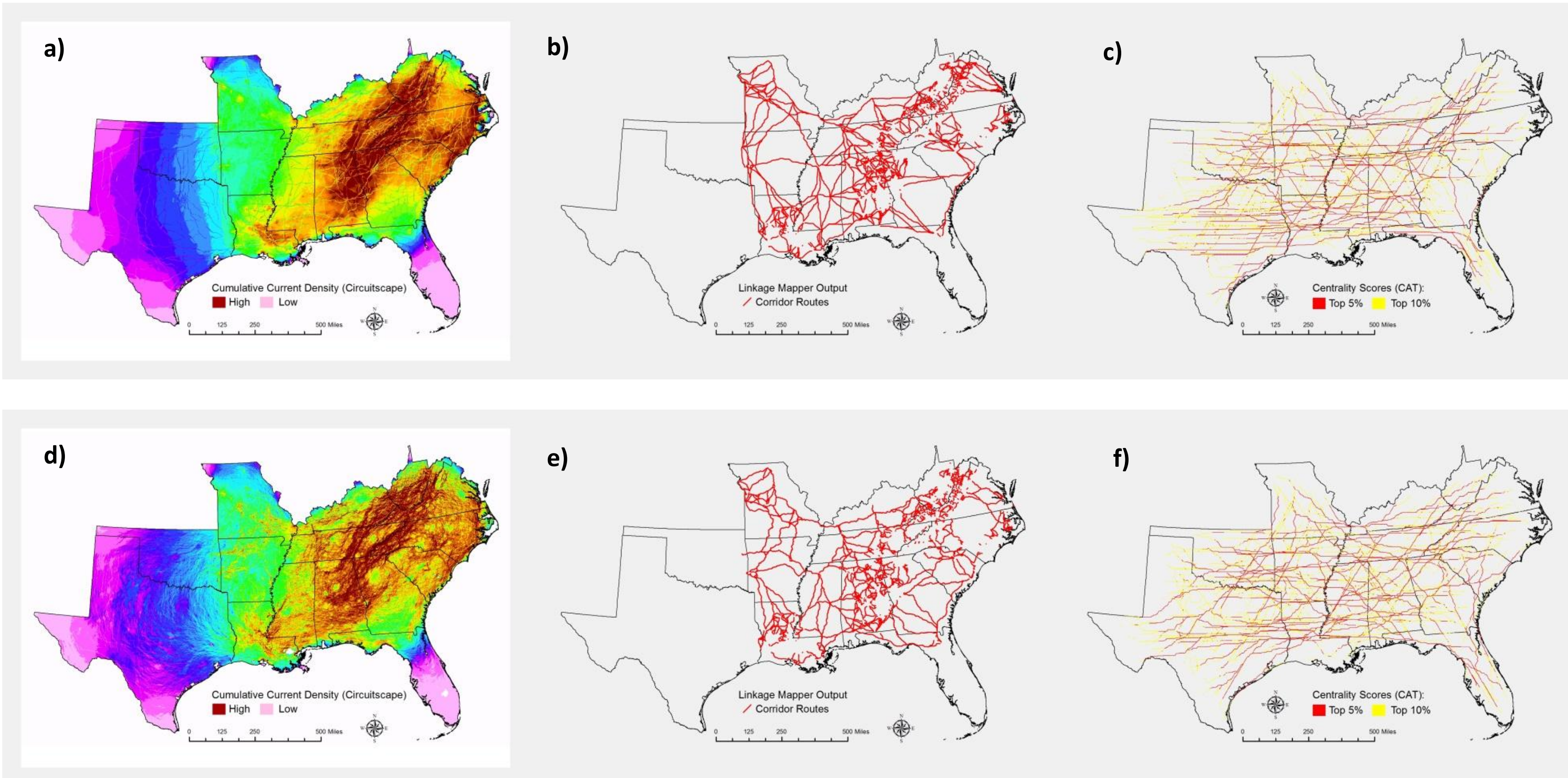

Figure 2. Connectivity analysis output for timber rattlesnake. Maps vary according to resistance layer and algorithm used. a) Niche resistance layer, Circuitscape algorithm; b) Niche resistance layer, Linkage Mapper algorithm; c) Niche resistance layer, CAT algorithm; d) Expert resistance layer, Circuitscape algorithm; e) Expert resistance layer, Linkage Mapper algorithm; and f) Expert resistance layer, CAT algorithm. No maps are available using an empirical resistance layer due to lack of data.

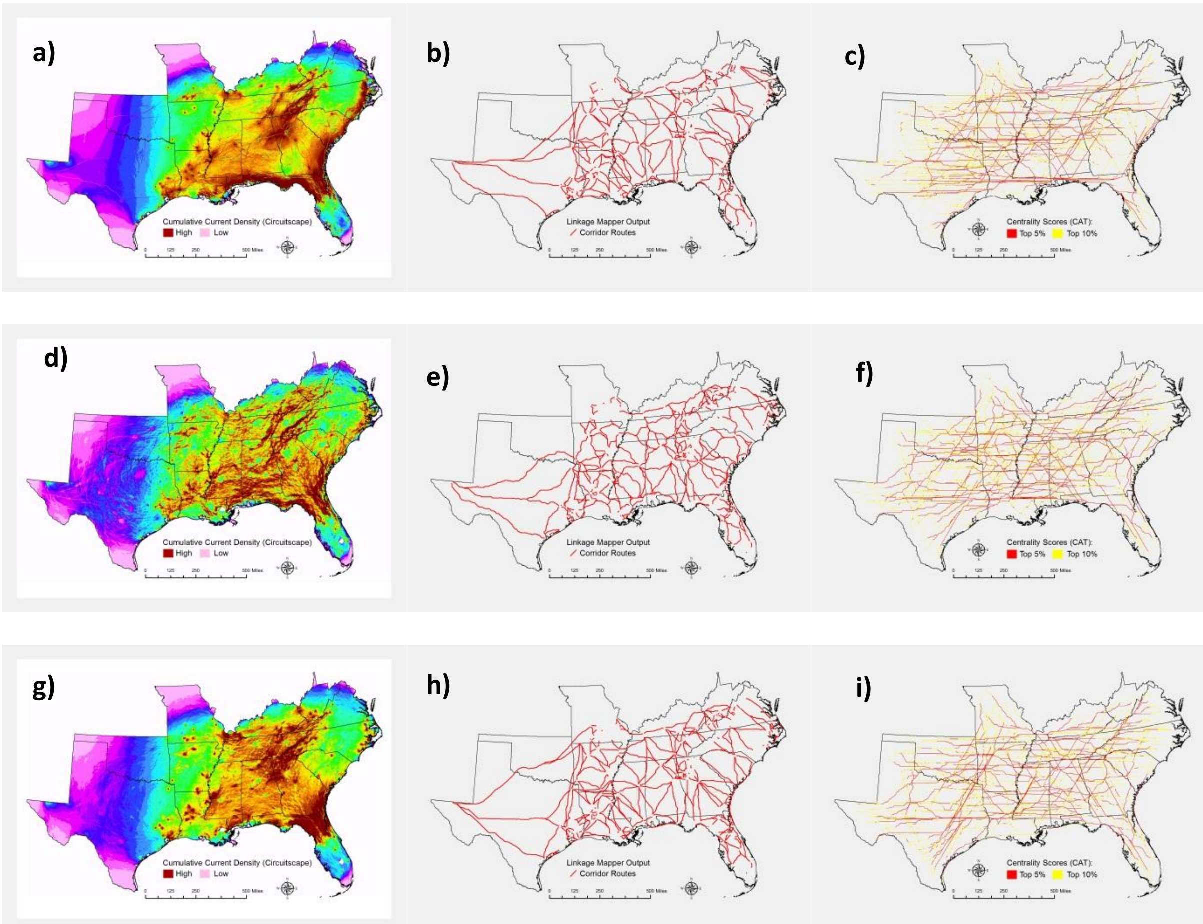

Figure 3. Connectivity analysis output for black bear. Maps vary according to resistance layer and algorithm used. a) Niche resistance layer, Circuitscape algorithm; b) Niche resistance layer, Linkage Mapper algorithm; c) Niche resistance layer, CAT algorithm; d) Expert resistance layer, Circuitscape algorithm; e) Expert resistance layer, Linkage Mapper algorithm; f) Expert resistance layer, CAT algorithm; g) Empirical resistance layer, Circuitscape algorithm; h) Empirical resistance layer, Linkage Mapper algorithm; and i) Empirical resistance layer, CAT algorithm.

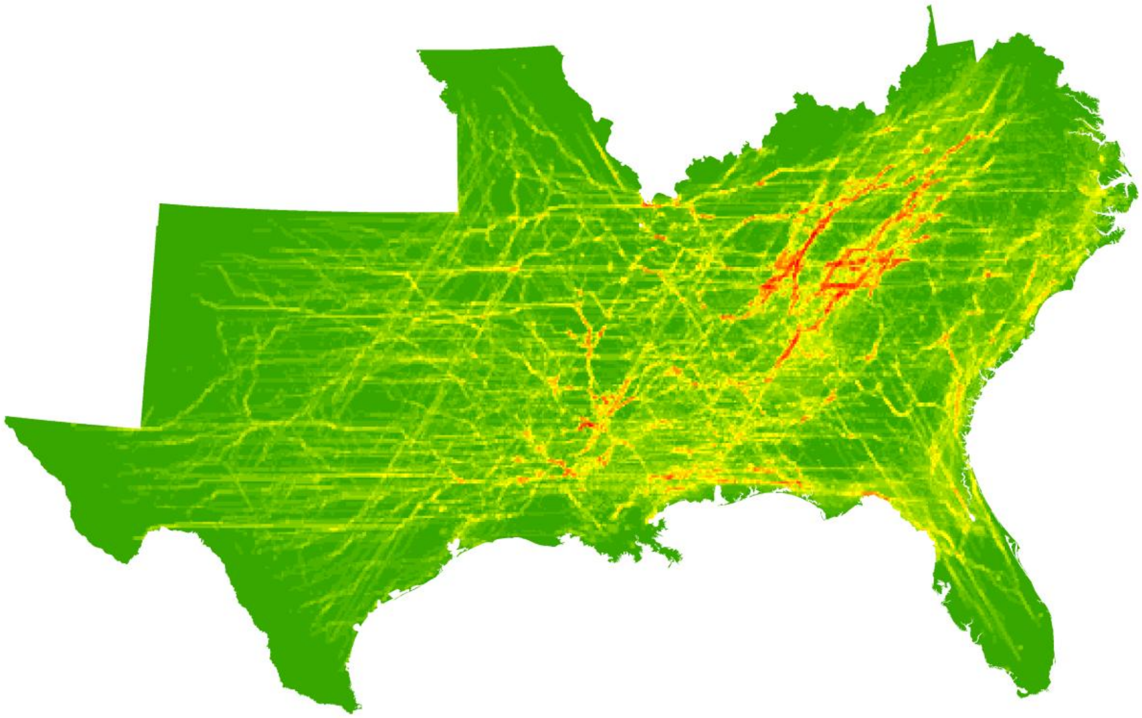

Figure 4. Output of ensemble modeling, in which all 21 outputs were overlaid and overlapping connectivity assessed. Scale ranges from dark green (0 model overlap) to red (14 model overlap).

Table 1. Proportion of overlap between all possible pairs of models, listed as focal species, resistance layer, algorithm. CS= Circuitscape, LM=Linkage Mapper, CAT=Connectivity Analysis Toolkit.

	bat expert CAT	**bat expert CS**	**bat expert LM**	**bat niche CAT**	**bat niche CS**	**bat niche LM**	**bear empirical CAT**	**bear empirical CS**	**bear empirical LM**	**bear expert CAT**	**bear expert CS**	**bear expert LM**
bat, expert, CS	0.2450											
bat, expert, LM	0.1898	0.2540										
bat, niche, CAT	0.1866	0.1522	0.1622									
bat, niche, CS	0.1935	0.5825	0.2337	0.1984								
bat, niche, LM	0.1331	0.2012	0.5145	0.1668	0.2496							
bear, empirical, CAT	0.2131	0.1364	0.1242	0.1127	0.1019	0.0920						
bear, empirical, CS	0.1600	0.2378	0.1126	0.1064	0.1569	0.0877	0.1408					
bear, empirical, LM	0.1228	0.1268	0.1397	0.0921	0.1162	0.1105	0.1684	0.1494				
bear, expert, CAT	0.2628	0.1634	0.1634	0.1493	0.1264	0.1004	0.2460	0.1210	0.1310			
bear, expert, CS	0.2330	0.3707	0.1617	0.1283	0.2392	0.1070	0.1643	0.5211	0.1468	0.1074		
bear, expert, LM	0.1853	0.1722	0.1722	0.1116	0.1371	0.1170	0.1365	0.1547	0.2802	0.2087	0.2184	
bear, niche, CAT	0.1863	0.1405	0.1370	0.2498	0.1382	0.1245	0.1049	0.1174	0.0909	0.1439	0.1261	0.1051
bear, niche, CS	0.1484	0.2633	0.1083	0.0960	0.2366	0.0947	0.0865	0.5114	0.1105	0.0954	0.4290	0.1336
bear, niche, LM	0.1320	0.1441	0.1521	0.1225	0.1559	0.1419	0.0885	0.1162	0.1967	0.0960	0.1171	0.2017
snake, expert, CAT	0.3428	0.1571	0.1410	0.1279	0.1384	0.0899	0.1980	0.1118	0.1210	0.3743	0.2148	0.2211
snake, expert, CS	0.2075	0.2576	0.1459	0.0872	0.1452	0.0801	0.1337	0.2586	0.1332	0.1533	0.3073	0.1769
snake, expert, LM	0.1501	0.1585	0.1800	0.0903	0.1668	0.1161	0.1193	0.1243	0.1377	0.1788	0.2137	0.2526
snake, niche, CAT	0.1482	0.1510	0.1153	0.1464	0.1480	0.1411	0.1304	0.1004	0.0923	0.1799	0.1491	0.1301
snake, niche, CS	0.1341	0.1737	0.1048	0.0663	0.2087	0.0767	0.0930	0.2297	0.0954	0.1268	0.2605	0.1500
snake, niche, LM	0.1000	0.1393	0.1241	0.0787	0.1515	0.1541	0.0980	0.1094	0.1075	0.1313	0.1399	0.1511

Table 1. con't.

	bear niche CAT	bear niche CS	bear niche LM	snake expert CAT	snake expert CS	snake expert LM	snake niche CAT	snake niche CS
bat, expert, CS								
bat, expert, LM								
bat, niche, CAT								
bat, niche, CS								
bat, niche, LM								
bear, empirical, CAT								
bear, empirical, CS								
bear, empirical, LM								
bear, expert, CAT								
bear, expert, CS								
bear, expert, LM								
bear, niche, CAT								
bear, niche, CS	0.1695							
bear, niche, LM	0.1615	0.1468						
snake, expert, CAT	0.1233	0.1131	0.0924					
snake, expert, CS	0.1028	0.1865	0.1060	0.1870				
snake, expert, LM	0.0923	0.1238	0.1224	0.1736	0.3023			
snake, niche, CAT	0.1677	0.1298	0.0914	0.1654	0.1476	0.1322		
snake, niche, CS	0.0925	0.2966	0.0897	0.1096	0.6460	0.2084	0.1410	
snake, niche, LM	0.0916	0.1196	0.1141	0.1205	0.2596	0.4156	0.1652	0.2343

Climate change connectivity analysis

Results indicate that on average under future climate conditions, for each of the 21 connectivity model outputs, the mean suitability of links decreased compared to current conditions (Table 2). The amount of decrease varied by model. The largest decrease was for the bat, niche resistance, Linkage Mapper model, and the smallest decrease was for the bear, empirical resistance, Linkage Mapper model. Overall, modeled links for the bear showed the smallest decreases in suitability, while the bat and snake both showed similar, larger decreases in suitability under climate change. Likewise, future difference z-scores for each model output show that for the bat and snake, links were on average > 2 standard deviations below the mean of current suitability, which is in the bottom 95^{th} percentile of the current suitability distribution. For the bear, z-scores indicate a more moderate decrease, with future suitability values on average within 0.5 standard deviations below the current mean.

The geographic distribution of changes in suitability also varied by species (Figures 5-7). For the bat, most links show a moderate or large decrease in suitability, with the exception of a few small links in the Southern Appalachians and Cumberland Plateau, in NC and TN. Links for the snake show a similar geographic distribution, with a larger number of links throughout the Appalachians and Cumberland Plateau in WV, VA, TN, and NC showing increased suitability in the future. For the bear, there are a few regions where links show increased suitability, including the Southern Appalachians, but also in the Mississippi Delta region in MS and LA, and along the Gulf and Atlantic Coastal Plains. Also for the bear, fewer links show a large decrease in suitability compared to the other two species.

Table 2. Current and future suitability for 3 focal species under climate changes scenarios. Average future z-score is a comparison of the distribution of future suitability values to current suitability values for all links under each model. The value represents the number of standard deviations away from the current mean suitability links are on average in the future.

Species	Resistance	Connectivity model	Mean current suitability	Mean future suitability	Mean difference	Prop. links with decreased suitability	Prop. links below current mean	Average future z-score
Bat - all			86.01	35.70	-50.30	0.96	0.92	-2.81
Bat	Expert	CAT	84.87	34.89	-49.99	0.96	0.92	-2.64
Bat	Expert	Circuitscape	85.13	35.55	-49.57	0.96	0.91	-2.64
Bat	Expert	Linkage Mapper	86.56	36.62	-49.94	0.96	0.92	-2.80
Bat	Niche	CAT	85.49	35.44	-50.05	0.96	0.92	-2.73
Bat	Niche	Circuitscape	85.66	35.52	-50.14	0.96	0.92	-2.80
Bat	Niche	Linkage Mapper	88.64	36.35	-52.29	0.97	0.93	-3.57
Snake - all			87.72	38.62	-49.11	0.82	0.80	-2.60
Snake	Expert	CAT	86.52	38.38	-48.14	0.82	0.80	-2.40
Snake	Expert	Circuitscape	86.62	38.71	-47.91	0.81	0.80	-2.39
Snake	Expert	Linkage Mapper	89.82	38.29	-51.53	0.82	0.82	-3.16
Snake	Niche	CAT	87.24	39.04	-48.20	0.81	0.80	-2.46
Snake	Niche	Circuitscape	87.12	39.08	-48.05	0.81	0.79	-2.46
Snake	Niche	Linkage Mapper	89.33	38.16	-51.17	0.83	0.82	-3.02
Bear - all			60.14	43.79	-16.35	0.70	0.64	-0.50
Bear	Empirical	CAT	57.70	42.62	-15.09	0.70	0.63	-0.44
Bear	Empirical	Circuitscape	58.61	43.02	-15.58	0.69	0.64	-0.46
Bear	Empirical	Linkage Mapper	55.66	40.84	-14.83	0.70	0.63	-0.45
Bear	Expert	CAT	59.93	43.55	-16.38	0.70	0.64	-0.49
Bear	Expert	Circuitscape	59.90	43.87	-16.03	0.70	0.64	-0.48
Bear	Expert	Linkage Mapper	61.34	44.27	-17.07	0.69	0.63	-0.53
Bear	Niche	CAT	61.96	45.26	-16.69	0.71	0.63	-0.51
Bear	Niche	Circuitscape	61.32	45.01	-16.32	0.70	0.62	-0.50
Bear	Niche	Linkage Mapper	65.66	46.15	-19.51	0.74	0.64	-0.65

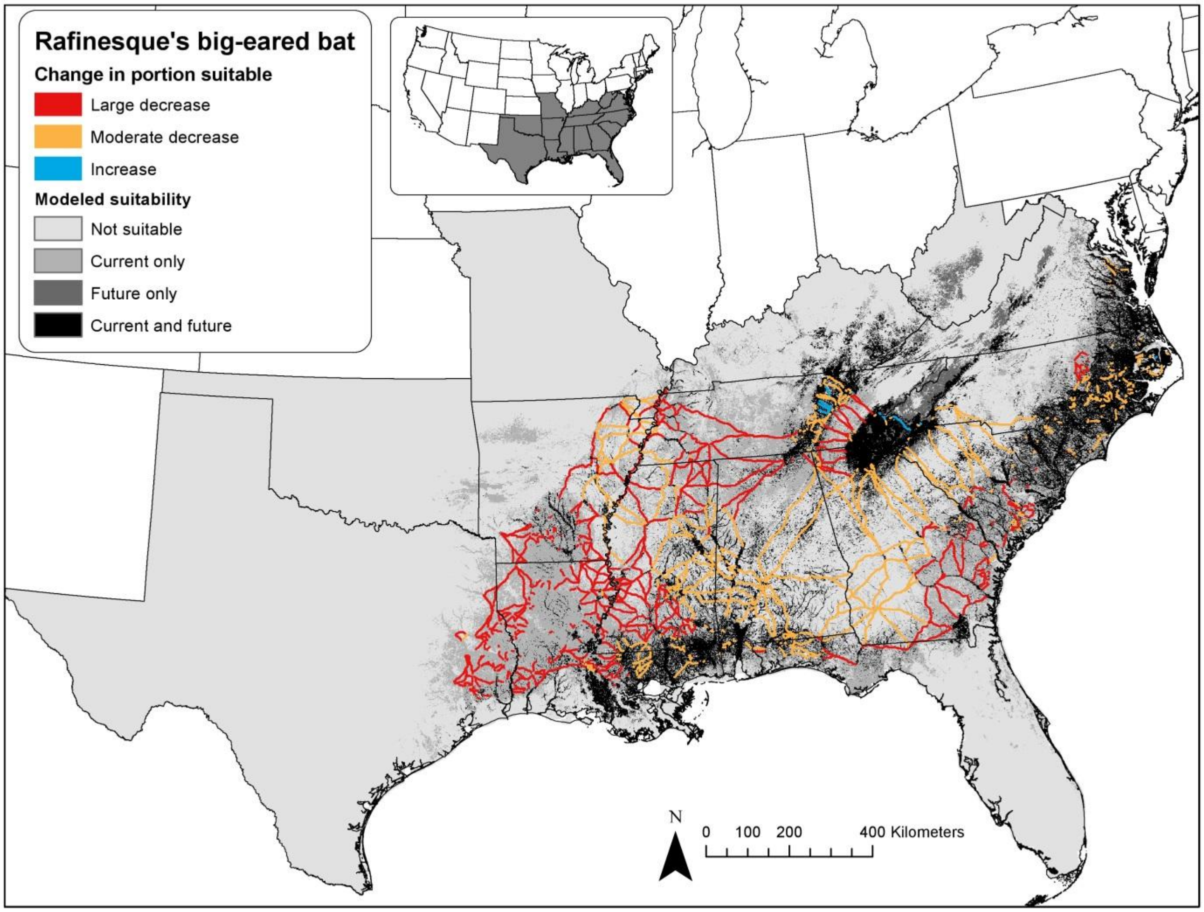

Figure 5. Current and future suitability of modeled linkages for Rafinesque's big-eared bats based on the Linkage Mapper algorithm and the niche model resistance layer.

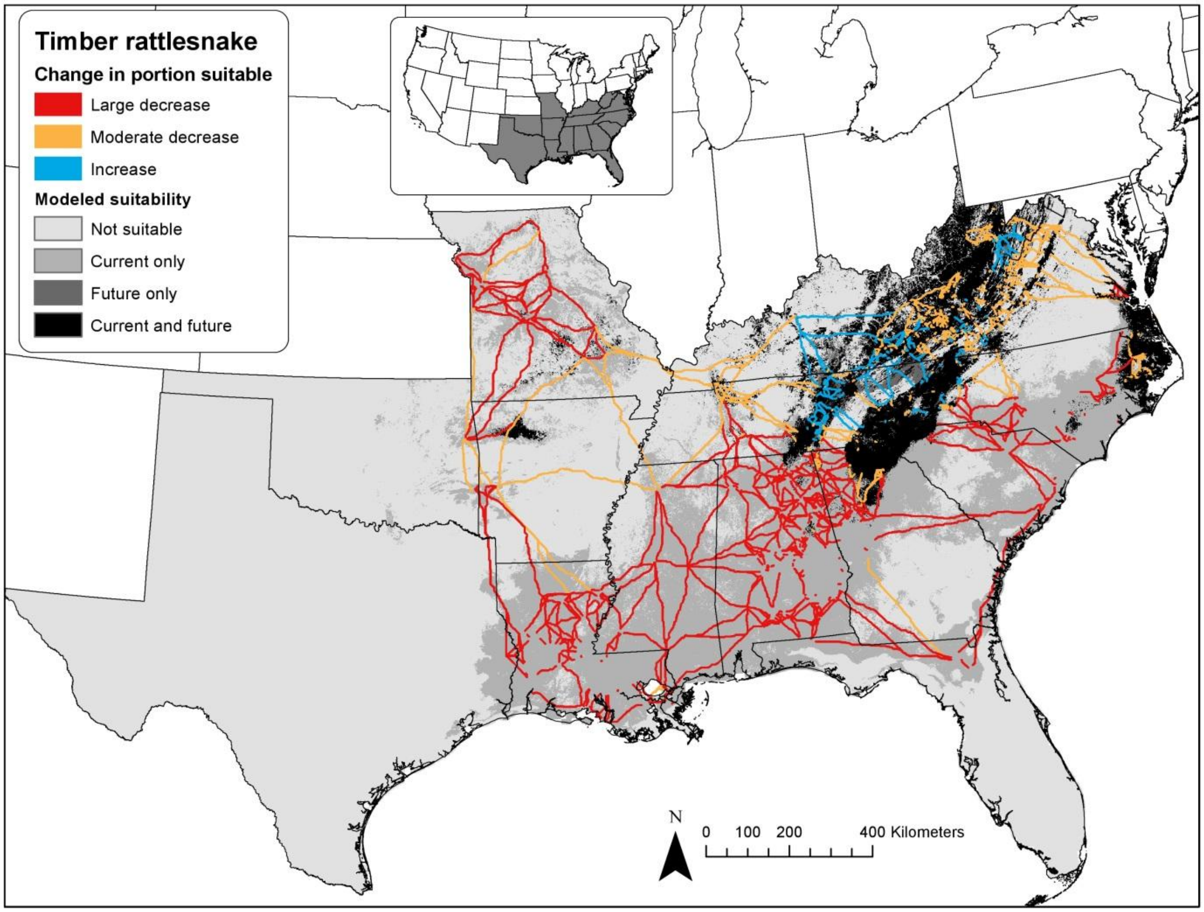

Figure 6. Current and future suitability of modeled linkages for timber rattlesnakes based on the Linkage Mapper algorithm and the niche model resistance layer.

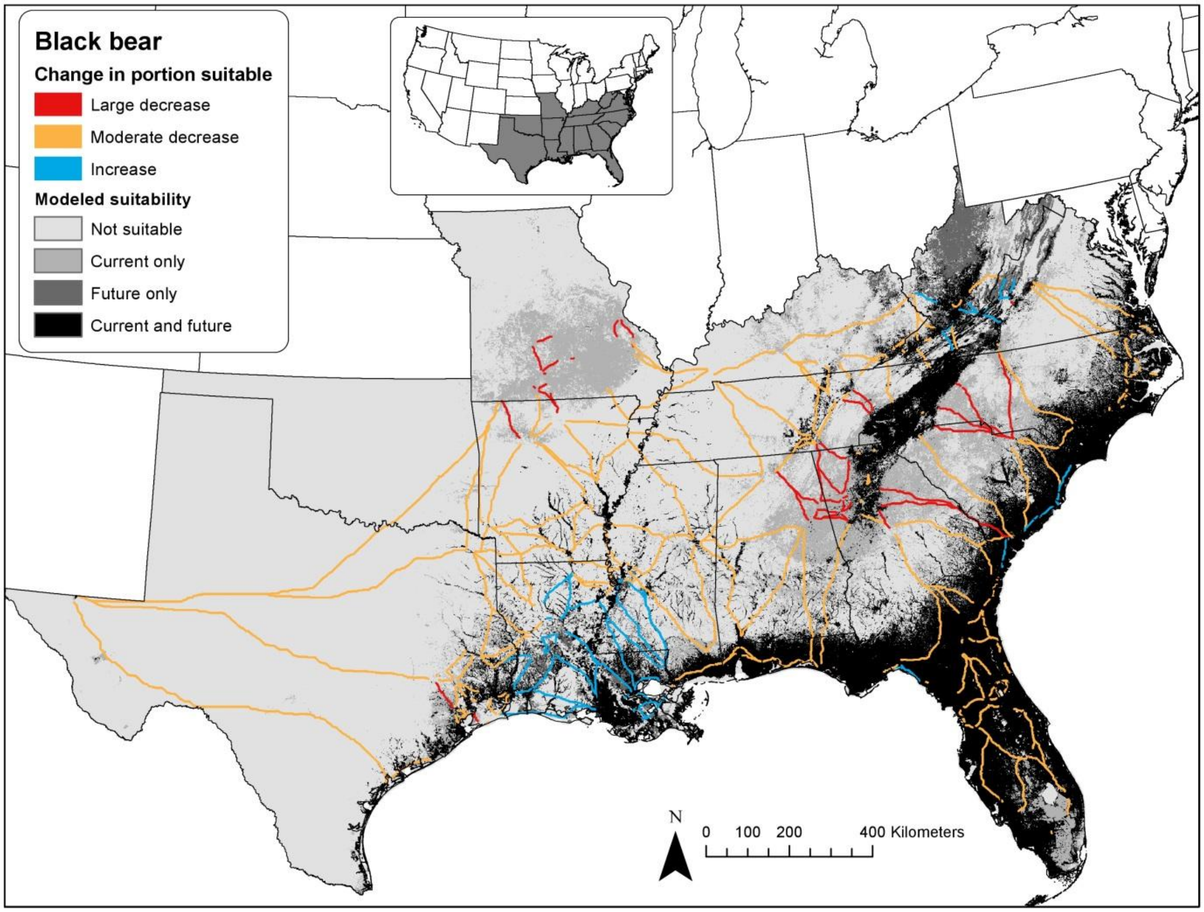

Figure 7. Current and future suitability of modeled linkages for black bears based on the Linkage Mapper algorithm and the niche model resistance layer.

7. ANALYSIS AND FINDINGS

Strategies for mapping connectivity

To our knowledge, this is the first attempt to model connectivity throughout the entire SEAFWA region with the broad goal of incorporating multiple species and multiple methodologies for comparison. The results of our analysis show that, for bottomland hardwood species at least, the southeastern US provides a complex picture of connectivity. Optimal linkages vary between each of the species we examined, and connectivity comparisons are complicated by the use of different methods. The low overlap between models suggests that it may not be appropriate to model connectivity using an "umbrella" species to represent the responses of multiple species. It is possible to identify connections suitable for suites of species, but only when considering all of their biologies; it is insufficient to make a plan for all three based only on the knowledge of one.

Connectivity appears to be both species-specific and method-specific, and is most likely assessed effectively through the consideration of multiple species and multiple methods. We suggest that ensembles of multiple models can be used to pinpoint areas contributing most to connectivity at the landscape scale. Based on our observation that predictions from connectivity models are largely contingent on methodological considerations, ensembles may provide the best means for reducing uncertainty and increasing accuracy of estimates of landscape connectivity. Regions identified as being critical for connectivity across multiple models are likely to be high-priority foci for conservation planning.

Climate change is likely to decrease connectivity overall, although this varies according to species and geographic region. Rafinesque's big-eared bats seem to be at greatest risk for decreased connectivity, with black bears having the lowest risk. The Appalachian region seems to be best at maintaining connectivity in the face of climate change for all three species. Ensembles may provide the best means for determining impacts of climate change as well.

Future research needs

Our analysis was limited to one habitat type and 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. For example, longleaf pine forests represent a small portion of the Southeastern US but support high biodiversity, and mapping connectivity between remaining patches may be critical for multiple species that are likely to be affected by climate change. Other habitat types, such as coastal lowlands or high elevation mountain ecosystems, would also benefit from connectivity analysis.

In addition, future research could also focus on Question 4 of our proposal: How will sea level rise affect the location of key connections? As sea level rise becomes a more critical issue throughout the SEAFWA region, knowledge of how linkages along the coast may be impacted could be beneficial to both coastal and inland managers, all of whom may see changes in water levels throughout the Southeastern US.

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 the threat of climate change. We examined connectivity of one type of habitat representative of the region as a whole, and developed methods to compare methodology of identifying linkages. Our results make it clear that there is no one optimal method for quantifying connectivity for a species or even habitat type. Managers should be aware that outcomes of connectivity modeling may be specific to the type of model used. Based on the suite of species we studied, it will be essential to consider multiple species planning for connectivity in a region. Climate change is likely to decrease connectivity overall, a result which is also species-specific and may vary by geographic region.

One difficulty in conducting this project was the complexity of data required to implement multiple modeling techniques. Source data for multiple species on movement and dispersal behavior, which is critical information for determining connectivity in many cases, is for some species limited or missing, thus highlighting the need for more research on individual species movement and behavior. In addition, comparisons between modeling techniques is challenging due to differences in outputs. Although connectivity modeling considered as a whole continues to evolve toward more sophisticated techniques with more possibilities for comparison, there are still multiple options for use and comparison.

We recommend that managers and others examining linkages for a specific region employ an ensemble approach to modeling. By employing multiple techniques to determine linkages, they are likely to get a more accurate representation of how species will use the landscape. Focusing on more than one species will also provide a more detailed look at how the landscape may be used in different ways by species e.g. short-distance vs. long-distance dispersers, or specialists vs. generalists. Incorporation of climate change is critical, as our research shows that most connectivity throughout the region will be negatively impacted.

9. MANAGEMENT APPLICATIONS AND PRODUCTS

By assessing connectivity across multiple species in the southeast and examining how it might be affected by climate change, we provide critical information to managers in making decisions about future land use. Our ensemble of models identified consensus choices to increase connectivity. These appear necessary components of an inter-connected landscape, even if they are insufficient to complete the effort. This information 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.

We worked with the following LCC members and others to inform the habitat and species selection process at the start of the project. Several of these individuals also participated in teleconferences to discuss mid-project results and suggest further directions that might be useful to them as managers.

John Tirpak, Science Coordinator (Gulf Coastal Plains and Ozarks LCC)
Rua Mordecai, Science Coordinator (South Atlantic LCC)
Laura Brandt, Wildlife Biologist (USFWS)
Timothy Breault, Coordinator (Peninsular Florida LCC)
Steve Traxler, Science Coordinator (Peninsular Florida LCC)
Cynthia Edwards, Science Coordinator (Gulf Coast Prairie LCC)

10. OUTREACH

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

Watling, et al. In Preparation. Effects of data inputs and modeling approaches on prediction for connectivity across large regions. Methods in Ecology and Evolution

Costanza, et al. In Preparation. The value of current landscape connections in future climates.

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 at over 1,500 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.