

Resilient Sites *and* Connected Landscapes

for Terrestrial Conservation

in the Lower Mississippi-Ozark Region

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Resilient Sites and Connected Landscapes for Terrestrial Conservation in the Lower Mississippi-Ozark Region.

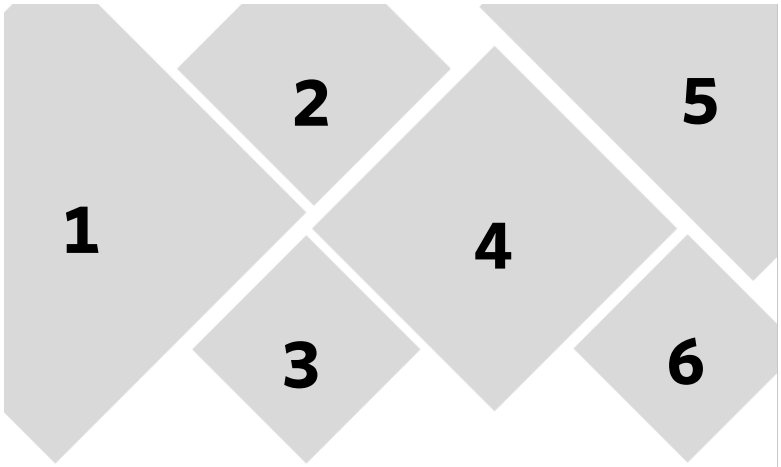
Draft February 24, 2020.

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Please cite as: Anderson, M.G., M. M. Clark, A. Olivero, and J. Prince. 2019. Resilient Sites and Connected Landscapes for Terrestrial Conservation in the Lower Mississippi-Ozark Region. The Nature Conservancy, Eastern Conservation Science.

This project was supported by a grant from the Doris Duke Charitable Foundation.



About the Cover:

1. Sunset in the Ouachitas of Arkansas.. © John Williams

2. Limestone outcrop on the top of a hill in Branson, MO. © Mike Fisher

3. Refugio-Goliad Prairie which spans 500,000 acres along the Gulf Coast between Houston and Corpus Christi. It is one of the largest and highest-quality expanses of coastal tallgrass prairie remaining in Texas. Although some native species have declined and even disappeared from the region, great biological diversity still thrives, making landscape-scale work possible.. © Kenny Braun

4. Longleaf pine with wiregrass understory at Kisatchie National Forest in Louisiana, United States, North America.. © Harold Malde

5. The rare Bog Coneflower (Rudbeckia scabrifolia) blooms in profusion in a high quality hillside seep. These impressive plants can reach heights of 6 feet or more. They are limited to extreme eastern Texas and western Louisiana. Here they are restricted to fire-maintained hillside seeps within longleaf pine savannahs. Here they grow among Pale Pitcher Plants (Sarracenia alata) and other flora characteristic of hillside seeps in the West Gulf Coastal Plain. These spectacular communities are disappearing due to land use conversion and the elimination of natural fire regimes.. © Matt Buckingham

6. Lauderdale Waterfowl Refuge - Sunset. © Guillaume Capron

Acknowledgements

This project was guided by a steering committee of conservationists from the Lower Mississippi – Ozark region, and without their engagement, feedback, critique, and review this work would not have come to fruition. We would like to thank members from the field offices of The Nature Conservancy including: Barbara Charry, Bryan Piazza, Charlotte Reemts, David Harlan, Douglas Zollner, Gabriel De Jong, Jacqueline Ferrato, James Cole, Jay Pruett, Jim Bergan, Katie Gillies, Rich Kostecke, Scott Lemmons, and Wendy Ledbetter.

Additionally, we appreciated the encouragement and support of many other Conservancy staff including Alex Littlejohn, Keith Ouchley, Michael Lipford, Kim Hall, and Joe Fargione. Grace Hancock ably assisted in budgeting and finance matters. Jim Platt helped with several aspects of the analysis related to geology, soils, landforms and programming expertise for the regional flow analysis.

We would also like to thank our conservation colleagues from other organizations and agencies who provided helpful insights and valuable perspectives on the region and its biodiversity, especially Bill Holimon and Theo Witsell of the Arkansas Natural Heritage Commission.

We gratefully acknowledge and thank Sacha Spector and Danielle Levoit of the Doris Duke Charitable Foundation for support of this work, and helpful feedback.

We also extend our thanks to ESRI for making ArcGIS software freely available to The Nature Conservancy. The complicated analysis and resulting beautiful maps in this report are a testament to ESRI's ongoing generosity.

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CHAPTER

INTRODUCTION 1

This report presents the results of a 3-year project to identify and map climate resilient sites across the **Lower Mississippi-Ozarks region** of the United States. This work was made possible by a grant from the Doris Duke Charitable Foundation (DDCF), along with contributions from the State Chapter and Regional Offices of The Nature Conservancy (TNC) within this geography. It is part of a set of analyses to identify a comprehensive and connected network of resilient lands across the United States.

Project History and Scope

The Nature Conservancy has been working for over ten years with support the Doris Duke Charitable Foundation (DDCF) to identify climate resilient sites in the United States. The Conserving Nature's Stage (CNS) approach has been applied to the United States Northeast, Southeast, Great Lakes and Tallgrass Prairie, Great Plains, and Pacific Northwest regions (Anderson and Ferree 2010; Anderson et al. 2012; Anderson et al. 2014a; Anderson et al. 2016a; Anderson et al. 2018a; Anderson et al. 2018b. Buttrick et al. 2015). All three geographies were analyzed using CNS methods pioneered by The Nature Conservancy's Eastern Conservation Science team led by Dr. Mark Anderson and further refined in each geography by teams of TNC scientists supported by regional Steering Committees. Our goal is to continue this work in the remaining ecoregions of the coterminous US and aggregate them into a single map.

In this project, we expanded the CNS approach to the Lower Mississippi and Ozark region, identifying the enduring geophysical drivers of biodiversity and the land characteristics that create resilience, and mapping a suite of places that capture these features across the region. We will also identify important pathways that connect these places to allow for dispersal and migration. We envision developing a blueprint for conservation priorities across this broad region, creating a resilient network that can link to similar networks previously identified in the eastern, central, and northwestern regions of the US (Anderson et al. 2016b; McRae et al. 2016), ultimately seeking to support investments that enhance the resilience of biodiversity as climate changes at a continental scale (see Saxon et al. 2005).

All results in this report are presented within a framework of **ecological regions** or "**ecoregions**" as defined by TNC based on the subsections delineated by the US Forest Service (USDA Forest Service ECOMAP Team 2007). Because each ecoregion represents an area of similar physiography and landscape features, it is an appropriate natural unit in which to evaluate geophysical representation and to compare sites. Within each ecoregion, the final datasets map resilience at the scale of 30-meter cells.

The focal geography of this study includes all or part of seven states (Figure 1.1). The region is defined by the boundaries of six TNC ecoregions, and encompasses portions of OK, MO, KS, AR, TX, LA, KY, TN, IL, and MS.

The Lower Mississippi-Ozark study area encompassed 6 ecoregions:

1. Ozarks
2. Ouachita Mountains
3. Upper West Gulf Coastal Plain
4. West Gulf Coastal Plain
5. Mississippi River Alluvial Plain
6. Gulf Coast Prairies and Marshes

Scientists and conservation planners from most of these states and provinces served on our Steering Committee and played an essential role in helping us to adapt the CNS methods to ecological drivers, biodiversity patterns, and land use characteristics that define this geography. Please see the Acknowledgements section for a list of all contributors.

Figure 1.1: Study Area. The six TNC ecoregions comprising the Lower Mississippi-Ozark study area (in colors) as well as the 10 states partially included.

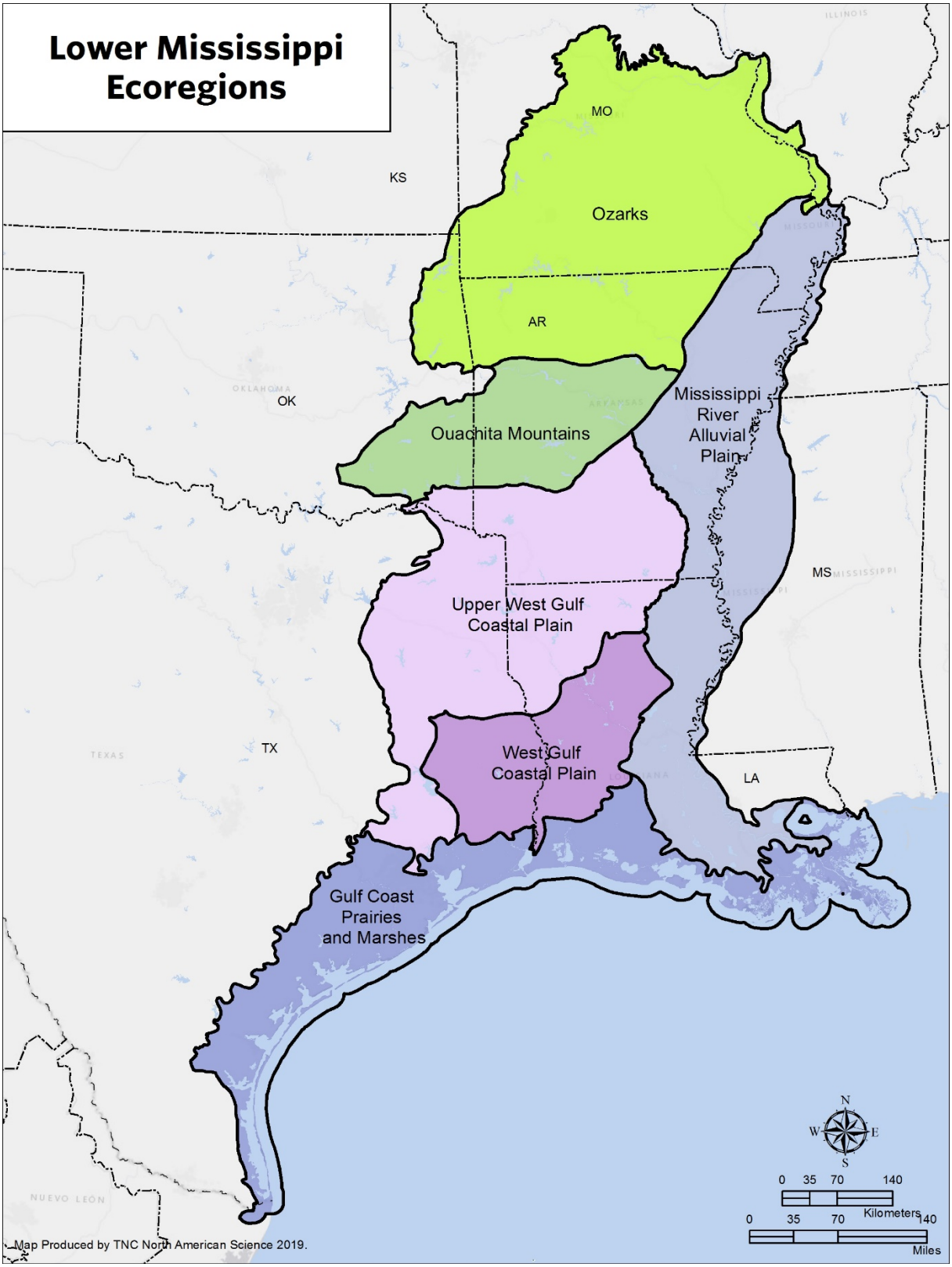
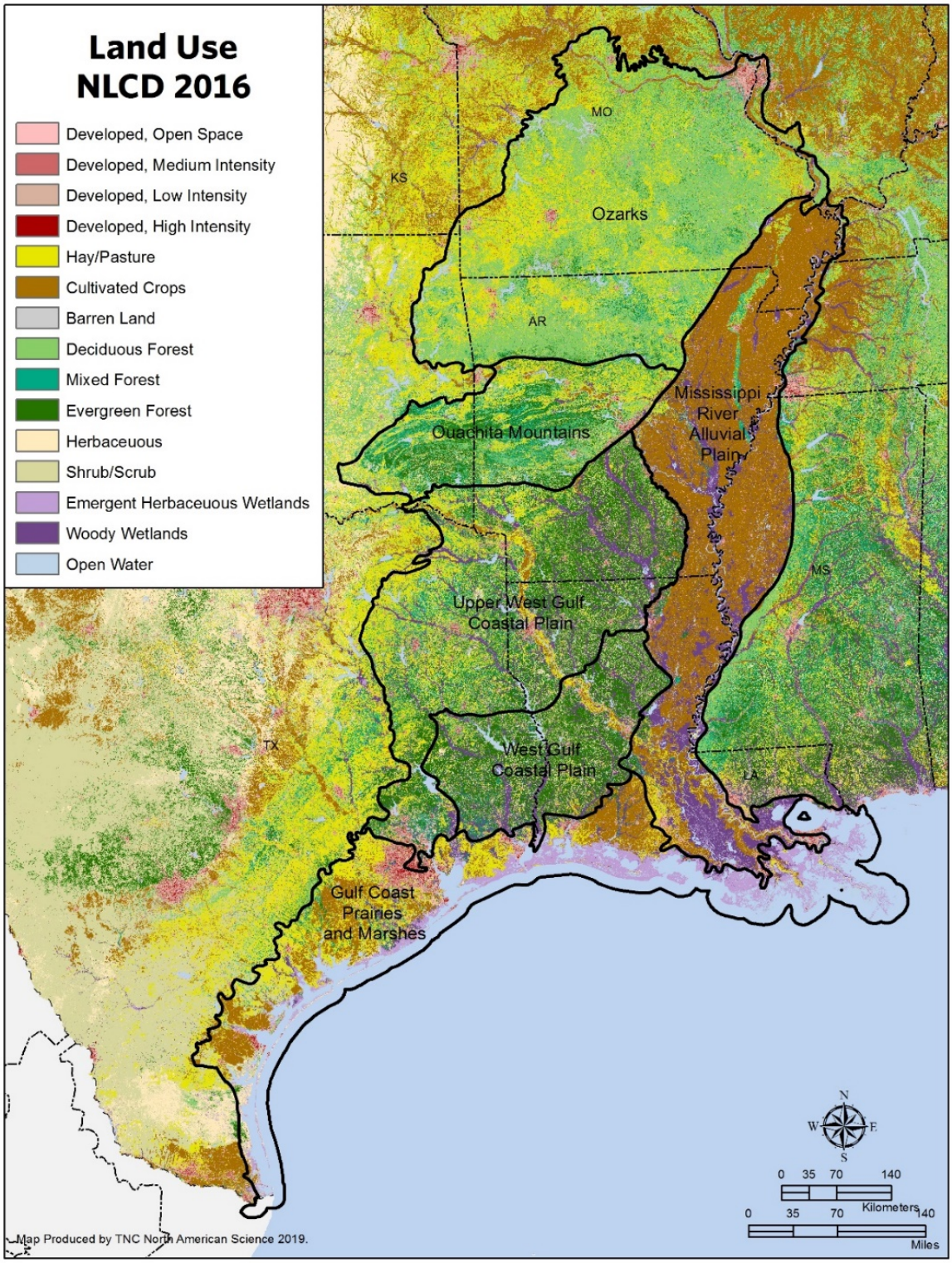


Figure 1.2: Land Use in the Lower MIssissippi-Ozark. Agriculture is the most common land use in the Lower Mississippi Alluvial Plain and Gulf Coast Prairies and Marshes ecoregions while the Ozarks, Ouachita Mountains, and West Gulf Coastal Plain have extensive forested areas.



Secured Lands

We compiled information on tracts of permanently protected conservation land covering all states in this study region. The information is part of TNC's "secured land" dataset defined as land that is permanently secured against conversion to development. This definition was developed by an international group of scientists to differentiate "secured land" from the International Union for Conservation of Nature (IUCN) term "protected areas" which refers to land with a formal designation of conservation value (Dudley 2008).

The secured lands dataset includes many tracts of land with no formal designation but substantial conservation value, such as reserves held by The Nature Conservancy, forest management lands held by the Canadian Crown, or "forever wild" easements held by a non-governmental conservation entity. In contrast, the dataset excludes some designated protected areas such as world biosphere preserves, as these areas are not formally protected from development.

To classify secured lands, we used a modified version of USFWS' GAP Status (Crist et al. 1998). Our version (TNC GAP) was similar in concept but used criteria that can be applied more easily than the USFWS criteria (Table 1.1). The criteria were:

1) Intent: the degree that owner, or managing entity is focused on maintaining natural diversity.
2) Duration: the owner or managing entity's temporal commitment to maintaining the land.
3) Effective management potential: the apparent capability of a managing entity to implement the intent and duration based on governance, planning, and resource levels. In the US, local, state and federal agencies, conservation NGOs, and land trusts are considered as effective managers.

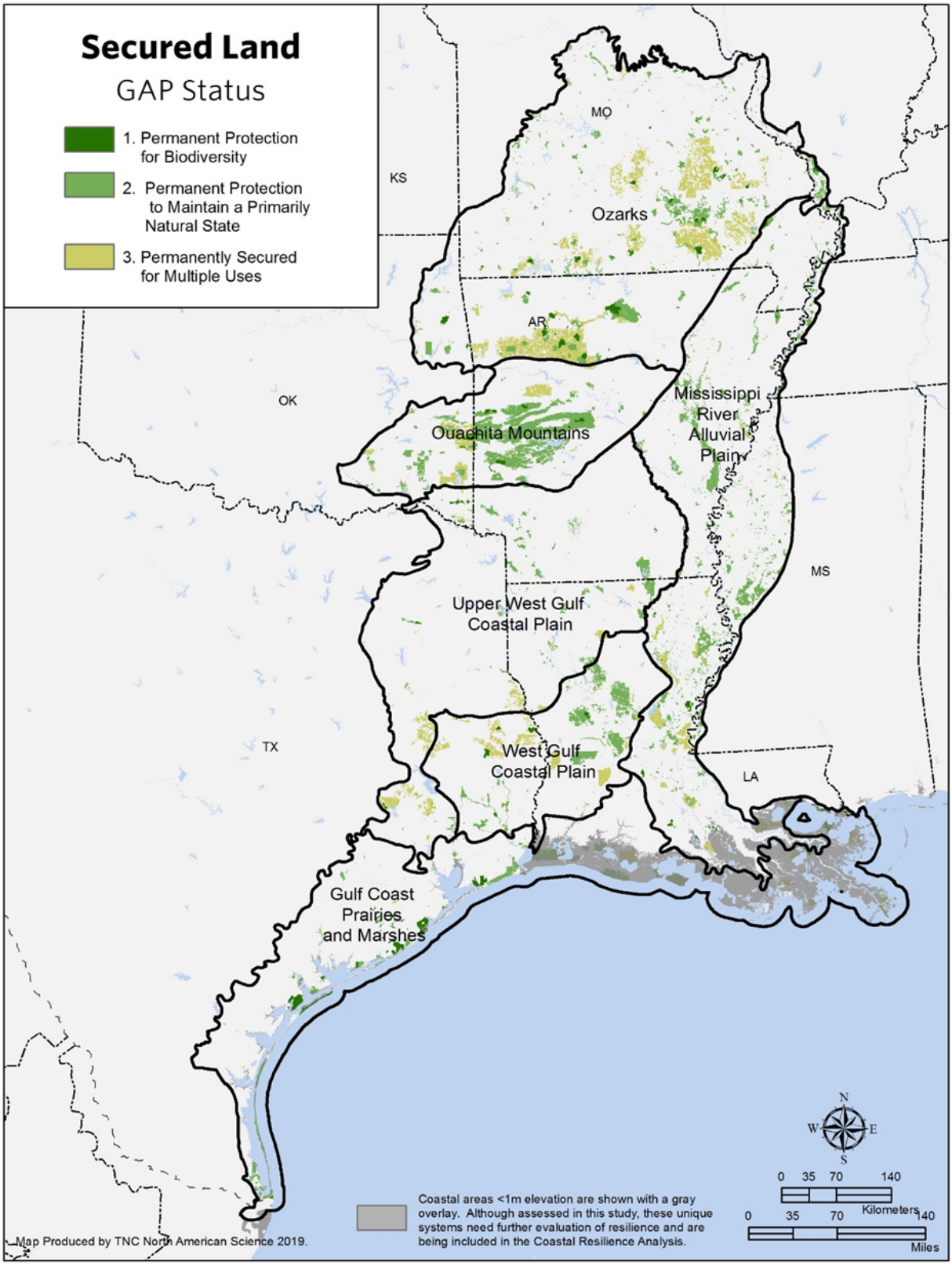
TNC GAP is a land classification system and it does not necessarily describe how protected the contained conservation targets are within a secured area (Table 1.1). For example, a species breeding on a secured parcel may be only partially conserved if their conservation calls for securement of multiple breeding areas and enough winter habitat. In this case, meeting the species conservation goal would require a network of secured lands each with the appropriate level of securement.

The Secured Lands dataset was compiled from over seventy sources and reflects land securement status through the end of the year 2018. Only parcels with permanent ownership duration were included in the mapped dataset. All parcels were assumed to meet the criterion of effective management. Management intent can change over time and it is not uncommon for conservationists to have a goal of moving the GAP status of a parcel from GAP 3 (secured for multiple-uses) to GAP 1 (secured for nature) (Figure 1.3).

Table 1.1:. Comparison of GAP status, IUCN and TNC GAP status definitions.

TNC GAP	GAP STATUS	IUCN	Selected Examples
TNC GAP 1 **Intent:** Nature conservation with little human interference **Duration**: Permanent	**GAP 1:** Areas having permanent protection from conversion of natural land cover and a mandated management plan in operation to maintain a natural state within which disturbance events can proceed without interference or are mimicked through management.	**Category Ia**: Strict Nature Reserves set aside to protect biodiversity **Category Ib:** Wilderness Areas are usually large unmodified or slightly modified areas, retaining their natural character and influence, without permanent or significant human habitation, which are managed to preserve their natural condition.	Research Natural Areas (RNA) Some TNC preserves where TNC controls management Wilderness Areas and Wilderness Study areas Forever wild easements
TNC GAP 2 **Intent:** Nature conservation with heavy management where needed **Duration**: Permanent	**GAP 2:** Areas having permanent protection from conversion of natural land cover and a management plan in operation to maintain a primarily natural state, but which may receive uses or management practices that degrade the quality of existing natural communities, including suppression of natural disturbance.	**Category III**: Natural Monument or Feature protected areas **Category IV**: Habitat/species management protected areas aim to protect species or habitats and management reflects this priority.	National Wildlife Refuges Areas of Critical Environmental Concern Some National Parks and county open space lands US Forest Service Special Interest Areas Some TNC conservation easement lands and preserves
TNC GAP 3 **Intent**: Multiple Uses. Typically, resource extraction, recreation and nature conservation **Duration**: Permanent.	**GAP 3** Areas having permanent protection from conversion of natural land cover for most of the area, but subject to extractive uses of either a broad, low-intensity type (e.g., logging) or localized intense type (e.g., mining).	**Category V:** Protected landscape/seascape where the interaction of people and nature over time has produced an area of distinct character with significant ecological, biological, cultural and scenic value. **Category VI**: Protected area with sustainable use of natural resources, generally large, with much of the area in a more-or-less natural condition and where a proportion is under sustainable natural resource management and exploitation is one of the main aims of the area.	State Forests and State Wildlife Areas US Forest Service and BLM land Most TNC Easements Most National/ State/ City /County Parks National Recreation Areas Open Space and Natural Areas

Figure 1.3: Secured lands. This map shows the secured lands in the study area by Gap status (see Table 1.1).



Process

To complete this study, we formed a core team of Conservancy scientists to complete the technical analysis and enlisted a Steering Committee to work with us to co-develop map products and communication materials.

To assemble the Steering Committee, we recruited colleagues representing each TNC state chapter and regional program within the study region. Working in partnership with these individuals and relying on their professional networks, we then reached out to external partners, representing state and federal agencies, academic institutions and non-profit organizations. The purpose of assembling such a large Steering Committee was two-fold. First, we needed the expertise and deep knowledge of fellow scientists across this broad geographic area to help us understand how the CNS concepts should be implemented in the Lower Mississippi-Ozark, given the geologic history, ecology, land use, and data availability in this region. Second, we wanted to develop a cohort of people from across the region that were invested in the process and products, and thus would be likely to use them in their own work and share the products with colleagues across their networks. The role of the Steering Committee included:

- Advising the core team on the most appropriate regional data sources and approaches for CNS implementation, promoting confidence in methods.
- Providing technical review of results and products (tools, maps, and reports).
- Connecting the TNC team with existing and future conservation applications.
- Assisting with outreach to additional partners to seek input and promote use of products.

Each 1.5 to 2-hour online conference call used an interactive format, in which preliminary results from the spatial analysis were shown and each participant was offered a time to comment on specific pre-identified questions. We also held a few targeted calls with a subset of committee members that focused on specific topics (e.g., wetlands, soils, conservation portfolios, energy development datasets, and outreach).

Summary of Concepts and Approach

The CNS approach to developing a network of resilient sites for the Central U.S. is based on several key observations. First, species diversity is highly correlated with geophysical diversity (Anderson and Ferree 2010, Lawler et al. 2015). We know abiotic factors, like soils and geology, shape ecosystems and their biodiversity, and historic evidence, along with studies from other climatic regions, suggest that these drivers will continue to influence the distribution and abundance of species even as climatic conditions change (Beier et al. 2015). Second, under a changing climate, species take advantage of local microclimates to persist in the landscape (Weiss et al. 1988, Suggitt et al. 2011, Roth et al. 2014, Albano et al. 2015). Yet, species populations can use microclimates and adjust to change only if the area is permeable and well connected (Heller and Zavaleta 2009). The idea of protecting examples of all geophysical settings, prioritizing those sites with the most microclimate diversity, and highest landscape permeability is the core concept of this project. Background on the approach and detail on how the results relate to current biodiversity patterns can be found in Anderson and Ferree (2010), Anderson et al. (2014a, 2014b), Anderson et al. (2016a) and the papers included in Beier et al. (2015).

We use the term **site resilience** to refer to the capacity of a site to adapt to climate change while maintaining diversity and ecological function (modified from Gunderson 2000).

Site Resilience

We define **site resilience** as ***the capacity of a site to maintain biological diversity, productivity and ecological function as the climate changes*** following Anderson et al. (2014b). This means that the character of the existing ecosystem, such as species assemblages and biotic structures, may change even as the core functions and biodiversity of the evolving ecosystem continue to provide the ecosystem services we value. Site resilience differs from the classic definition of resilience in the ecological literature, which holds that an ecosystem demonstrates resilience if it quickly returns to a steady-state equilibrium after a disturbance (Holing 1973). Under changing conditions, however, there is no steady-state to return to. Over time, the definition of resilience in the published literature has evolved to include change—for example Gunderson's (2000) definition, *"the capacity for renewal in a dynamic environment."* The meaning also varies depending on the object being impacted (e.g., wildlife species, plant communities, human communities). The *American Heritage Dictionary* defines **resilience** as "*the ability to recover quickly after change or misfortune*." Our definition of resilient sites, actual mapped places, revives an idea of land health that originated with Aldo Leopold (1949): "*Health is the capacity of the land for self-renewal. Conservation is our effort to understand and preserve this capacity.*"

We assume that if conservation succeeds, each geophysical setting will support species that thrive in the conditions influenced by the physical properties of the setting, although the site may contain different species in the future than are present now. For example, sandy sites would continue to support species that benefit from

well-drained, nutrient-poor conditions, while sites in fertile calcareous loams would support species that thrive in alkaline nutrient-rich conditions. **Geophysical setting** is thus broadly defined either based on bedrock or surficial soil texture, depending upon soil depth. We look to the current distribution of species, communities, and terrestrial system types, including wetlands, to help us understand what key characteristics are shifting across the landscape and could thus be captured by this coarse filter, but expect that the specific species and communities on a given example of setting will change over time.

A climate-resilient conservation portfolio includes sites representative of all geophysical settings selected for above-average levels of microclimatic variation and proportion of natural land cover. Chapter 2 describes how we mapped geophysical settings across the entire study area, using data on geology and soil characteristics, as well as information on soil depths. To guide this process, we refer to spatial data on the occurrence patterns of rare species and natural communities, as these data help us identify relationships between the geophysical settings, and distinct patterns of biotic expression. In the Lower Mississippi-Ozark region, this involved delineating the region into areas most influenced by surficial sediments (e.g., calcareous loams, deep loess, sand), and areas more closely tied to underlying geology (e.g., acidic granite, circumneutral sedimentary, calcareous sedimentary).

The value of conserving a spectrum of physical settings is based on empirical evidence that this approach will help us meet goals of representation, i.e., protection of the breadth of existing biodiversity (Anderson and Ferree 2010), but there are many choices to make to determine how this is accomplished. For example, of all the possible sand plains that could be conserved, which ones are the most likely to remain functional and sustain biological diversity into the future? Chapter 3 describes the site-based characteristics that promote sustained ecosystem function and diversity, and the methods we used to assess and map them. The first characteristic, **landscape diversity**, is an estimate of the number of microclimates and climatic gradients available within the local area. It is measured by counting the variety of landforms (e.g., hillsides with different slopes and aspects; dry, moist, or wet flats), and the density, configuration, and connectivity of wetlands. South-facing slopes will typically be warmer and drier that similar slopes that face northeast; these types of differences provide local variation in climate that provide additional climate "niches" relative to areas without topographic variation. We expect that microclimate diversity buffers species against regional climatic effects by providing them with a range of local climates, many of which might be suitable for extending a species' ability to persist at a site. By this logic, we expect that the diversity and persistence of species within a local area increases with high landscape diversity relative to other examples of the same geophysical setting (Weiss et al. 1988).

Local connectedness, the second site-based characteristic we use an indicator of sustained ecosystem function and diversity, is defined as the number of barriers to species movement and the degree of fragmentation within the local area. A highly permeable landscape has no or few barriers (low habitat fragmentation) and promotes resilience by allowing plant and animal movements and the reorganization of communities. Roads, development, agriculture, dams, and other structures create

barriers, or resistance, that interrupts or redirects movement and, therefore, lowers the permeability. Maintaining a connected landscape is the most widely cited strategy in the scientific literature for building resilience (Heller and Zavaleta 2009). Connectivity has in fact been hypothesized to explain why relatively few extinctions occurred during the Quaternary (2.5 million years BCE to present), another period of rapid climate change (Botkin et al. 2007)—albeit not as rapid as the current climate change (Holocene/Anthropocene; Masson-Demotte et al. 2013).

Initial sections of this report are focused on mapping site resilience. In Chapter 2, we describe mapping and classification methods used to identify all the distinct geophysical settings in the region. Chapter 3 introduces methods designed to quantify the physical and structural aspects of landscapes using models that measure a site's physical complexity including variety of microclimates (landscape diversity), natural cover (local connectedness), and combined resilience factors (integration of landscape diversity and connectedness). In Chapters 4 and 5 we present the results, identifying resilient sites across individual ecoregions and the full study area, respectively. Subsequent chapters focus on linking resilient areas into a conservation network based on climate flow and biodiversity values.

Importantly, the use of geophysical settings and ecoregions ensured that landscape diversity and local connectedness were ranked relative to sites of the same underlying type within an ecoregion. Thus, the resulting maps of resilient sites are always relative to the setting and ecoregion. Some geophysical settings, such as calcareous loams, have subtler microclimates and are more fragmented (i.e. have less site resilience) than other settings, but our goal was to identify the most resilient sites for each geophysical type. This ensured that we were mapping a blueprint of resilient sites that could sustain all biological diversity and was not biased towards a soil or bedrock. The analysis was performed within each of the six ecoregions, and the regional map is a composite of the individual ecoregion maps.

DATA SOURCES

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Ecological Stratification Working Group. 1995. A National Ecological Framework for Canada. Agriculture and Agri-Food Canada, Research Branch, Center for Land and Biological Resources Research and Environment Canada, State of the Environment Directorate, Ecozone Analysis Branch, Ottawa/Hull. Report and national map at 1:7,500,000 scale. http://sis.agr.gc.ca/cansis/nsdb/ecostrat/index.html

USDA Forest Service. 2007. Ecological Subregions: Provinces, Sections, and Subsections of the Conterminous United States. http://fsgeodata.fs.fed.us/other_resources/ecosubregions.php.

DEFINING THE GEOPHYSICAL SETTINGS

CHAPTER
2

This chapter describes our process to characterize and classify the Lower Mississippi-Ozark study area into distinct geophysical "stages" based on the elevation, geology, and soils. Our premise is that the characteristics of a geophysical setting represent enduring features that influence biotic differences in the flora, fauna, and natural communities (e.g. due to differences in pH, nutrients, drainage, erodibility) now, and these differences will continue to favor or select against different subsets of species under future climates. These physical characteristics often also correlate with human land use patterns because properties such as bedrock type, soil texture and chemistry contribute to the value and suitability of sites for agriculture, development, or mining.

In addition to shaping parent materials and soils, geophysical environments tend to share topographic characteristics and land use properties, both of which are key components of our site resilience metric (Chapter 3). Typically, bedrock-based environments are more topographically complex and have more intact natural landcover than deep soil environments, which are generally flatter and more likely to be converted to agriculture. Within these deep soil settings, remaining natural areas often have poorer soils or more topographic diversity than the surrounding farmlands due to the conversion of sites that are easiest to farm.

The correlation between the geophysical settings and site resilience factors highlights the important roles that settings play in this study. Geophysical settings are key drivers of biological diversity, so representation of the full range of settings is a critical conservation goal. Further, the correlation between setting types, topography, and land use suggests that direct comparisons of our site diversity metrics would favor some settings over others. As we determined how to partition the study area into geophysical settings, we considered these dual roles as (1) "coarse filters" for capturing the full range of abiotic conditions that support biodiversity, and as (2) a spatial stratification prior to identifying examples of sites that have the most microclimatic variety and natural cover. Without a stratification to ensure "apples to apples" comparisons, our results would be biased towards bedrock-based settings and their associated flora and fauna due to the higher topographic relief and lower conversion rate on those settings.

Ecoregions

We assessed the geophysical settings within the larger context of natural ecoregions. Ecoregions are large contiguous units of land with similar environmental conditions (landforms, geology, and soils) which share a similar climate and a distinct assemblage

of natural communities and species. The term “ecoregion" was coined by J.M. Crowley (1967) and later popularized by Robert Bailey of the US Forest Service (USFS). In recent decades, ecoregions have become a defining construct of larger conservation efforts because they provide an ecological context for understanding landscape-scale conservation activities by enabling the evaluation of properties considered critical to conserving biodiversity such as representation, complementarity, redundancy, ecological function, and endemism.

The TNC ecoregions used for this analysis are modified from Bailey (1995) and were based on the subsections delineated by the U.S. Forest Service (USDA Forest Service ECOMAP Team 2007).In comparison to Bailey’s ecoregions, TNC’s grouping of subsections puts more emphasis on physical characteristics and natural communities and less on climatic patterns. We made one revision to then ecoregions for this analysis which to update the border between the Upper West Gulf Coastal Plain and the Mississippi River Alluvial Plain to the EPA Level III linework (US Environmental Protection Agency 2013) which more closely matched the landform patterns along that edge section. The Lower Mississippi study area encompassed 6 ecoregions (Figure 2.1):

1. Ozarks
2. Ouachita Mountains
3. Upper West Gulf Coastal Plain
4. West Gulf Coastal Plain
5. Mississippi River Alluvial Plain
6. Gulf Coast Prairies and Marshes.

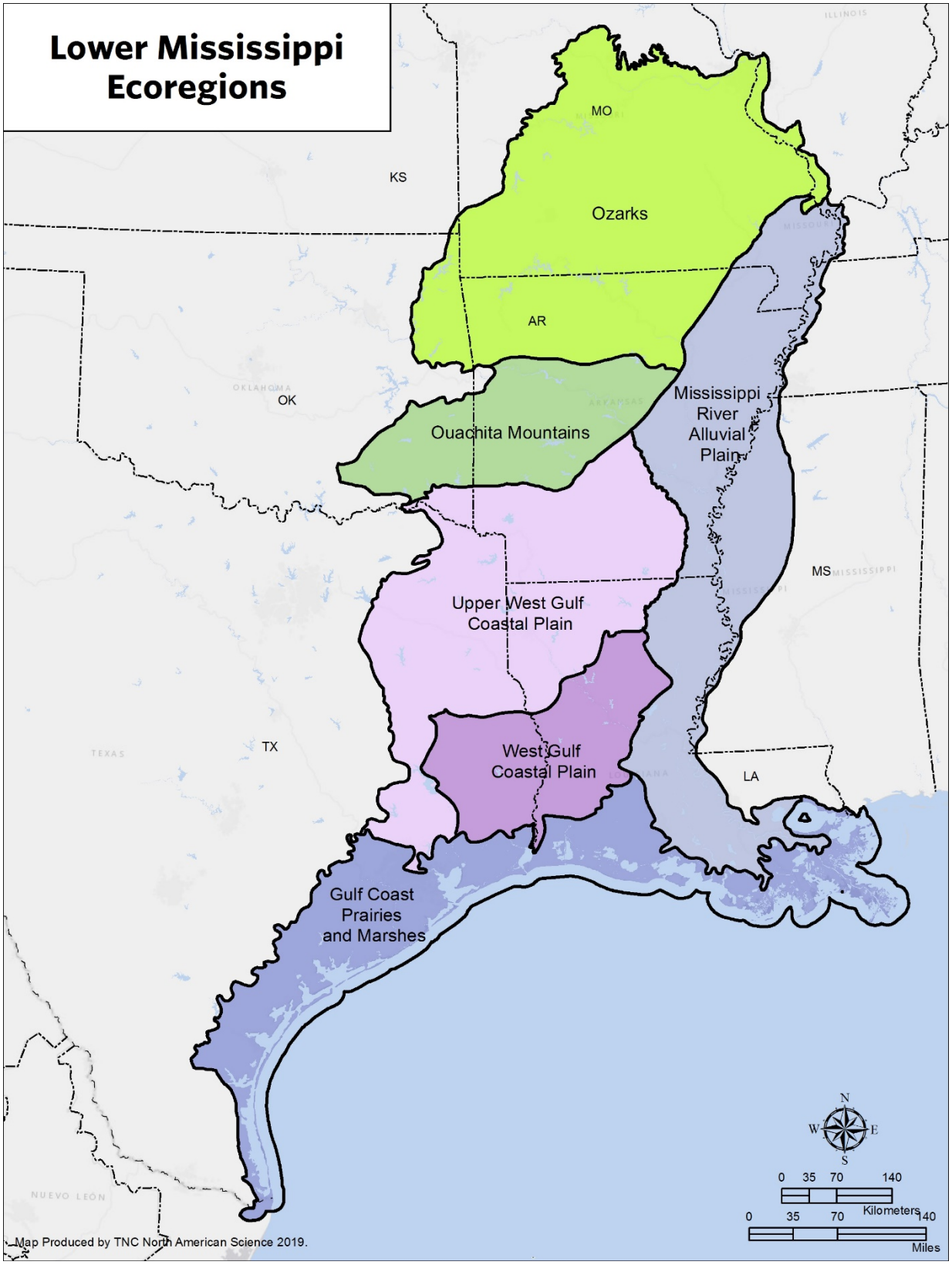
Geophysical Settings

First, we discuss the definition of each geophysical setting, and the data sources, thresholds and distinctions used to map it in the Lower Mississippi-Ozark study area. In the later sections, we summarize the natural communities and species associated with each setting.

The section on delineating settings is divided into five parts:

1. Concepts and Confirming Data
2. Delineating the Surficial vs. Bedrock Zones
3. Classifying and Mapping the Bedrock Geology
4. Classifying and Mapping the Surficial Sediments
5. Integrating Bedrock Geology and Soil Texture
6. Integrating Elevation Zones

Figure 2.1: Ecoregions. TNC Ecoregions included in the study area.



Concepts and Confirming Data for Delineating Settings

To map the geophysical settings, we first split the study area into a region of deep surficial soils and a region of shallow bedrock-based soils. The surficial (deep soil) settings were further divided based on soil texture. Ranging from deposits of pure sand to wind-blown loess to silts and clays these surficial settings support many of the region's iconic communities, such as alluvial floodplains, coastal prairies and tidal marshes. The bedrock settings were further divided based on the composition and alkalinity of the bedrock. These settings support species adapted to thinner dry soils, and natural communities and features like limestone glades and sandstone outcrops.

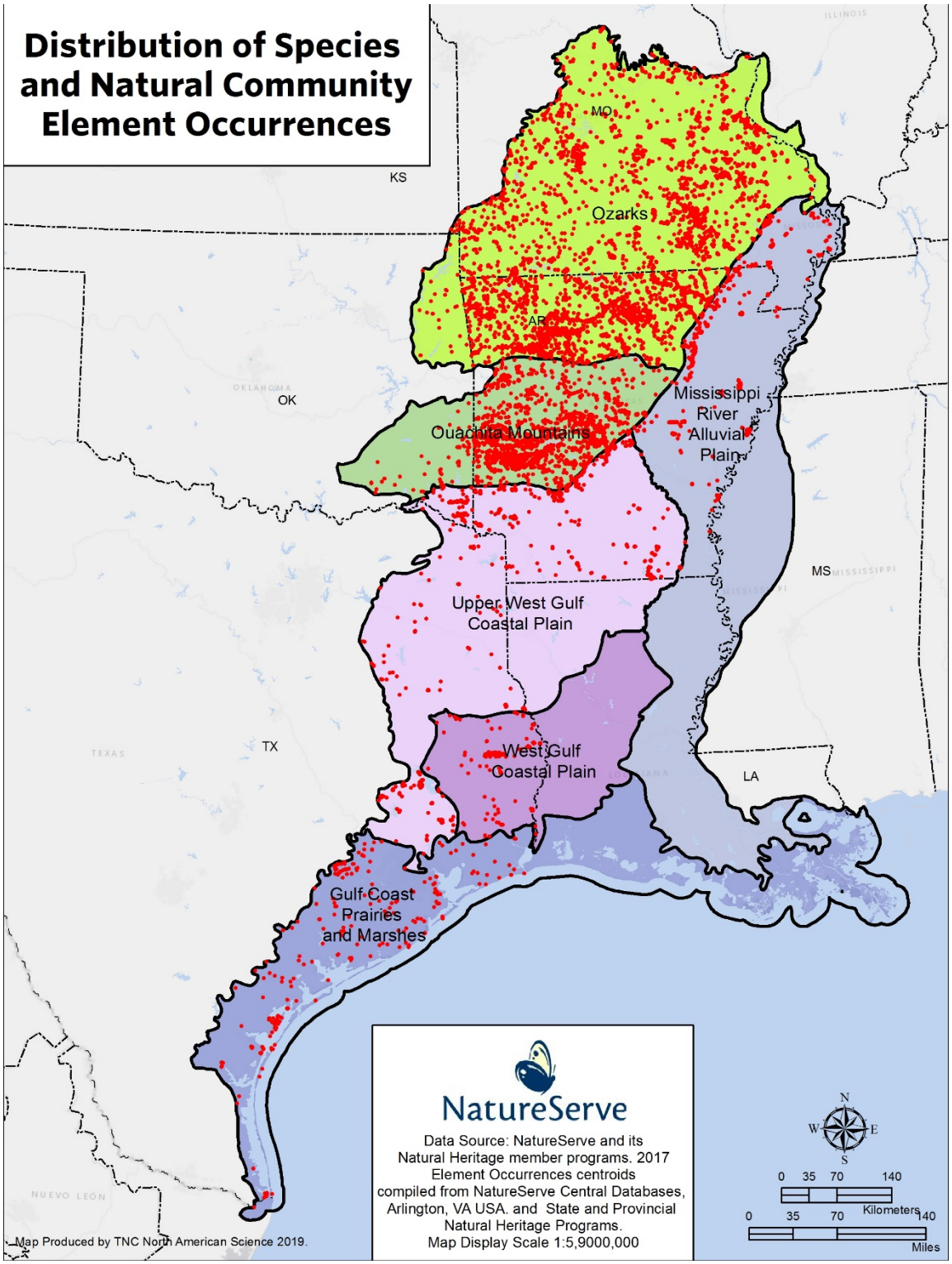
To gauge the accuracy of various soil and geology data layers, and to confirm the biological distinctiveness of each setting, we compiled point locations of 12,364 natural community and rare species occurrences (sources listed in Element Occurrence Data Sources at the end of this chapter). This invaluable biotic information consisted of points and polygons called "element occurrences" or "EOs" (i.e., elements of natural diversity), and were provided by State Natural Heritage Programs and NatureServe, who track and collect this information using ground inventory methods. In contrast to many other regional or national datasets, the spatial precision of EO locations is extremely high. The high precision made it possible to use these points locations to identify important transitions and thresholds within each geophysical characteristic, and to evaluate the relative value of different geology, soil, or pH datasets, especially those that were coarser in scale.

Each EO represents an area of land or water where a species, population or distinct natural community type was present (NatureServe 2002). Natural Heritage Programs generally create EOs for native species considered at-risk within their jurisdictions, and for all representative natural communities. Each mapped location of an EO has an associated level of mapping accuracy, and these are recorded at three levels (seconds, minutes and general), which range from highly precise locations mapped on 1:24,000 scale maps to lower precision mapping.

Natural Communities are described and mapped in accordance with a state natural community classification, most of which are published and available on-line (i.e., on NatureServe Explorer, http://explorer.natureserve.org). A natural community is defined as an assemblage of interacting plants, animals and other organisms that repeatedly occurs under similar environmental conditions across the landscape and is predominantly structured by natural processes rather than modern anthropogenic disturbances (NatureServe 2002). Because natural communities are often linked to distinct geophysical settings (e.g., limestone glade or loess hill prairie), the natural community data are extremely helpful for assessing the accuracy of various geology and soil type datasets, providing an additional line of evidence that helps us to refine our delineation of setting types, and correctly map their distributions. Species data are more complete for vertebrates and vascular plants but include selected species of invertebrates from groups such as beetles, snails, and butterflies.

One challenge we encountered is a strong variation in EO sampling/mapping intensity across the Lower Mississippi. The distribution of EOs was skewed towards the northern part of our focal area, with 83% coming from the Ozarks or Ouachita Mountains ecoregion.

Figure 2.2: Element Occurences. Distribution of Species and Natural Community Element Occurrences (shown as red dots) from NatureServe and Partner Natural Heritage Programs.



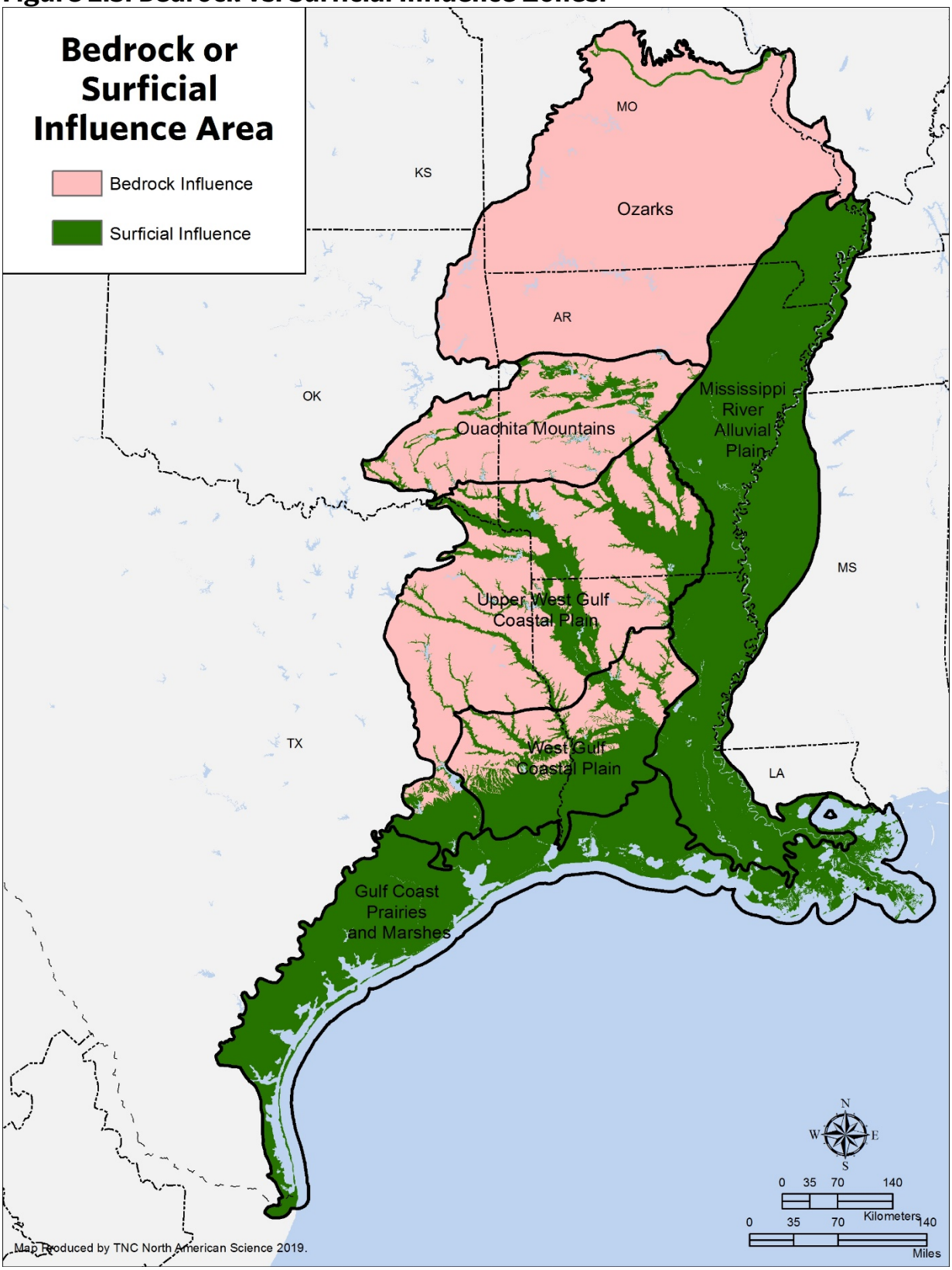
Delineating the Surficial and Bedrock Zones

Our first step in mapping the geophysical settings was to separate the region into areas of deep surficial deposits and areas of shallow to patchy soils where the underlying bedrock type influences the natural communities. The natural communities, associated species, and ecological processes differ markedly between these two environments, which separate the deep soil fertile plains, loess hills, and floodplains from the more restricted areas of bedrock outcrops, bluffs, glades, and shallow prairie and slope communities.

To identify and map the surficial/bedrock split, we reviewed the areas mapped as bedrock vs. unconsolidated sediment classes in the dataset: US Geological Survey *State Geologic Mapping Compilation* (*various scales*; Horton et al. 2017 various scales 1:150,000-1:500,000). We compared this division to a similar split between discontinuous or patchy surficial material vs. deep soil in the national USGS Surficial Materials in the Conterminous United States (Soller et al. 2009) which was compiled from over 30 sources and maps of surficial deposits at a 1:5,000,000 scale. Although courser in scale than the state bedrock datasets, Soller's categorical assignment of areas as discontinuous or patchy (defined as map units where the sediments are patchy in distribution; bedrock commonly is exposed at land surface) matched very closely the areas mapped as bedrock in the state finer resolution mapped geology datasets. Additionally, the bedrock area encompassed nearly all the known shallow-soil Natural Heritage element occurrence community locations.

Given the finer spatial mapping scale of the state bedrock geology, we decided to use the state bedrock data polygons as the base-map for delineating a bedrock vs. surficial zone. However, we enhanced the map in a few places where it appeared Soller et al. (2009) did a better job of matching the landforms or matching across state boundaries. For example, in the Upper West Gulf Coastal Plain and West Gulf Coastal Plain ecoregion areas of Arkansas and Louisiana polygons mapped as unconsolidated sediments in the state geology dataset were mapped as bedrock in Soller et al (2009) and as circumneutral to acidic sedimentary bedrock in the directly adjacent areas in Texas. Further, this potentially bedrock area occurred at the southern extent of a landform pattern that indicated a continuous natural extension of a hill/ridge landform. In this case, we overrode the state dataset and mapped the area as sedimentary bedrock following the boundaries of Soller et al. 2009. This modification made the settings across the Texas, Arkansas and Louisiana border more consistent and continuous and made ecological sense.

Figure 2.3: Bedrock vs. Surficial Influence Zones.



Classifying and Mapping the Bedrock Geology

We placed the bedrock classes from US Geological Survey *State Geologic Mapping Compilation (various scales*; Horton et al. 2017) into a simplified set of ecologically relevant classes following the scheme of Anderson and Ferree (2010). Using attribute data from the compiled geology dataset, we reviewed each geologic taxonomic type based on name and description, and we assigned it to one of the simplified classes using information on the bedrock's component rock types, genesis, chemistry, weathering properties and texture. In some cases, source polygons had multiple rock type assignments in their major and minor class codes, and we resolved the assignment of geologic taxonomic types by overlaying Natural Heritage Program edaphically driven rare species and natural community EO locations and reviewing whether the match was consistent with particularly source major rock types. When rock types were classified differently on either side of a state or country boundaries, we resolved the difference using the supplemental information from a variety of sources.

The seven predominant rock components of the bedrock classes are described below:

Circumneutral Sedimentary: sedimentary or meta-sedimentary rock with no reported alkaline components. This group included sandstone, siltstone, mudstone, claystone, shale, conglomerate, arenite, argillite, arkose, and bentonite rocks. (e.g., Anderson and Ferree 2010).

Calcareous Sedimentary: alkaline sedimentary or metasedimentary rock with high calcium content. This group included limestone, marlstone, calcarenite, carbonite, chalk, coquina, marble and marl.

Calcareous Sedimentary - Dolostone: areas of pure dolostone were separated out in the Ozarks ecoregion given the different ecological communities found on dolostone vs. other limestones and mixes of calcareous sedimentary rocks.

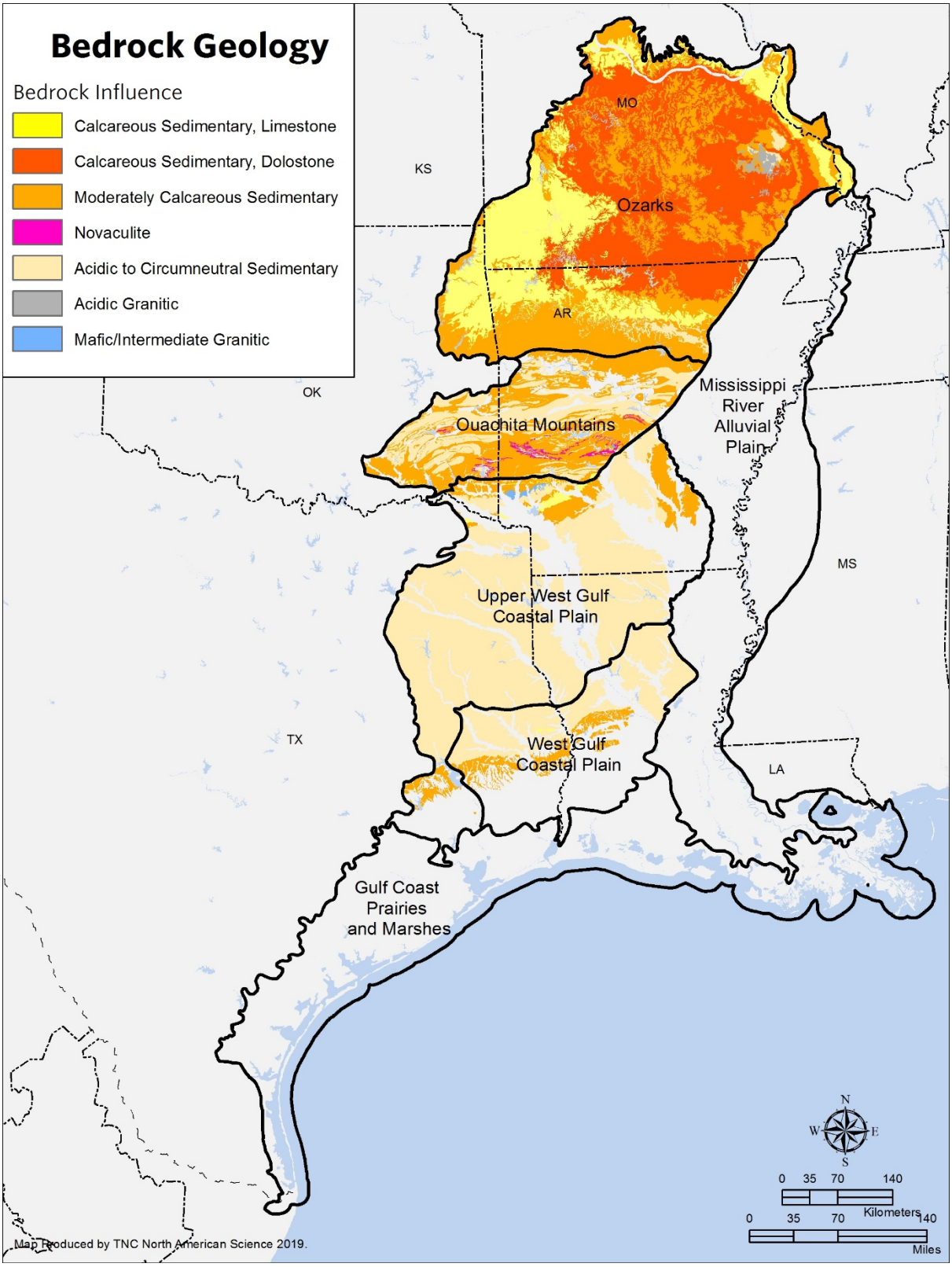
Moderately Calcareous Sedimentary: moderately alkaline sedimentary or meta-sedimentary rock with some calcium but less than rocks in the calcareous rock class. This group is composed of calcareous shales or mixed sedimentary rocks with one or more calcareous components, calcium-silicate, and calcium-silicate schist rocks.

Acidic Granitic: quartz-rich, resistant acidic igneous and meta-igneous rock including very high grade meta-sedimentary rock. This group is primarily composed of granite, granodiorite, dacite, rhyolite, pegmatite, migmatites, quartzite rocks.

Mafic/Intermediate Granitic: quartz-poor alkaline to slightly acidic igneous and meta-igneous rock. This group includes: anorthosite, gabbro, diabase, basalt, diorite, andesite, syenite, trachyte, greenstone, amphibolite, epidiorite and granulite.

Novaculite: Novaculite, also called Arkansas Stone, is a microcrystalline to cryptocrystalline rock type that consists of silica in the form of chert or flint. Novaculite is very hard and dense and resistant to erosion and the novaculite beds stand out as ridges in the Ouachita Mountains.

Figure 2.4: Bedrock Geology. Results of the compilation and classification of state-based geology datasets into a single Lower Mississippi map.



Classifying and Mapping the Surficial Sediment

We created a spatially comprehensive regional dataset of surficial texture by integrating data from new POLARIS dataset developed by the Program in Atmospheric and Oceanic Sciences Lab, Princeton University, Princeton, NJ, USA (POLARIS 2018). This new complete map of soil series probabilities covers the contiguous United States at a 30 m spatial resolution using available high-resolution geospatial environmental data and a state-of-the-art machine learning algorithm to remap and expand the extent of the Soil Survey Geographic (SSURGO) database. POLARIS provided a spatially continuous, internally consistent, quantitative prediction of soil series. It offered solutions to the primary weaknesses in SSURGO: 1) unmapped areas throughout the western U.S. were gap-filled using survey data from the surrounding regions, 2) the artificial discontinuities at political boundaries were removed, and 3) the use of high-resolution environmental covariate data lead to a spatial disaggregation of polygons.

To simplify and focus on the texture classes within the upper 30-m of soil only, we created an overall weighted average of the available near surface depths of 0-30 cm for percent sand, silt, and clay. With these percentages, we assigned each 30-m pixel to one of the 12 USDA Soil Triangle Categories and these were then further grouped into 5 major texture groups (see below). The 30-m pixel scale soil data were also further smoothed using a circular 100-acre focal maximum function to essentially map the dominant soil type within the 100-acre area surrounding each cell. This helped to remove many small single cell speckles in the raw POLARIS data and consolidated the mapped soils into larger scale dominant soil type areas more similar in scale to the bedrock setting polygons to give the settings a more consistent mapping resolution.

The resultant surficial soil setting types are described briefly below:

Sand: Loamy Sand, Sand
Sand is a coarse-grained substrate composed of loose rock particles smaller than gravel but larger than silt (>0.2 mm). Sand substrates are typically well drained and nutrient poor.

Loam: Loam, Sandy Loam, Sandy Clay Loam
Loam is a relatively fertile soil reflecting a mixture of sand, silt and clay. In this region, analysis of the soil pH and alkalinity in the STATSGO, POLARIS, and SURRGO dataset suggested that all loams were calcareous in nature.

Silt: Silty Loam, Silty Clay Loam, Clay Loam, Silt:
Silts are fine-grained substrates of a size between sand and clay. Silts typically transported by water and deposited during evaporation. Soils with a high silt content have an increased nutrient and water holding capacity and are often poorly drained.

Clay: Clay, Silty Clay, Sandy Clay
Clays are very fine-grained substrates typically transported by water and deposited during evaporation. Soils with a high clay content have an increased nutrient and water holding capacity and are often poorly drained.

We also created two additional surficial categories that were not taken directly from the soil category but indicated distinct surficial environments.

Loess:
Loess is very fine silt material transported and deposited by wind. "Deep loess" in this region is distinct in its form and ecological influence, as it has been molded by wind into hills, and supports loess hill prairies and other loess related communities. We mapped loess as any area with >= 70% silt in the base POLARIS % silt dataset

Mixed Alluvial Sediments:
Mixed alluvial areas are floodplains with a complex mix of textures, often loam with very small patches of sands or clays throughout. They are influenced by the pattern of flood deposition and flood scour from repeated interactions with a river which maintain the mosaic of soil types. Because they are unified by a riverine process, we did not want to break down this area into a finer current distinction of soil textures and types. We mapped "mixed alluvial sediments" as any surficial sediments falling within the 100-year floodplain zone as defined by a new high-resolution model, produced by the flood-mapping organization Fathom, that simulates floods on all rivers across the entire continental United States (Wing et al 2017).

The patterns in soil texture classes were studied in each ecoregion to arrive at the dominant surficial texture classifications and clean up small variations.

Mississippi River Alluvial Plain and the Gulf Coast Prairies and Marshes

These ecoregions entirely dominated by surficial materials with no bedrock areas were mapped. In these ecoregions, we mapped five soil classes: Sands, Loams, Silts, Clays, and Loess. Mixed Alluvial Sediments where mapped in the GCPM along the mainstems of small to large rivers draining to the coast, but not in the MRAP as the latter was essentially a huge alluvial derived system.

West Gulf Coastal Plain

This ecoregion included a bedrock dominated northern half and a surficial dominated southern half. For the southern surficial dominated area, we mapped Sand, Loam, Fine Silts/Clay, and Mixed Alluvial surficial settings. We found the alluvial areas along the small to large rivers encompassed nearly all the clays and so we lumped the tiny remaining area of clays outside the alluvial areas in with the other fine textured silts (lumped class 3 and 4) because they were not extensive enough to stand as a unique settings and we had no natural communities indicating they were unique.

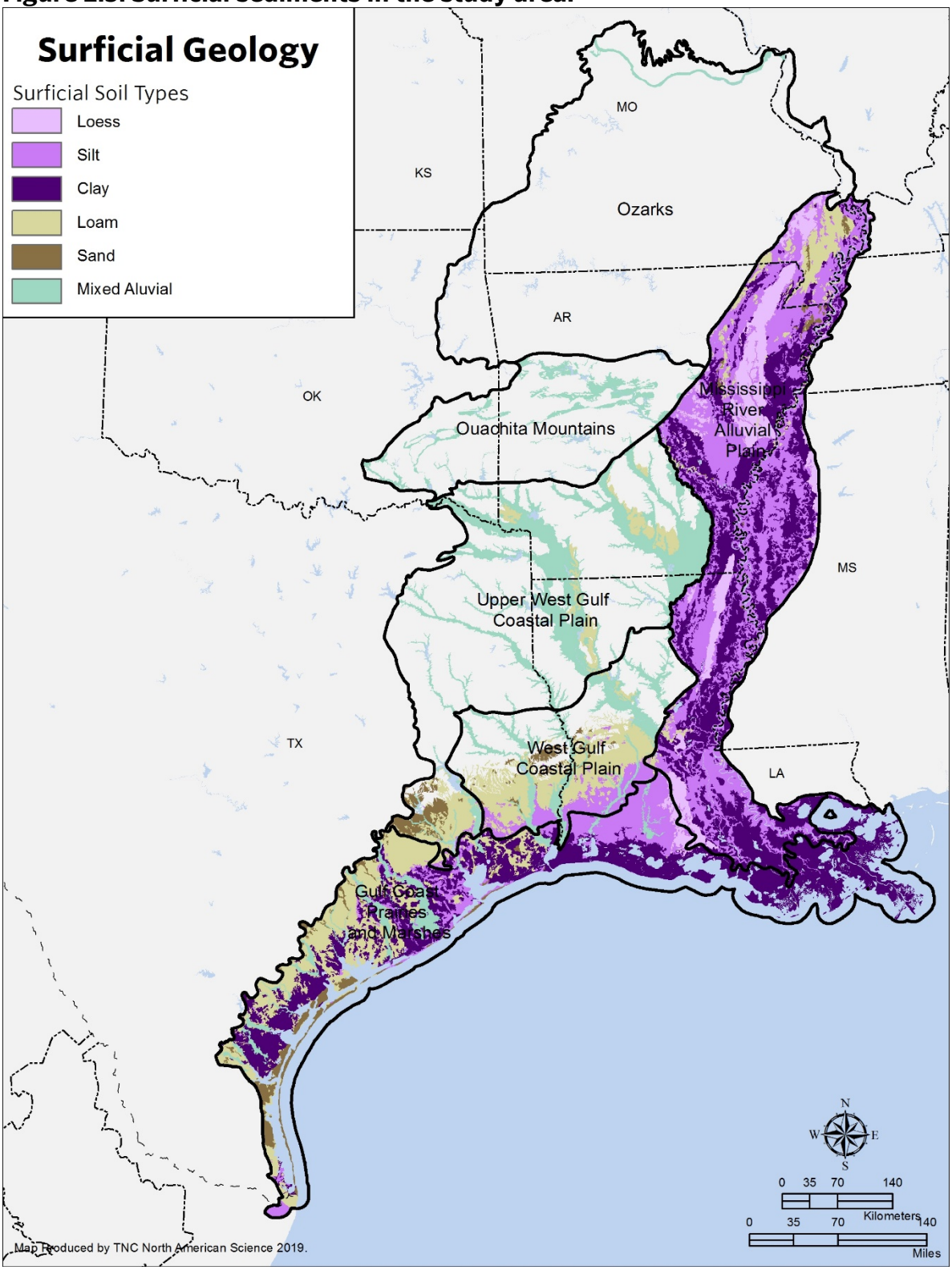
Upper West Gulf Coastal Plain

This ecoregion had only two surficial types: Loam and Mixed Alluvial. The loam was found on the upper Pleistocene terraces and the more mixed alluvial settings were found within the small to large river floodplains.

Ouachita Mountains and Ozarks

These ecoregions were dominated by bedrock and the only surficial setting was "Mixed Alluvial" soils along the small to large rivers and along the very large Missouri River.

Figure 2.5: Surficial sediments in the study area.



Integrating Bedrock Geology and Surficial Substrates

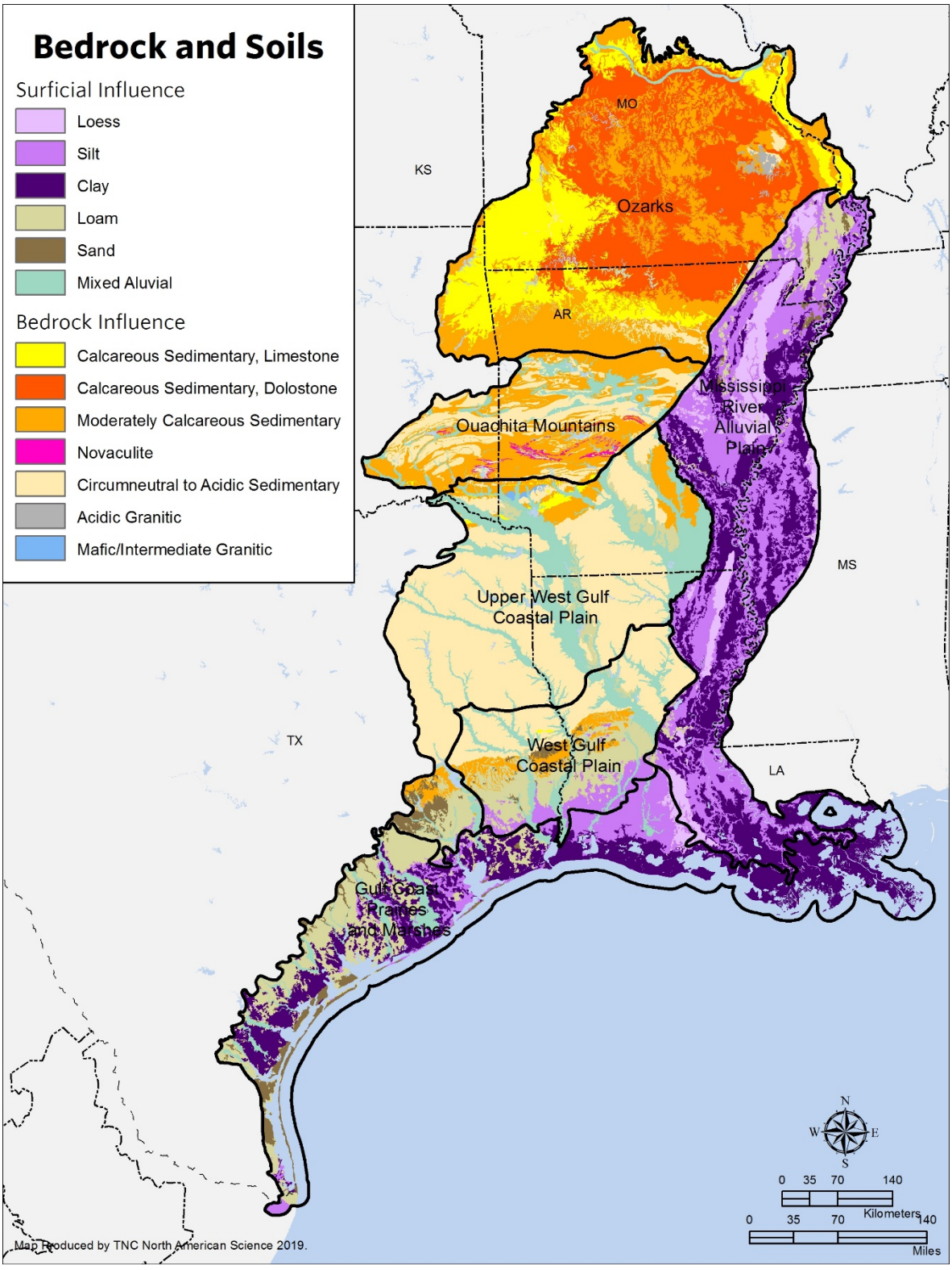
To create the final geology setting map for the study area, we combined the six surficial classes and the six bedrock classes to fully cover the study area with the appropriate bedrock or surficial settings. Small patches of any setting may be nested within a different dominant setting type, but for our purposes we eliminated small occurrences less than 1000 acres to focus on larger patches more likely to support the flora and fauna typical of the setting. The smoothing was done using a combination of the "Eliminate function" and the Euclidean "nibble" function in ArcGIS to replace small areas with the closest adjacent bedrock or surficial setting type.

The bedrock settings represent 51.5% and the surficial settings represent 48.5% of the region. The two most common bedrock settings were Circumneutral to Acidic Sedimentary (17%) and Moderately Calcareous Sedimentary (15%). The two most common surficial settings were Clay (15%) and Silt (12%).

Table 2.1: Acres of each Bedrock and Surficial Setting within the Lower Mississippi Study Area

	SETTING	ACRES	PERCENT
Bedrock Settings	Acidic Granitic	461,810	0.34
	Calcareous Sedimentary	8,590,504	6.34
	Calcareous Sedimentary, Dolostone	12,703,893	9.37
	Circumneutral to Acidic Sedimentary	23,324,058	17.21
	Mafic/Intermediate Granitic	75,047	0.06
	Moderately Calcareous Sedimentary	20,546,044	15.16
Surficial Settings	Clay	19,880,405	14.67
	Loam	13,952,971	10.30
	Loess	3,939,851	2.91
	Mixed Alluvial	11,781,760	8.69
	Sand	4,084,724	3.01
	Silt	16,178,997	11.94
Grand Total		135,520,062	100.00

Figure 2.6: Bedrock and Soils. The twelve geology classes of the study area.



Elevation Zones

The study region encompasses an elevation gradient that ranges from high elevation mountains in Ozarks and Ouachita Mountains to low relief coastal area of the Mississippi Alluvial Plain and Gulf of Mexico. To account for changes in the vegetation and fauna associated with elevation we identified and mapped three elevation zones (Figure 2.7).

Coastal: <20 ft. 15% of study area.
Moderate Elevation: 20-1800 ft. 85% of study area.
High Elevation: > 1800 ft. Less than 1% of study area

Like the minimum mapping unit for the geology, we smoothed the results of this intersection of elevation zone to eliminate small occurrences of individual elevation-geology setting polygons less than 1000 acres in size. Small patches of any setting may be nested within a different dominant setting type, but for our purposes we focus on larger patches because they are more likely to "represent" that setting, i.e., support the flora and fauna typical of the setting.

We combined the three elevation zones with the twelve geological classes to create a total of 20 geophysical settings (Table 2.2, Figure 2.8). There were 36 possible combinations but some of these never occur.

Table 2.2: Acres of each Geophysical Setting within the Study Area

	SETTING	ACRES	PERCENT
Coastal	Coastal Elevation, Clay	9,728,394	7.18
	Coastal Elevation, Loam	4,322,240	3.19
	Coastal Elevation, Loess	207,366	0.15
	Coastal Elevation, Mixed Alluvial	613,836	0.45
	Coastal Elevation, Sand	2,819,693	2.08
	Coastal Elevation, Silt	2,555,554	1.89
Moderate	Moderate Elevation,Acidic Granitic	461,810	0.34
	Moderate Elevation,Calcareous Sedimentary	8,590,504	6.34
	Moderate Elevation,Calcareous Sedimentary, Dolostone	12,703,893	9.37
	Moderate Elevation,Circumneutral to Acidic Sedimentary	23,250,256	17.16
	Moderate Elevation,Mafic/Intermediate Granitic	75,047	0.06
	Moderate Elevation,Moderately Calcareous Sedimentary	20,004,196	14.76
	Moderate Elevation,Clay	10,152,011	7.49
	Moderate Elevation,Loam	9,630,731	7.11
	Moderate Elevation,Loess	3,732,485	2.75
	Moderate Elevation,Mixed Alluvial	11,167,923	8.24
	Moderate Elevation,Sand	1,265,032	0.93
	Moderate Elevation,Silt	13,623,443	10.05
High	High Elevation, Circumneutral to Acidic Sedimentary	73,802	0.05
	High Elevation, Moderately Calcareous Sedimentary	541,848	0.40
Grand Total		135,520,062	100.00

Figure 2.7: Elevation Zones. The three major elevation zones in the Lower Mississippi-Ozark study area.

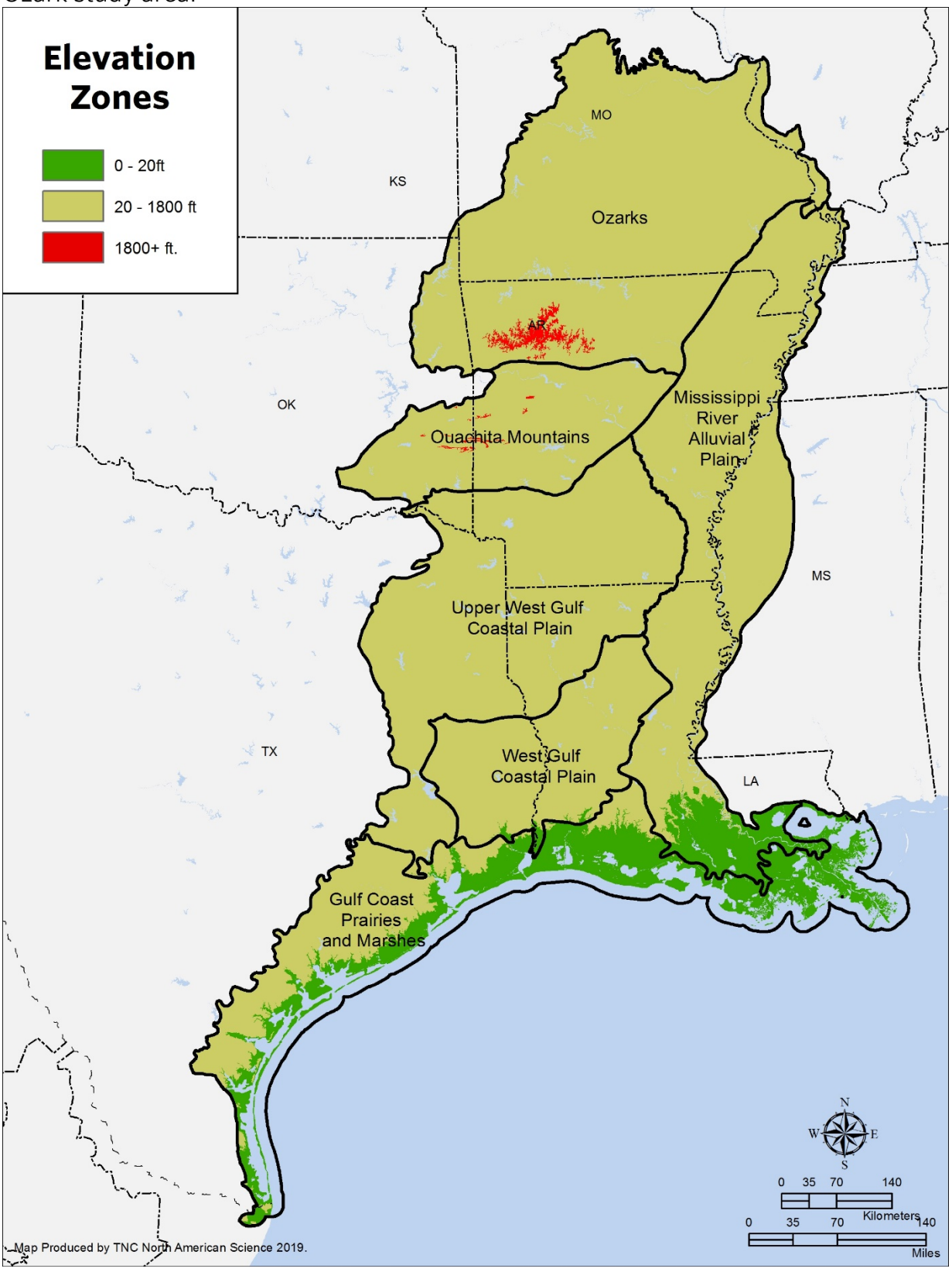
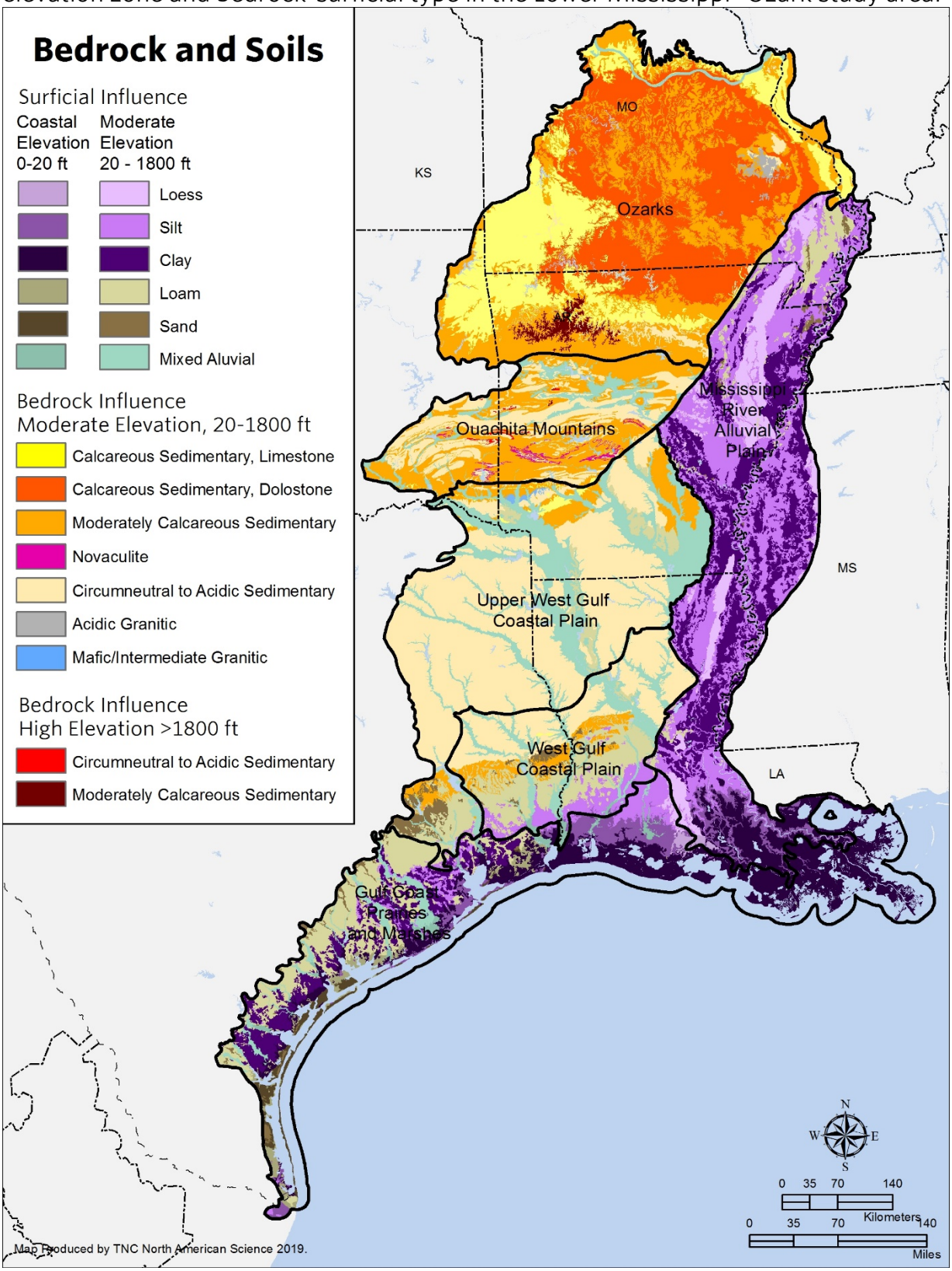


Figure 2.8: Geophysical Settings. The geophysical settings are a combination of elevation zone and bedrock-surficial type in the Lower Mississippi- Ozark study area.



Characterizing the Geophysical Settings

The following descriptions of the geophysical settings highlight the key characteristics of each physical environment, and the associated species and communities.

Geophysical Settings and their Current Biota

The land's geologic substrate influences the type and diversity of natural communities and species found on the site. We assessed the current associations between the current biota and each geophysical setting by overlaying 93,204 locations of species and natural communities provided by the State Natural Heritage Programs and described above. The results are summarized to give users an indication of the type of biodiversity that each geophysical setting favors. We expect the future species composition to be of a similar ecological character but perhaps not the same taxa. Evidence from other climate zones suggest that the geophysical settings will continue to support distinct flora and fauna even under different climatic regimes. For example, around the globe and under many climates, limestone areas favor cave-adapted species and a distinct alkaline-tolerant flora, and these differ from the drought and fire-adapted species more common in sand (Kroeber, 2002). Familiar ecosystem and community types may be present in some form in the future, but their exact composition and structure could vary widely from their current expression.

The summaries below list the species and communities that occur in the described geophysical setting more than any other setting. The lists were developed by overlaying the Natural Heritage Program element occurrences and using a simple chi-square test to determine the species that occurred in the setting more than would be expected by chance. This translates to 50-100% of the known occurrences being found in the setting.

Surficial Settings

CLAY

Clay (15%) is a very fine-grained substrates with individual grain sizes less than 2 micrometers. Transported by water or deposited during evaporation, they may indicate ancient lakes and wetlands.

Communities (State Names)

Marsh hay Cordgrass-Saltgrass Herbaceous Vegetation
(Spartina patens-distich is spicata herbaceous vegetation)
Gulf Cordgrass-Little Bluestem Herbaceous Vegetation
(Spartina spartinae-schizachyrium scoparium var. Littoralis herbaceous vegetation)
Texas Ebony-Snake-Eyes Shrubland
(*Pithecellobium ebano-phaulothamnus spinescens shrubland)*
Mesquite-Granjeno Woodland *(Prosopis glandulosa-celtis pallida woodland)*
Blackbrush Shrubland *(Acacia rigidula shrubland)*

Birds

Common Moorhen *(Gallinula chloropus)*, King Rail *(Rallus elegans)*, Purple Gallinule *(Porphyrio martinica*)

SILT

Silt (13%) is a fine-grained substrates with individual grain sizes intermediate between sand and clay. It often exists as soil deposited at the bottom of a water body or along floodplains and bottomlands. Soils are typically poorly drained and abundant with wetlands and waterbodies. Loess communities (described) below are formed in wind deposited silt.

Communities (State Names)

Wet-Mesic Bottomland Forest
Wet bottomland forest
Bottomland Flatwoods.
Swamp and Shrub swamp

Invertebrates

Ohio Pigtoe (*Pleurobema cordatum)*

LOESS

Loess (3%) is a silt-sized sediment transported and deposited by wind. Loess is uncommon in this region being restricted to a hill slopes and ridges in the Mississippi Alluvial Plain.

Communities (State Names)

Loess Ridge

Plants

Savannah Milkweed *(Asclepias obovate)*

LOAM

Loam (10%) is a fertile three-way mix of sand, silt and clay. These soils are relatively well drained and can be extremely productive for agriculture.

Communities (State Names)

Dry Longleaf Pine/Beakrush Woodland
(Pinus palustris/rhynchospora spp. Woodland)
Houston Coastal Prairie
(Muhlenbergia capillaris grassland)
Eastern Upland Coastal Prairie
(Andropogon gerardii - panicum virgatum - schizachyrium scoparium - schizachyrium tenerum - helianthus mollis grassland)
Water Oak-Coastal Live Oak Forest
(Quercus nigra-quercus virginiana forest)

Plants

Pondberry *(Lindera melissifolia)*, Corkwood *(Leitneria floridana*)

SAND

Sands (3%) are composed of loose rock particles smaller than gravel, and deposits are well-drained and nutrient poor. Sand deposits often found in the low elevation and coastal regions.

Communities (State Names):
Seacoast Bluestem-Gulfdune Paspalum Herbaceous Vegetation
(Schizachyrium scoparium-paspalum monostachyum herbaceous vegetation)
Gulf Cordgrass - Little Bluestem Wet Prairie
(Spartina spartinae - schizachyrium scoparium grassland)
Coastal Live Oak-Redbay Woodland
(Quercus virginiana-persea borbonia (palustris?) Woodland)
Sea Oats-Bitter Panicum Herbaceous Vegetation
(Uniola paniculata-panicum amarum herbaceous vegetation)
Shore Bluestem - Gulfdune Crowngrass Tallgrass Prairie
(Schizachyrium littorale - paspalum monostachyum grassland)

MIXED ALLUVIAL

Mixed alluvial sediment areas (9%) are floodplains with a complex mix of textures, often loam with very small patches of sands or clays throughout

Communities (State Names):
Coastal Live Oak-Pecan Upland Woodland
(Quercus virginiana-carya illinoensis upland woodland)
Swamp Chestnut Oak-Willow Oak Forest
(Quercus michauxii-quercus phellos forest)
Gulf Cordgrass-Little Bluestem Herbaceous Vegetation
(Spartina spartinae-schizachyrium scoparium var. Littoralis vegetation)
Arkansas Cherokee Prairie, Dry Phase
(Schizachyrium scoparium - dichanthelium spp. - buchnera americana - echinacea pallida grassland)
Sand Bar
Dry Loess/Glacial Till Woodland

Plants
Cumberland Sand-Reed *(Calamovilfa arcuate)*, Purple Fringeless Orchid *(Platanthera peramoena)*, Hardhack *(Spiraea tomentosa)*, Short-Leaf Skeleton Grass (*Gymnopogon brevifolius)*, Rose Pogonia *(Pogonia ophioglossoides)*, California Bulrush *(Schoenoplectus californicus)*, Fragrant Ladies'-Tresses (Spiranthes odorata).

ACIDIC to NEUTRAL SEDIMENTARY BEDROCK

Sedimentary or meta-sedimentary rock (17%) with no reported alkaline components. This group includes sandstone, siltstone, mudstone, claystone, shale, conglomerate, arenite, argillite, and arkose. Soils are thin to well developed but bedrock is typically close to the surface.

Communities (State Names)

Beakrush-Sphagnum Herbaceous Vegetation
(Rhynchospora (oligantha, gracilenta)-sphagnum spp. Herbaceous vegetation)
Longleaf Pine/Little Bluestem-Coneflower Woodland
(Pinus palustris/schizachyrium scoparium-rudbeckia grandiflora woodland)
American Beech-White Oak-Maple Forest
(Fagus grandifolia-quercus alba-acer (barbatum, leucoderme) forest)
Sweetbay Magnolia-??? Wetland Woodland
(Magnolia virginiana-persia borbonia (palustris?) Wetland woodland)
Shortleaf Pine-Post Oak-Blackjack Oak-Southern Red Oak Forest
(Pinus echinata-quercus stellata-quercus marilandica-quercus falcata forest)
Mesic Sandstone Forest
(Mesic sandstone forest)
Bluejack Oak-Longleaf Pine Woodland
(Quercus incana-pinus palustris woodland)
Post Oak-Blackjack Oak-Black Hickory-(??? Oak-??? Oak) Forest
(Quercus stellata-quercus marilandica-carya texana-(quercus shumardii-quercus velutina) forest)
Bluejack Oak-Shortleaf Pine Woodland
(Quercus incana-pinus echinata woodland)

Amphibians
Fourche Mountain Salamander (*Plethodon fourchensis)*, Rich Mountain Salamander (*Plethodon ouachitae)*, Kiamichi Slimy Salamander (*Plethodon Kiamichi)*, Western Diamondback Rattlesnake (*Crotalus atrox)*

Birds
Red-Cockaded Woodpecker (*Picoides borealis)*

Mammals
Southeastern Myotis (Myotis austroriparius)

Plants
Ouachita Blazing-Star (*Liatris compacta)*, Maple-Leaf Oak (*Quercus acerifolia)*, Pelton'S Rose-Gentian (*Sabatia arkansana)*, Hay-Scented Fern (*Dennstaedtia punctilobula)*, Prairie Wild Hyacinth (*Camassia angusta)*, Prickly Gooseberry (*Ribes cynosbati)*, Brome Sedge (*Carex bromoides ssp. Bromoides)*, Crested Fringed Orchid (*Platanthera cristata)*, Missouri Spurge (E*uphorbia missurica)*, Spinulose Wood Fern (*Dryopteris carthusiana)*

MODERATELY CALCARIOUS SEDIMENTARY BEDROCK

Moderately alkaline sedimentary or meta-sedimentary rock with some calcium but less than rocks in the calcareous rock class. This group (15% of region) is composed of calcareous sandstones, calcareous shales or mixed sedimentary rocks with one or more calcareous components, calcium-silicate, and calcium-silicate schist rocks

Communities (State Names)

Presumably the "sandstone" in the names listed below refer to the calcareous sandstones typical of this region

Sandstone Glade
Dry Sandstone Woodland
Mesic Sandstone Forest
Dry-Mesic Sandstone/Shale Prairie
Pond Shrub Swamp and Marsh
Dry-Mesic Sandstone Forest
Dry-Mesic Sandstone Woodland
Little Bluestem-Indiangrass-Needlegrass Herbaceous Vegetation
(Andropogon gerardii-schizachyrium scoparium-stipa leucotricha herbaceous vegetation)
West Gulf Coastal Plain Fleming Calcareous Prairie
(Schizachyrium scoparium - rudbeckia missouriensis - grindelia lanceolata - (liatris mucronata) grassland)

Birds

Henslow's Sparrow (*Ammodramus henslowii)*, Black-Throated Green Warbler (*Dendroica virens)*, Sharp-Shinned Hawk (*Accipiter striatus)*, Willow Flycatcher (*Empidonax traillii)*, Sedge Wren (*Cistothorus platensis)*

Mammals

Indiana Bat (*Myotis sodalist)*, Ozark Big-Eared Bat (*Corynorhinus townsendii ingens)* Eastern Small-Footed Bat (*Myotis leibii)*, American Badger (Taxidea taxus)

Herptiles

Queen Snake (*Regina septemvittata)*, Ornate Box Turtle (*Terrapene ornata ornate)*, Hurter's Spadefoot (*Scaphiopus hurterii)*, Graham'S Crayfish Snake (*Regina grahamii)*

Plants

Ozark Chinquapin (*Castanea pumila var. Ozarkensis)*, Kentucky Lady's-Slipper (*Cypripedium kentuckiense)*, Waterfall'S Sedge (*Carex latebracteata)*, Moore's Delphinium (*Delphinium newtonianum)*, Ozark Spiderwort (*Tradescantia ozarkana)*, Arkansas Alumroot (*Heuchera villosa var. Arkansana)*, Ouachita Indigo-Bush (*Amorpha ouachitensis)*, Browne'S Waterleaf (*Hydrophyllum brownie)*, Open-Ground Whitlow-Grass (*Draba aprica)*, Small-Head Pipewort (*Eriocaulon koernickianum)*, Yellow Mandarin (*Prosartes lanuginose)*, Harperella (*Ptilimnium nodosum)*, Ovate-Leaf Catchfly (*Silene ovata)*, Ouachita Twistflower (*Streptanthus squamiformis)*, French's Shooting-Star (*Primula frenchii).*

CALCARIOUS SEDIMENTARY BEDROCK

Alkaline sedimentary or metasedimentary rock with high calcium content. This group included limestone, marlstone, calcarenite, carbonite, chalk, coquina, marble and marl. 6% of region. Dolostone is treated separately in the next category.

Communities (State Name)

Dry-Mesic Chert Prairie
Dry-Mesic Chert Forest
Chert Glade
Hardpan Prairie
Dry-Mesic Limestone/Dolomite Prairie
Dry Limestone/Dolomite Prairie
Ozark - Coldwater - Creek
Ozark - Special Communities - Cave Stream
Dry Chert Cliff

Birds

Willow Flycatcher *(Empidonax traillii)*

Herptiles

Oklahoma Salamander *(Eurycea tynerensis)*, Great Plains Skink *(Plestiodon obsoletus)*

Invertebrates

Neosho Mucket (*Lampsilis rafinesqueana)*, Ozark Cave Amphipod (*Stygobromus ozarkensis)*, A Predaceous Diving Beetle (*Heterosternuta phoebeae)*, A Springtail (*Arrhopalites clarus)*, Ellipse (*Venustaconcha ellipsiformis)*, A Cave Obligate Planarian (*Dendrocoelopsis Americana)*

Plants

Miterwort (*Mitella diphylla)*, Ozark Trillium (*Trillium ozarkanum)*, Rough Hawkweed (*Hieracium scabrum)*, Swamp Milkweed (A*sclepias incarnata ssp. Incarnata)*, Tassel-Flower (*Brickellia grandiflora)*, Wood Anemone (*Anemone quinquefolia var. Quinquefolia)*, Barren-Strawberry (*Waldsteinia fragarioides)*, Showy Lady's-Slipper (*Cypripedium reginae)*

Arkansas Fatmucket (*Lampsilis powellii),* Ouachita Creekshell (*Villosa arkansasensis),* Speckled Pocketbook (*Lampsilis streckeri)*

CALCARIOUS SEDIMENTARY BEDROCK - DOLOSTONE

Dolostone is an alkaline sedimentary rock with high calcium content. Areas of pure dolostone were separated out in the Ozarks ecoregion given the different ecological communities found on dolostone vs. other calcareous rocks. (9% of region)

Communities (State Names)

Glade
Dolomite Glade
Cave
Ozark Fen
Dry Chert Woodland
Dry Limestone/Dolomite Cliff
Dry Limestone/Dolomite Woodland
Dry-Mesic Chert Woodland
Cave Spring
Moist Limestone/Dolomite Cliff
Prairie Fen

Invertebrates

Bleedingtooth Mussel (*Venustaconcha pleasii)*, Rainbow (*Villosa iris)*, Snuffbox (*Epioblasma triquetra).*

Herptile

Ozark Hellbender *(Cryptobranchus alleganiensis bishop)*

Plants

Trelease'S Larkspur (*Delphinium treleasei)*, Beaksedge (*Rhynchospora capillacea)*, Large Indian-Breadroot (*Pediomelum esculentum)*, Yellow Coneflower (*Echinacea paradoxa var. Paradoxa)*, Western Wallflower (*Erysimum capitatum var. Capitatum)*, Bush's Skullcap (*Scutellaria bushii)*, Elliott'S Sida (*Sida elliottii)*, Lead-Plant (*Amorpha canescens)*, American Squaw-Root (*Perideridia Americana)*, Gattinger'S Prairie-Clover (*Dalea gattingeri)*, Heart-Leaf Plantain (*Plantago cordata)*, Virginia Mountain-Mint (*Pycnanthemum virginianum)*

ACIDIC GRANITIC and MAFIC/INTERMEDIATE GRANTIC

Quartz-rich, resistant acidic igneous and meta-igneous rock including very high grade meta-sedimentary rock. This group is primarily composed of granite, granodiorite, dacite, rhyolite, pegmatite, migmatites, quartzite rocks covering 3% of the region. The only occurrence in the regions is Taum Sauk mountain in the Missouri Ozarks, and once volcanic dome that has eroded away to its granitic roots, The volcanic origin is visible as rocky openings called igneous glades. The granitic rock maybe mixes with outcrop of extrusive igneous rock (Mafic) which covers 0.06% of the region. Taum Sauk is the highest point in Missouri.

Communities (State Names)

Igneous Glade
Dry Igneous Woodland
Dry-Mesic Igneous Forest
Dry-Mesic Igneous Woodland
Dry Igneous Cliff
Moist Igneous Cliff
Igneous Talus

Plants

The glades that can harbor unusual desert-adapted plants and animals, such as Sundrop flower (*Oenothera sp*) and the eastern collared lizard (Crotaphytus collaris). Rare species include Leafy Bulrush (*Scirpus polyphyllus)*, Blueberry Hawthorn (*Crataegus brachyacantha) and* Loesel's Twayblade (*Liparis loeselii). MAFIC:* Missouri Spurge (*Euphorbia missurica)*, Pelton'S Rose-Gentian (*Sabatia arkansana)*

NOVACULITE

Novaculite is a microcrystalline to cryptocrystalline rock type that consists of silica in the form of chert or flint. Novaculite is very hard and dense and resistant to erosion and the novaculite beds stand out as ridges in the Ouachita

Communities (State Names)

Post Oak Novaculite Woodland
Novaculite Glad

No element occurrences intersected any novaculte outcrops but the community has been described as a woodland is known from outcrops of novaculite (and other substrates) in the Ouachita Mountains of Oklahoma and possibly Arkansas. Typical canopy dominants are Quercus stellata, Ulmus alata, Quercus marilandica, Juniperus virginiana, Pinus echinata, Carya texana, and Fraxinus americana. Common herbaceous species are Schizachyrium scoparium, Eupatorium altissimum, Helianthus hirsutus, and Sporobolus clandestinus. This community occurs as small areas (0.5-10 acres), scattered on ridges and upper slopes. Outcrops and talus are scattered throughout, with calcareous inclusions.

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CHAPTER 3

ESTIMATING SITE RESILIENCE

The physical characteristics of a site—its topography, soil characteristics, and the presence of wetlands—can buffer resident species from the direct effects of climate change. Plants and animals experience climate at such local scales that a landscape with topographic variation is experienced as a mix of microclimates: dry to wet, or cool to hot depending on slope position and aspect. Microclimates allow species to find pockets of suitable moisture and temperature even where the average background climate appears unsuitable. Intact sites with little fragmentation and a large variety of microclimates may enable species to persist longer, even indefinitely, under a changing climate, because individuals and populations can shift their locations locally to take advantage of the microclimate variation.

Wetlands, including groundwater-fed springs and seeps, riparian wetlands, prairie potholes, and playas also can be used to indicate relative differences in site resilience for areas with flatter topography. The extent and variety of wetlands is likely to provide a good indicator of even subtle differences in topography and soils that contribute to microclimate variation, especially differences in moisture levels.

Sites with little fragmentation and many microclimates are hypothesized to have high **site resilience** because the climatic variation allow them to retain diversity and ecological functions longer than sites that are fragmented and flat. In this section, we describe the concepts, methods, and data used to estimate the relative resilience of any given site. The two factors important to the estimate—**landscape diversity** and **local connectedness**—are discussed separately, because the tools for assessing and measuring them are distinctly different.

Section 1: Landscape Diversity

Our first climate resilience factor - Landscape Diversity- addresses variation in topography, elevation and wetness as indicators of microclimate variation.

Projections of future climate patterns should inform our conservation strategies, but it's important to remember that these data are regional averages over large areas while species experience climate at very local scale. Changes in global and regional climate interact with local factors such as topography and landform to modify microclimate conditions in patterns that are much more predictable at local scales. Understanding and mapping these landscape-based indicators of local climatic variation is the focus of this section.

Landscape-based climatic variation is substantial, on par with, and often greater than expected climatic changes for a region. These variations can be measured in even a gently rolling landscape, such as Northern England, where temperature loggers placed across gradients of slope, aspect and elevation have revealed site differences in monthly maximum temperatures exceeding 34^0 F (Suggitt et al. 2011). In California's serpentine grasslands, microtopographic thermal climates also showed a 34^0 F difference between maximum values at different slopes (Dobkin et al. 1987). In these grasslands, areas of high local landscape diversity are important for long-term population persistence of butterfly species and their host plants under variable climatic conditions (Weiss et al. 1988). Vegetation, with its high moisture content, moderates the effect of topography on temperature variation, but even in heavily forested landscapes, variation in aspect and topography can create large differences in temperature. For instance, in the Southern Blue Ridge Mountains scientists have measured a 25^0F difference between a hot south-facing slope and a cool sheltered ravine in mid-summer (P. McMillan, pers. comm., October 2010).

The distribution of moisture in a landscape is also correlated with topography and aspect. Topography has been found to explain 40%-72% of soil moisture variation in Appalachian forests (Yeakley et al. 1998). In grasslands, aspect alone can explain as much of 20% of the local differences in soil moisture (Bennie et al. 2006 & 2008). Many studies of landscape-based climate variation show how strongly local climatic variation explains species distribution patterns, suggesting that understanding microclimates is a key to understanding species persistence (Ashcroft et al. 2009, DeFrenne et al 2013, Dobrowski 2011, Pincebourde et al. 2016, Yeakley et al. 1998).

Topography redistributes temperature and precipitation so dramatically that in some landscapes no areas experience the "average" regional climate: basins are wetter, summits are dryer, south-facing slopes are hotter, and north-facing slopes are cooler. Coarse-scale models predicting the loss of all suitable habitats for plants in the Swiss Alps conversely predicted the persistence of suitable habitats for all species when they were rerun at local scales that captured topographic diversity (Randin et al. 2009).The term "microclimatic buffering" (Willis and Bhagwat 2009) has been coined for the situation where climate interacts with topography, moisture and aspect to create suitable climatic combinations for species in areas where coarse-scale climate models suggest unsuitable climate. In effect, microclimates "buffer" the resident species from the direct effects of regional climate change.

By mapping a landscape's relevant variation in topography, aspect and moisture, we can incorporate proxies for microclimate variations into conservation planning. Specifically, the number and variety of topographically-derived microclimates present at a site—its **landscape diversity**—can be used to estimate the capacity of the site to maintain biological diversity over time (Anderson et al. 2014a).

In this section we describe our methods to quantify landscape diversity at a relatively fine scale across the study area, and to estimate the number of species-relevant microclimates in 40 ha circle around every 30-m cell. Our spatial models were built from continuous surfaces of digital elevation data, and the landscape diversity estimates were derived from topography, aspect and moisture estimates. The latter step included:

1. Landform Variety: the variety of landforms derived from topographic position, slope and aspect.
2. Wetland Influence: the density of wetlands (including playas), and small waterbodies.

Landform Variety

Landforms are natural features of the earth's surface created by topography - collectively the set of landforms comprises a region's terrain. A single landform can be described as a combination of topographic position, aspect, slope, and moisture (e.g. moist north-facing toeslope). The distribution of landforms in a landscape determines local vegetation patterns because these characteristics drive stable patterns of temperature and moisture, and correlate with exposure, nutrient availability, and soil depth (Barnes et al 1982, Forman 1995). Landform variation may create subtle biotic variation or distinct habitats such as a depression wetland, cove forest, or summit grassland.

The basic landform unit (a.k.a. ecological land unit, land facet, land segment, elementary landform, or relief unit) is the smallest homogeneous division of the land surface at a given scale. Because each unit is characterized by attributes such as elevation, slope, aspect, exposure, moisture, and topographic position, they can be used at a proxy for topographically-based microclimates, and the number and variety in an area can provide an estimate of the number of microclimates available to species.

To map landforms and quantify microclimates, we developed a GIS model that divides and classifies a continuous terrain surface into one of 17 landforms. Our methods are based on those of Fels and Matson (1997), and are described in detail elsewhere (Anderson 1999, Anderson et al. 2012). To delineate landforms, we started with a 30-m digital elevation model (DEM; Gesch 2007, Canada Digital Elevation Data 2011), and use it to derive estimates of slope, aspect, land position, and moisture accumulation for each pixel in the study area. For each of these variables, we defined thresholds that allowed us to partition values into different zones (Figures 3.1 and 3.2) that corresponded with recognizable distinctions that had meaning relative to species distributions, or other ecological patterns, and could be verified with data collected in the field. The primary divisions in the model were based on relative land position and slope, and then slopes were further divided by aspect, and flats by moisture accumulation (Figures 3.1-3.3).

To create the landform model, we generated the following initial datasets as grids from the 30-m DEM:

- Topographic Position Index: We evaluated the elevation differences between any cell and the surrounding cells within a search radius of 350 m and scored it using a topographic position index (TPI). For example, if the model cell was, on average, higher than the surrounding cells, then it was considered closer to the hill top (a more positive position value), and conversely, if the model cell was, on average, lower than the surrounding cells, then it was considered closer to the slope bottom (a more negative position value).

- Slope: Degree of slope was calculated as the difference in elevation between two neighboring cells, expressed in degrees.
- Aspect: Aspect was calculated using the GIS Aspect tool which fits a plane to the z-values of a 3 x 3 cell neighborhood around a center cell. The direction the plane faces is the aspect for the center cell.
- Moisture Index: We calculated a moisture index using a flow accumulation model which maps variation in moisture accumulation and soil residence time using the equation: *Moist index = ln [(flow accumulation + 1) / (slope + 1)]*.

We used National Wetlands Inventory (NWI) datasets (U. S. Fish and Wildlife Service 2017) to calibrate the moisture index and set a threshold for dividing flat areas into place where moisture is more likely (moist flat) or less likely (dry flat) to accumulate. To address strong patterns in moisture availability across the study area, we examined each ecoregion separately, and defined moist areas as those with a moisture index greater than one-half (>= 0.5) Standard Deviation (SD) above the mean value of the moisture index under known wetlands for that ecoregion. This criterion effectively captured the known wetlands in the study region without overpredicting moist areas far outside of the known wet places. The moisture index threshold, i.e., ranged from the low threshold value of 1400 in the Mississippi River Alluvial Plain and the Gulf Coast Prairies and Mashes to a high value of 2780 in the Ouachita Mountain ecoregion.

Mapped wetlands were then added to the model as an additional landform called "wet flat" to denote areas where current wetlands existed in any form: emergent, forested, or scrub-scrub wetland. These wetland areas are assumed to be a more permanent source of wetland habitat than was described for the "moist flat" landforms in upland land cover and were thus a significant microclimate refuges.

The mapped wetland patches included all NLCD 2011 emergent and forested wetlands and all NWI wetlands of type emergent, forested, or scrub-scrub greater than 2 acres. Subcodes within the NWI dataset were used to remove anthropogenically created or highly altered wetlands tagged as: excavated, impounded, spoiled, farmed, or water regime artificially flooded. Our mapping focus was on naturally occurring, naturally maintained, and the most permanent wet flat landforms. Wet flats were also limited to cells falling on flat and gentle slope landforms to clean up small errors in the NLCD due to remote sensing erroneously mapping wetlands on shaded slopes. Any NWI wetland pixels now under NLCD 2011 developed or row crop agriculture were also removed to update the dataset with recent wetland conversion which was not accounted for in the NWI given the varying date of its creation.

Open water was added last as another unique landform by mapping any perennial lake, pond, stream, river, or sea/ocean polygons >2 acre in size from the National Hydrography Medium Resolution Version 2 (USGS 2017) dataset. Spatially, we restricted the "open water" landform to NHD waterbody areas also mapped as "open water" in the NLCD 2011 land cover dataset to make the edges of the waterbodies agree with our master land cover and land area dataset. We did not include the many thousands of smaller "open water" pixels that are present in the NLCD 2011 landcover dataset (and some finer resolution hydrography datasets) because visual inspection and expert review confirmed nearly all small waterbodies in this area were dammed, artificially created stock ponds, or farm ponds that could be

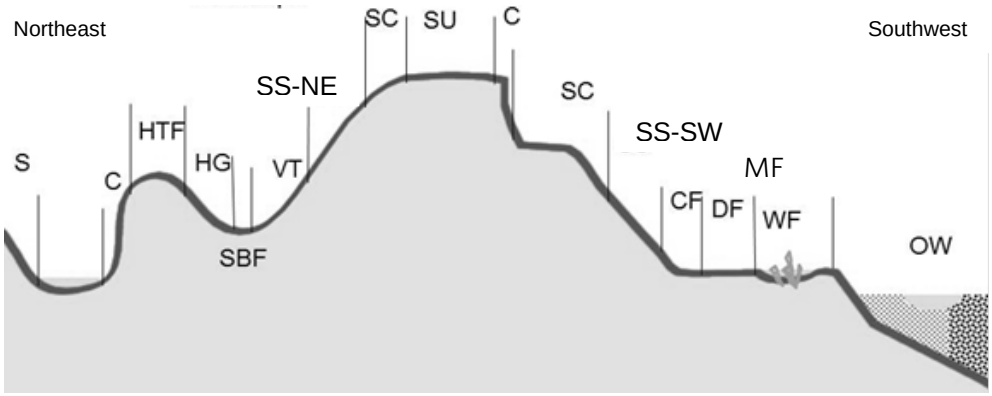
easily removed in the future. Non-permanent waterbodies, noted as such in the NHD as impermanent or in NWI wetland data, were left as part of the wet flat and moist flat landforms.

We combined the datasets for topographic position, slope, aspect, wet flats, moist flats, and water to create a continuous grid of landforms. For example, a south-facing side-slope (landform 23) was defined by land position, slope and aspect, whereas a moist flat (landform 39) was defined by land position, slope and moisture accumulation (Figure 3.2). The landform model can theoretically distinguish any number of units, but we used a 17-unit model that our past assessments using species and community occurrence data where these divisions matched recognizable environments with differing vegetation, especially in the herbaceous layer. We worked with our Steering Committee to evaluate results at various stages using maps of familiar locations and comparisons of different site types, such as those shown in Figure 3.3.

To identify areas with the highest diversity of microclimates, we calculated the variety of landforms in a 40.4 ha (100-acre) circle surrounding every 30-m cell (Figure 3.4) using a focal variety analysis. This search area corresponds to roughly a 350-m radius around each focal cell and was chosen because it provides the best discrepancy between cells (highest between-cell variance), and is reasonable for a wide range of species, in that it suggests local population movements could access a 40.4 ha (100-acre) neighborhood.

In the count of landforms each type was given 1 point except for wet flats which were given 1 more point if they occurred in the focal circle, bringing the total possible score to 18. We made this change to account for the importance of wetlands and moisture in this region, particularly in flat landscapes where other microclimate refuges were limited. If for example two sites had the same total number of landform/microclimates but only one contained “wet flats”, the site with the wet microclimates would score higher.

Figure 3.1: Distribution and Definitions of Landforms.



S - Steep slope (SW and NE aspects): a steeply sloping escarpment, headwall, ledge, or bluff, less vertical than a cliff. The accumulation of rock fragments at the base creates talus slopes.

C - Cliff: a high, steep or overhanging face of rock or earth. Cliffs provide nesting places for birds and crevice-rooting ferns.

HTF - Hilltop flat: the level top of a low hill with low local relief, rising slightly above surrounding lowlands.

HG - Hill gentle slope: the sloping sides of a hill or rounded land surface with low local relief, rising slightly above surrounding

SBF - Slopebottom flat: the flat channel in a narrow steep-sided ravine, commonly V-shaped in cross section. Slopebottom flats usually contain streams.lowlands.

VT - Valley/toeslope: the hillslope position that forms the gently inclined surface at the base of a hillslope. Toeslopes in profile are commonly gentle and linear, forming depositional environments.

SS – Sideslope (SW and NE aspects): the hillslope profile position that forms the moderately steep middle portion of the hill or mountain. Bounded by convex shoulder and concave footslope.

SC -Slope crest: a slope crest or shoulder is the hillslope position that forms the convex, erosional surface near the top of a hillslope, transitioning from summit to sideslope.

SU -Summit/ridgetop: the topographically highest position of a hillslope profile with a nearly level surface. Typically, summits have thin soils and extreme winds.

CF - Cove/footslope (SW and NE aspects): refers to the hillslope profile position that forms the concave surface at the base of a hillslope. A moist, nutrient-rich, depositional setting.

DF - Dry flat: a level plain or flat land surface in a low landscape position that does not accumulate water.

MF - Moist flat: a level plain or flat land surface in a low landscape position that accumulates some water.

WF - Wet flat: the nearly level to gently concave bottom surface of a flat basin that accumulates substantial water. Most wetland habitats are found in wet flats.

OW - Water/lake/river: open waterbodies, often in the center of a wet flat and large river segments.

Figure 3.2: The Underlying Slope and Land Position Model used to Map Landforms.
Adapted from Fels and Matson 1997.

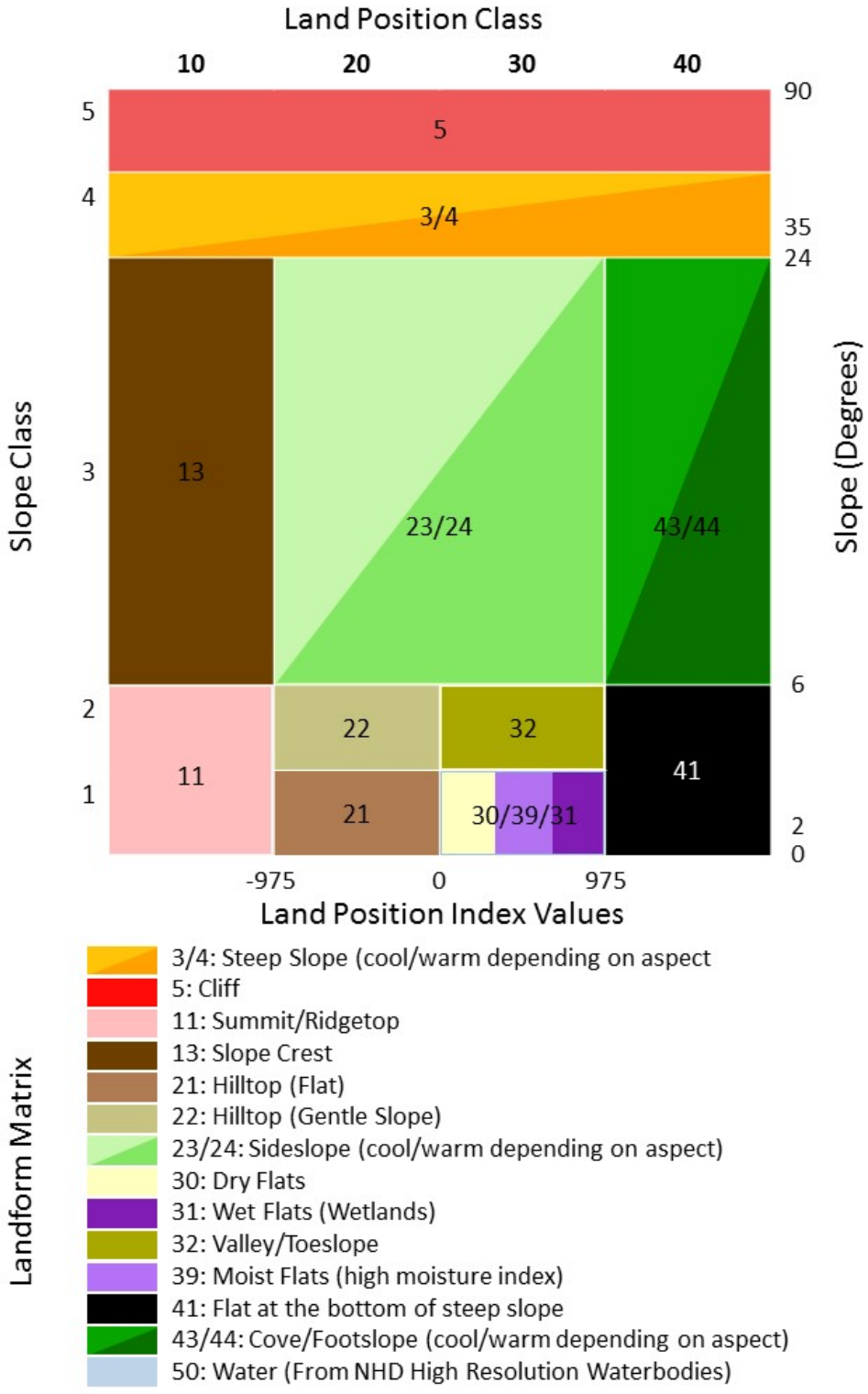


Figure 3.3: The 17-unit Landform Model. These images show how the landform model partitions the landscape based on slope, aspect, land position, and moisture accumulation using the Palo Duro Canyon, Armstrong Texas, Southern Shortgrass Prairie Ecoregion, as an example. The area includes a wide spectrum of landforms—from steep slopes, sideslopes, and coves in the canyon to flatter surrounding plains where gentle hills, dry flats, and playa wetflat areas are common. **A)** The area in shaded relief, **B)** with an overlay of the landforms. **C)** A 3-D representation.

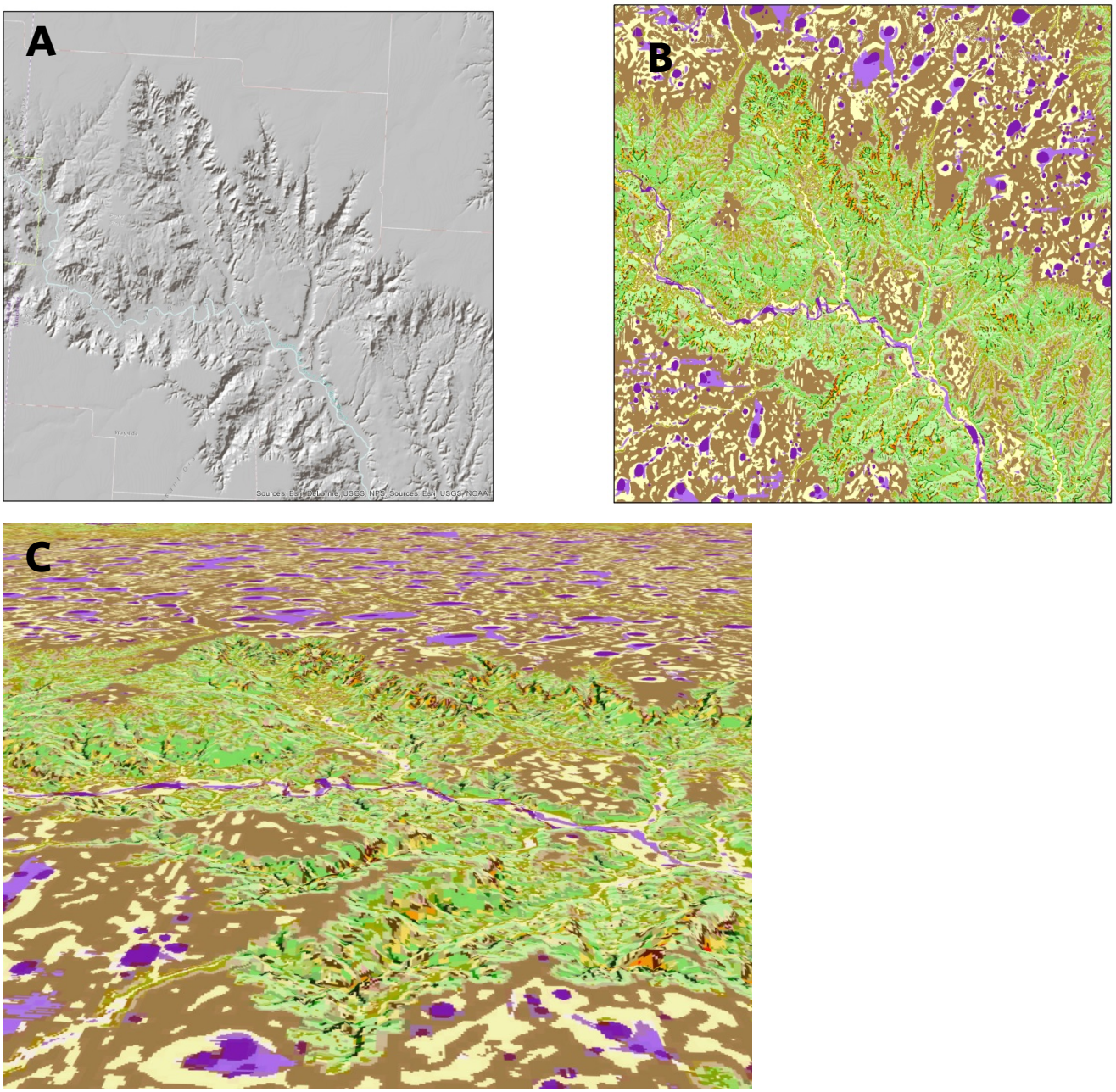


Figure 3.4: Landforms. The Lower Mississippi focal region mapped as 17 landform types. These landforms are used to characterize the region's topography and to calculate the landform variety metric (30m cell mapping resolution).

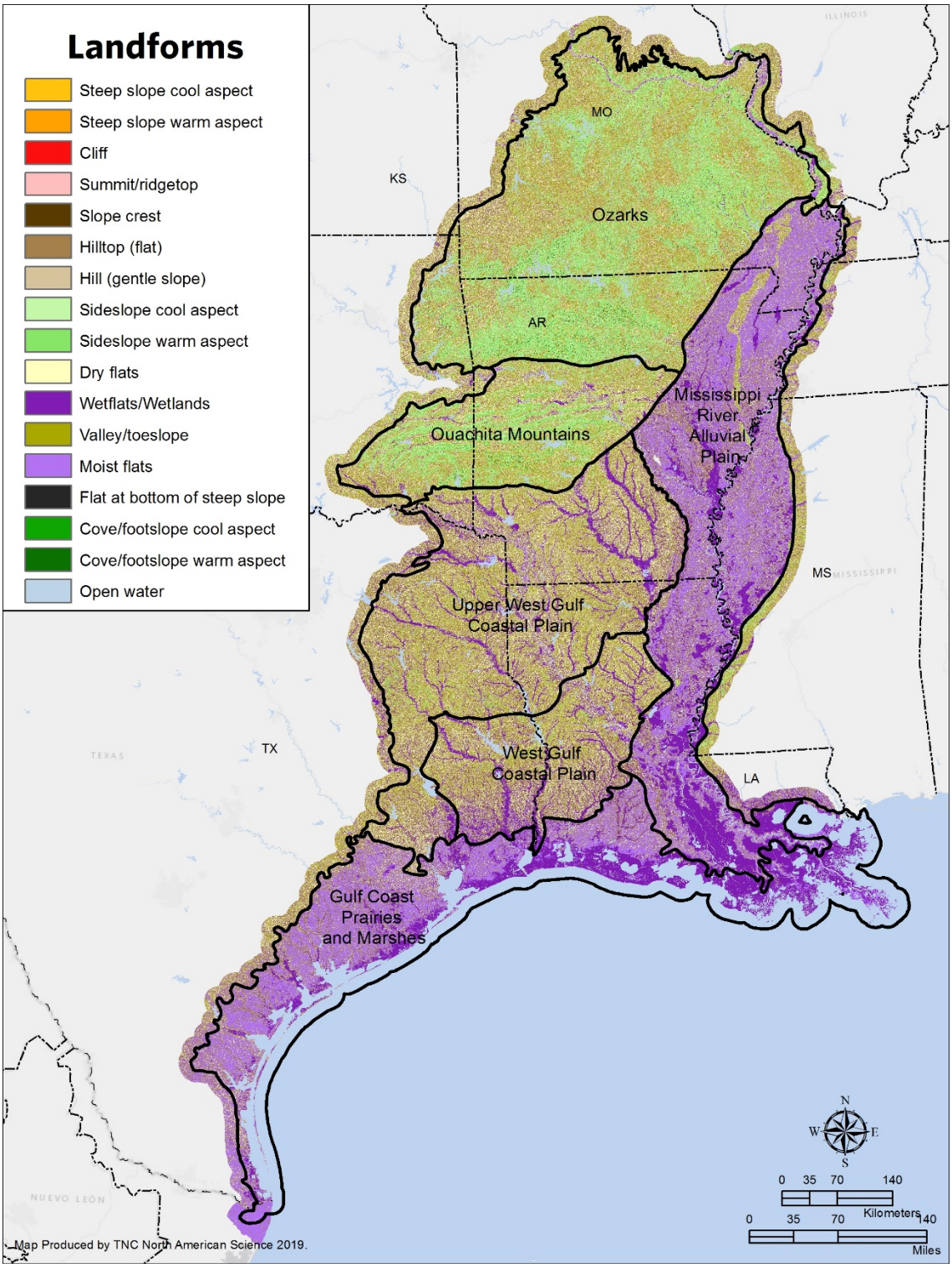
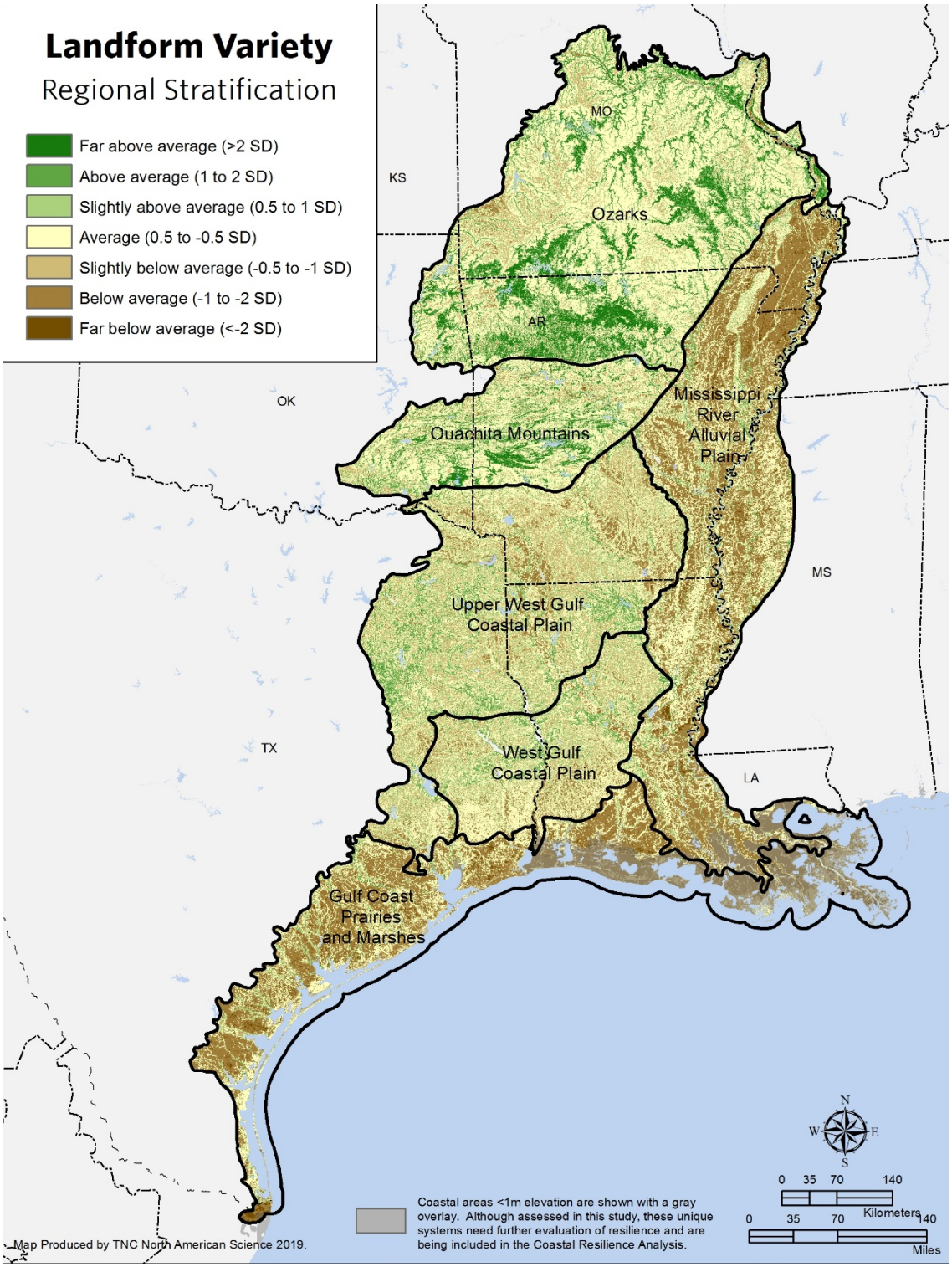


Figure 3.5: Landform Variety. The distribution of the counts of number of landforms in a 100-acre circle for the full Lower Mississippi-Ozark study area. Areas with higher landform counts (more topographic variation) appear in green, and lower counts (flatter) appear brown. When applied to resilience this is recalculated by ecoregion.



Wetland Influence

In low relief areas where landform variety is inherently low, microtopographic variation determines where moisture accumulates. As the climate changes, persistent wetlands will become increasingly important because they retain soil moisture longer and preserve a mixture of organic and wetland soils. Further, wetland basins tend to have high evapotranspiration rates and play a unique role in moderating the climate and sustaining the resilience of a landscape (Geiger et al. 2003). Protecting wetlands and riparian corridors has been suggested as one of the single best actions in promoting resilience and in sustaining biodiversity (Naiman 1993, Fremier 2015).

Because of their singular importance in providing water and moist microclimates we calculated a wetland density metric to measure and evaluate wetland areas. Our goal was to account for the importance of wetlands by adjusting the landscape diversity metric to include an independently derived wetland-influence metric. When combined with the estimates of microclimatic variation based on all landforms, this effectively increases the positive influence of wetlands on the site resilience score (Figure 3.6).

We expect that the parts of the landscape that contain wetlands will continue to be important under variable climates even though the size and wetness of the areas are likely to change. However, small isolated wetlands are often more vulnerable to shrinkage and disappearance than wetlands embedded in a landscape dense with other wetlands, and the wetland density metric allowed us to identify and map these dense areas.

To analyze the distribution of current wetlands, we compiled a base dataset of mapped wetlands as discussed above in the landform section. This included all NLCD emergent and forested wetlands and all NWI wetlands larger than 2 acres (emergent, forested, or scrub-scrub). Subcodes within the NWI dataset were used to remove anthropogenically created wetlands (i.e. excavated, impounded, spoiled, farmed, artificially flooded) to focus on mapping only naturally occurring wetlands (Figure 3.7).

We calculated a **wetland density** score using the same scale as landform variety: the percentage of wetlands within a 40.4 ha (100-acre) circle centered on each 30-m cell using a focal mean function in GIS. We excluded open water from the density calculation so that density was relative to the amount of land. Because dense wetland areas are, almost by definition, big and flat, we calculated the metric at two scales (100-acres and 1000-acres) to provide better discrimination between sites that might look identical at the 100-acre scale. To do this, we further weighted the score by assessing the wetland density of a larger 404 ha (1000-acre) circle around each focal cell and calculating the percentage of wetlands in this larger area. We combined this into one value for each cell, giving twice the weight to value from the smaller (closer to the focal cell) circle.

Z-Scores: To integrate the two scales, we transformed the values to approximate a normal distribution and then calculated a standardized normalized score (Z score) for each scale. A standard normal transformation (Z-score) is used throughout this project for combining datasets.

The formula for calculating the Z-scores is:

$$z = \frac{x - \mu}{\sigma}$$

The cell score "x" minus the mean score of all cells "μ" divided by the standard deviation of all cells "σ

Areas with no wetlands (wetland density of zero) were assigned to the lowest Z score value of -3.5 SD. We combined the scores search distances using the formula:

*Wetland Density = (2*100-acre wetland density + 1000-acre wetland density) / 3.*

To final result combining both scales was again transformed to Z-scores using mean and SD calculated from only cells where wetlands were present to yield a final wetland density score; areas with no wetlands were assigned the lowest (-3.5 SD) score (Figure 3.8).

Final Landscape Diversity Score

To create a final map of landscape diversity, we combined the Z-score grid of landform variety with the Z-score grid of wetland density to merged them into a single score by taking the maximum value of either grid (Figure 3.6). For each cell, we used the maximum of the following two options as the final landscape diversity score:

1. Landform Variety Z Score
2. (Landform Variety Z + Wetland Score Z) / 2

By using the maximum value, the wetland density was only incorporated in cells where it increased the base landform variety score.

The final result was transformed to Z-scores scale to assure the final mean was zero and the standard deviation was 1 across the whole study area (Figure 3.9).

Figure 3.6: Landform, Landform Variety, and Wetland Scores. These figures illustrate how the wetland density score complements the landform variety score in places where there is little landform variation (average landform variety score) but a high density of wetlands (high wetland density score).

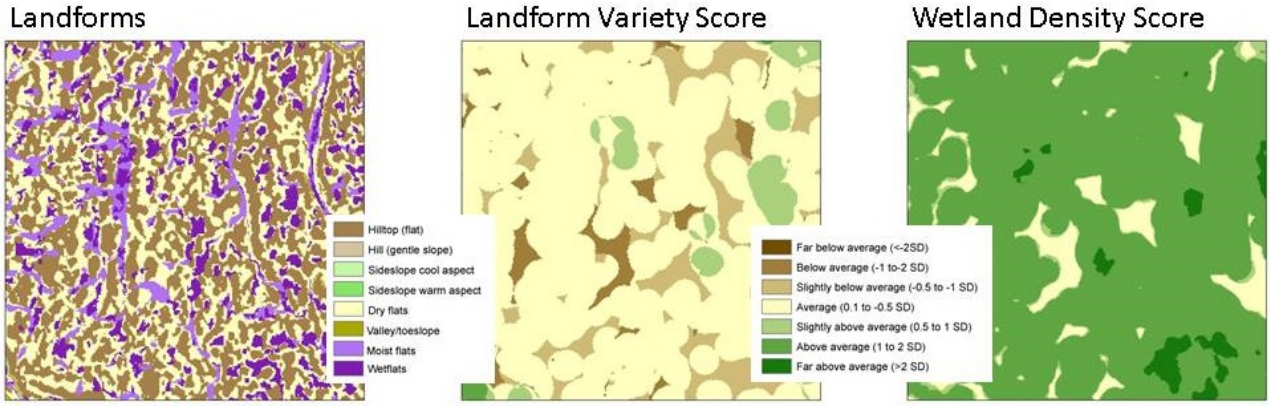


Figure 3.7: Wetlands in the Lower Mississippi-Ozark study area. The distribution of wetlands and small waterbodies in the region.

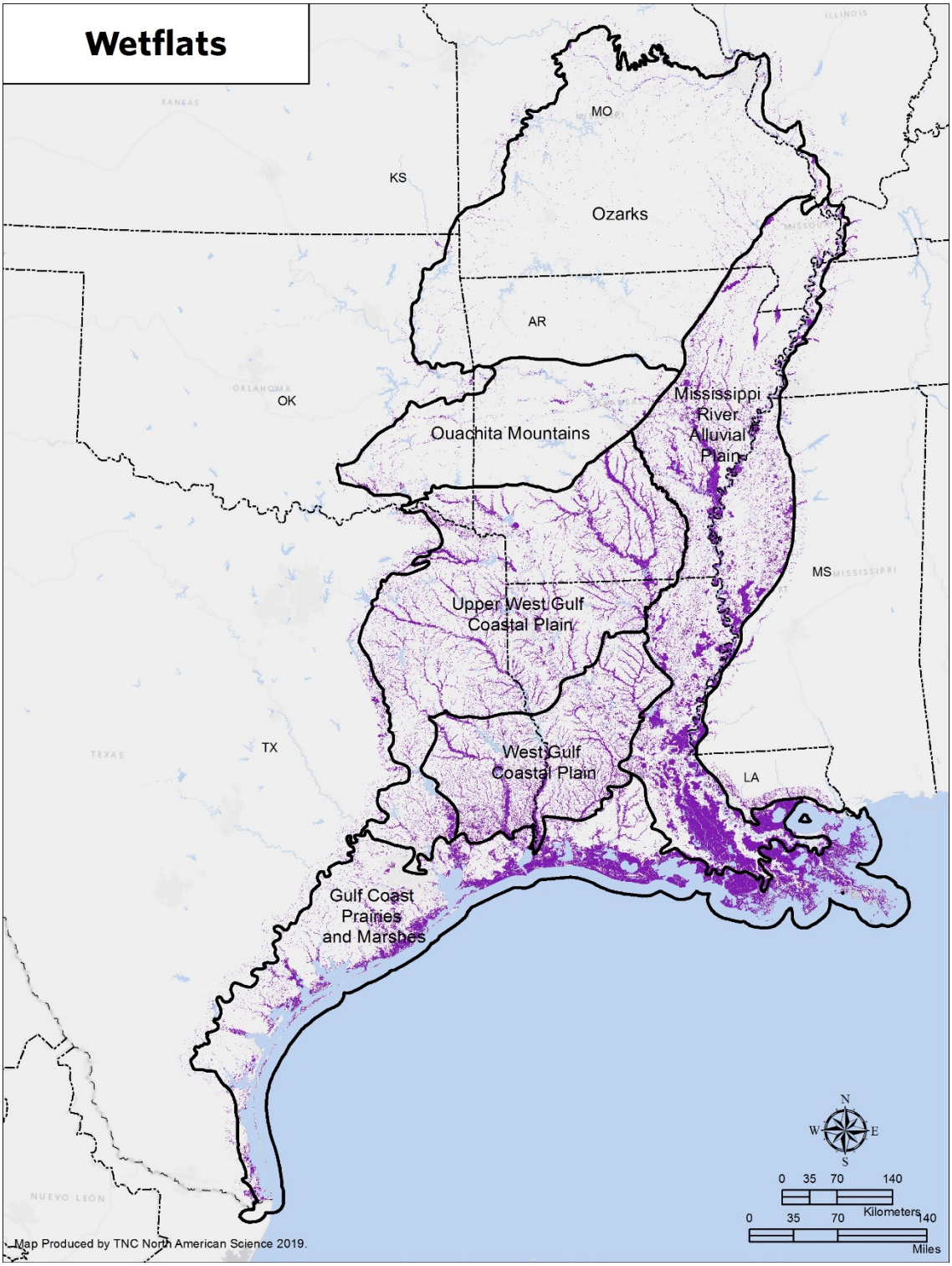


Figure 3.8: Wetland Density in the Lower Mississippi-Ozark study area. Weighted density of wetlands in 40- and 404-hectare circles around each central cell compared to the regional average.

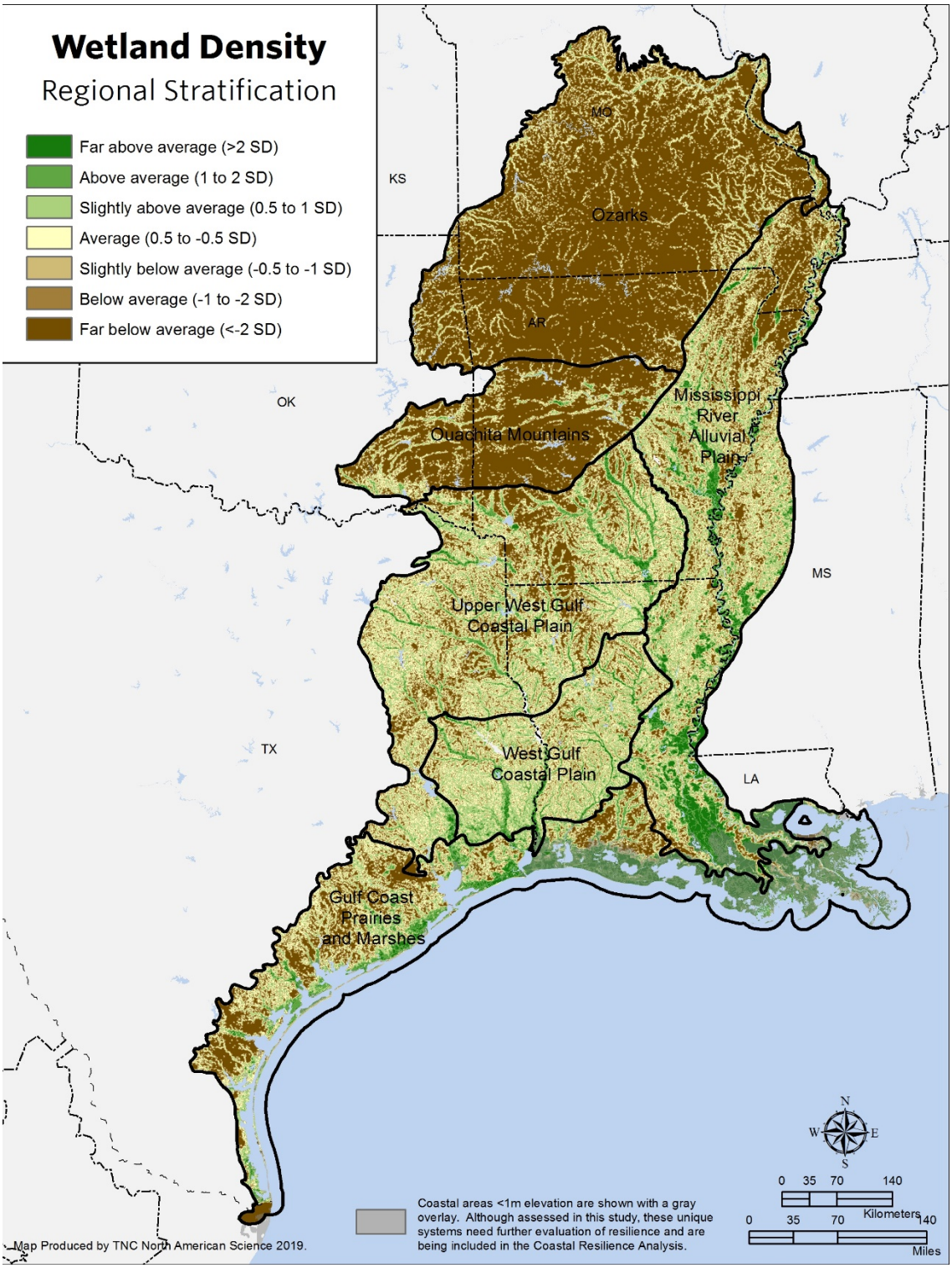
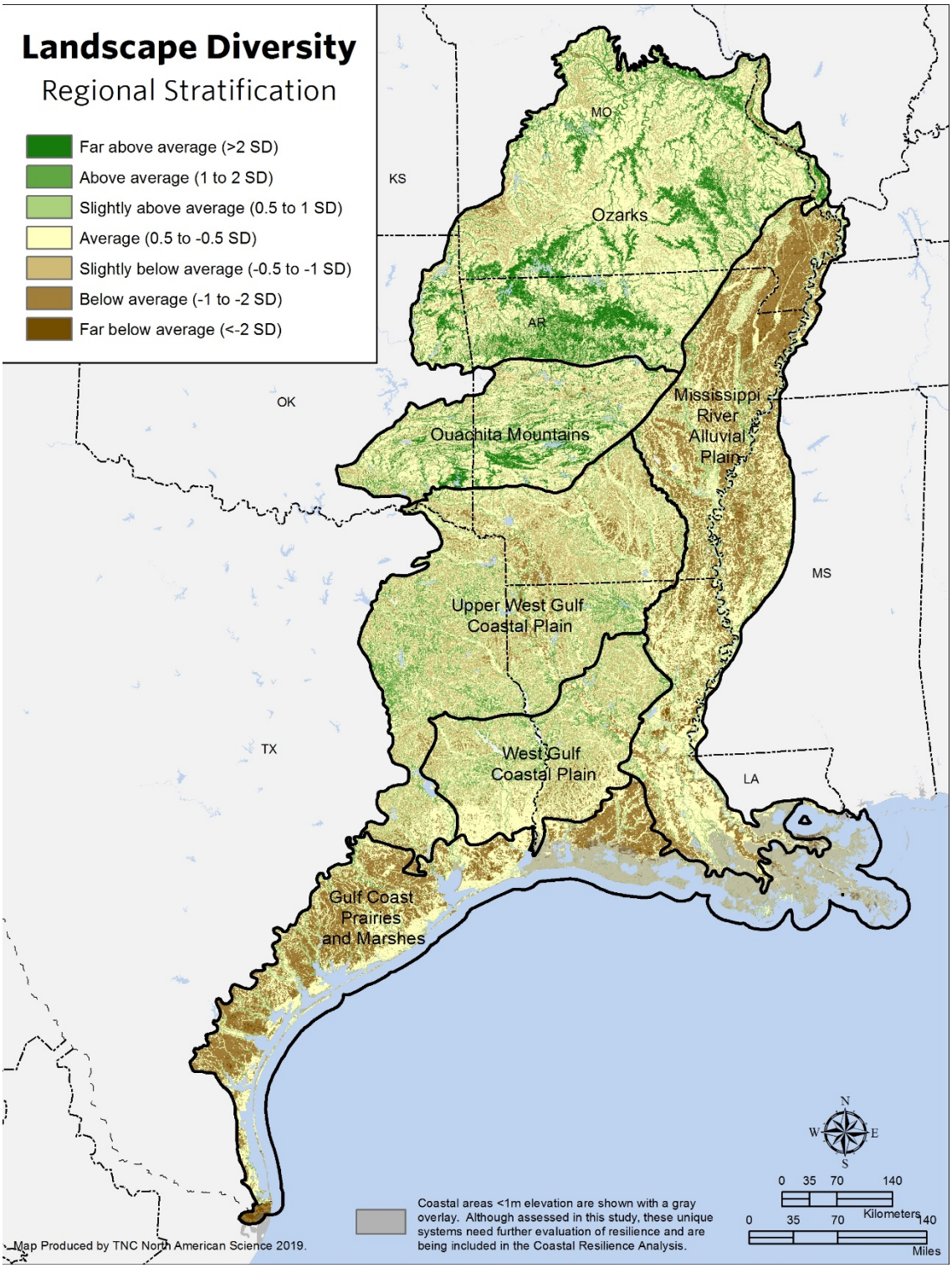


Figure 3.9: Landscape Diversity of the Lower Mississippi-Ozark study area. Landscape diversity based on the combined values of landform variety and wetland influence. Values are relative to the entire study area.



Section 2: Landscape Permeability

Climate change is expected to alter seasonal temperature and precipitation patterns, and intensify disturbance cycles of fire, drought, and flood. Rapid periods of climate change in the Quaternary, when the landscape was comprised of continuous natural cover, resulted in many changes to species distributions but few extinctions (Botkin et al. 2007). Now, pervasive fragmentation across the U.S. disrupts ecological processes and impedes the ability of many species to adapt to change. Industrial agriculture, development, roads, and other barriers will likely impair the ability of species populations to move, and for nature to adjust to rapid change, leading to depleted environments and less diversity. Not surprisingly, the need to maintain **connectivity** has emerged as a point of agreement among scientists researching key strategies for helping biodiversity adapt to climate change (Heller and Zavaleta 2009, Krosby et al. 2010). In theory, maintaining a permeable landscape, when done in conjunction with protecting and restoring enough areas of high-quality resilient habitat, should facilitate the expected range shifts and community reorganization of species. Regional scale models suggest that the rate of natural migration for plants will not keep pace with the rate of climate change (Iverson et al. 1999; Iverson et al. 2004; Iverson and McKenzie 2013), highlighting the importance of microclimate buffers and refugia, and the need for species to be able to move locally to take advantage of them.

We prefer the terms '**permeability**' and **'connectedness'** over 'connectivity' because the latter is defined as the capacity of individual species to move between areas of habitat via corridors and linkage zones (Lindenmayer and Fischer 2006). Accordingly, analyses of connectivity entail identifying linkages between specific places, usually patches of good habitat or natural landscape blocks with respect to a species (Beier et al. 2011). In some studies, areas to connect have been defined by level of legal protection (e.g., Belote et al. 2016), which is particularly problematic in area with little protection but many large expanses of natural habitat in private ownership. Our emphasis on permeability reflects a goal of facilitating large-scale reorganization of species in response to climate change, which we suggest requires a comprehensive and continuous analysis: all organisms, in all directions, over many years.

Landscape permeability is a measure of landscape structure: the hardness of barriers, the connectedness of natural cover and the arrangement of land uses. It is defined as *the degree to which regional landscapes, encompassing a variety of natural, semi-natural and developed land cover types, will sustain ecological processes and are conducive to the movement of many types of organisms* (definition modified from Meiklejohn et al. 2010). Accordingly, we developed methods that map permeability as a continuous surface, not as a set of discrete cores and linkages. Our aim was to create a surface that reveals the implications of the landscape structure with respect to the continuous flow of natural processes like dispersal, migration and recruitment.

We developed two analytical models to assess different aspects of permeability. The first, **local connectedness,** starts with a focal cell and estimates the resistance to flows outward from the cell in all directions. The second, **regional flow,** examines broad east-west and north-south flow patterns across the entire region. Both metrics estimate how flow becomes blocked, slowed, redirected, or channeled due to the spatial arrangement of human land uses and the remaining natural lands. The local connectedness metric was used in estimating the resilience of a site and the

descriptions below refer to this metric. Regional flow analyses for the study areas is discussed in a later chapter of his document.

Local Connectedness

The **local connectedness** metric estimates the resistance/permeability surrounding a focal cell if movements were to flow outward in all directions from its center point. As a component of resilience, this metric estimates how easily species can access the microclimates within their local neighborhood based on the arrangement of roads, industrial agriculture, development and other human structures that create resistance to movement by creating barriers or increasing the risk of harm.

In the local connectedness model, the permeability of two adjacent cells increases with the similarity of those cells with respect to their land cover. If adjacent landscape elements are identical (e.g., forest to forest), then there is no disruption in flow. A contrasting element (e.g., forest to developed land) creates resistance and the connection is presumed to be less permeable. Organisms can and do move across different landscape elements, but the sharper the contrast is in structure, surface texture, exposure, or chemistry, the more likely it is that movement will be altered or slowed. The degree to which a cell alters the flow arriving from an adjacent cell is its **resistance**, and the corresponding land use is assigned a **resistance weight** based on its expected resistance.

Creating a Resistance Grid

Our analysis of resistance began with a step of sorting the landscape into three basic landscape elements and assignment of general resistance weights from 1-20:

1. Natural lands (resistance weights 1-5): Landscape elements where natural processes are unconstrained and unmodified by human intervention. Examples include grasslands, wetlands, and forests.
2. Agricultural or modified lands (resistance weights 5-9): Landscape elements where natural processes are modified by direct, sustained and intentional human intervention. Nutrients are often depleted and use by species may be constrained by management actions or chemical applications, fencing, and other barriers.
3. Developed lands (resistance weights 8-20): Landscape elements dominated by the direct conversion of physical habitat to buildings, roads, parking lots, or other infrastructure associated with human habitation and commerce. Vegetation is highly tended, manicured, or controlled.

Methods to quantify and objectively assign resistance weights have included similarity indices based on vegetation types or land cover classes (B. Compton personal communication 2009, Compton et al. 2007). Our weighting scheme was generalized with respect to vegetation types such that any natural land cover element adjacent to another natural land cover element was scored with a low resistance value assuming that dispersal and population movement requirements are less specific than those for breeding. In addition, our goal was to maintain the natural relationships and connections between all types of natural land and was not targeted towards a specific species (Hunter 2002, Ferrari and Ferrarini 2008, Forman and Godron 1986).

To create the resistance grid, we combined and integrated several datasets representing land cover, land use, roads, railroads and agriculture. The primary data source was the 30-m 2011 NLCD, which identifies each grid cell as belonging to one of 16 classes of land cover (Homer et al. 2015). We made several upgrades to the basic land cover data that substantially improved their performance as resistance grids. These included improved mapping of:

1) Oil and gas development
2) Wind energy development
3) Natural lands and artificial barrens and mines
4) Waterbodies
5) Roads and railroads
6) Energy transportation – pipelines and powerlines
7) Agricultural modifications
8) Industrial Forests

Table 3.1: Resistance scores. The land cover categories from the National Landcover Classification Database (NLCD) and the corresponding resistance scores assigned to each for assessing landscape permeability in the Lower Mississippi.

Land Cover Code (NLCD)	Land Cover Description	Resistance Score	Source
21	Developed, Open Space	8	NLCD 2011
22	Developed, Low intensity	8	NLCD 2011
23	Developed, Medium Intensity	9	NLCD 2011
24	Developed, High Intensity	20	NLCD 2011
31	Barren Land, non-natural	10	NLCD 2011
32	Barren Land, natural	1	NLCD 2011
41	Deciduous Forest	1	NLCD 2011
42	Evergreen Forest	1	NLCD 2011
43	Mixed Forest	1	NLCD 2011
52	Shrub/Scrub	1	NLCD 2011
71	Grassland/Herbaceous	1	NLCD 2011
81	Hay/Pasture	1	NLCD 2011
82	Cultivated Crops	7	NLCD 2011
90	Woody Wetlands	1	NLCD 2011
95	Emergent Herbaceous Wetlands	1	NLCD 2011

Oil and Gas Development:

With about 200,000 active and inactive wells, the study area is clearly impacted by oil and gas development. Oil and gas development results in both direct and indirect effects on species movement. Roads and well pads fragment the landscape and the noise associated with pumping and daily vehicle traffic amplify the effect of fragmentation discouraging the movement native species and favoring invasive species. Hydraulic fracking uses large amount of water, which can exacerbate water stress in this by drought-prone region.

We collected oil and gas well data from all the states in the study area (Table 3.2). To estimate the spatial effects of oil and gas wells on resistance to movement, we formed an oil and gas working group within the Steering Committee to help calibrate the data, guide the analysis, and review results. Based on the Steering Committee members' observations, and discussion of existing research, we set a goal of giving the highest density oil and gas areas (>16 wells per square mile) a resistance effect equal to that of medium-density development. We used a two-pronged approach to accomplish this where part of the score comes from the resistance weight, and part comes from the density and pattern of development. To estimate the resistance of the well pads themselves, we created a 540 x 540-meter well pad area around each well point. The 540 m square was chosen because at that size, the highest density well pads (>16 wells per square mile) form a continuous coverage. To account for the cumulative and indirect effects of dense oil and gas development (traffic and noise) we generated a point density grid based on the individual well points (no well pads) and using a kernel density function which is sensitive to (and sometimes magnifies) small differences. We included both inactive wells and active wells in the density calculation, but inactive wells received 1/10 the weight of active wells. We converted the density grid to a resistance surface using a graduated weighting so cells with a higher density of points had higher resistance (Table 3.3 Figure 3.10).

Table 3.2: Oil and Gas Source Data. For each state, this table lists the data source, number of wells, and shows how the well classification was divided into active and inactive wells.

Arkansas 30,593 wells	Source: Arkansas GIS Office https://gis.arkansas.gov/product/arkansas-oil-and-gas-wells/ **Active:** Active, Permitted, Spud **Inactive:** Inactive, Plugged
Oklahoma 11,162 Wells	Source: Oklahoma Corporation Commission (excel database) https://www.occeweb.com/Orawebapps/OCCORaWebAppsone.html There is a field for active and inactive
Texas 1,308,669 wells	Source: Texas Railroad Commission - http://www.rrc.state.tx.us/about-us/resource-center/research/data-sets-available-for-purchase/digital-map-data/digital-map-data-statewide-prices/ **Active:** Brine Mining Well, Dry Hole Well, Gas Well, Horizontal Drainhole, Injection Disposal Well from Gas, Injection Disposal Well from Oil/Gas, Injection Disposal Well from Oil, Injection Disposal Well, Oil Well, Oil/Gas Well. Shut in Well (Gas), Shut in Well (Oil), Sidetrack well Surface Location, Storage Well, Water Supply from Oil, Water Supply Well. **Inactive:** Canceled Location, Core Test, Observation Well, Permitted Location, Plugged Gas Well, Plugged Oil Well, Plugged Oil/Gas Well
Louisiana 240,864 Wells	Source: http://sonris-www.dnr.state.la.us/gis/dnld/download.html **Active:** Active – Injection Aquifer Remediation, Active Injection Community Salt Water Disposal, Action Injection ER—Injection (Water), Active Injection Produced Salt Water, Active Producing Gas, Active Producing Oil, Approval to Construct Injection Well, Permitted, Reverted to single completion No product Specified, Shut-In Dry Hole Future Utility No Product Specified, Shut-In productive Future Utility Gas, Shut-In productive Future Utility Oil, Temporarily Abandoned Well no product Specified **Inactive**: Orphan Well Eng Gas, Orphan Well Eng Oil, Orphan Well Injection and mining not product specified, Dry and Plugged gas, Dry and Plugged no product specified, dry and plugged oil, formation storage gas, Permit expired, plugged and Abandoned Dry Gas, plugged and Abandoned Gas, plugged and Abandoned Oil, plugged and Abandoned Dry no product specified, Plugged Back. Unable to locate.
Missouri 10,470 Wells	Source: https://dnr.mo.gov/geology/geosrv/oilandgas.htm Has Well Status Field.
Mississippi 16,766 Wells	Source: County spreadsheet from **Active:** Active Injection, Closed In (producing well), Completed Well, Drilling, Domestic Gas Well, Producing, Stand-by (Injection Well) **Inactive:** Appears to be plugged and Abandoned No Records, Appears to be plugged/Abandoned Surv. Inspect, Dry and Abandoned, Plugged and Abandoned

Table 3.3: Well Density Resistance Weights.

Well Density	Resistance Weight
0 – 1 wells per square mile	0
1-2 wells per square mile	0.2
2-4 wells per square mile	0.4
4-8 wells per square mile	0.6
8- 16 wells per square mile	0.8
16 wells per square mile	1.0

To create a single integrated layer, the well pad area was given a resistance score of a 9, and the well density resistance weights (Table 3.3.) were added to the base score from land cover. For example, an area that was not on a well pad and had natural cover (resistance = 1) but was within an area of 4-8 wells per square mile (resistance = 0.6) got a resistance value of 1+0.6 = 1.6. An agricultural area that has 4-8 wells per square mile got a resistance score of 7 (agriculture) plus 0.6 (well density) = 7.6.

Wind Energy:

There are only a few locations of industrial scale wind turbines in the Lower Mississippi – Ozark region, but we wanted to make sure they were captured in the resistance grid. Although wind power is one of the cleanest and sustainable energy sources, there are a variety of environmental impacts associated with wind energy that may affect the connectedness of the area surrounding a turbine. The landcover at the base of the wind turbine is permanently disturbed, and a larger area is disturbed during construction. There are also impacts from the roads connecting the turbines. Research is ongoing on the effect of turbines on wildlife. The impact on birds and bats is the most well studies and the area of impact varies depending on the species.

To represent wind energy development in our resistance dataset, we used the United States Wind Turbine Database which is a joint project funded by U.S. Department of Energy (DOE) Wind Energy Technologies Office (WETO) via the Lawrence Berkeley National Laboratory (LBNL) Electricity Markets and Policy Group, the U.S. Geological Survey (USGS) Energy Resources Program , and the American Wind Energy Association (AWEA) (Hoen et al. 2019). It is a continuously updated GIS dataset of land-based and offshore wind turbines in the United States.

To map the impact in the local connectedness score, we used a 1-mile kernel density with the same resistance weights as oil and gas development (Table 3.4). Due to lower impact of wind development on the habitat in this landscape for many species (though clearly not all) relative to oil and gas development, we did not inflate the area of the turbine base, as we had done with the well heads. Our final coverage for the effect of wind development is shown in Figure 3.11.

Figure 3.10: Oil and Gas Well Density. The density of oil and gas wells in study area based on source data from every state and province.

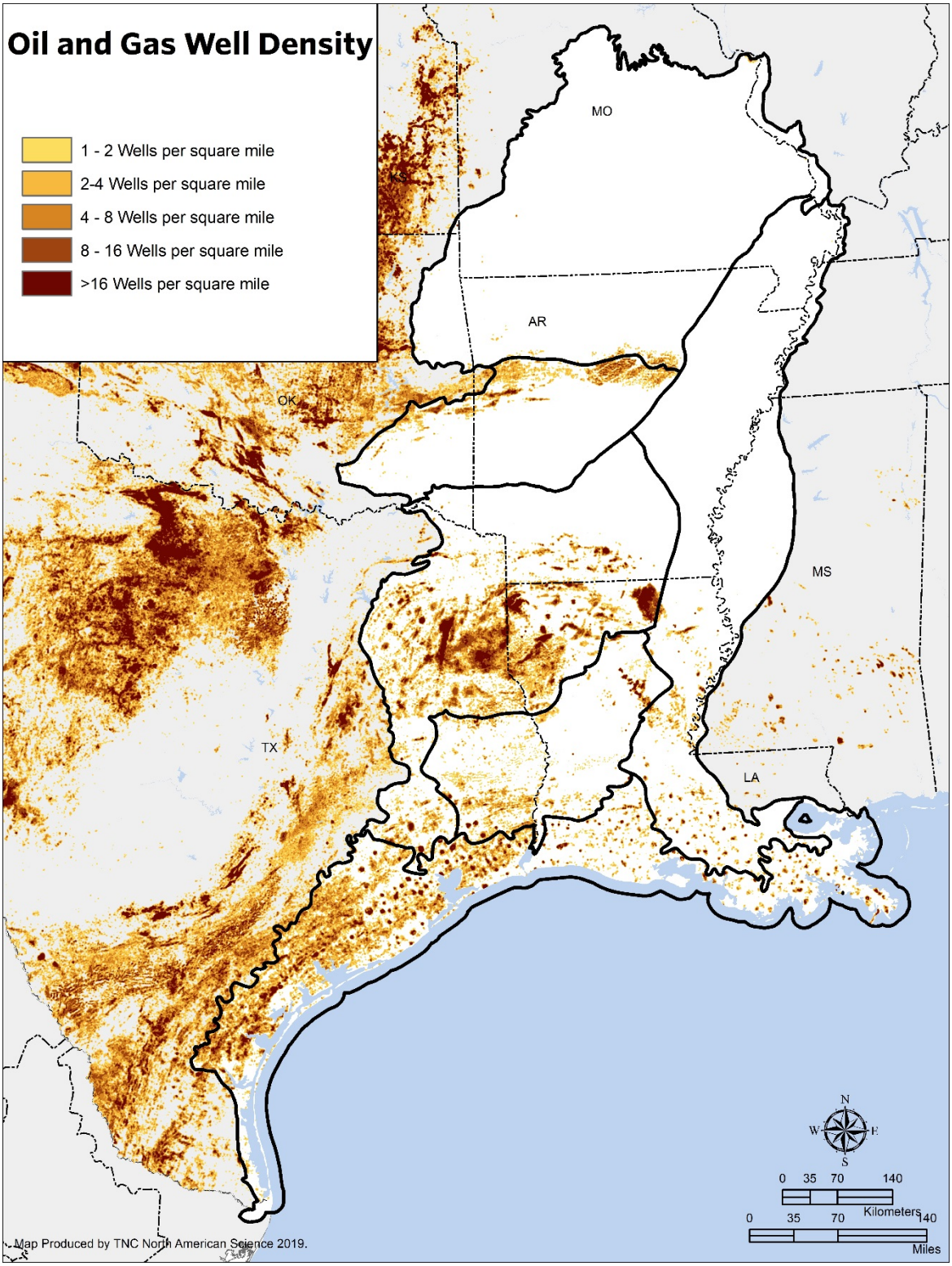
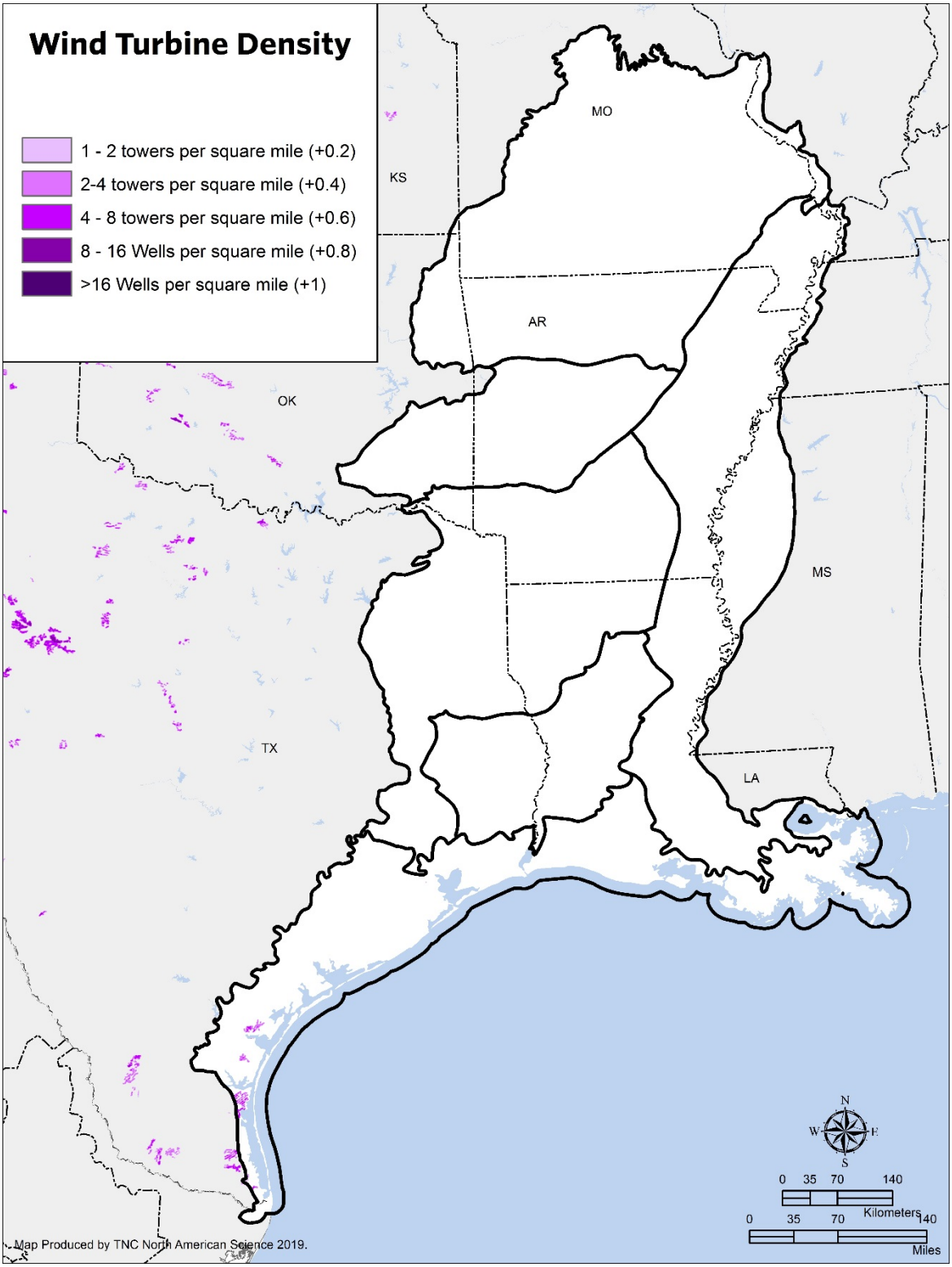


Figure 3.11: Wind Turbine Density. The density of wind turbines in the study area based on FAA Digital Obstacle data set and the US Wind Turbine database.



Barrens:

In the land cover datasets, the category "barrens" often mixes developed lands such as oil and gas wellheads with natural barrens such as riparian areas, mudflats, and sandy bare soil. To distinguish between developed and natural barrens, we visually inspected all barrens larger than 50 acres using satellite imagery and manually assigned them to one category or the other. For polygons less than 50 acres in size, we used decision rules based on the degree of development, shore line, agriculture, and roads in the surrounding 1000 acres to classify them into natural and non-natural barrens. After these rules were applied, some areas had conflicting results, and did not get classified; these we assigned to "natural". A subset of these barrens was visually inspected to confirm that the majority were natural.

Mining operations were identified using USGS's significant topographic changes in the United States Dataset (USGS 2018), which captures areas of topographic changes from surface mining, urban development, and landfills. Areas identified in this dataset were given a score same as "developed barrens".

There were several key natural areas that we suspected could show up as "barrens." To make sure they were correctly classified in the resistance grid, we compiled and used the Natural Glades in Missouri and Arkansas (2016) dataset to identify natural glades in these two states. We used the PAD-US dataset and the TNC protected lands dataset to identify lands that were permanently protected for biodiversity calculated the resistance in these lands to be natural(PAD-US http://www.protectedlands.net/; TNC Lands http://www.tnclands.tnc.org/). Also, based on steering committee comments, we used the PAD US dataset to identify NRCS wetland conservation easements and scored these the same as natural.

Natural barrens were assigned a resistance score of "1," the same as natural cover. Developed barrens and surface mines were assigned a resistance score of "10" to reflect their highly developed and modified nature.

Waterbodies:

We adjusted the resistance score of waterbodies to reflect their size, because very large waterbodies impede the movement of terrestrial species more than small streams or ponds. To quantify the effect of waterbody size, we first created a waterbody file from the waterbodies in the landforms (see Chapter 2) and the NLCD cells classified as water. We assigned water within 200 m of a shoreline a resistance value of "1," water between 200 and 400 m of a shoreline received a resistance value of "3,"and water greater than 400 m from a shoreline was given a value of "5" to reflect a stronger barrier as the waterbody size increases (Figure 3.12). Streams and ponds that had less than 200 m of shoreline were all assigned a "1."

Roads:

The 2011 NLCD landcover data set (Homer et al. 2015) contains an embedded roads data set from the Bureau of Transportation Statistics that does not align with the newer and more accurate 2016 Tiger Road dataset (U.S. Census Bureau 2017). To correct this issue, we removed the older roads from the NLCD and replaced them with roads from the Tiger 2016 dataset. To do this, cells in the 2011 NLCD's "developed open space" class were shrunk by one pixel to remove linear road pixels but not the larger

developed areas. Values for these cells were replaced with the majority value of the surrounding pixels. Next, the 2016 Tiger roads were "burned in" on top of the 2011 NLCD replacing the older road data with the more recent data. Similarly, we burned road data from the National Road Network (National Road Network 2017) into the compiled Canadian land use data, which did not contain information on roads except for major highways.

Unpaved roads, including forest management roads, are unevenly mapped in the U.S. landcover dataset, even though they collectively constitute substantial road networks in some parts of the region. To map unpaved roads, we used data from OpenStreet Map (2017) which is an open source global dataset built by a community of mappers that contribute and maintain data about roads and trails. We extracted roads tagged as "track" which includes roads used primarily for agriculture and forest logging (i.e., two-track roads). This class of roads is usually unpaved but may include paved roads. Trails and paths that are not wide enough for a two-track vehicle are excluded from this class. Although the quality and consistency of this dataset is not known, visual inspection suggested that it was more comprehensive than any other available dataset for mapping unpaved roads.

We assigned major roads a resistance score of 20 (e.g., multi-lane interstate highways, MTFCC code S1100) and secondary roads a resistance score of 10 (e.g. two-lane county highways, MTFCC codes S1200, S1630, SS1780). Residential roads were assigned a score of a resistance score of a 7 (MTFCC code S1400, S1640). Cells were assigned an additional resistance point if they contained one or more unpaved roads. For example, the resistance of agriculture cells with unpaved roads increased from a "7" to a "8" (Table 3.4).

Energy Transportation – Pipelines and Powerlines:

To account for the influence of energy infrastructure, we added the locations of pipelines and powerlines to the landcover datasets. To do this, we obtained power industry GIS data (Ventyx 2017, used with permission). We selected all transmission lines in service by voltage class, and all in-service natural gas pipelines. These were incorporated into the landcover dataset using power industry standard right-of-way widths: 30-m width for transmission lines <230 kilovolts, and 180-m width for lines > 230 kilovolts. All pipelines were given a 30-m width (Duke Energy 2019). Underground powerlines are occasionally in the Ventyx data and where this was specified, we tagged them in the dataset.

We assigned transmission lines a resistance of "7" and pipelines were assigned a resistance score of "4" (Table 3.4).

Agricultural Modifications

Rice fields are flooded much of the year and they provide important habitat for migrating birds. Before development, these areas would likely have been classified as wet prairies with freshwater wetlands but that ecosystem is 99% lost to farming and development. Rice fields may be replacing the ecosystem services of the wetlands so we weighted rice agriculture as "5" relatively close to natural. We use Cropscape data,

to identified areas that were in rice agriculture in the majority of the last 7 years (United States Department of Agriculture 2018).
Hay/Pasture is often a mixed land cover class in the NLCD. In the coastal plain, these areas can be natural or adjacent to natural grazing lands. In the mountains, hay/pasture lands are more dissimilar to the natural forested landscape and are more likely to be harvested hay agriculture. In the Coastal Plain ecoregions (Upper West Gulf Coastal Plain, West Gulf Coastal Plain, Mississippi River Alluvial Plain, Gulf Coast Prairie and Marshes), hay/pasture lands received a resistance score of a 1. In the mountain ecoregions (Ozark, Ouachita) hay pasture was given a resistance score of a 3.

Industrial Forests

Industrial forests dominate much of the Southeastern Coastal Plain but are not separated as a distinct type in the NLCD land cover where they are simply classified as forest. To identify industrial forests, we used a Global Forest Change dataset (Hansen et al 2013) that uses satellite imagery to detect areas where forests have been lost or gained (regrowth) over the last 15 years (Figure 3.13). We classified all land that have recently been cut or regrown as industrial forest.

In this region there is a strong hunting and fishing ethic and the best management practices employed by forest owners are designed to support wildlife and game populations. The steering committee agreed that in contrast to other parts of the southeast, here industrial forest creates only slight barriers to connectivity. Therefore, we increased the resistance only slightly. We assigned industrial forests a resistance score of "1.5" as this land use is subject to frequent cutting, road development and other anthropogenic disturbances, and typically has less groundcover (Figure 3.24). An exception was when the industrial forests were on land that was permanently secured against conversion (GAP Status 1 – 3). For the secured lands we used the Protected Areas US (PAD-US) dataset. Because these lands, by definition, are being managed for natural values we assigned them a lower resistance score of "1.2."

Figure 3.12: Waterbodies and the Zones used in the Resistance Weighting. The left panel shows a satellite image of a waterbody. The same waterbodies appear in the right panel symbolized in blue. Darker blues indicate higher resistance values at 0-200, 200-400, and 400+ m.

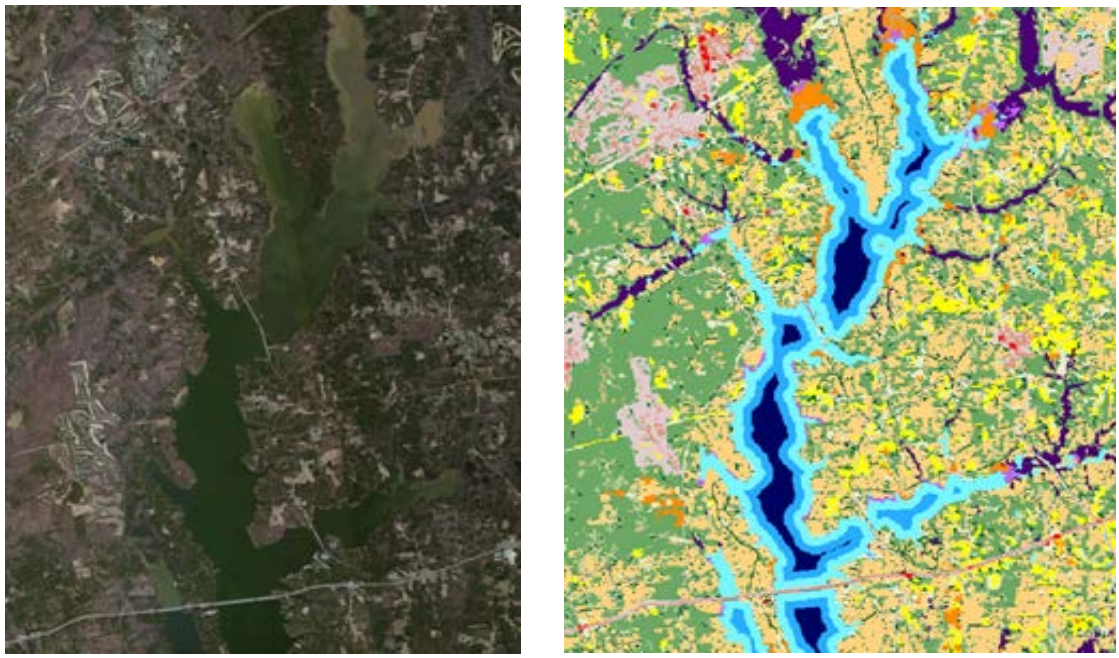


Figure 3.13: Industrial Forest. The left panel shows a satellite image of industrial forests, and the right panel shows the same area with mapped areas of recent forest loss or gain in orange.

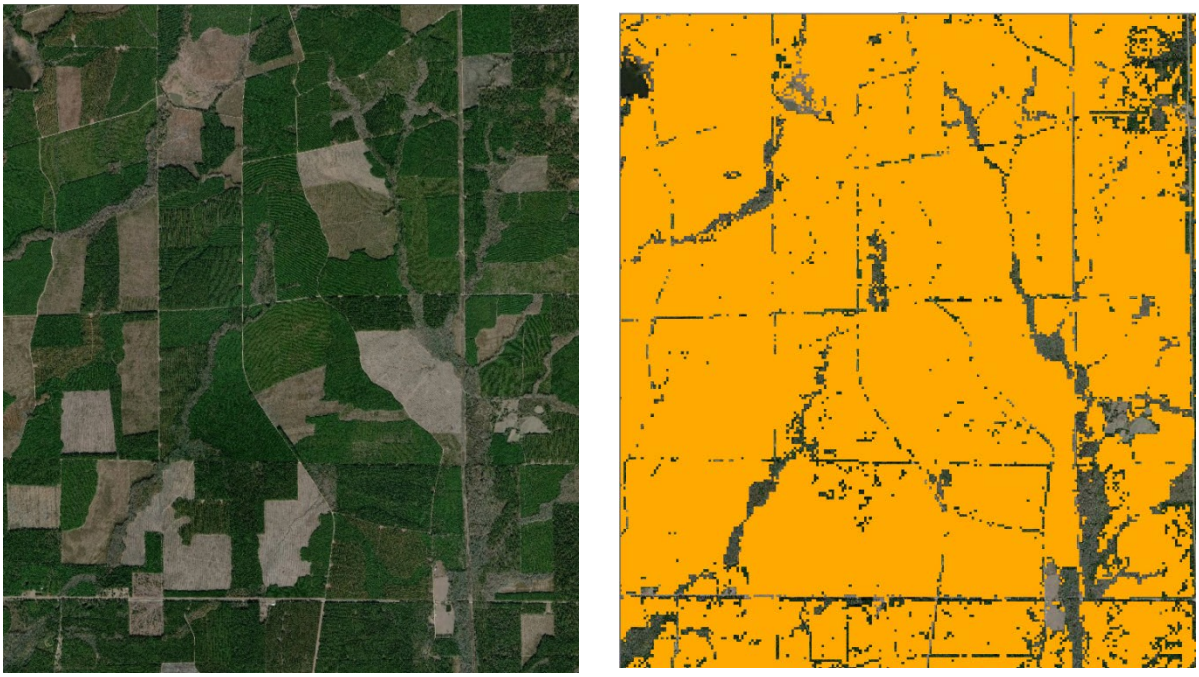


Table 3.4. Summary of Weights and Data Sources for Water, Roads and Energy Infrastructure.

Category	Resistance weight	Source
Waterbodies: Distance to Shoreline		
<200 m	**1**	**NLCD, NHD, NHN, ArcGIS Analysis**
200 - 400 m	3	NLCD, NHD, NHN, ArcGIS Analysis
>400 m	5	NLCD, NHD, NHN, ArcGIS Analysis
Roads & Railroads		
Major Roads	**20**	**Tiger 2016**
Minor Roads	10	Tiger 2016
Residential Roads	7	Tiger 2016
Dirt Roads	Resistance +1	Open Street Map Tracks (US) and Tiger Vehicular Trail (4WD) S1500 (US)
Railroads	9	CTS 2016
Energy Transportation		
Transmission Lines	**7**	**Ventyx 2017**
Pipelines	4	Ventyx 2017

Mapping Local Connectedness

Connectedness refers to the connectivity of a focal cell to its ecological neighborhood when the cell is viewed as a source (Compton et al. 2007). The analysis estimates the extent to which ecological flows outward from a cell are impeded or facilitated by the surrounding landscape. In the connectedness model, the theoretical spread of a species or process outward from a focal cell is a function of the resistance values of the neighboring cells and their distance from a focal cell out to some maximum distance where the influence is considered zero.

We mapped local connectedness using a resistant kernel model developed by Brad Compton of the University of Massachusetts (Compton et al. 2007), who helped us run the model for the complete study region. The first step in running the model was to convert the 30-m landcover and roads data in to a "resistance" grid by coding each land cover class with the resistant weights described above (Table 3.1, 3.3, & 3.4). Next, we assigned a maximum distance of 3 km to the model (the default value recommended by the software developer) to represent the distance where the influence on the focal cell is zero. The computationally intensive model estimates the resistance around each cell based on a weighted sum of the resistance of all cells in the 3-km radius. The focal cell is then scored between 0 (least connected) and 100 (perfect connectedness). The map of all focal cell scores creates a continuous wall-to-wall estimate of local connectedness (Figures 3.14 and 3.15).

Figure 3.14: Examples of Four Resistant Kernel Cells shown with the Land Cover and Roads Map. The focal cell is the central point of each kernel and the spread, or size, of the kernel reflects the amount of constraints. The score for the focal cell is based on the area round the cell (i.e., the constraints) and is shown here in a bluish-purple color. Kernel A is the most constrained and has the lowest connectedness score, while D is the least constrained and has the highest connectedness score.

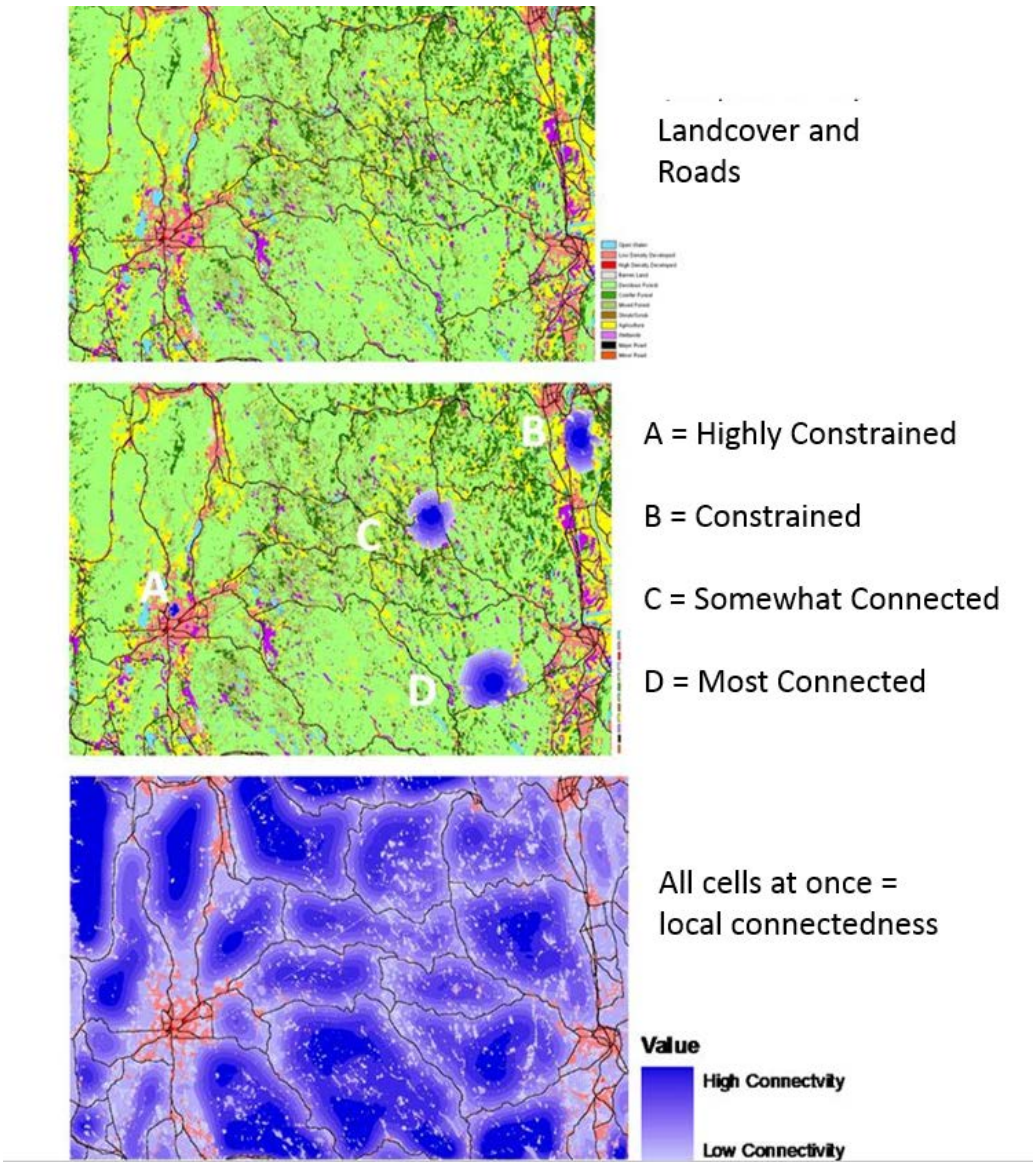
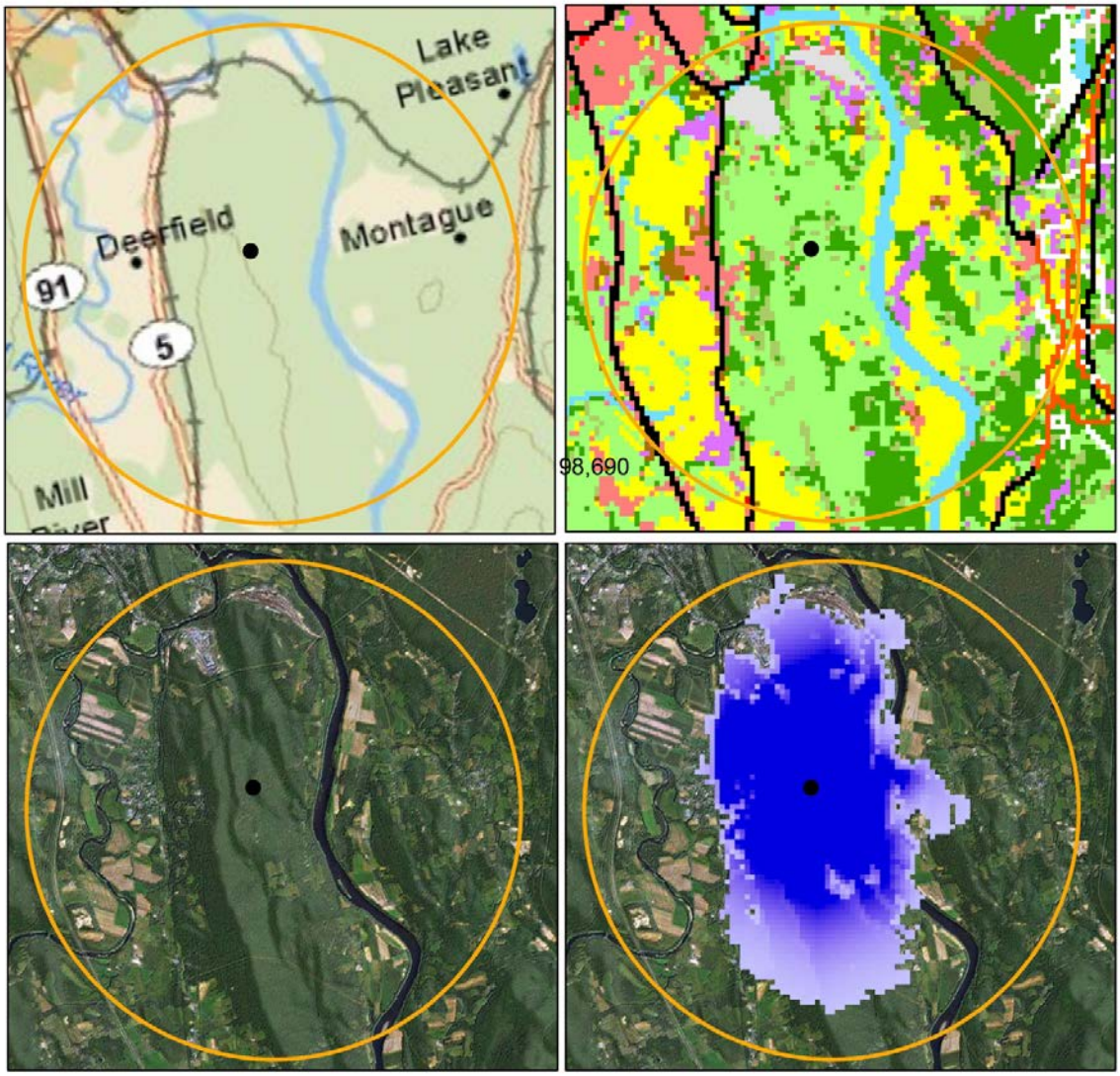


Figure 3.15: Detailed look at Kernel B in Figure 3.14. The top left image shows the topographic map. The top right image shows the land use grid details. The bottom left panel shows the aerial image with the 3-km circular resistant kernel distance outlined in orange. The bottom right box shows the kernel spread. Kernel B is constrained on the west by roads and railroads and on the east by water. The kernel can flow well through the natural landscape in the north and south direction.



The result was a grid of 30-m cells for the entire region where each cell was scored with a local connectivity value from 0 to 1. The actual scores had a mean of 0.55 and a standard deviation of 0.31 for the region. Numerical scores were transformed to Z-scores so they could be combined with the landscape diversity scores. Sample areas within the study region were visually assessed to ensure that the results accurately reflect connectedness and to understand the distribution of values (Figure 3.16).

The final map of connectedness values, scored relative to the region as a whole, is shown in Figure 3.17.

Figure 3.16: A Gallery of Satellite Images and their Corresponding Local Connectedness Scores. The resistant kernel (RK) scores and regional Z-scores are based on a roughly circular site positioned at the center of each image (not shown).



RK Value = 0.015
Regional Z Score = -1.75 SD



RK Value = 0.025
Regional Z Score = -1.5 SD



RK Value = 0.19
Regional Z Score = -1.0 SD



RK Value = 0.32
Regional Z Score = -0.5 SD



RK Value = 0.45
Regional Z Score = 0 SD (mean)



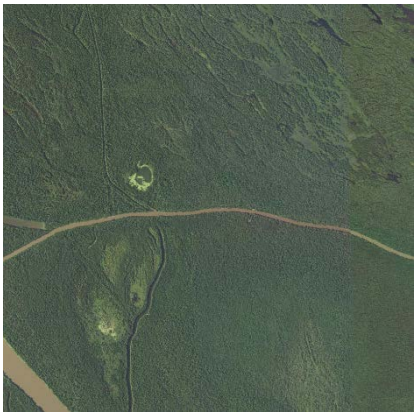
RK Value = 0.58
Regional Z Score = 0.5 SD



RK Value = 0.80
Regional Z Score = 1.0 SD

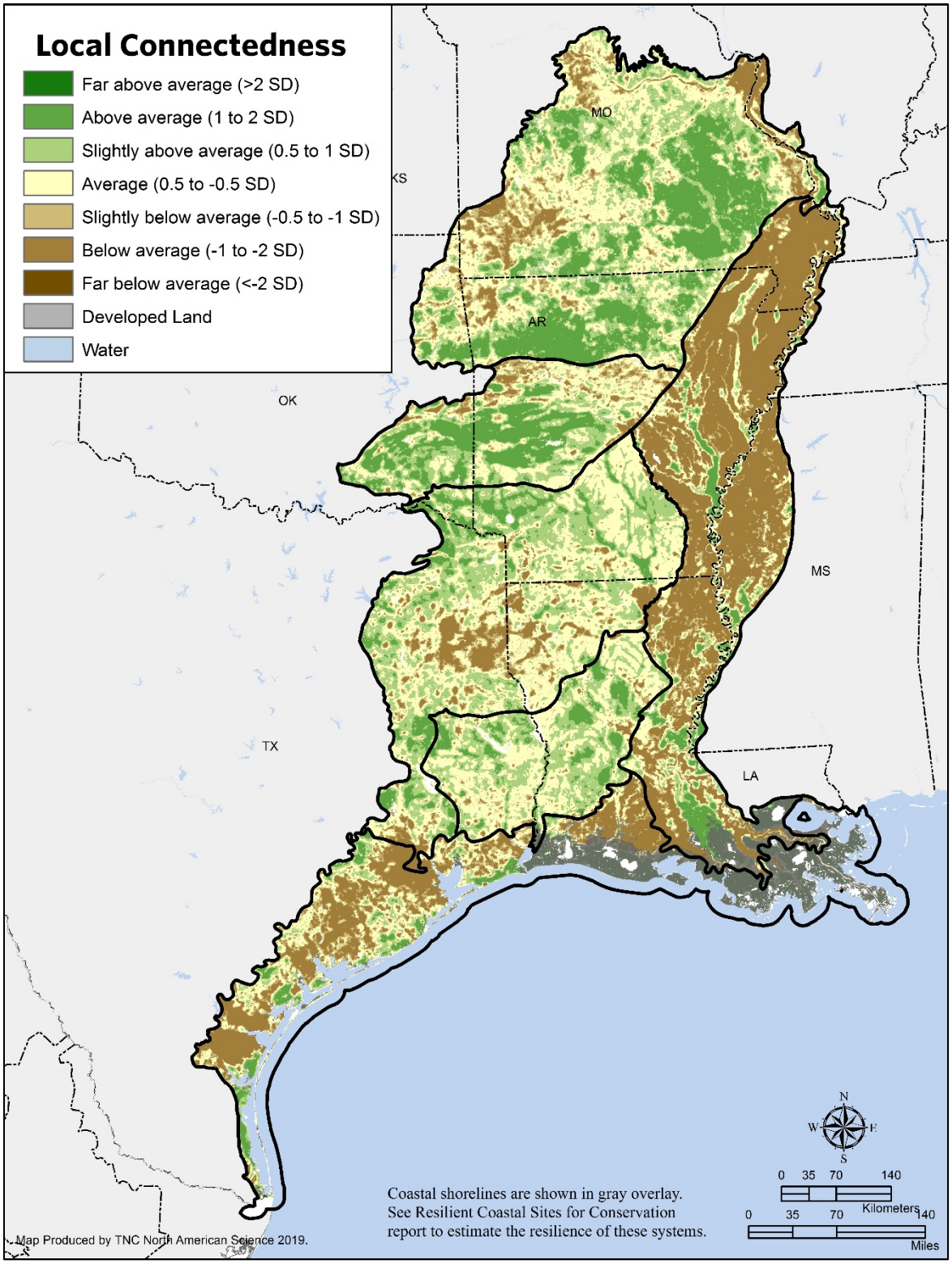


RK Value = 0.83
Regional Z Score = 1.5 SD



RK Value = 0.915
Regional Z Score = 1.9 SD

Figure 3.17: Local Connectedness. This map estimates the degree of connectedness of a cell with its surroundings within a 3-km radius, compared to the regional average.



Section 3: Combined Resilience Factors

We combined the landscape diversity and local connectedness scores into an integrated resilience score (Figure 3.18). The integrated score is useful for mapping the areas where those factors combine to create high resilience, but we also encourage users to look closely at the individual factors as they reveal interesting and different information about the landscape. Although this map (Figure 3.18) accurately reflects the absolute scores, it is not the final map for this project because the study area boundaries are arbitrary. The final map repeats the process of scoring values relative to the mean for each ecological region, and then assembles the ecoregion results into a composite map (ecoregion maps are in Chapters 4, the composite map is in Chapter 5).

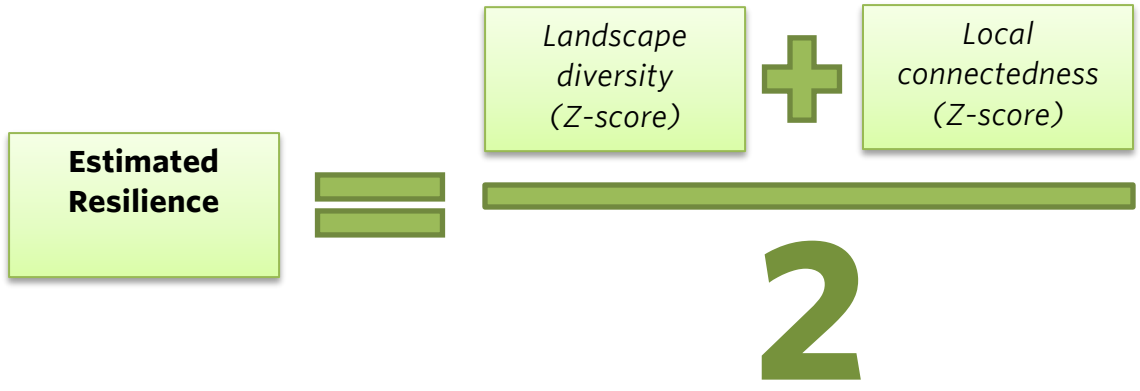
To ensure the two factors—landscape diversity and local connectedness— had equal weight in the integrated score, we transformed each metric to standardized normalized scores (Z-scores) so that each has a mean of 0 and a standard deviation of 1. The normalized score prevents factors with a larger mean or variance from having more influence.

A standard normal transformation (Z-score) is used throughout this project for combining datasets. The formula for calculating the Z-scores is:

$$z = \frac{x - \mu}{\sigma}$$

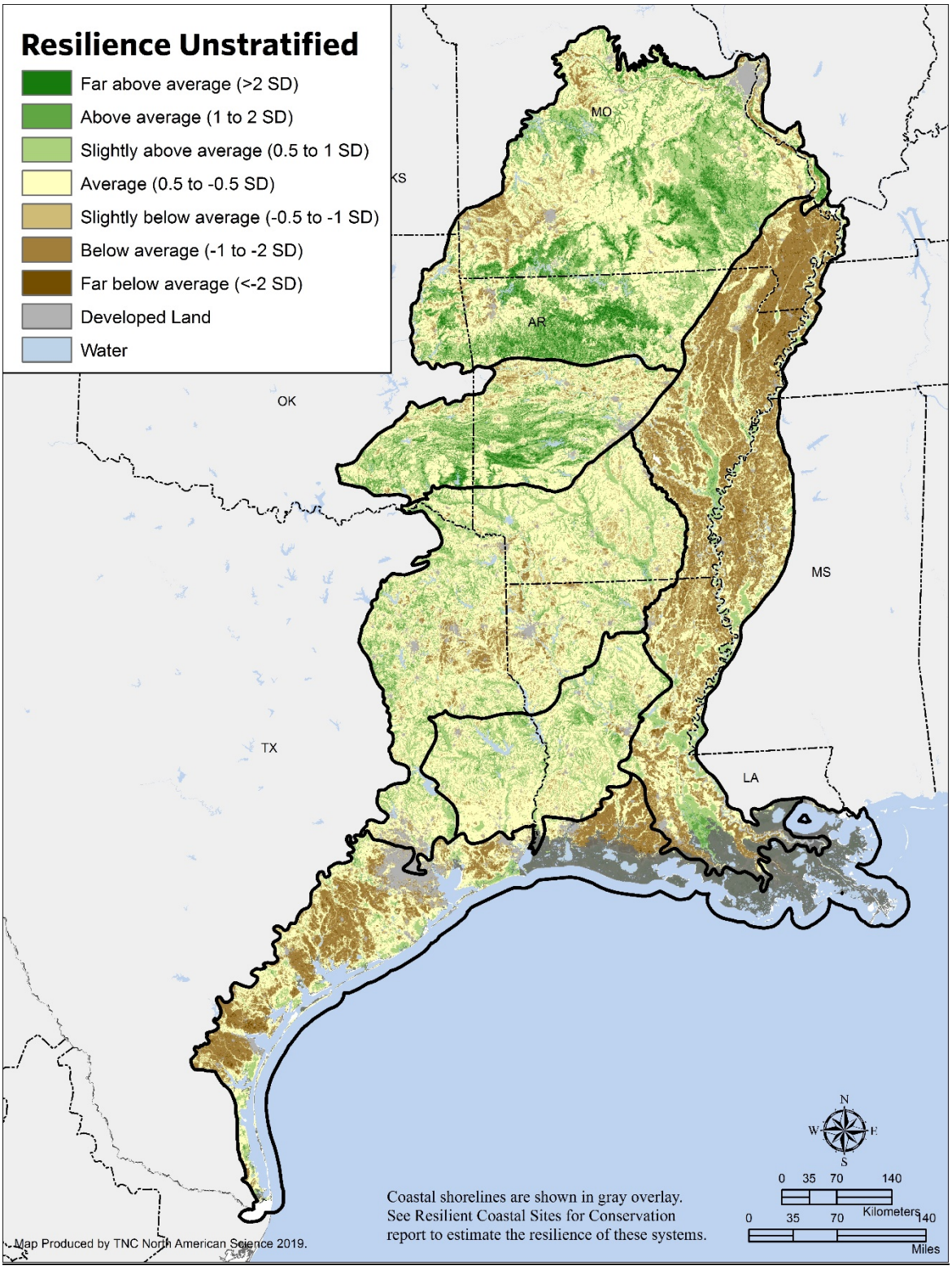
The cell score "x" minus the mean score of all cells "μ" divided by the standard deviation of all cells "σ"

The estimate of resilience for each 30-m cell was equal to:



`

Figure 3.18: Unstratified Resilience Score. This map shows the raw cell scores for estimated resilience (landscape diversity + local connectedness) before we stratified the score by ecoregion and geophysical setting.



DATA SOURCES

This section lists spatial datasets and their source documentation. Other reference materials are listed in the Literature Cited section at the end of the report.

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ECOREGIONAL RESULTS

CHAPTER 4

In this chapter, we present site resilience results for the six ecoregions of the Lower Mississippi - Ozark region. As described in Chapter 1, we define site resilience as "the capacity of a site to adapt to climate change while maintaining biological diversity and ecological function" (following Anderson et al. 2014b). As described in Chapters 2 and 3, in each ecoregion, we mapped the geophysical settings and identified areas with relatively higher site resilience based on their landform (microclimate) diversity and local connectedness.

The six ecoregions (Figure 4.3) fall into three basic types in terms of their physical structure. The Ozarks and Ouachita Mountains are characterized by rough topography and deciduous or mixed forest cover. The Upper and Lower East Gulf Coastal Plain have gentler coastal plain topography and are dominated by conifer or mixed forest. The Mississippi Alluvial Plain and Gulf Coast Prairie and Marshes are both low-relief regions dominated by marshes, swamps, wet prairies, and agriculture.

As with all of The Nature Conservancy's resilient site assessments, we use these ecoregions and geophysical settings as stratification factors. Therefore, scores across ecoregions and settings are not directly comparable. For example, a site that scores above-average for resilience in the flat and fragmented Mississippi Alluvial Plain would likely score average or even below average in the more topographically diverse and intact Ozark Mountains. Results for the whole study area are presented in Chapter 5.

Resilience and Vulnerability

As we shift from describing our methods (Chapters 2 and 3) to presenting results, it is important to remember that our goal was not to predict species responses to a particular climate change scenario, but rather to identify sites within each ecoregion and on each geophysical setting, that will have accessible (i.e., locally connected) climate options which will benefit species under *many* possible scenarios. Over time, these sites will be exposed to shifts in climate patterns, which in turn are likely to promote changes in species composition, and shifts in key functions and ecological processes. As these responses occur, we expect that these more complex and connected sites will sustain higher levels of biological diversity and ecological function. Coarse-scale climate models can provide useful estimates of the directional changes in temperature, and (with higher levels of uncertainty) project future changes in

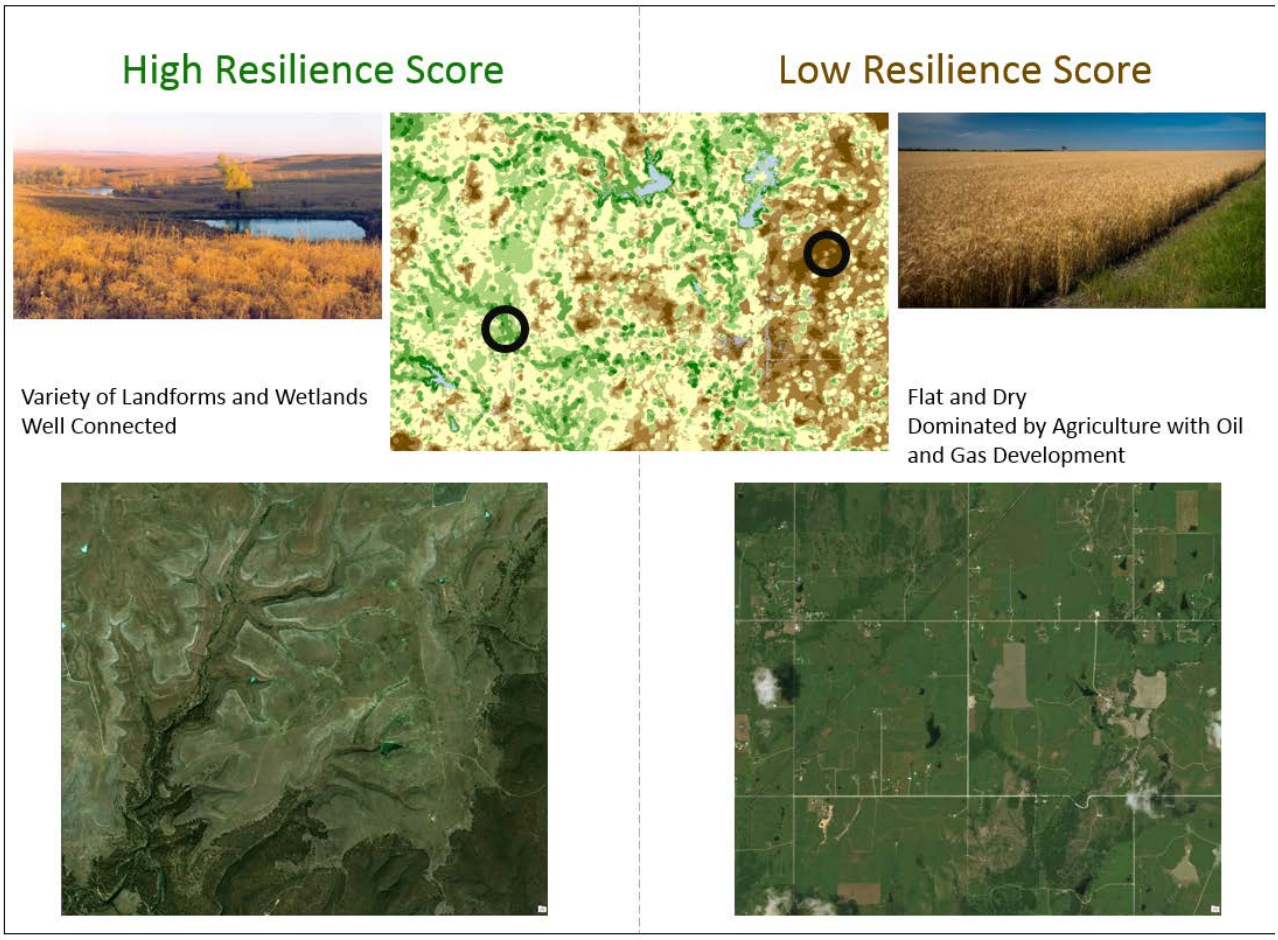
precipitation and related variables like evaporative demand. However, within the extent of a single spatial unit of a mapped climate projection (typically a 100-km grid cell, about 62 miles per side) of a mapped climate projection, we expect to see a wide range of local climate conditions (temperature and available moisture), due to the shape of the land, and characteristics of the soil and dominant vegetation (see full discussion in Chapter 3). These landscape and vegetation-based variations are relatively uncoupled from regional averages across multiple climate model grid cells, and often much larger in variance. For example, ten bogs in the Adirondacks were estimated to have an average of 128 ± 9 growing season days based on PRISM climate models, but in-situ temperature loggers found them to be much cooler and more variable (mean = 73 ± 33, Langdon in prep).

Our focus was on mapping the most persistent drivers of the local variation, the landscape characteristics, and then applying them to subsets of each ecoregion delineated by geology and surficial sediments (see Chapter 2). We cannot predict the biotic responses of species nor the interactions between species, but by identifying and conserving sites with characteristics that increase options for species and communities to adapt, we can help identify sites most likely to set the stage for nature to remain resilient.

In this study, resilience to climate change and its converse, vulnerability to climate change, are relative concepts for which we do not have absolute thresholds. We defined a **resilient site** as one with more of the characteristics (microclimatic buffering and connectedness) that maintain species and functions than the average site in the ecoregion. We expect that these sites will support an array of specialist and generalist species, even as the species composition and ecological processes change. In contrast, **a vulnerable site** was defined as one where natural connectivity is disrupted and fragmented, and there are limited options for species to shift to a more suitable microsite as the regional climate changes. Vulnerable may be quite important in terms of current biodiversity values, but they will likely need more management to retain those values. At a regional scale, vulnerable sites may be more likely than resilient sites to show a net loss of biological diversity over time, as resident species are lost and opportunistic "weedy" species adapted to high levels of disturbances and anthropogenic degradation may be more likely to thrive. Correlative evidence to support this was found in the Northeast where high-scoring resilient sites contained significantly more of the known biodiversity locations (including 75% of the target species) and low-scoring vulnerable sites contained significantly less ($p < 0.0001$, Anderson et al. 2014a).

Climate change is expected to greatly exacerbate the degradation of vulnerable sites, through multiple mechanisms, including the dominance of generalist species described above. However, to the extent that a site retains natural forms of landcover, it will likely continue to perform many natural services, such as contributing to cleaner air, sequestering carbon, providing wildlife habitat and recreational opportunities, and filtering water. Without a doubt, vulnerable sites may have much value, but relative to other comparable sites (mapped here as those sites in the same ecoregion, and on the same geophysical setting), they are places where the impact of climate change may be felt most severely, and where it may be most difficult to sustain the full suite of natural functions and species diversity that could occur on the site over time (Figure 4.1).

Figure 4.1: Estimated resilience and vulnerability. This image compares two sites (landscape photos paired with aerial overviews, and corresponding circled areas in the resilience map) in northeastern Oklahoma in the Osage Plains/Flint Hills ecoregion. The site on the left, located in the Joseph H. Williams Tallgrass Prairie Preserve, has greater landscape diversity and connectedness, and scores higher (green) for resilience. The agricultural area in the images on the right is flatter and more fragmented, contributing to lower (brown) resilience scores.



Mapping Resilience

The maps in this chapter illustrate the relative resilience of sites in relation to their geophysical setting, the ecoregion, and the larger study area. The results are intended to support conservation strategies by identifying each ecoregion's most resilient areas using objective and repeatable criteria that could be observed in the field and were not dependent on knowing the future climate. In earlier chapters, we explained the logic and evidence for this approach, and here we want to help users understand and interpret the results.

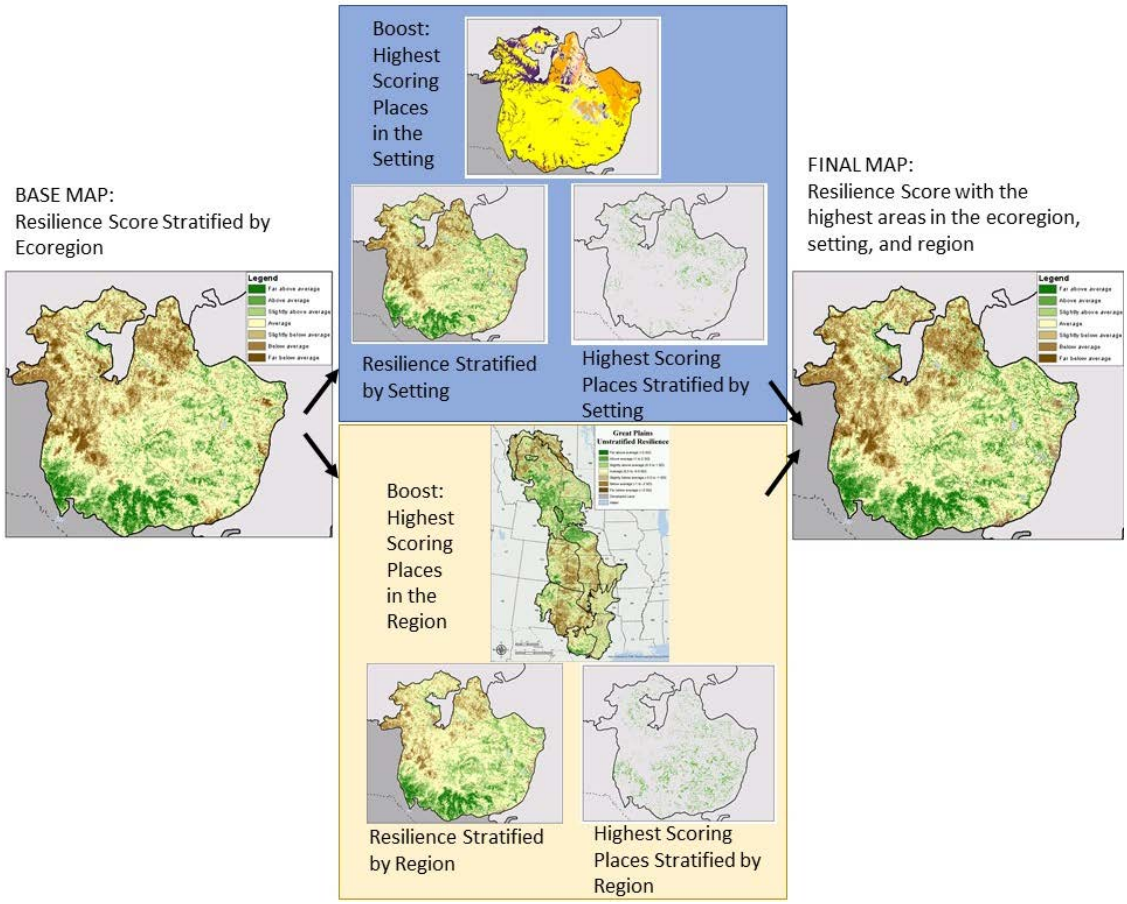
The legends for all the maps of resilience and its components are on a relative scale based on a standard normal distribution (Z-scores). This transformation converts the data to a scale where the mean is equal to 0 and each standard deviation is equal to 1. Thus, a site score of 1 SD means the site is one standard deviation above the average value of all sites in the ecoregion on the same setting. Based on a normal distribution, this translates to a score that is roughly 84% higher than other comparable sites. For example, if the site is on sandstone in the Ouachita Mountains, then a score of 1 SD means the site has greater landscape diversity and local connectedness than 84% of the other sites on sandstone in the Ouachita Mountain ecoregion, and thus is scored as more resilient. All map legends reflect this scale:

Score	Numeric Value	Meaning	Interpretation
Far below average	(<-2 SD)	Below 98%	**Most Vulnerable**
Below average	(-1 to -2 SD)	Below 84%	**More Vulnerable**
Slightly below average	(-0.5 to -1 SD)	Below 69%	**Somewhat Vulnerable**
Average	(-0.5 to 0.5 SD)	Between 31-69%	**Average**
Slightly above average	(0.5 to 1 SD)	Above 69%	**Somewhat Resilient**
Above average	(1- 2 SD)	Above 84%	**More Resilient**
Far above average	(>2 SD)	Above 98%	**Most Resilient**

Use of this scheme assumed that the raw scores followed a normal distribution, i.e., that a plot of the resilience values for each 30-m cell would show a bell-shaped curve centered on the mean, with roughly two-thirds of all observations falling within one standard deviation of the mean. We examined the distribution patterns and, when necessary, transformed the data using log- or rank-based transformations to approximate a normal distribution.

Resilience values in Z-scores are always relative to some population or distribution. For example, to estimate the resilience of sites in the Ouachita Mountains, we selected all the cells in the ecoregion, calculated their average resilience score based on landscape diversity and local connectedness, then normalized them to identify the places that were above-average. What we can say with confidence is: the high scoring sites have the greatest number of microclimates and least amount of fragmentation relative to other sites in the same ecoregion. Because different ecoregions have different average scores, what scores average in one ecoregion might score high in another.

Figure 4.2: Integration Across Stratification Levels. The resilience scores are relative to the ecoregion with boosts for certain geophysical settings or the highest scoring sites in the study area to correct for bias. This example from the Edwards Plateau, a Texas Ecoregion that is part of the Great Plains region, shows how the stratification by Ecoregion, Setting, and Region effects the final map. Although the improvements are relatively minor this method corrects for biases towards certain geophysical settings and brings out the highest scoring sites in the whole study area.



The final ecoregion site resilience map contains two modifications to adjust for biases against sites that 1) *were not* the highest in the ecoregion but *were* the highest for their geophysical setting in the ecoregion, and 2) *were not* the highest in the ecoregion, but *were* the highest in their setting or in the entire study region.

The method for creating the maps followed a linear progression (Figure 4.2). First, we calculated the resilience Z-scores relative to the ecoregion irrespective of geophysical setting. Next, we repeated the process, this time normalizing the resilience scores relative to each geophysical setting within the ecoregion. We compared the two scores cell-by-cell and where the geophysical setting score was both greater than 1 SD for the setting and greater than the ecoregion score, we replaced the ecoregion score with the setting score. This had the effect of boosting the score for settings that had mean

scores below the ecoregion mean score and corrected for bias caused by inequality of microclimates and connectedness across settings. Next, we added a regional override to elevate cells that scored the highest in the whole study area. For this we calculated the resilience score relative to the entire study region irrespective of ecoregion or setting. We compared the regional score cell-by-cell with both the ecoregion score and the geophysical setting score. Where the regional score was both greater than 1 SD for the region and greater than the ecoregion and setting scores, we replaced the existing score with the regional score. This had the effect of boosting the score in places where the regional score was higher than the ecoregional or setting mean.

The adjustments not only corrected for differences between geophysical settings, it also ensured that by skewing the distribution slightly toward resilient and away from vulnerable we did not miss potentially resilient sites

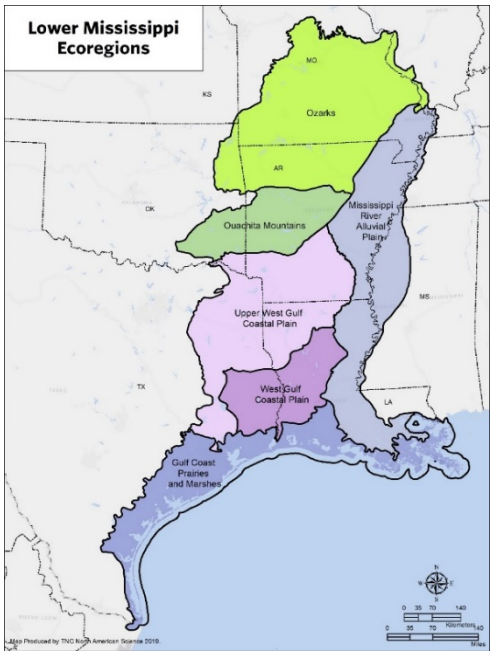
Results Overview

For each of the six ecoregions, we present a series of maps and figures that provide information on geophysical settings and site resilience scores. The methods underlying these results are addressed in detail elsewhere in the report (Chapters 2 and 3), although we provide a short description of each map below. Region-wide results are presented in Chapter 5.

For each ecoregion, we present the results as five maps and three charts:

1) Map of Geophysical Settings
2) Map of Landscape Diversity
3) Map of Local Connectedness
4) Map of Resilience Scores
5) Map of Resilient Examples of each Geophysical Setting
6) Chart of Land Securement and Conversion by Geophysical Setting
7) Chart of the Relative Abundance of Each Setting
8) Chart of the Distribution of Resilience Values by Geophysical Setting

Figure 4.3. Ecoregions



All maps show scores relative to settings within ecoregions with a regional override where appropriate. Raw scores for each geophysical setting are presented in the last chart. Explanations of each map and chart, and, in some cases, the method of mapping, are described below.

1) Map of Geophysical Settings
The geophysical settings maps show the type and distribution of surficial sediments or bedrock influenced areas in the ecoregion. Details on geophysical setting definitions and associated species and communities are in Chapter 2.

2) Map of Landscape Diversity
The landscape diversity metric evaluates the number of species-relevant landforms within a 40-ha (100-acre) moving window, and incorporates a wetland influence metric that increases the score in flat areas where wetlands are dense and topographically connected. Flat dry areas score lower and areas with more variation in topography or higher wetland density score higher.

3) Map of Local Connectedness
Local connectedness measures how intact the physical? connections are between natural ecosystems within a local (3-km) landscape. Areas in green score above-average, indicating that landcover is in a natural state (e.g., grassland, forest, etc.) conducive to movement of plant and animal populations. In contrast, below-average

areas in brown are fragmented and dominated by non-natural land cover. Roads, large water bodies, and other barriers also contribute to lower local connectedness scores.

4) Map of Resilience Scores
This map shows the estimated resilience score of each cell based on its landscape diversity and local connectedness scores. Resilience scores are calculated relative to the ecoregion, with overrides for cells that are the highest scoring in its geophysical settings or the highest scoring in the whole study area (see Mapping Resilience). Areas in green are above-average and estimated to be more resilient to climate change. Areas in brown are below-average and estimated to be more vulnerable to climate change.

5) Map of Resilient Examples of each Geophysical Setting
The map shows only the grid cells that score above-average for estimated resilience based on Map 4. Each high scoring grid cell is colored with its corresponding geophysical setting to reveal the most resilient examples of each geophysical setting. These maps are useful in understanding how resilient areas correspond the underlying geophysical structure, and for identifying where conservation action could address a particularly physical habitat. For example, if sandstone was identified as underrepresented in the ecoregion's current conservation lands (described in 8, below), this map shows where the most resilient areas are for conservation.

6) Chart of Land Securement and Conversion within each setting type
For each geophysical setting, this figure shows the percentage of land converted to development or agriculture, the percentage permanently secured for conservation (GAP 1-3), and the percentage of remaining natural land by its relative resilience (see Chapter 5 for a map of land securement).



This ecoregion description was adapted from Ozarks Conservation Ecoregional Assessment (TNC 2003)

The Ozark ecoregion encompasses nearly 24 million acres in parts of Missouri, Arkansas, Oklahoma, Illinois, and a small corner of Kansas. Along with the Ouachita region to the south, the Ozarks form the only significant highland region in mid-continental North America. Parts of this region have been continually exposed for a least 225 million years. Because of high habitat diversity and antiquity of the landscape, Ozark biota are characterized by an unusually high level of species disjunctions and endemism, with more than 160 endemic species.

High levels of topographic, geologic, edaphic and hydrologic diversity exist throughout the Ozarks, resulting in a wide range of habitat types. This is a region of rugged uplands with copious exposed rocks and variable soil depths. Landscape ranges from extensive areas of karst terrain on irregular plains, to highly dissected regions with steep hills and deeply entrenched valleys, as well as limited areas of ancient low mountains with elevations up to 925 meters (3000 feet). There are also smaller, linear areas of alluvial terrain and major riparian features.

Bedrock geology includes exposures of Precambrian igneous rocks in the eastern part of the Missouri Ozarks surrounded by alternating zones of Paleozoic sandstone and carbonate sedimentary rocks. Structurally, the Ozarks consist of a dome that has been slowly uplifted and eroded, resulting in a distinct landscape pattern. The oldest igneous rocks are exposed at the center of the uplift in southeast Missouri and surrounded by regions of Cambrian and Ordovician-aged shallow water carbonates and beach sandstone strata. Further from the center are areas of younger Mississippian sedimentary rocks, including limestones and limited areas of riparian-derived freshwater sandstones.

Figure 4.4: Ozark Geophysical Settings.

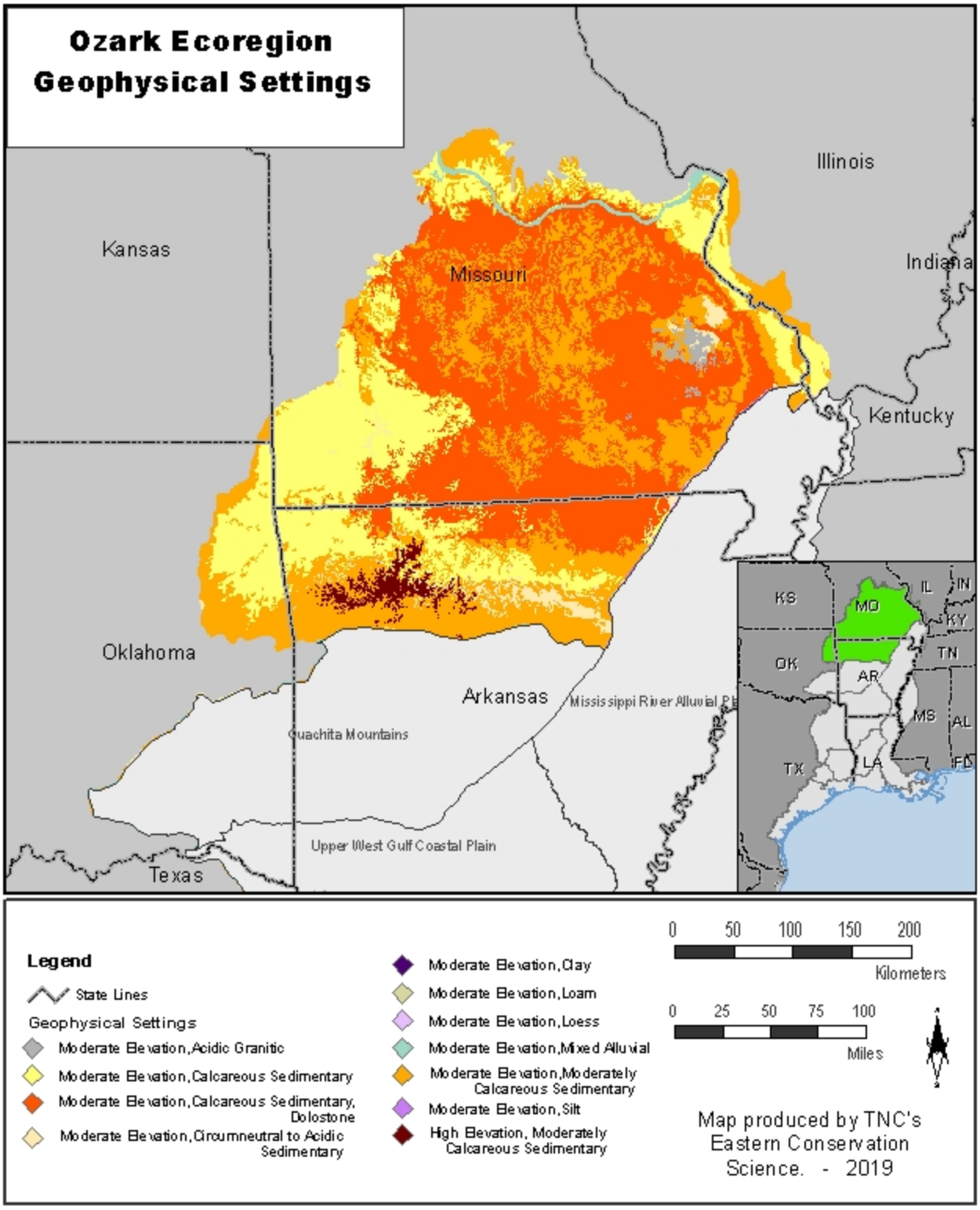


Figure 4.5: Ozark Landscape Diversity.

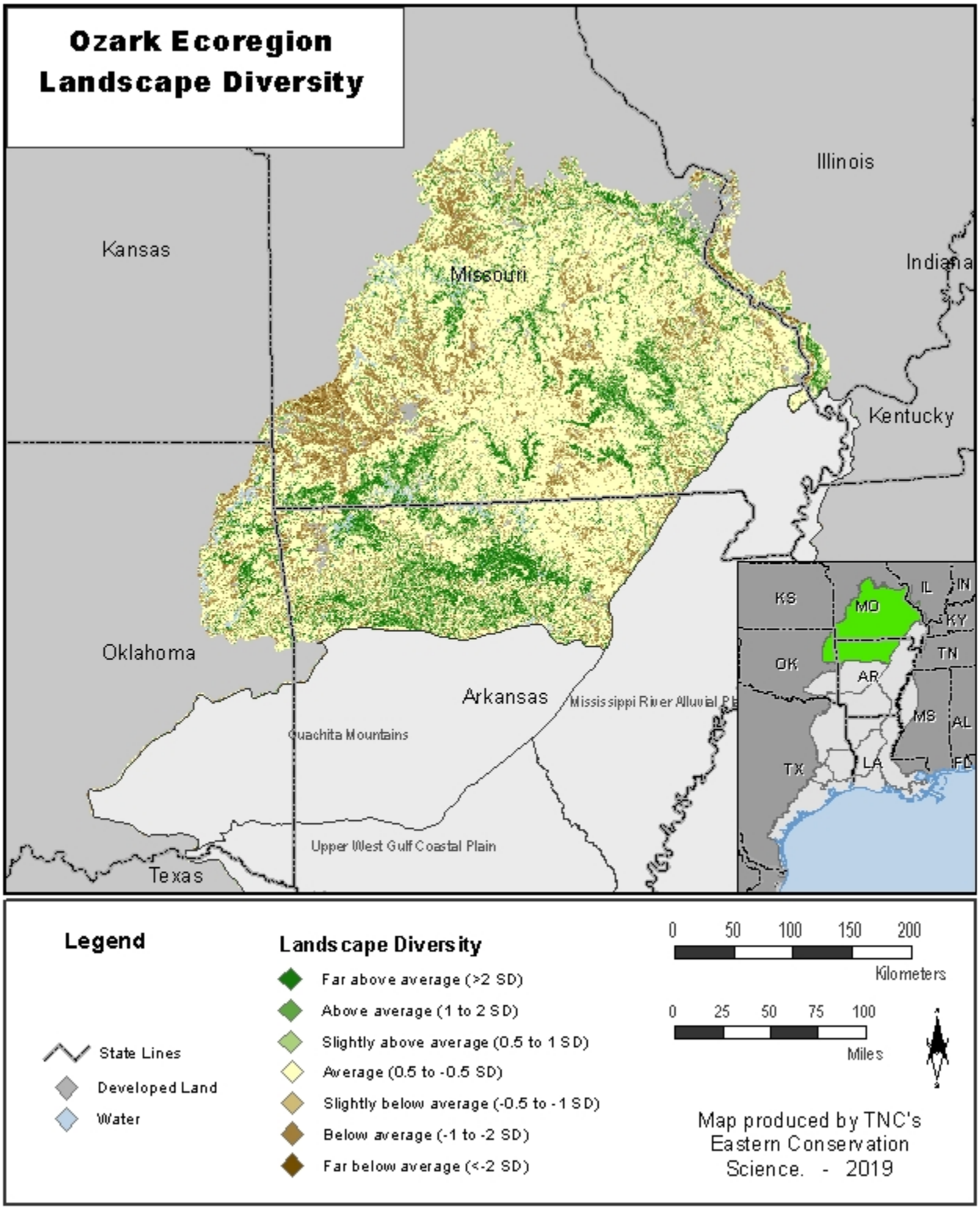


Figure 4.6: Ozark Local Connectedness.

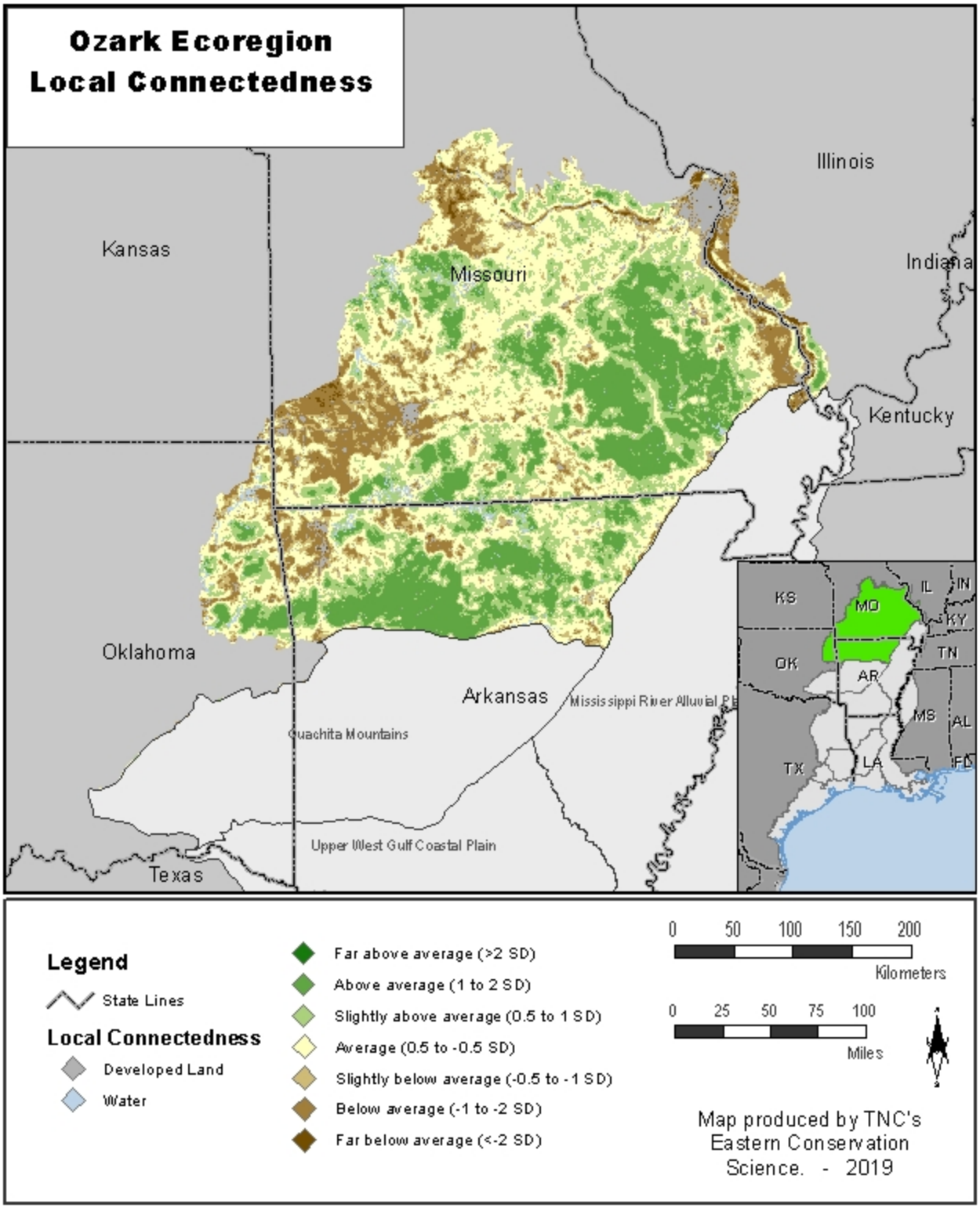


Figure 4.7: Ozark Site Resilience Scores.

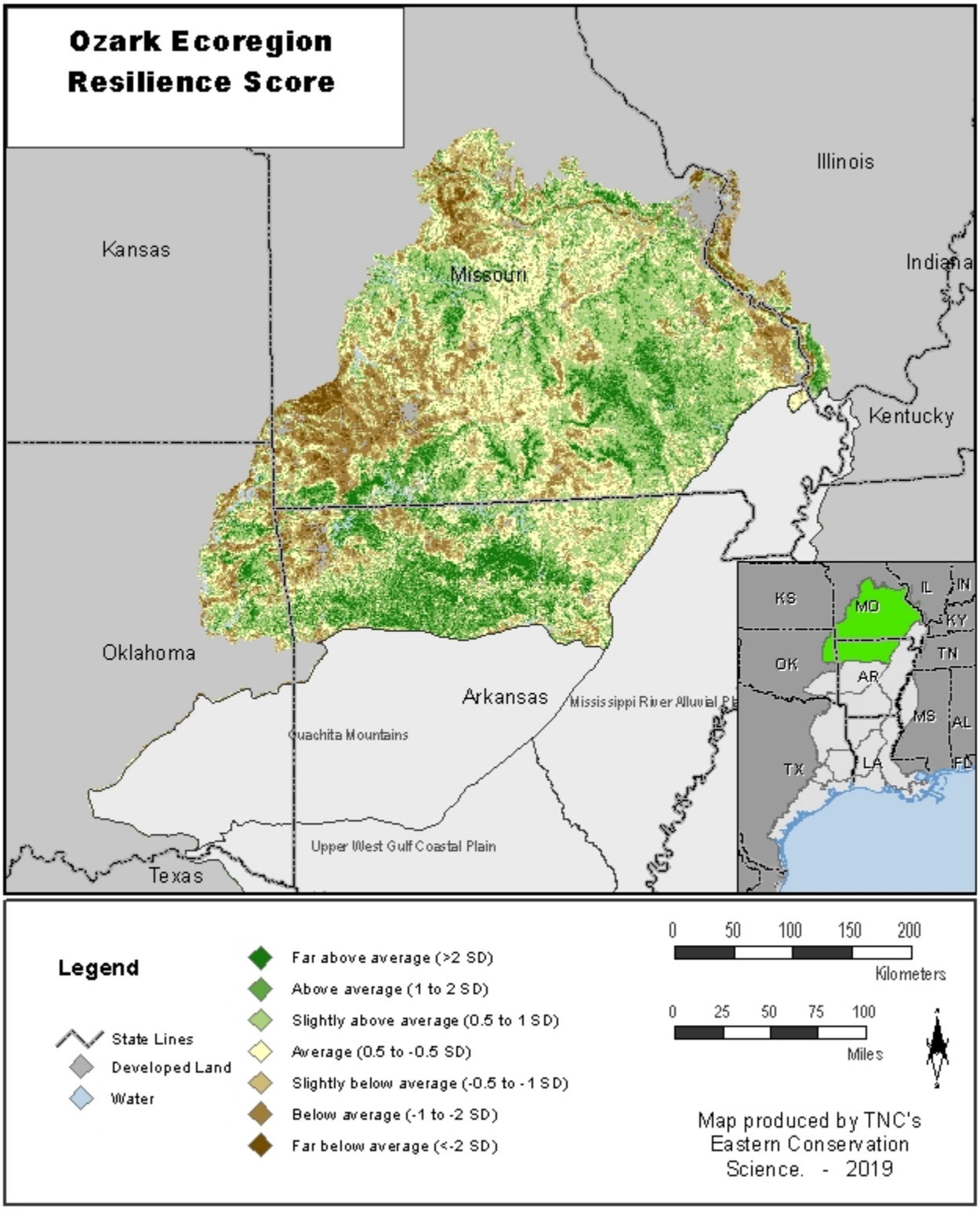


Figure 4.8: Resilient Areas (>0.5 SD) for Each Geophysical Setting Within the Ozark Ecoregion. All geophysical settings are well represented.

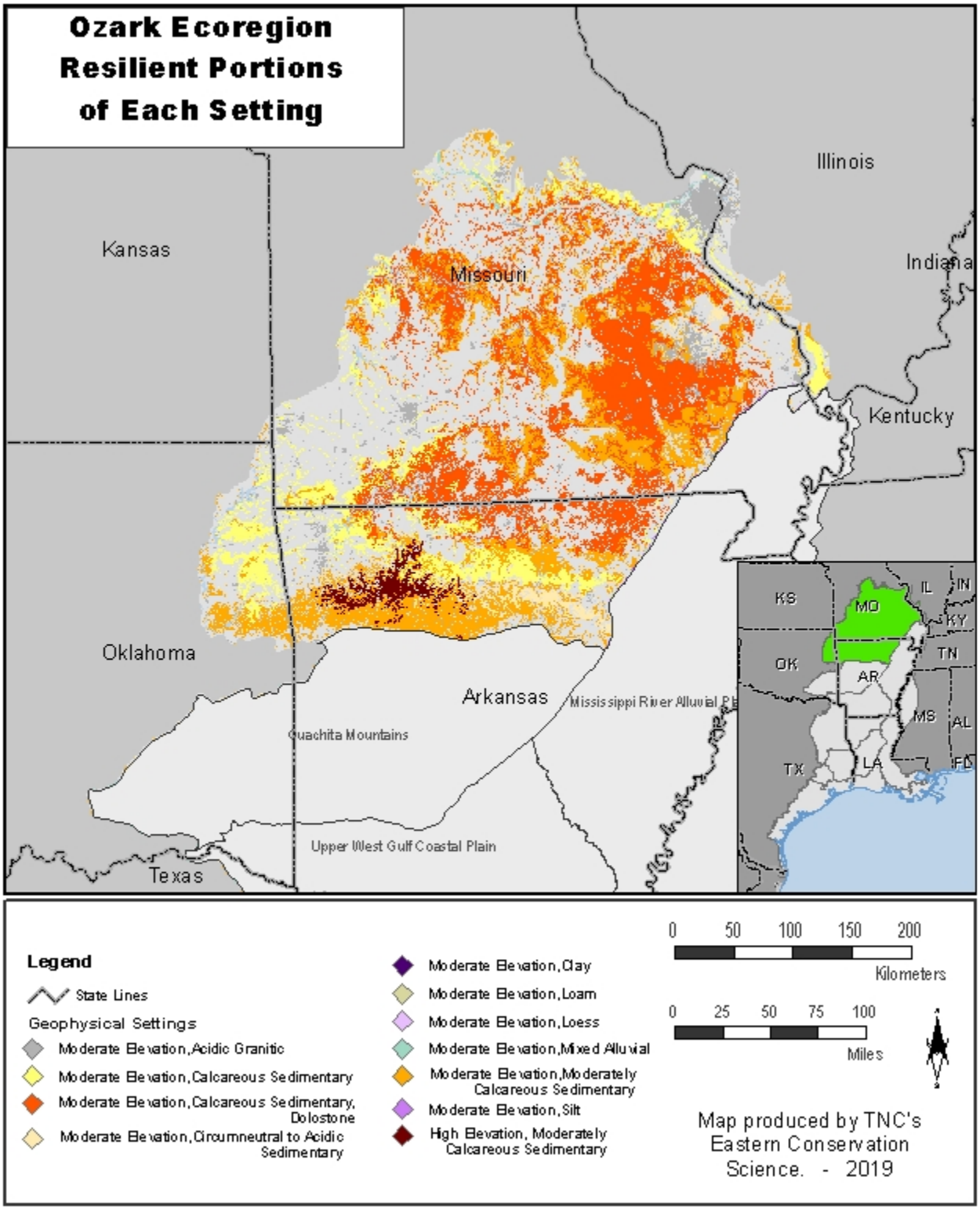
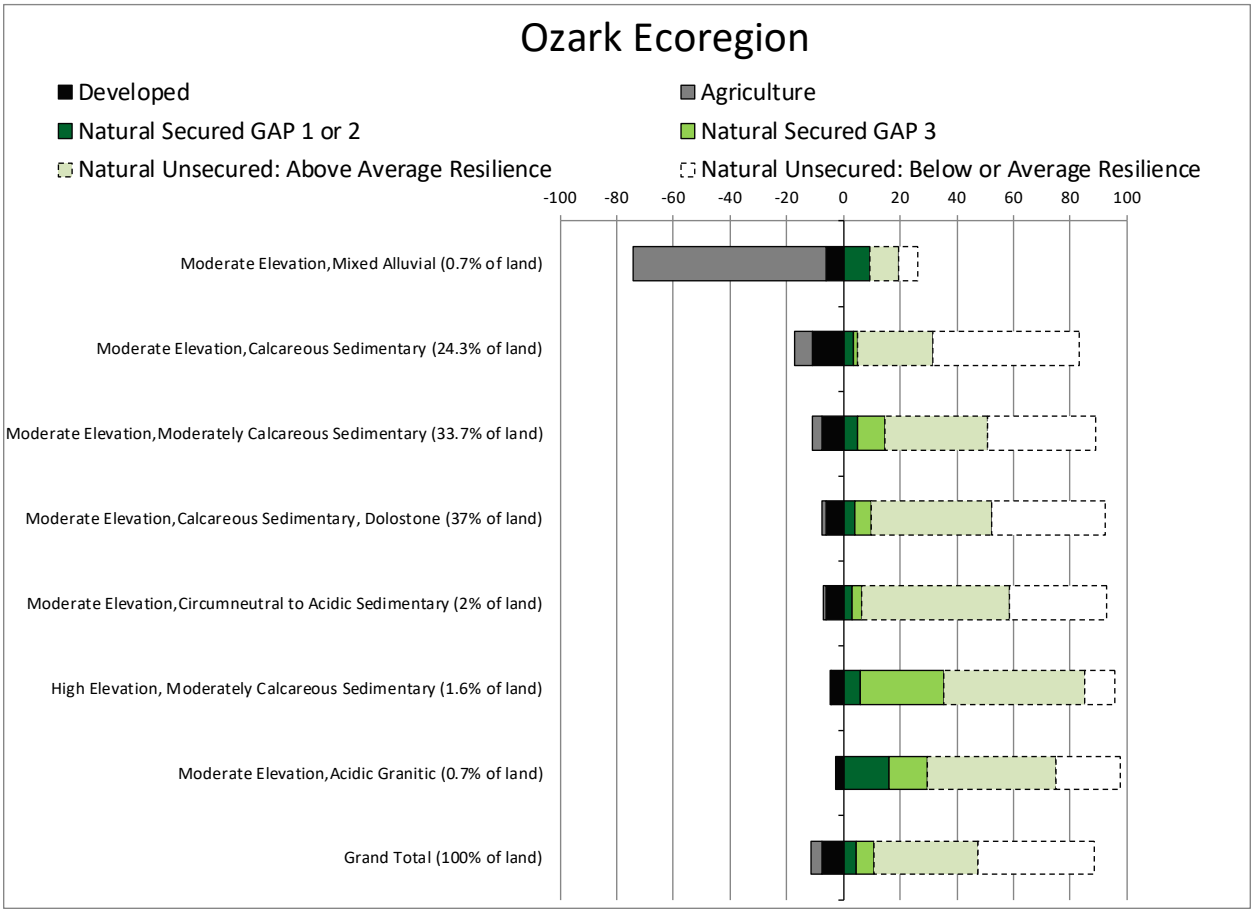


Figure 4.9: Conversion and Securement of the Ozark Ecoregion by Geophysical Setting. This ecoregion is 11% converted and 10% secured, a ratio of nearly 1 to 1. Within this ecoregion, 37% of the land area (12.3 million acres) is resilient unsecured natural land.





Ouachita Mountains

Photo credit: Scott Simon/TNC

This ecoregion description was adapted from Ouachita Mountains Ecoregional Assessment (TNC, *2003)*.

The Ouachita Mountain Ecoregion includes parts of Arkansas and Oklahoma. It comprises a landscape of approximately 11.48 million acres of rugged mountain ridges, broad valleys, and the headwaters of several large river systems. The complex geological formations and soils of this forested landscape have created a tremendous diversity of habitat reflected in a biodiversity of ancient lineage; the Ouachitas have been available for continuous occupation by terrestrial and aquatic life for 225 million years, and are a center for endemism in North America.

The Ouachita Ecoregion is home to 48 endemic species and 68 species with limited ranges. More than one-third of the endemic species are aquatic. There are fourteen federally listed species and 28 others that are recognized as potentially endangered by the United States Fish and Wildlife Service (USFWS) in the ecoregion. There are 79 terrestrial communities identified in the ecoregion, 9 of which are endemic.

The Ouachita Mountains are very diverse in terms of aspect, slope and bedrock. The valleys between the ridges are underlain by shale and have a gentle relief. The ridges are composed of sandstone and chert and extremely steep slopes with numerous rock exposures. The ridge tops often have shallow soils and rock glaciers have formed the steepest slopes. The Ouachita Mountains are located in the humid subtropical zone. Hot, sultry summers and moderately cool winters with some snow, but no accumulations, are normal. The climate is controlled by two different air masses. Warm, moist air from the Gulf of Mexico generally dominates especially in the spring and summer. Cooler, dryer air from the Central Plains enters the area in the winter.

Figure 4.10: Ouachita Mountains Geophysical Settings.

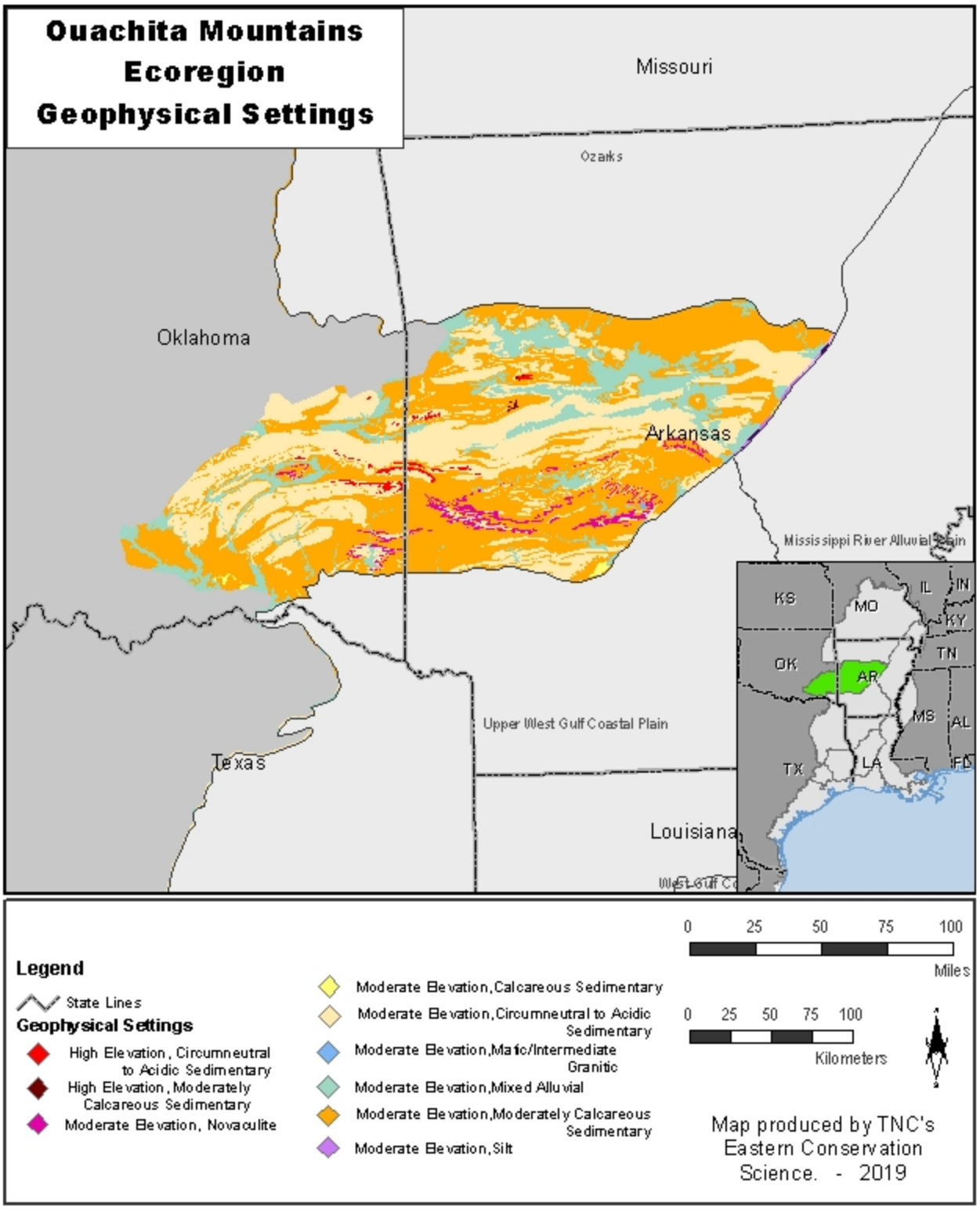


Figure 4.11: Ouachita Mountains Landscape Diversity.

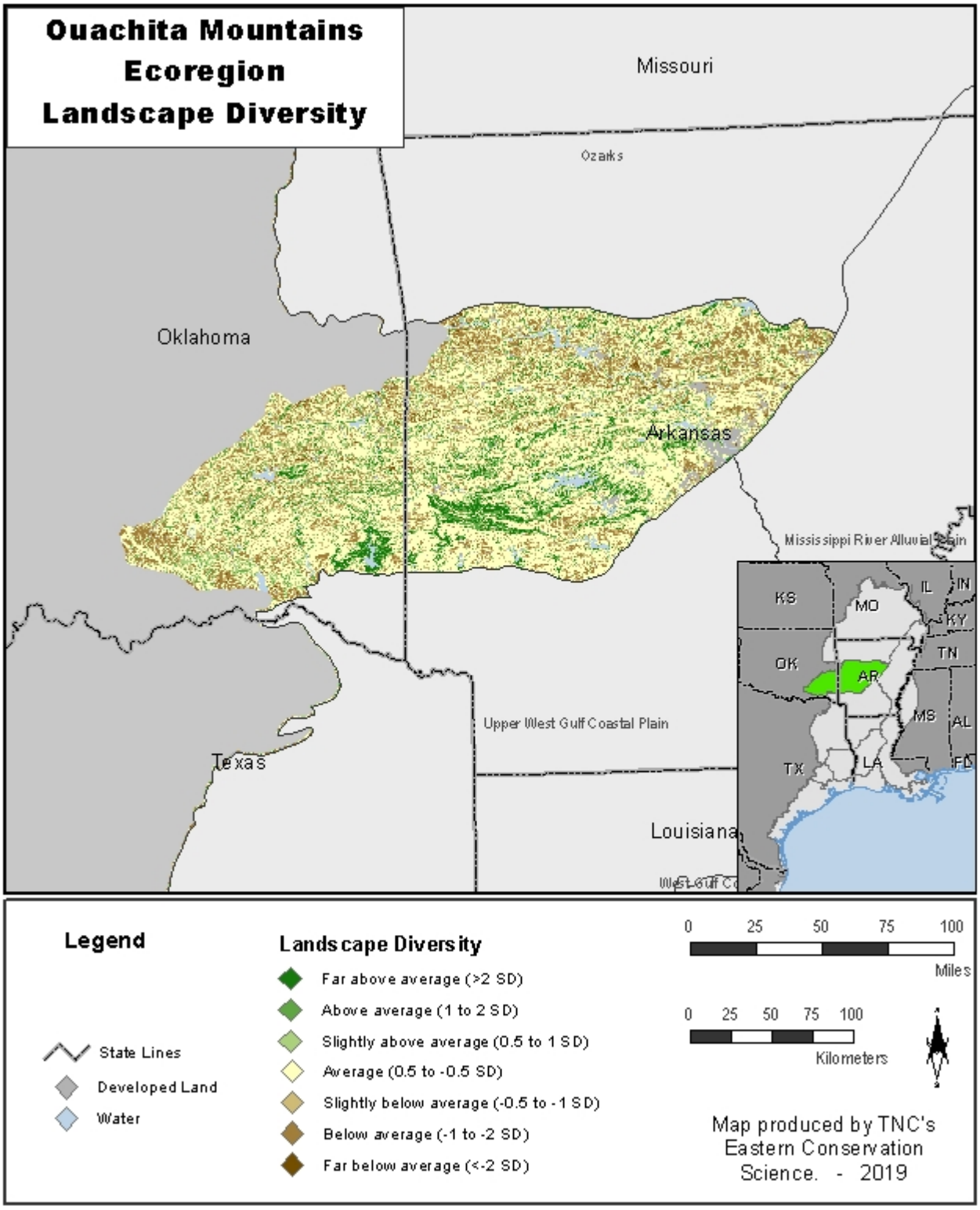


Figure 4.12: Ouachita Mountains Local Connectedness.

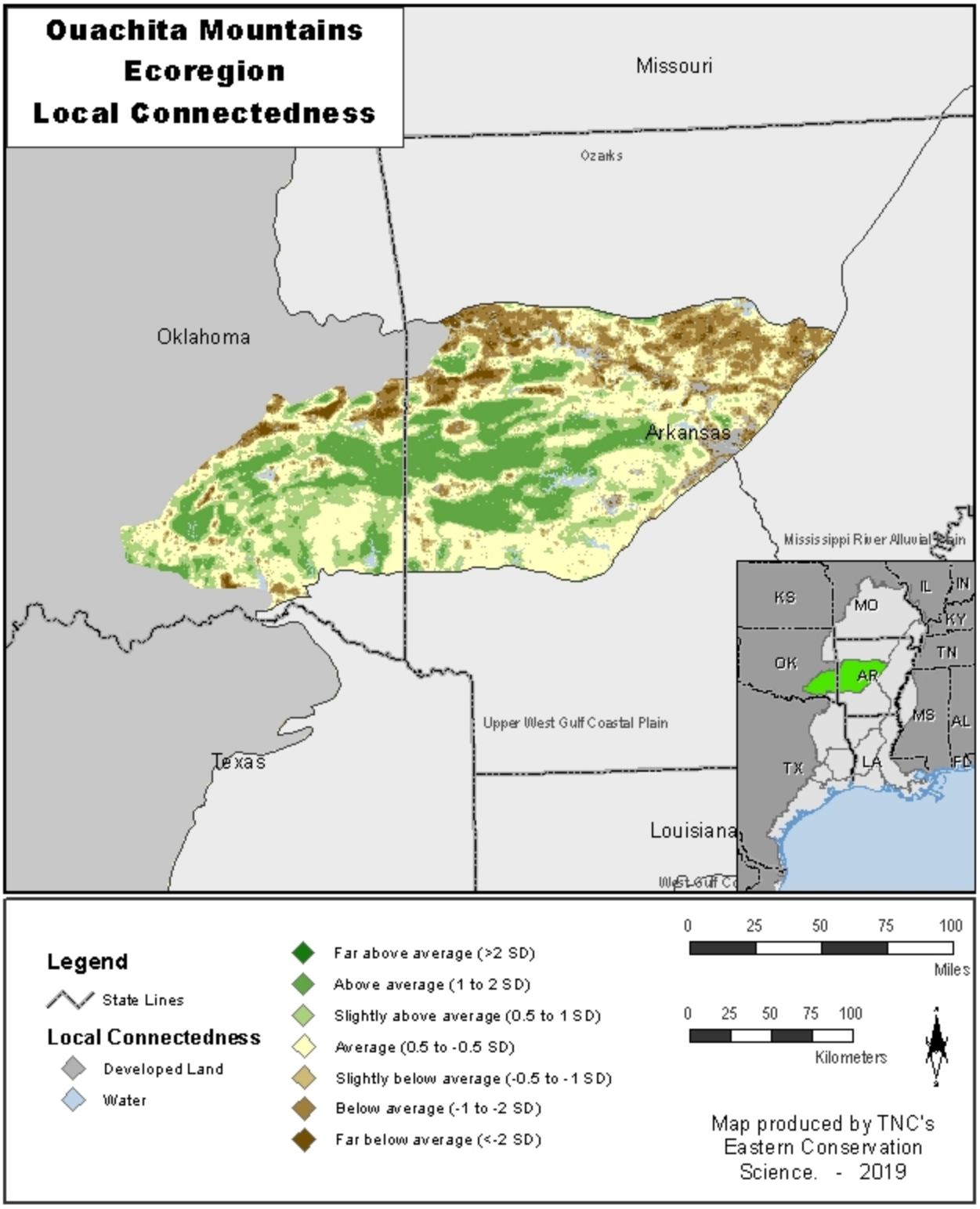


Figure 4.13: Ouachita Mountains Site Resilience Scores.

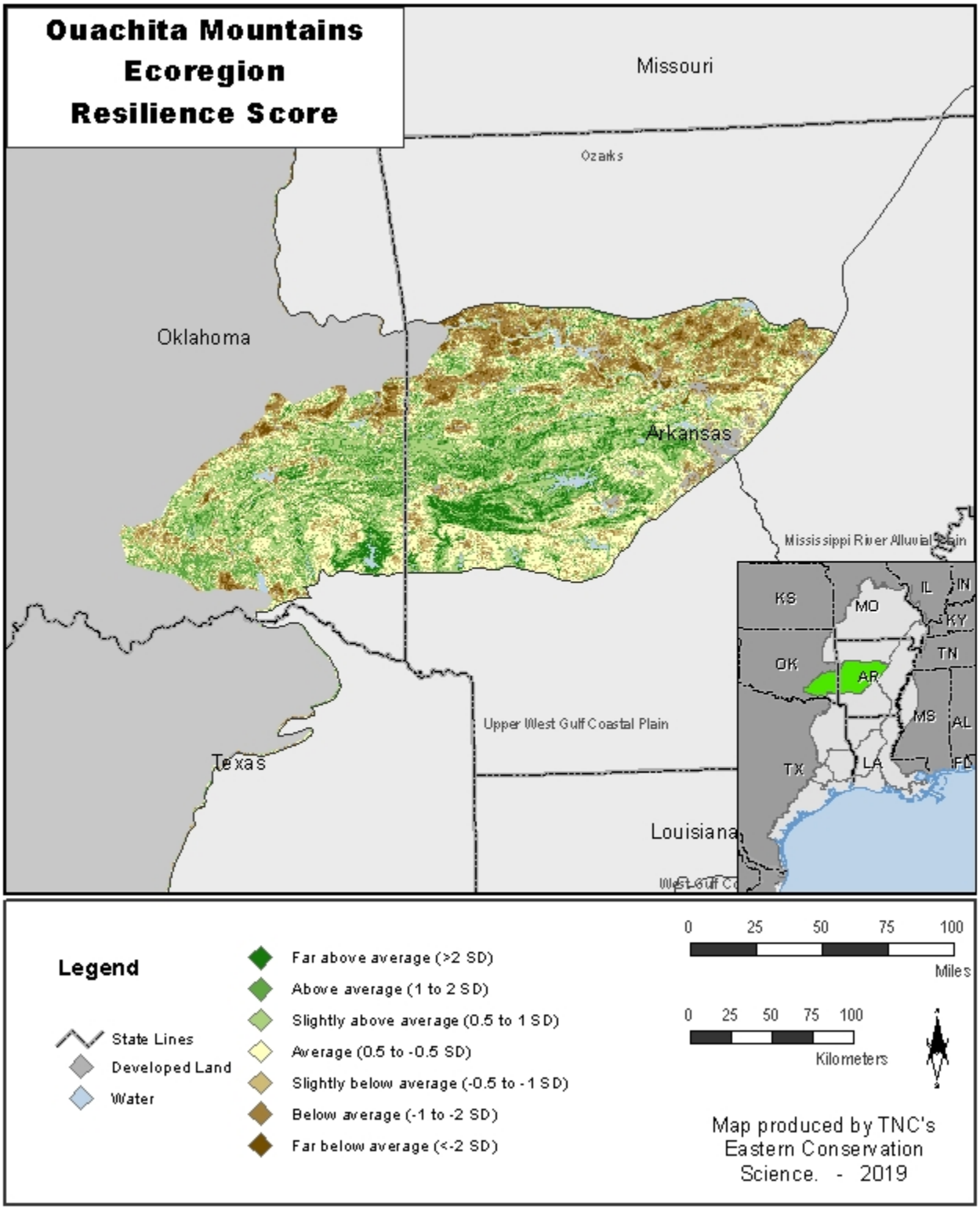


Figure 4.14: Resilient Areas for Each Geophysical Setting Within the Ouachita Mountains Ecoregion.

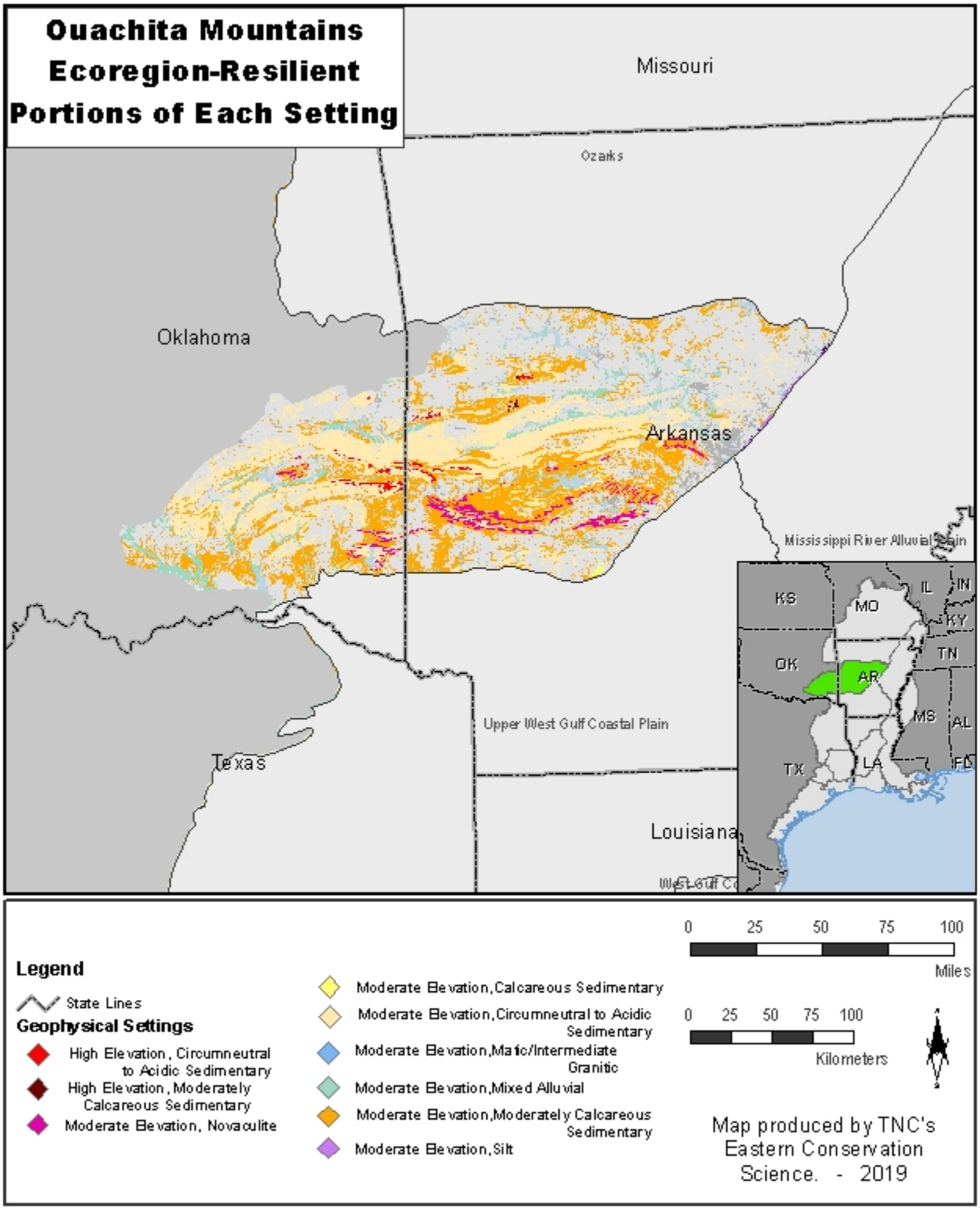
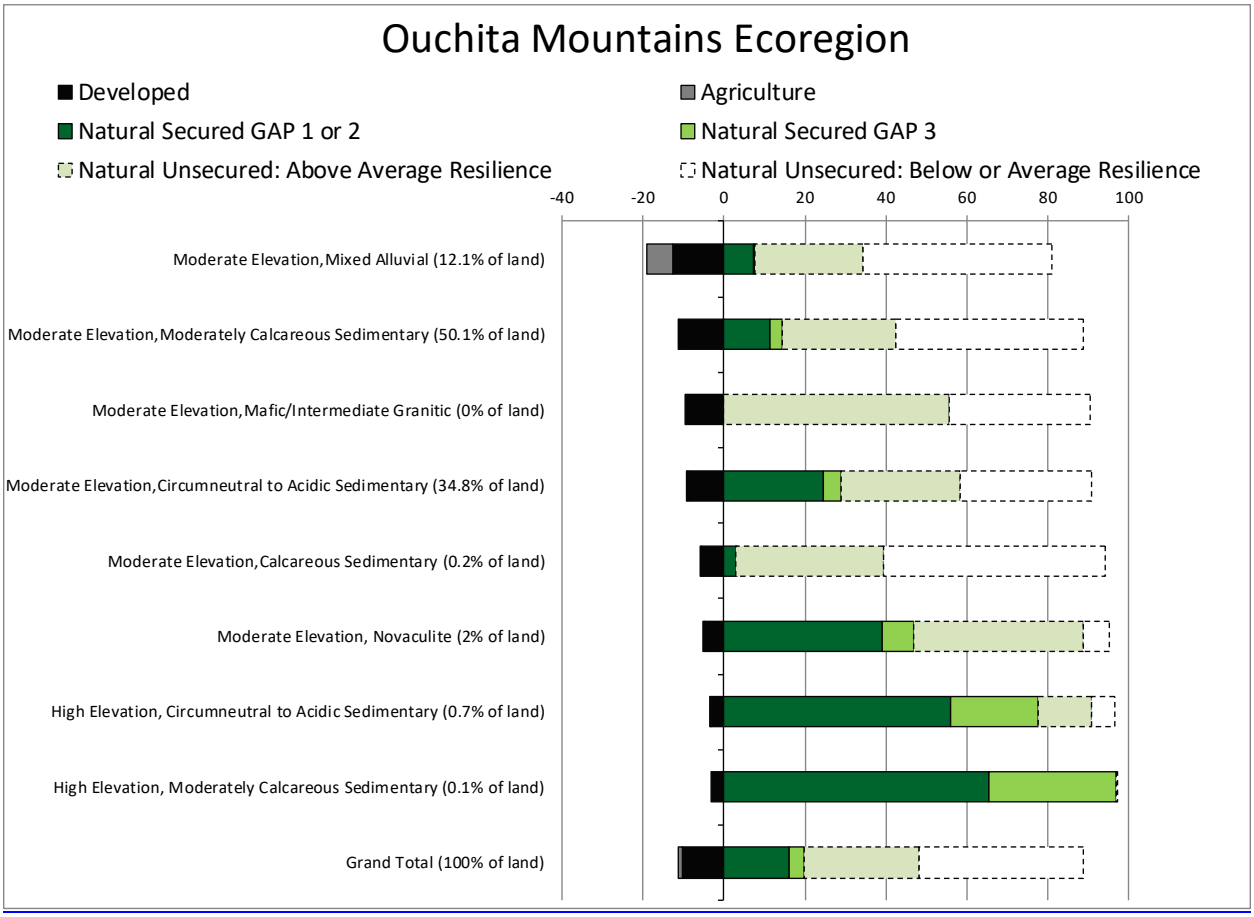


Figure 4.15: Conversion and Securement of the Ouachita Mountains Ecoregion by Geophysical Setting. This ecoregion is 11% converted and 20% secured, a ratio of nearly twice as much securement as conversion. Mixed alluvial sediments are the most converted setting. Within this ecoregion, 29% of the land area (3.2 million acres) is resilient unsecured natural land.





Upper West Gulf Coastal Plain

Photo credit: Terre Noire – S. Simon, 2001

This ecoregion description was adapted from Upper West Gulf Coastal Plain Ecoregional Plan (TNC 2002).

Upper West Gulf Coastal Plain, covers an area of approximately 26,250,000 acres covering parts of Arkansas, Louisiana, Oklahoma, and Texas. Topography ranges generally from flat to rolling hills, with occasional ravines and erosional bluffs. Elevation ranges from a high of 850 feet to less than 10 feet above sea level.

The Upper West Gulf Coastal Plain is composed largely of shallow clays, sands, marl, gravels, bedded gravels and clays, and marine sediments associated with the Cretaceous period, approximately 50 million years ago. Recent geologic formations include Quaternary age Pleistocene deposits and Holocene alluvial deposits.

Terrestrial ecosystems include upland dry-mesic, mesic bottomland, and hydric areas. Bottomlands are dominated by hardwood forests, primarily oak species, and more deeply flooded areas frequently have cypress and cypress-tupelo swamp vegetation. Upland areas have shortleaf and loblolly pine forest, mixed pine-hardwood communities, glades, and woodlands. Prairies occur on blackland soil sites depending on fire history and soil depth.

The ecoregion is home to 15 endemic species and 59 species with limited ranges. Six federally listed endangered species and two listed threatened species occur in the ecoregion.

Terrestrial ecosystems in this ecoregion are stressed by improper forestry practices, development, conversion and agriculture, and fire suppression as their source. Though the ecoregion is 51% forested, most of that area is under commercial management.

Figure 4.16: Upper West Gulf Coastal Plain Geophysical Settings.

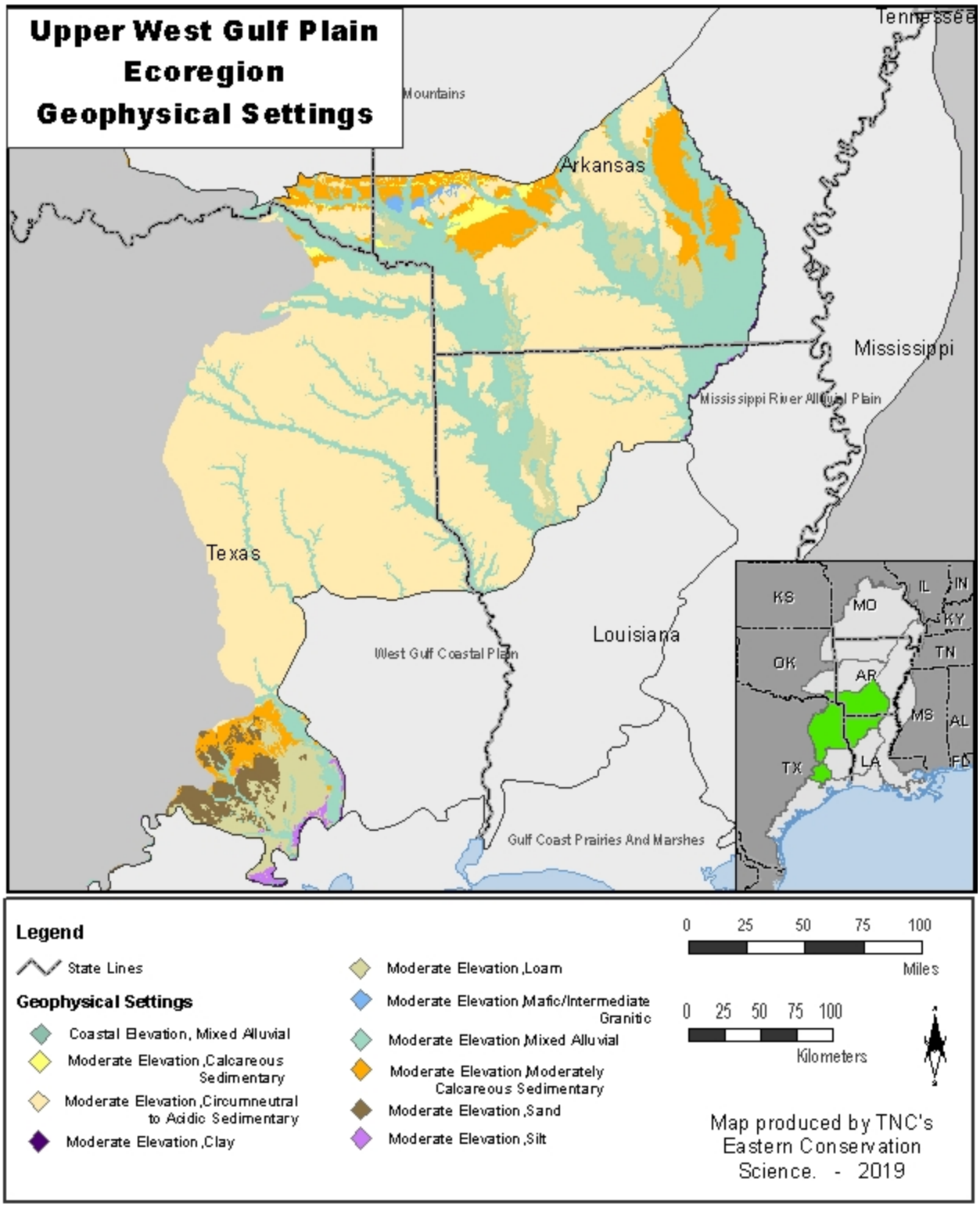


Figure 4.17: Upper West Gulf Coastal Plain Landscape Diversity.

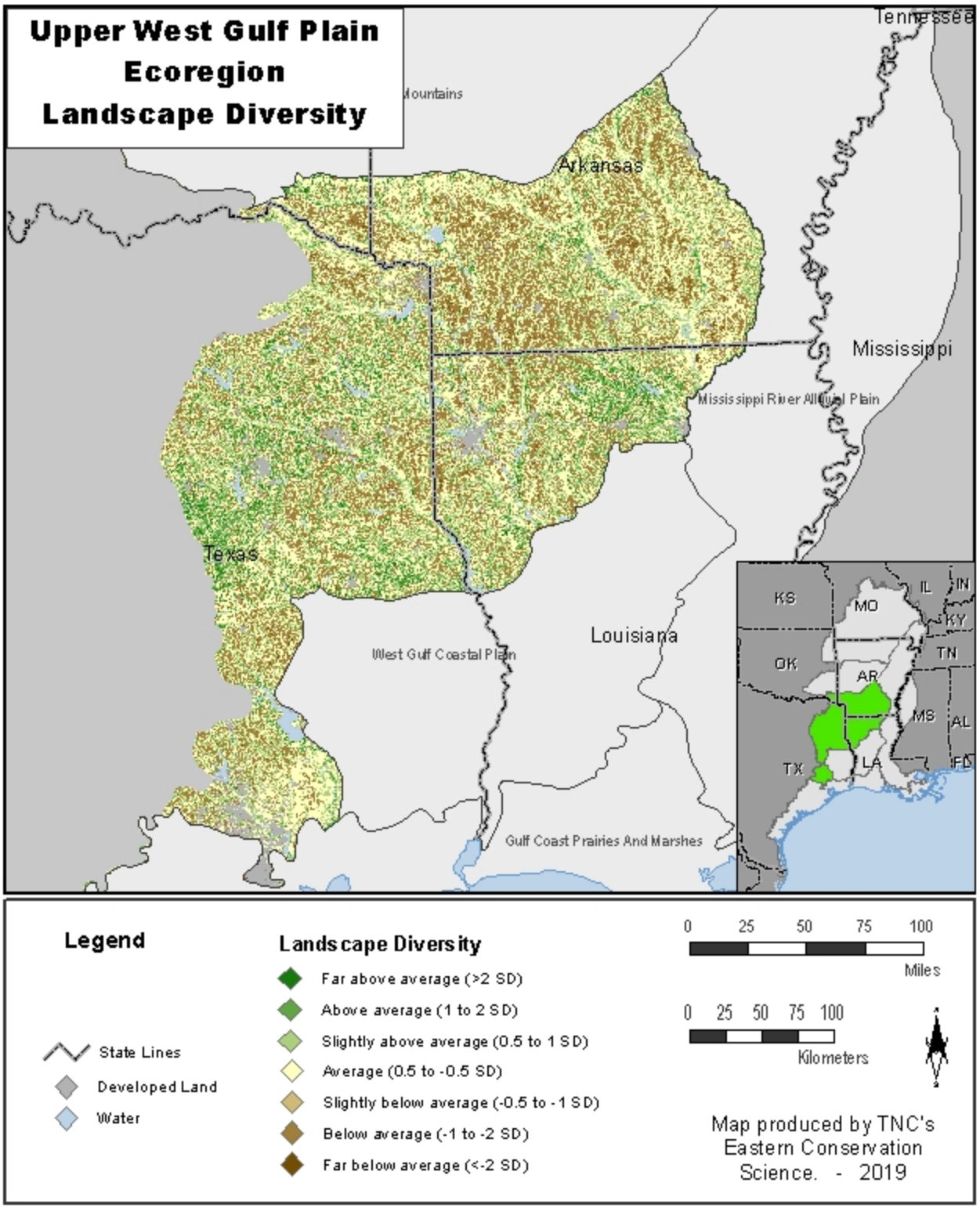


Figure 4.18: Upper West Gulf Coastal Plain Local Connectedness.

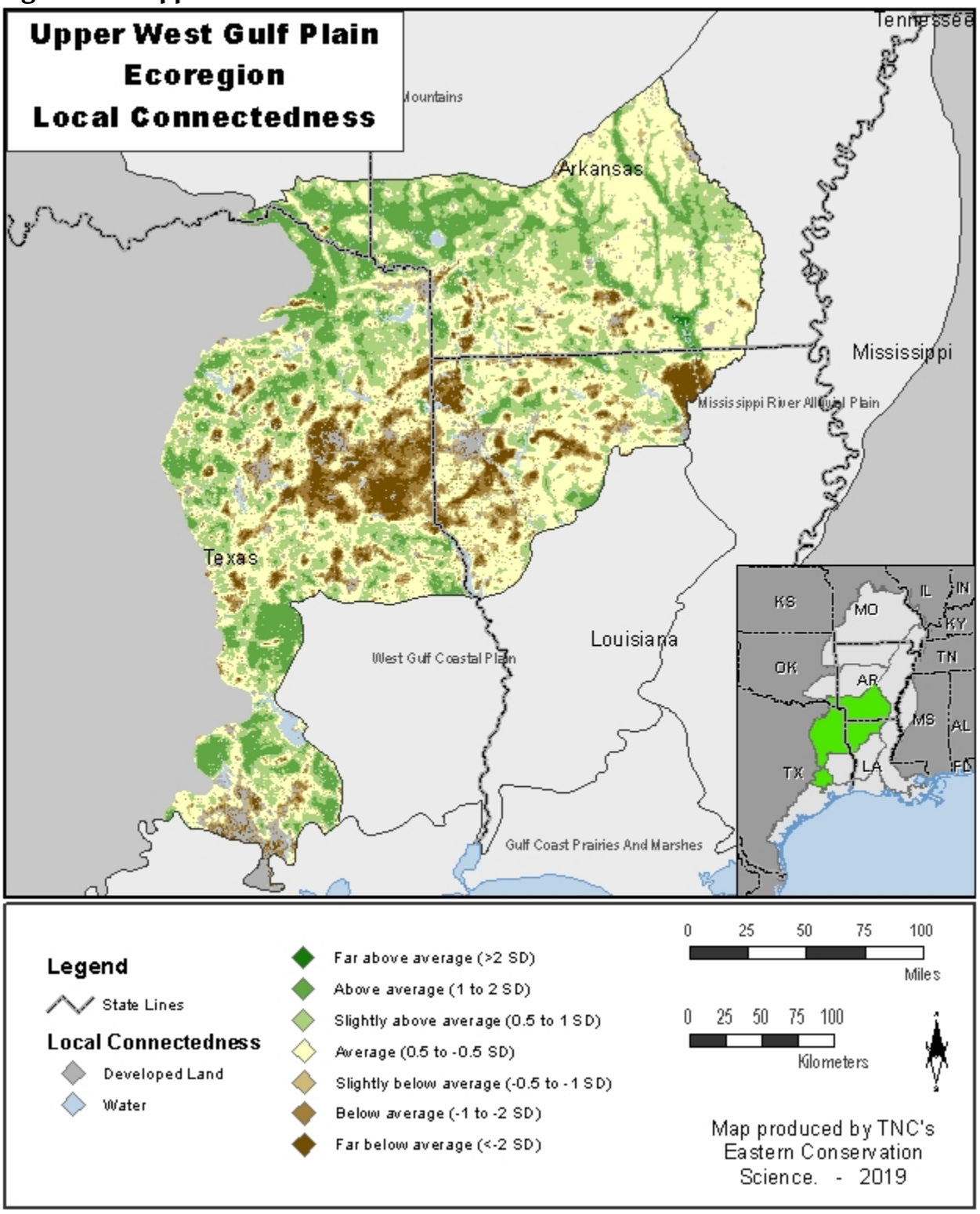


Figure 4.19: Upper West Gulf Coastal Plain Site Resilience Scores.

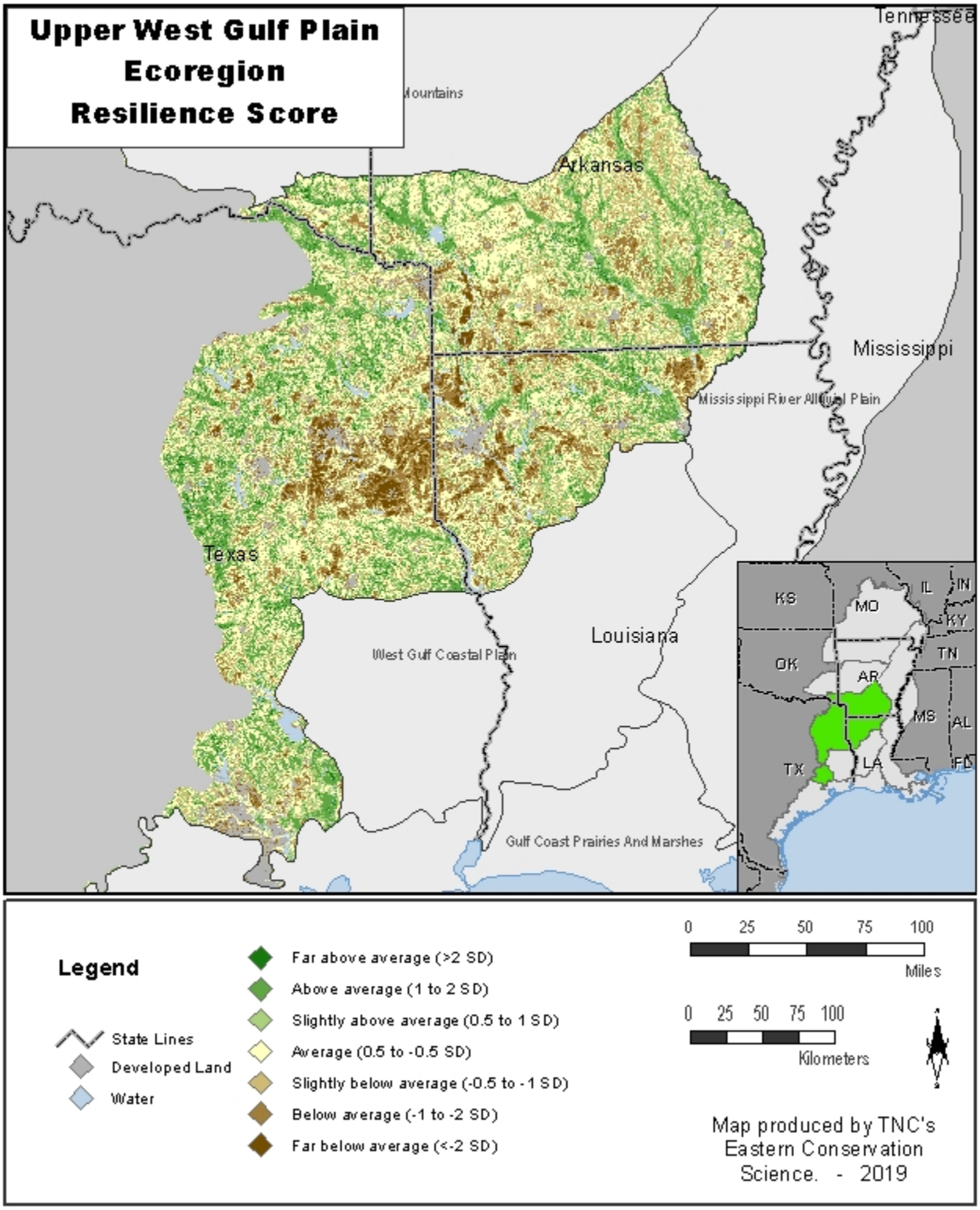


Figure 4.20: Resilient Areas for Each Geophysical Setting Within the Upper West Gulf Coastal Plain Ecoregion.

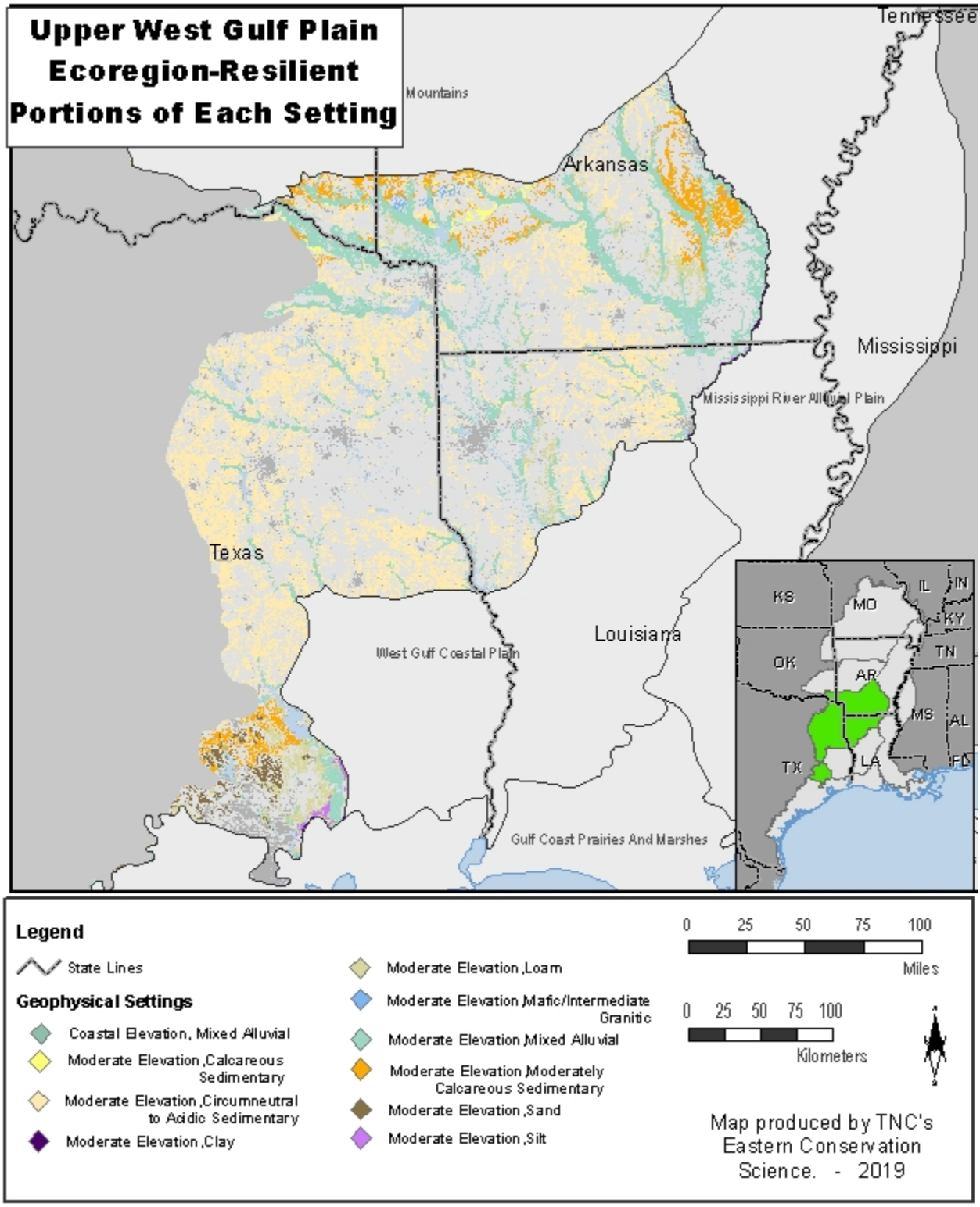
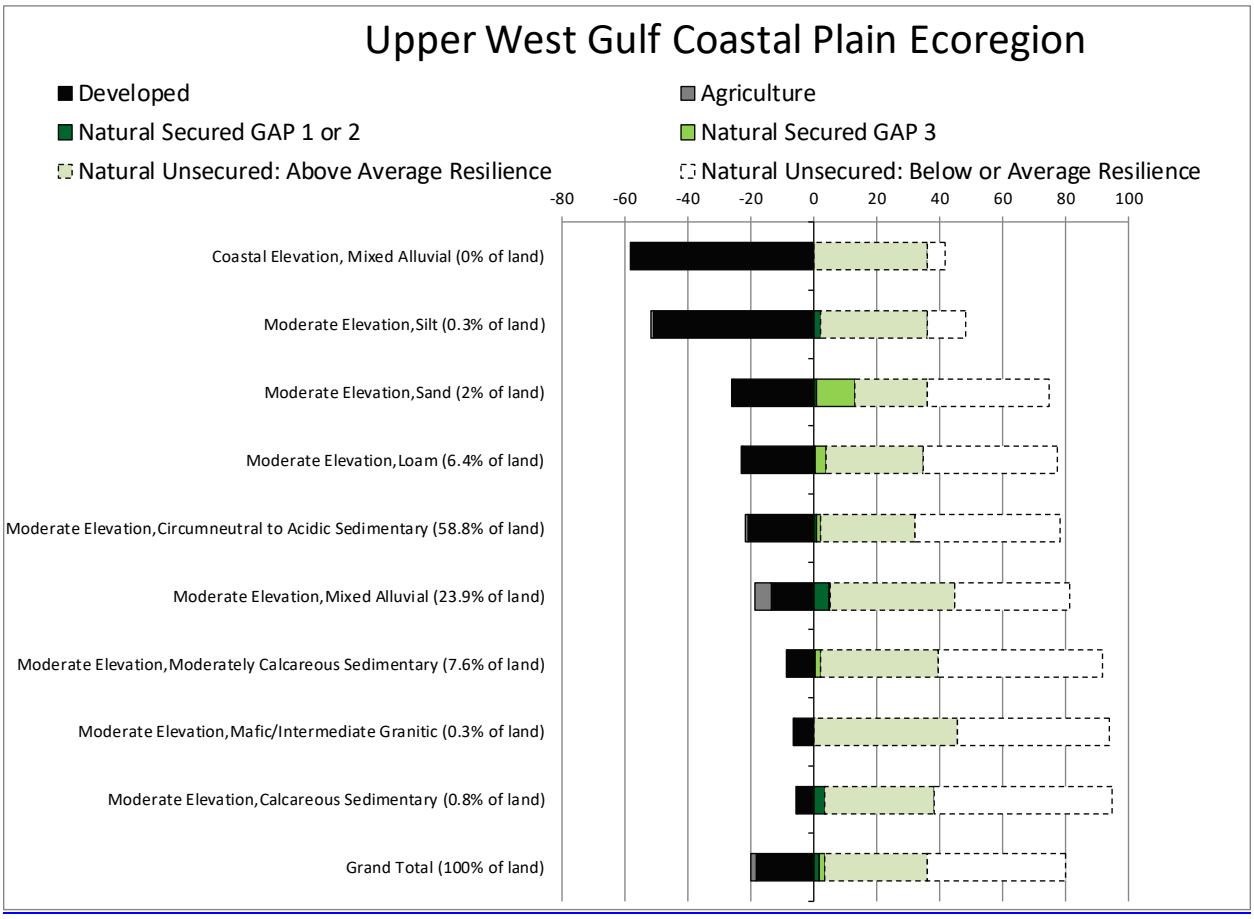


Figure 4.21: Conversion and Securement of the Upper West Gulf Coastal Plain Ecoregion by Geophysical Setting. This ecoregion is 20% converted and 3% secured, a ratio of converted to secured of 6 to 1. Surficial settings, especially mixed alluvial, silt, sand and loam are the most converted environments. Within this ecoregion, 33% of the land area (8.3 million acres) is resilient unsecured natural land.





This ecoregion description was adapted from The West Gulf Coastal Plain Ecoregional Conservation Plan (TNC, 2003)

The West Gulf Coastal Plain ecoregion encompasses approximately 17,500 sq. mi. in eastern Texas and western Louisiana, extending from the western edge of the Mississippi River floodplain in Louisiana to the Trinity River in Texas, and from the prairies and marshes of the Gulf Coast north to the mixed pine-hardwood dominated rolling hills of encompassing the historic range of longleaf pine (*Pinus palustris*) dominated uplands on the coastal plain west of the Mississippi River.

The geomorphology of the West Gulf Coastal Plain is largely a result of deposition and subsequent uplift of continenal and marine sediments from the end of the Cretaceous period to Pleistocene. The dominant landforms consist of nearly level to moderately rolling plains, with elevations ranging form 80-660ft. Surface geologic formations in the ecoregion occur in a series of belts that roughly parallel the present shoreline of the Gulf of Mexico. Soils are composed of fine, sandy surface soil, clayey and loamy sand subsoil, and gravel.

The predominant natural vegetation in the West Gulf Coastal Plain ecoregion is longleaf pine (Pinus palustris) woodland on the uplands and broad flats and mixed-hardwood forest along major river floodplains. Dry uplands occur in deep, well-drained sandy soils on ridgetops, broad uplands, and stream terraces. Longleaf pine may dominate natural stands, but it often occcurs in mixed stands with sand post oak, bluejack oak, black hickory, and shortleaf pine. Mesic uplands occur on moderately well-drained loamy soils on broad uplands and gentle slopes. Longleaf pine is almost always dominant in the overstory but hardwoods may include post oak, southern red oak, and flowering dogwood. Ground cover growth is often luxuriant supporing a highly diverse assortment of species. Wet flatwoods are found on nearly level plains with poorly drained, nutrient-poor soils and a seasonaly high water table. The species-rich ground cover is dominated by native grasses and sedges.

Figure 4.22: West Gulf Coastal Plain Geophysical Settings.

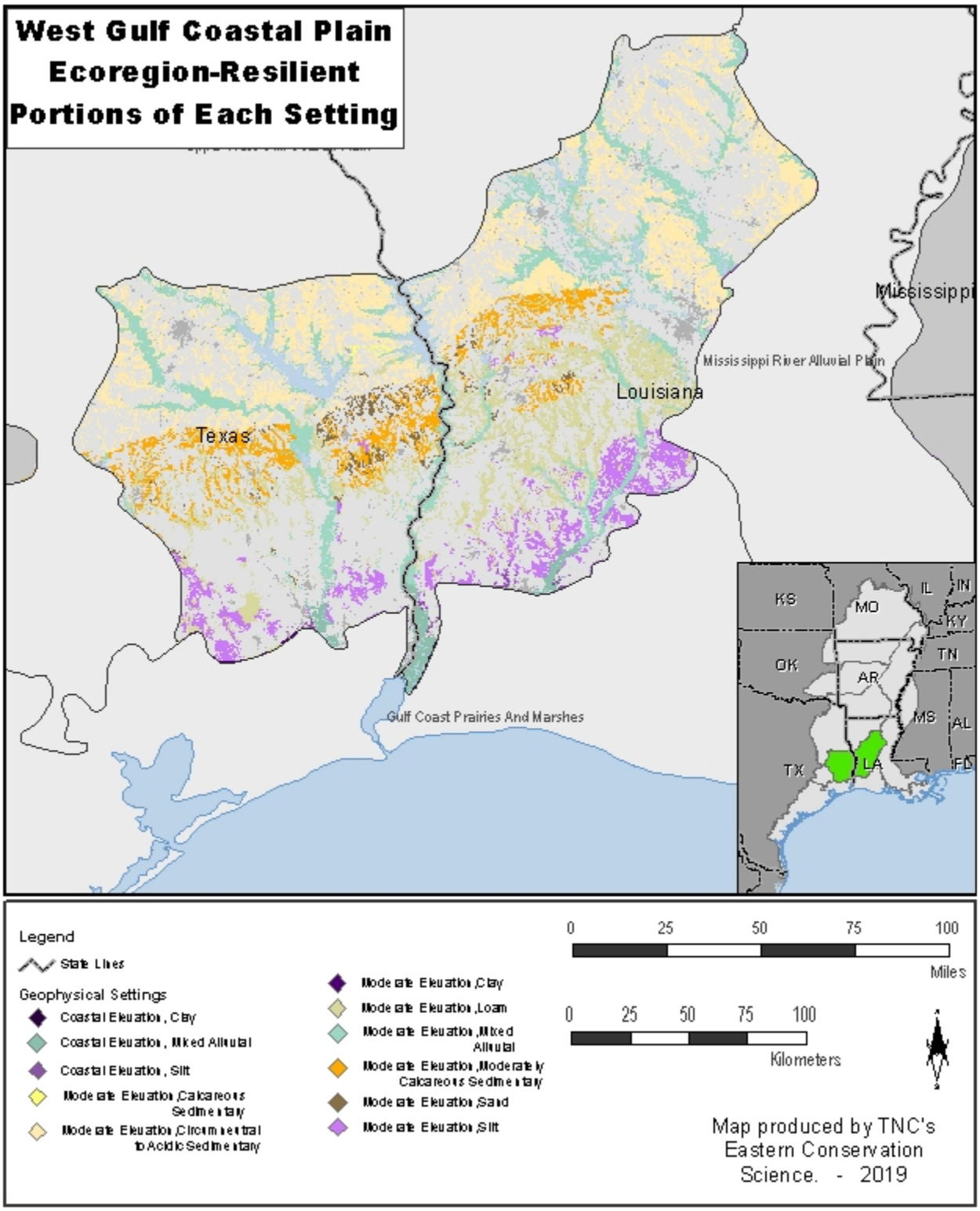


Figure 4.23: West Gulf Coastal Plain Landscape Diversity.

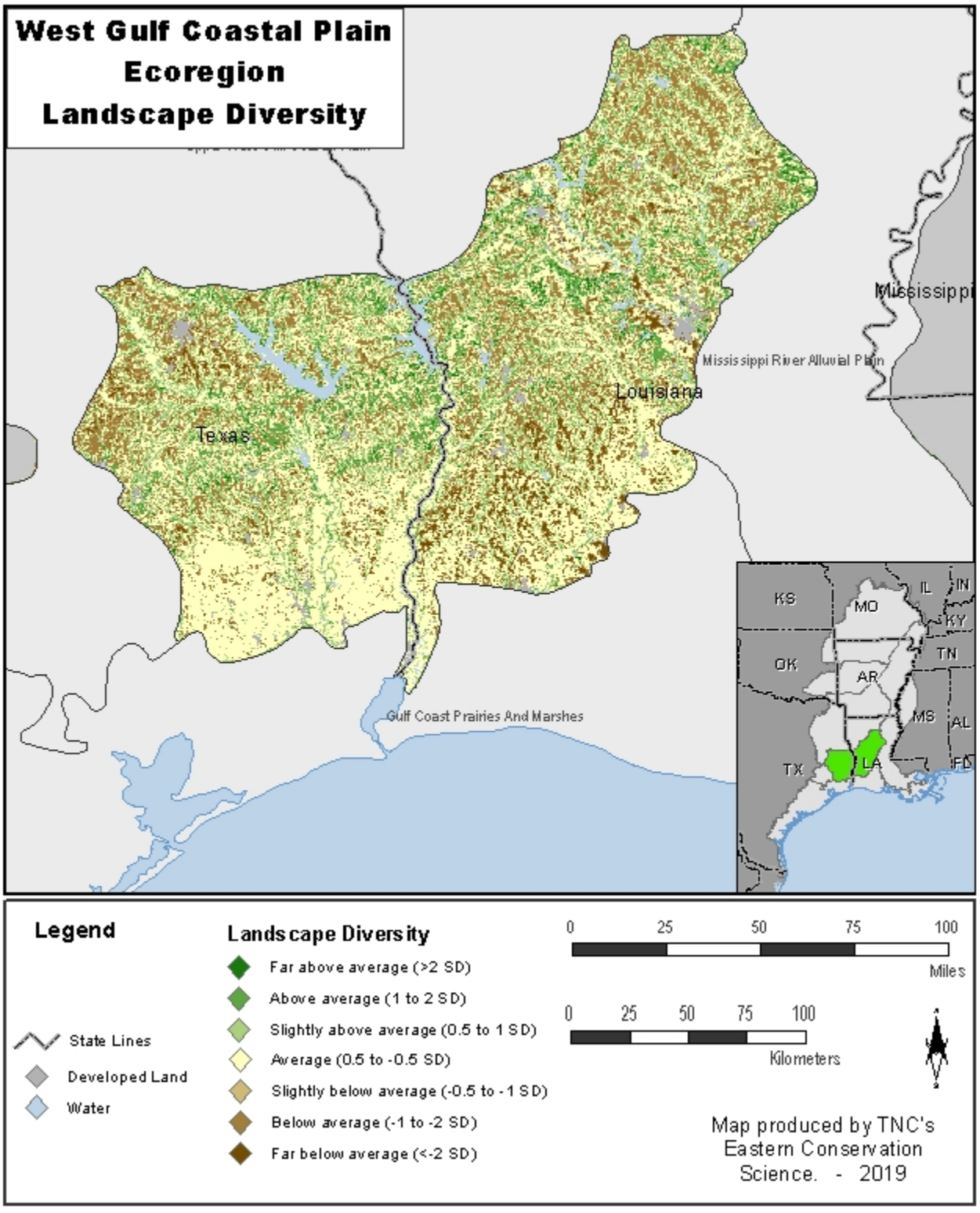


Figure 4.24: West Gulf Coastal Plain Local Connectedness.

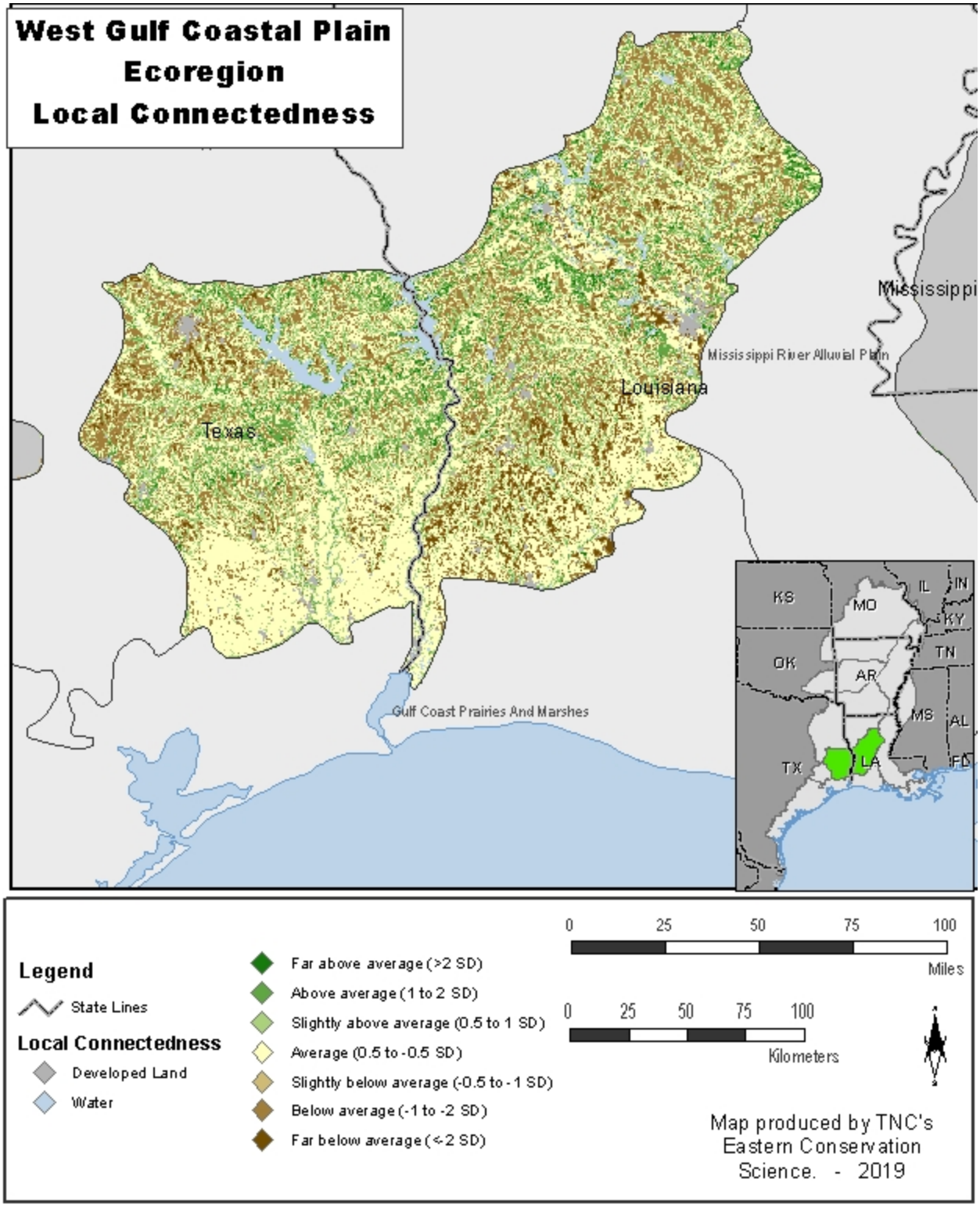


Figure 4.25: West Gulf Coastal Plain Site Resilience Scores.

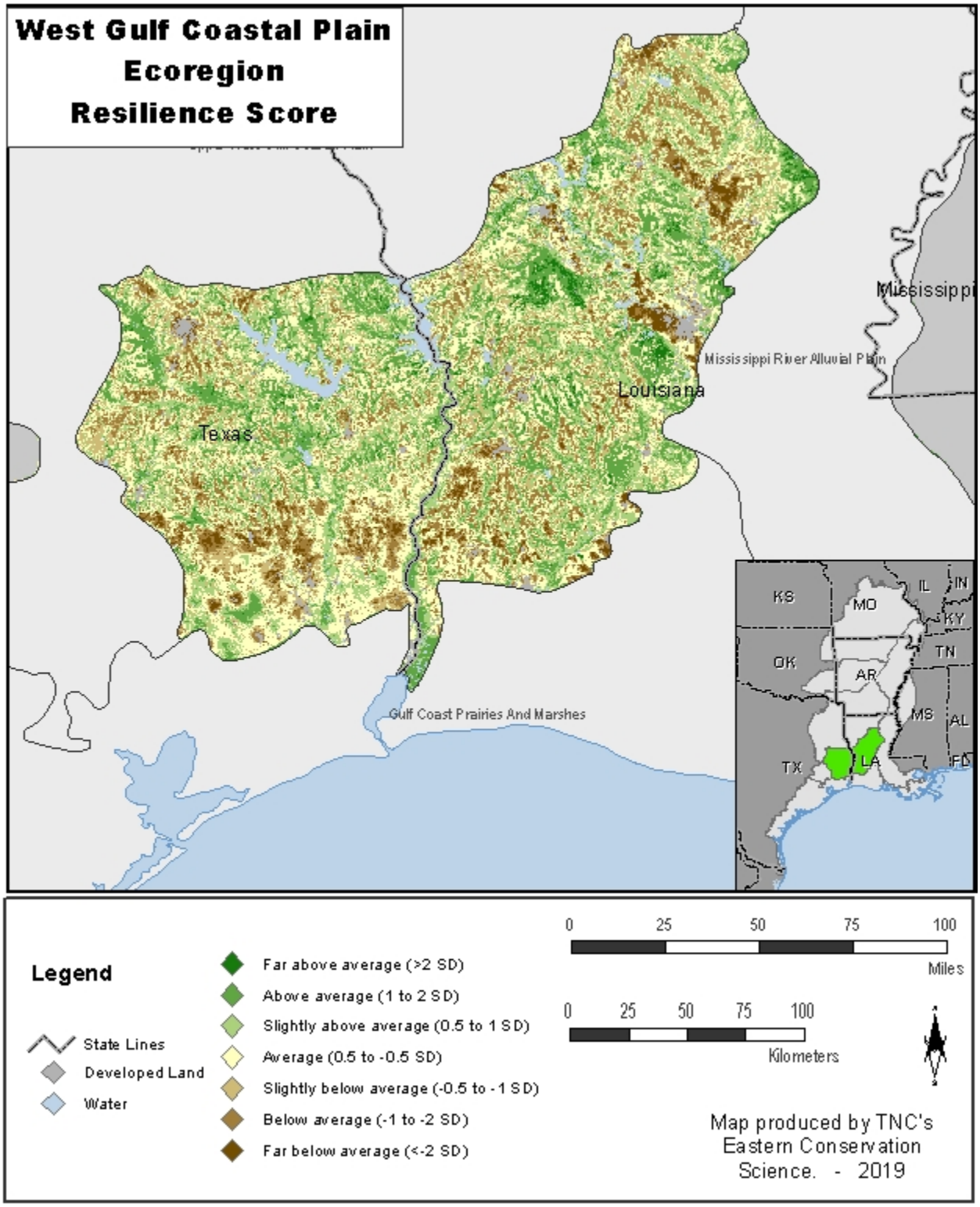


Figure 4.26: Resilient Areas for Each Geophysical Setting Within the West Gulf Coastal Plain Ecoregion.

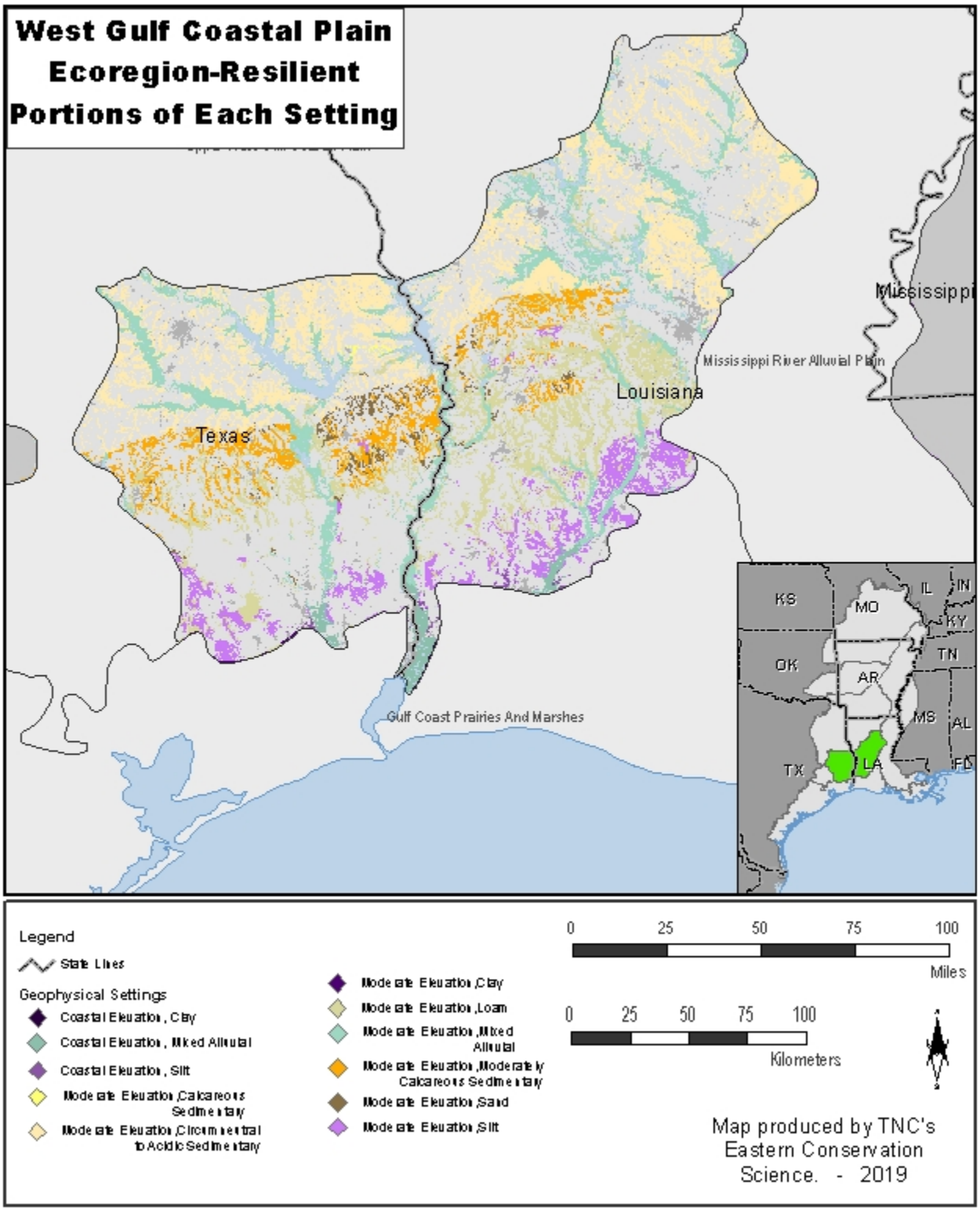
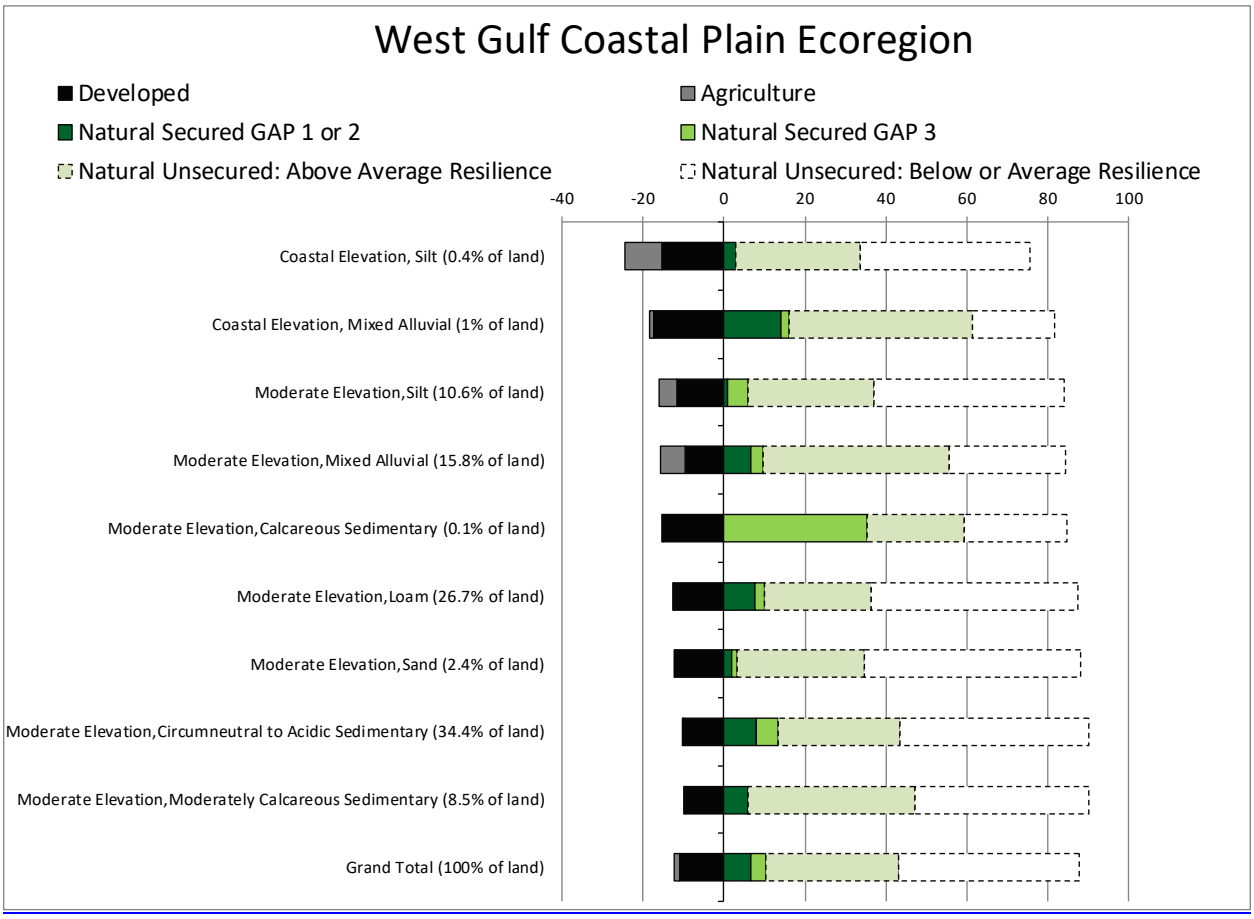


Figure 4.27: Conversion and Securement of the West Gulf Coastal Plain Ecoregion by Geophysical Setting. This ecoregion is 13% converted and 10% secured, a ratio of nearly 1 to 1. Fine grained silt and mixed alluvial settings are the most converted. Within this ecoregion, 33% of the land area (3.4 million acres) is resilient unsecured natural land.





Mississippi River Alluvial Plain

Photo credit: Nancy Webb

This ecoregion description was adapted from Conservation Planning in the Mississippi River Alluvial Plain (TNC 2002).

The Mississippi River Alluvial Plain is a 9.7 million ha floodplain-based ecoregion that includes part of Illinois, Kentucky, Tennessee, Missouri, Arkansas, Louisiana, Mississippi, and Texas. It includes several uplands (e.g. Macon Ridge, Grand Prairie, and Crowley's Ridge) and most of the Atchafalaya Basin, but excludes the Red and Ouachita River Alluvial Plains and coastal areas south of the Atchaflalaya Basin.

Its most defining feature is the Mississippi River which flows south over the Mississippi Embayment, a structural trough in the earth's crust. Elevational differences of only a few inches result in great difference in soil saturation characteristics and thus the species of plants that grow there. As a result, much variability exists within the bottomland hardwood ecosystem ranging from the bald cypress/tupelo swamp community on frequently inundated sites to cherrybark oak/pecan community found on sites subjected to temporary flooding. Between these are more transition overcup oak/water hickory, elm/ash/hackberry, and sweetgum/red oak communities.

River floodplain systems are highly productive and provide exceptional habitat for a variety of vertebrates including foraging and spawning fish, amphibians, and reptiles. Over 240 fish species, 45 species of reptiles and amphibians, and 27 species of mussels depend on the river and floodplain systems of Mississippi River Alluvial Plain.

While this ecoregion has experienced extensive alteration, hundreds of thousands of acres of public land have been purchased as state wildlife management areas and federal wildlife refuges, and the potential for significant restoration is very high.

Figure 4.28: Mississippi River Alluvial Plain Geophysical Settings.

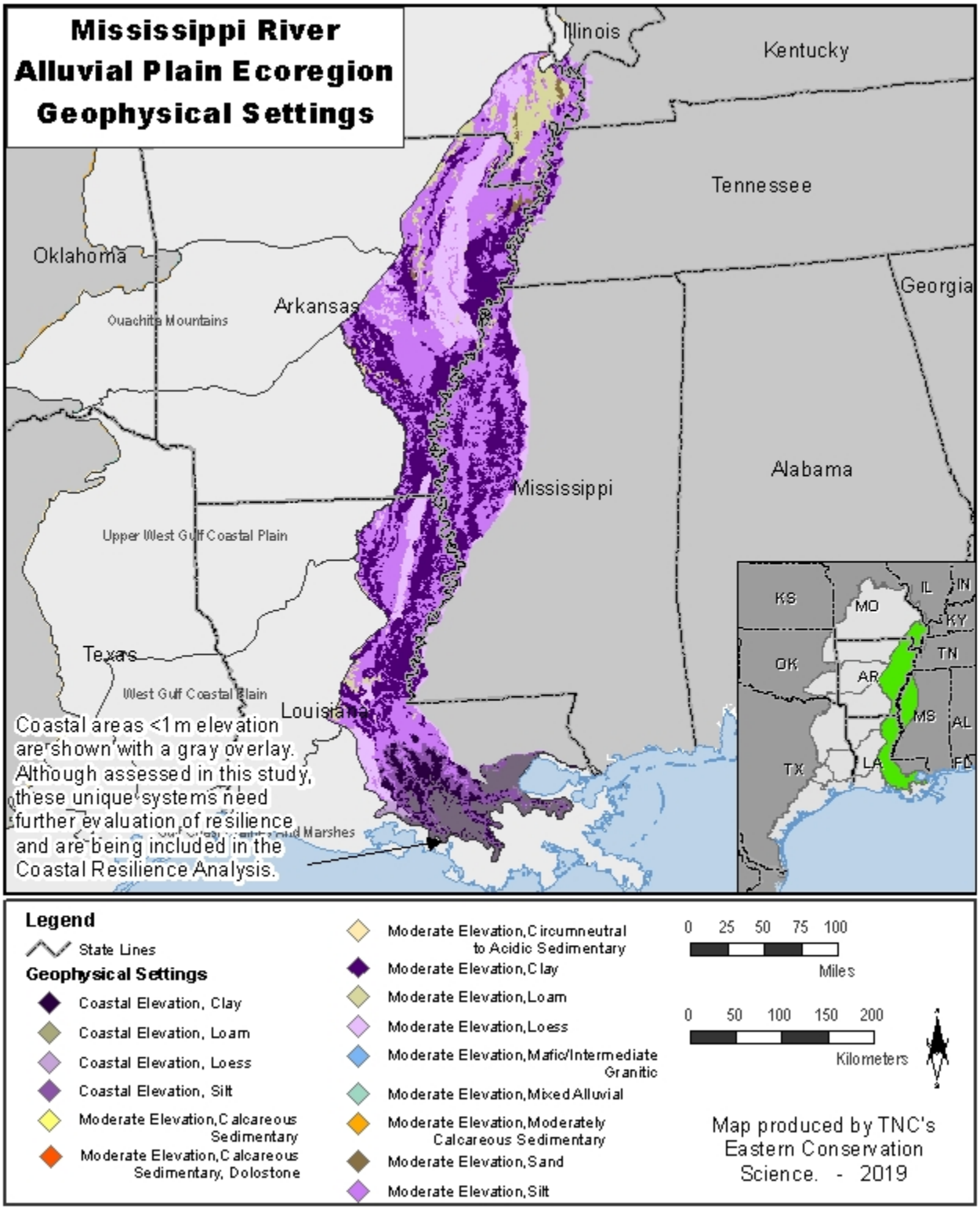


Figure 4.29: Mississippi River Alluvial Plain Landscape Diversity.

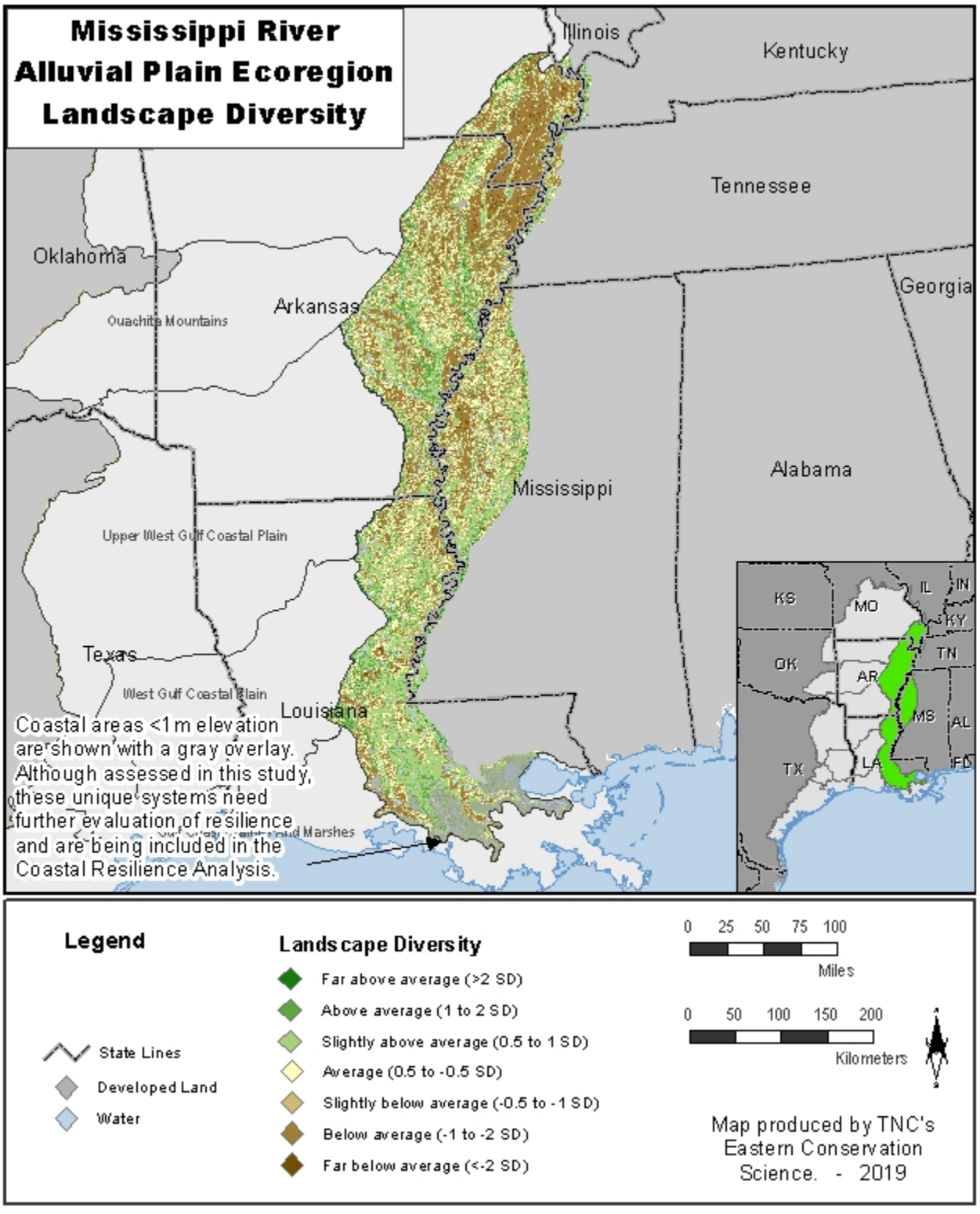


Figure 4.30: Mississippi River Alluvial Plain Local Connectedness.

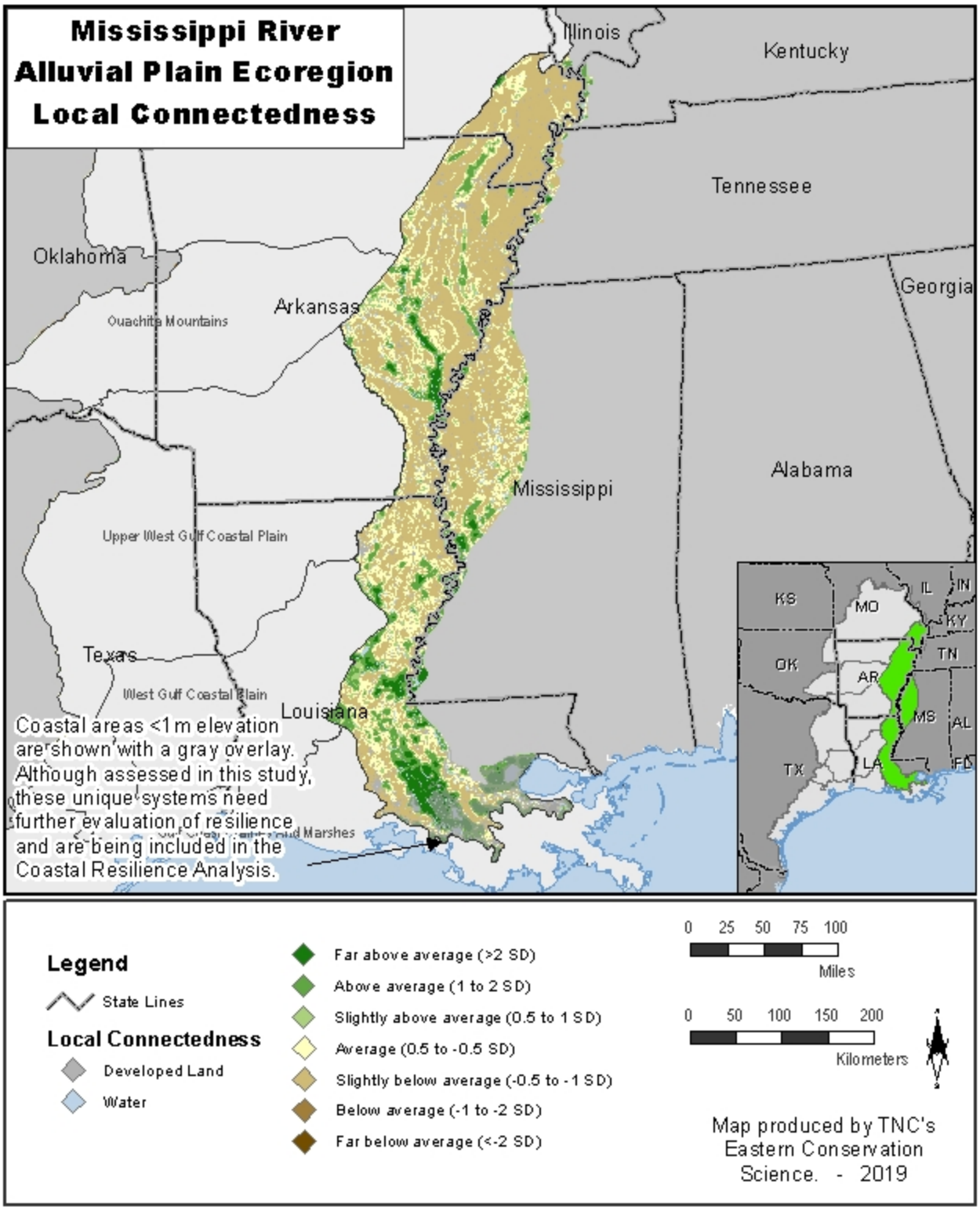


Figure 4.31: Mississippi River Alluvial Plain Site Resilience Scores.

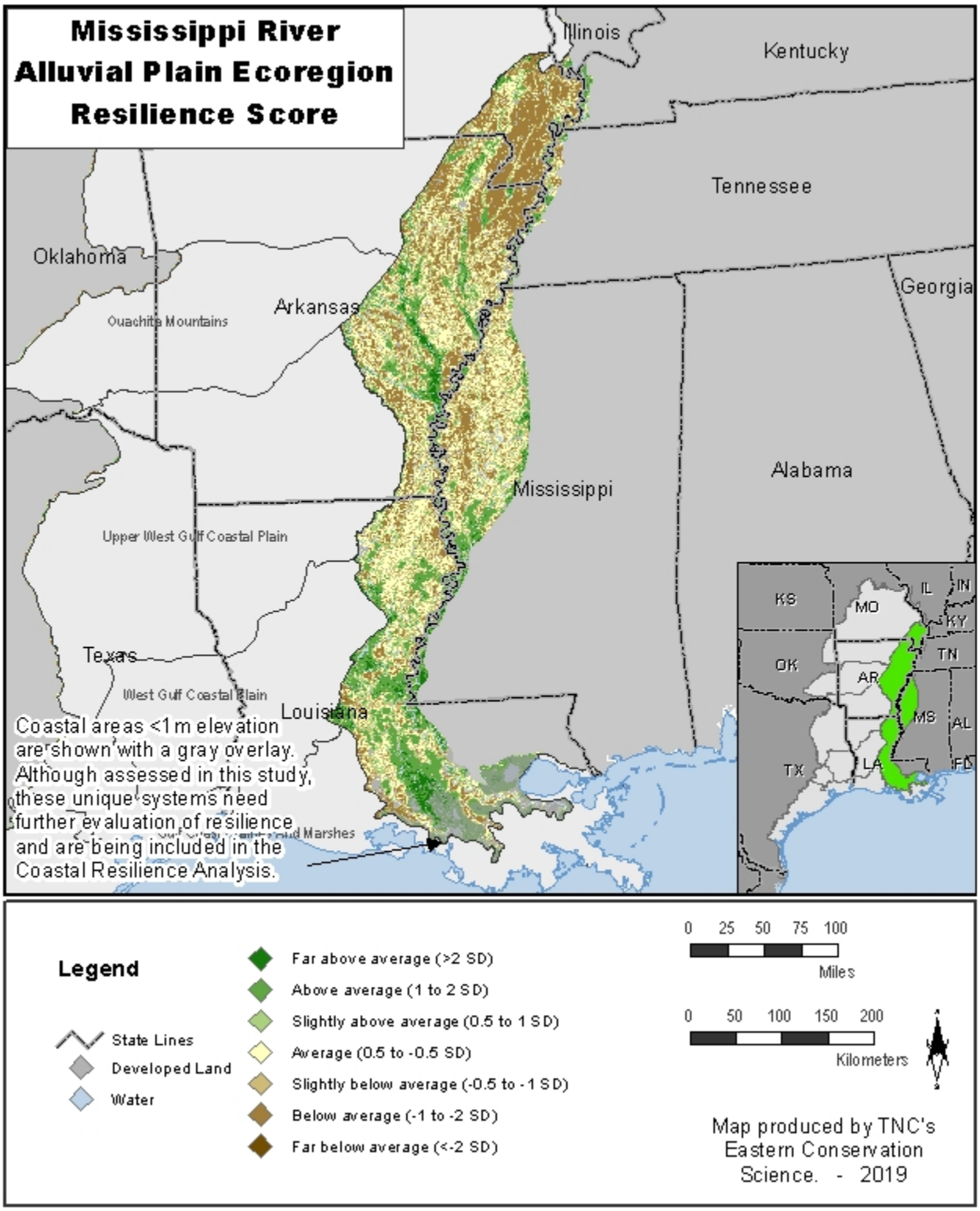


Figure 4.32: Highest Resilience Score Areas for Each Geophysical Setting Within the Mississippi River Alluvial Plain Ecoregion.

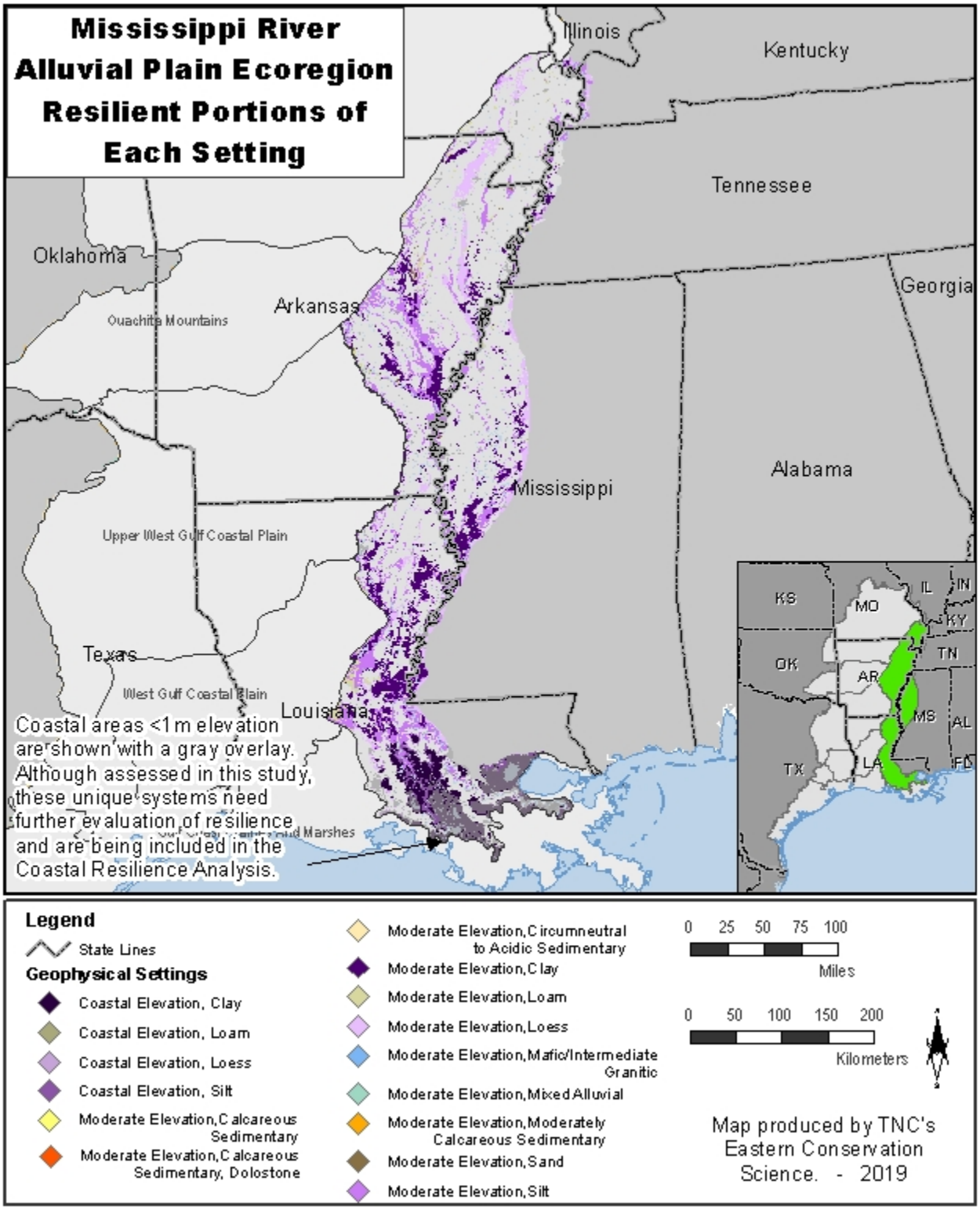
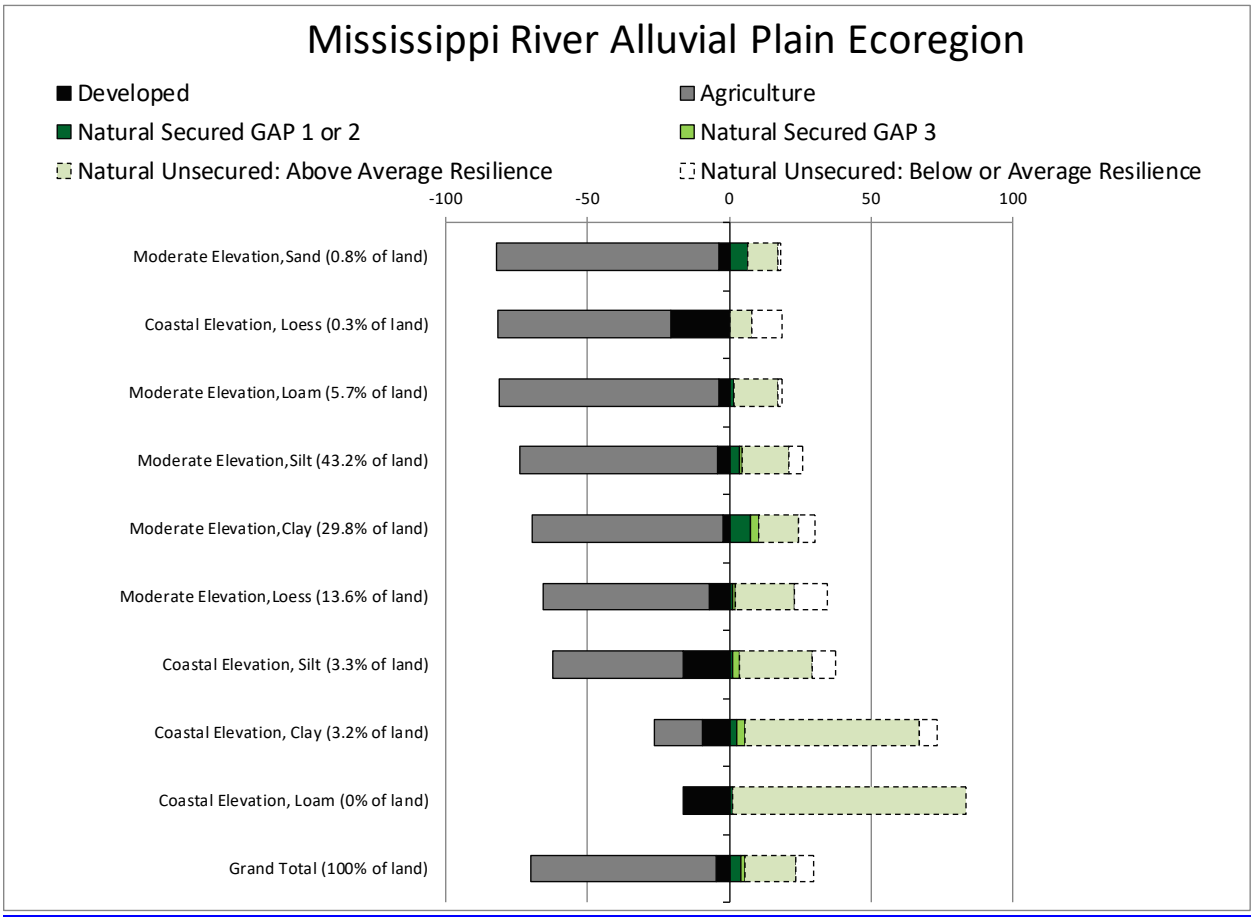


Figure 4.33: Conversion and Securement of the Mississippi River Alluvial Plain by Geophysical Setting. This ecoregion is 70% converted and 6% secured, a ratio of 13 acres converted to every 1 secured. Within this ecoregion, 18% of the land area (4.4 million acres) is resilient unsecured natural land.





Gulf Coast Prairies and Marshes

Photo credit: XXXXXXX

This ecoregion description is adapted from The Gulf Coast Prairies and Marshes Ecoregional Conservation Plan (TNC 2002).

The Gulf Coast Prairies and Marshes Ecoregion encompasses two countries, two states, 22 primary bays, 19 major rivers, and nearly 600 miles of shoreline. The number and types of birds in the ecoregion is among the greatest anywhere in the United States or Canada, and it is also renowned for its butterfly and reptile diversity. The region's productive bays and estuaries are virtual factories, producing fishes and shellfish upon which the people of the ecoregion depend economically, and which constitute important links in the food chain for many marine organisms.

Before European settlement, the region was composed of a mosaic of tallgrass coastal prairie, riparian bottomland hardwood forests, ephemeral freshwater wetlands, canebrake swamps, extensive coastal forests, chenier woodlands, freshwater tidal wetlands, brush mottes and corridors, barrier islands, estuaries, saltwater marshes, hypersaline lagoons, and Tamaulipan Thornscrub habitats

Today freshwater wetlands have been reduced by 30%, coastal forests have been cleared and fragmented, the chenier woodlands of the upper Texas coast are essentially gone, and less than 2% of the tallgrass coastal prairie remains.

Most wetland losses were attributed to subsidence (mostly induced by anthropomorphic sources [oil/gas extraction]), deepwater intrusion (a.k.a., channelization), agriculture, and urban/rural development.

More than 1/3 of the combined population of Texas and Louisiana and over 70% of these states' industrial base, commerce, and jobs are located within 100 miles of the coastline. The ecoregion also supports the world's second largest petrochemical complex and some of the United States' busiest port facilities.

Climate change, as indicated by sea level rise, is a key threat to this ecoregion. See companion report Resilient Coastal Sites for the Gulf of Mexico: https://www.nature.org/resilientcoasts

Figure 4.34: Gulf Coast Prairies and Marshes Geophysical Settings.

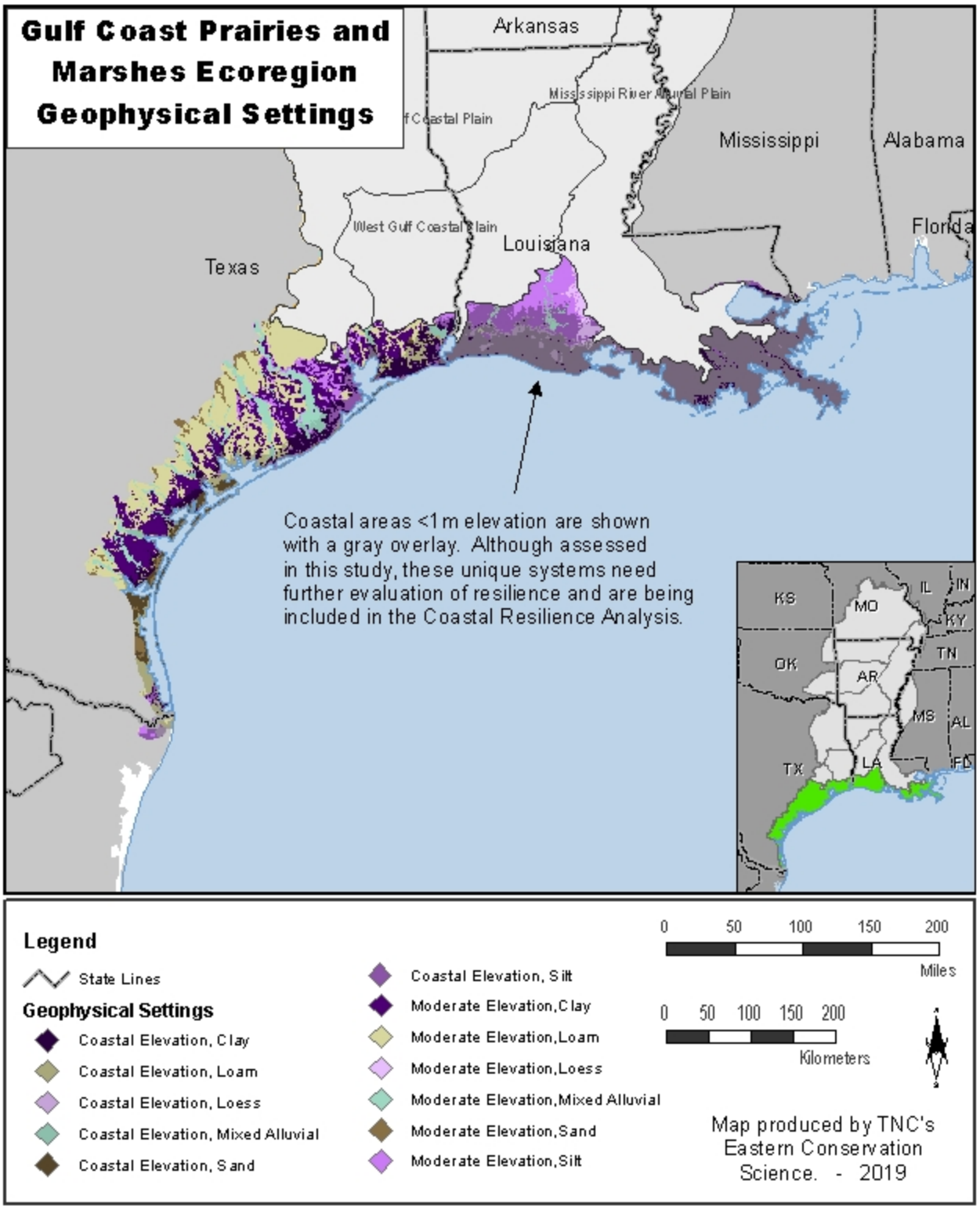


Figure 4.35: Gulf Coast Prairies and Marshes Landscape Diversity.

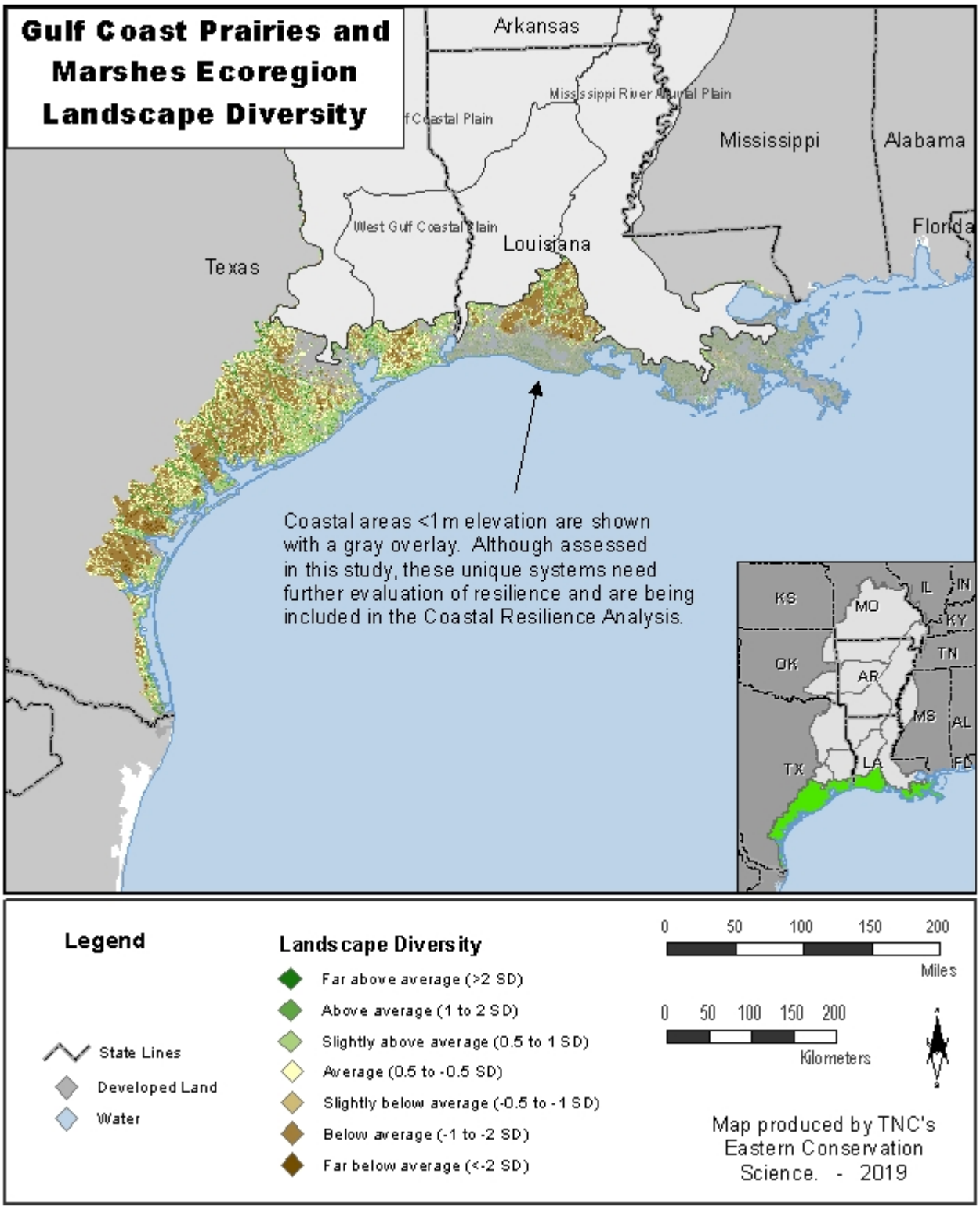


Figure 4.36: Gulf Coast Prairies and Marshes Local Connectedness.

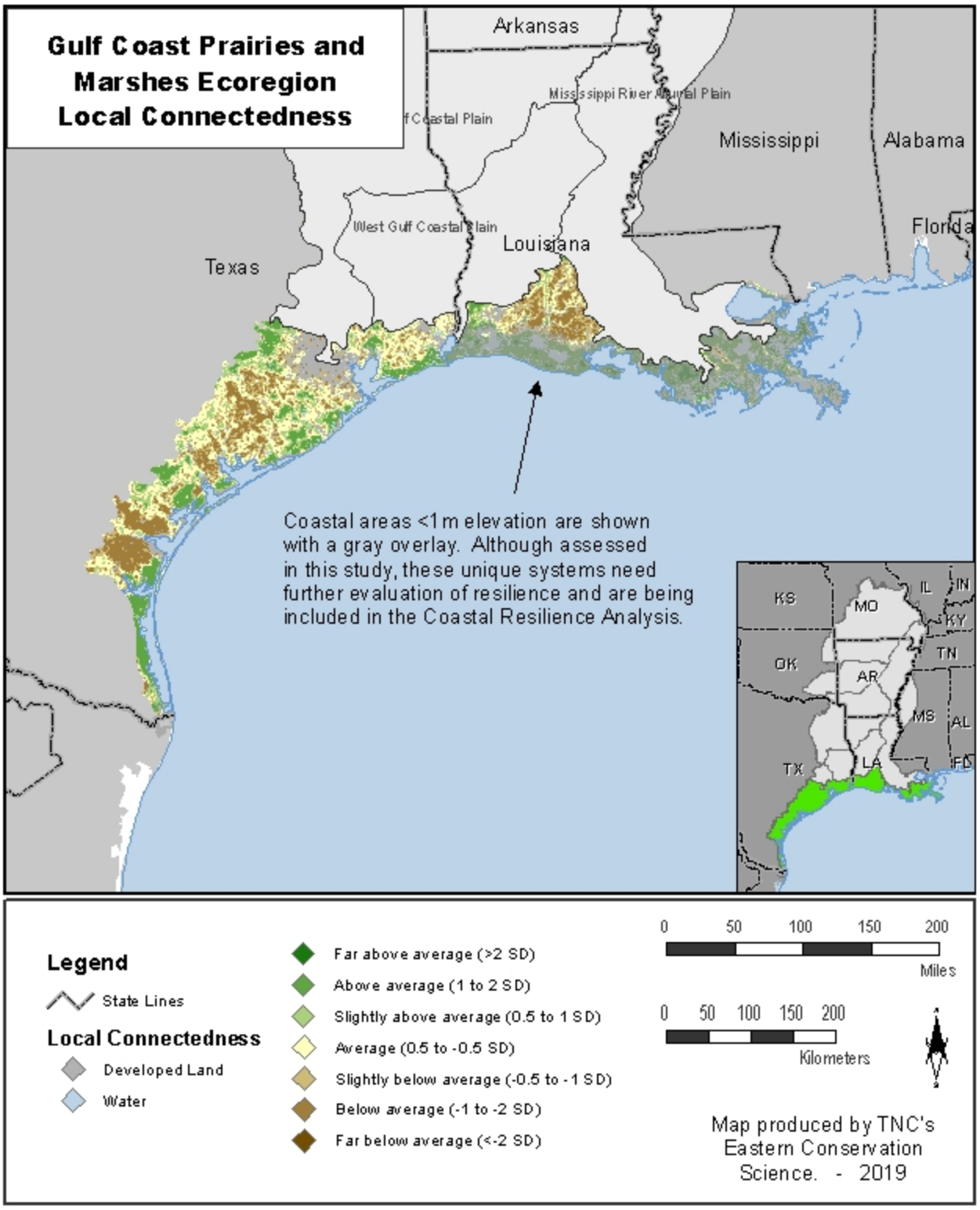


Figure 4.37: Gulf Coast Prairies and Marshes Site Resilience Scores.

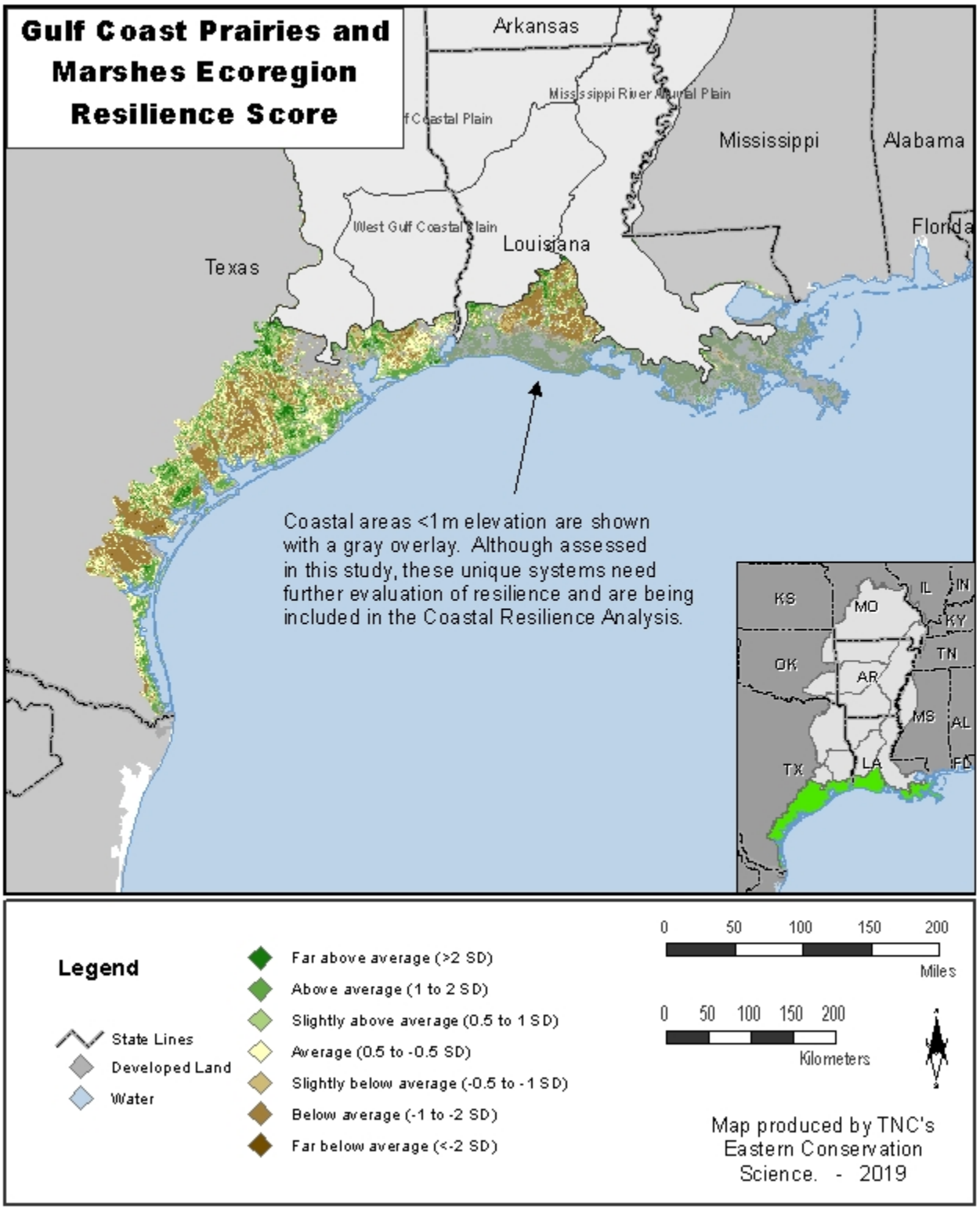


Figure 4.38: Resilient Areas for Each Geophysical Setting Within the Gulf Coast Prairies and Marshes Ecoregion.

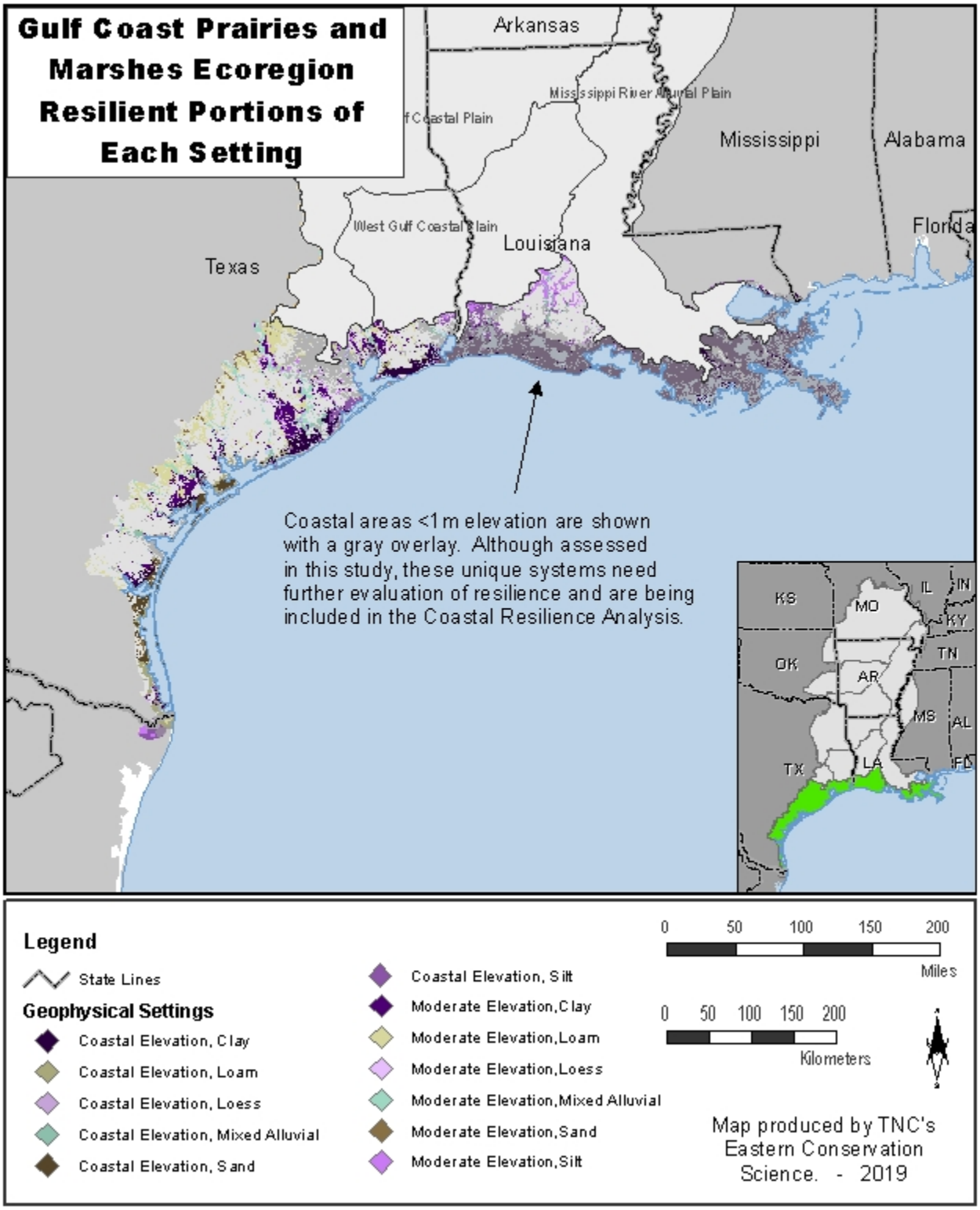
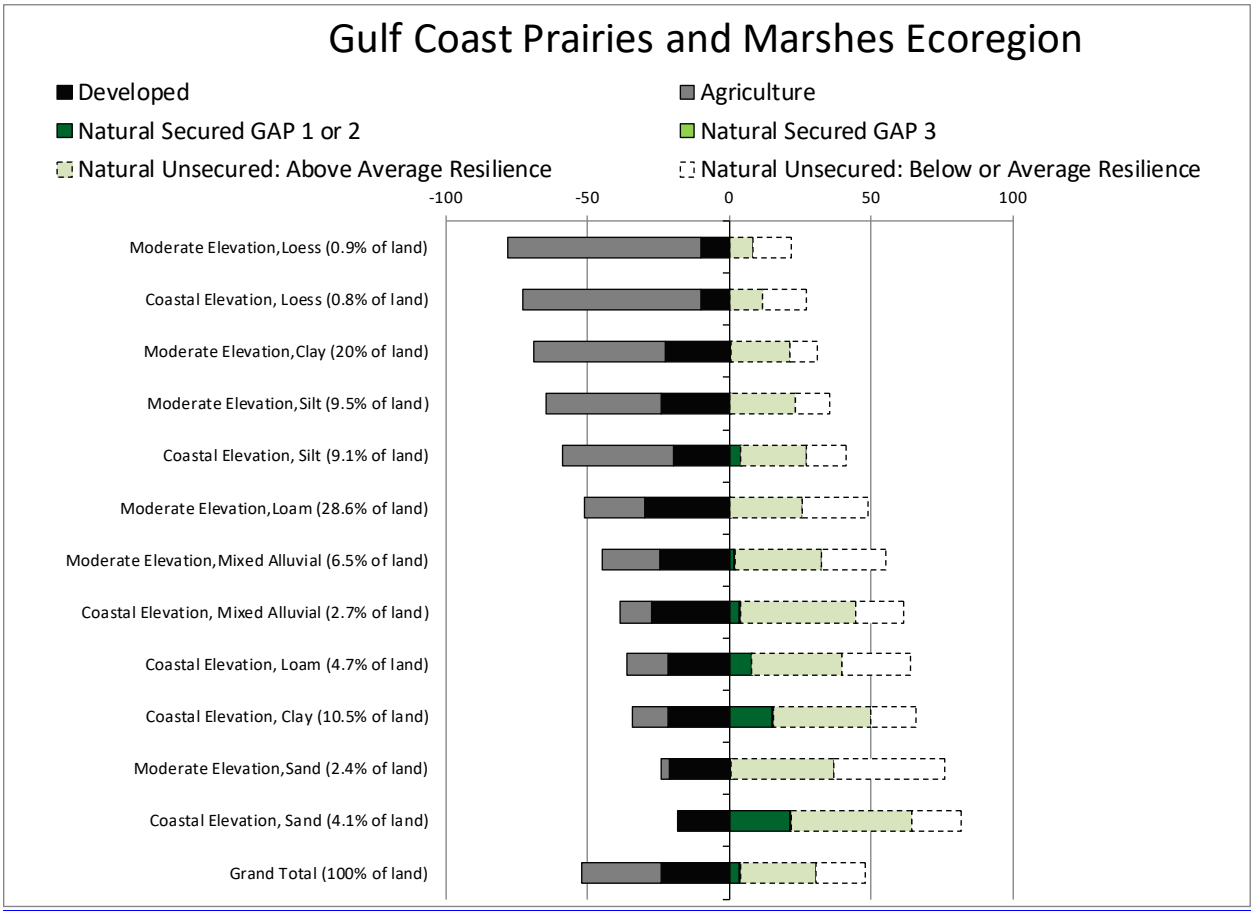


Figure 4.39: Conversion and Securement of the Gulf Coast Prairies and Marshes Ecoregion by Geophysical Setting. This ecoregion is 52% converted and 4% secured, a ratio of 14 to 1 (the highest in the study area). Within this ecoregion, 27% of the land area (3.4 million acres) is resilient unsecured natural land. Note only land area >1m elevation was included in this summary.



ECOREGION PLAN REFERENCES

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The Nature Conservancy. 2002. Conservation Planning in the Mississippi River Alluvial Plain. The Nature Conservancy. Baton Rouge, LA, USA.

CHAPTER

5

REGIONAL RESULTS

In the previous chapters, we described the rationale and methods behind Conserving Nature's Stage (introduced in Chapter 1), including how we defined geophysical settings (Chapter 2), and assessed the components of site resilience (Chapter 3). In Chapter 4, we presented the ecoregion-by-ecoregion results. In Chapter 5, we combine the ecoregion results into a composite final map for the whole Lower Mississippi-Ozark region, and provide assessments and metrics at this large scale.

We analyze the regional map in three ways: first, we view the results relative to different scales (region, ecoregion, and geophysical setting); second, we examine the extent to which each geophysical setting is currently conserved within the Lower Mississippi-Ozark region's protected lands; and third, we compare the results with the portfolio of biodiversity sites resulting from The Nature Conservancy's ecoregional planning efforts. Following these sections, we also briefly provide key points and ideas gleaned from discussions with our Steering Committee on how metrics of site resilience relate to factors that are likely to drive the persistence of the dominant ecosystems.

Site Resilience across Multiple Scales

To create a final site resilience map for the study region we rolled up the individual ecoregion maps presented in Chapter 4 into one composite map (Figure 5.1) and replaced the ecoregion score with the regional score in places where the regional score was higher (Figure 5.2). The latter step, which we called applying a "regional override," ensures that the highest-scoring sites in the Lower Mississippi study area retain their high regional score. This override is needed when a high proportion of an ecoregion is relatively resilient and thus the "average" for the ecoregion is much higher than the average for the entire set of ecoregions. The final site resilience map also incorporates a smoothing algorithm that is applied at the ecoregion boundaries to decrease any artificially sharp contrasts at the ecoregion edges. Details on implementing the regional override and smoothing algorithm are given below in "Methods for Creating the Regional Resilience Map".

The final resilience map (Fig 5.2, Table 5.1) places 40.7% or just over 48 million acres in the above average resilience category for the land above the coastal 1m elevation zone. 19.5% is just slightly above average (0.5-1SD), 17.5% is above average (1 to 2 SD), and 3.7% is far above average (>2SD). Although the data is shown in a single map,

users should remember that the scores are relative to each ecoregion. For example, a resilience score of 2 SD (two standard deviations above the mean) in the relatively fragmented Mississippi Alluvial Plain, is not equivalent in an absolute sense to a resilience score of 2 SD in the more intact Ozark and Ouachita Mountain ecoregions, because the mean score of the latter ecoregion is higher. We intentionally used this relative scale so we could identify resilient areas across the full spectrum of geophysical settings and ecoregions, and by association support conservation planning that captures the full spectrum of biological diversity. If biological diversity were concentrated only in rocky dolomite soils, for example, then it would be easy to conserve diversity simply by focusing on this one geophysical setting. However, that approach would miss all the inherent diversity of the sandy coastal plain or the alluvial settings along major rivers. The differences in soils and topography that drive biological diversity also underlie the differences in land use patterns, contributing to differences in degree of protection.

Table 5.1: Regional Site Resilience. Acres and percent by resilience category.

Resilience Categories	Acres	% of Land
Far above average (> 2 SD)	4,364,947	3.7
Above average (1 to 2 SD)	20,642,595	17.5
Slightly above average (0.5 SD to 1 SD)	22,998,236	19.5
Average (0.5 SD to -0.5 SD)	29,493,925	25.0
Slightly below average (-0.5 SD to -1 SD)	15,990,059	13.6
Below average (-1 SD to -2 SD)	17,808,202	15.1
Far below average (<-2 SD	1,821,206	1.5
Developed	4,694,627	4.0
Total Acres of Land	117,813,797	100.0

Figure 5.1: Site resilience results for each ecoregion are combined to make the regional map.

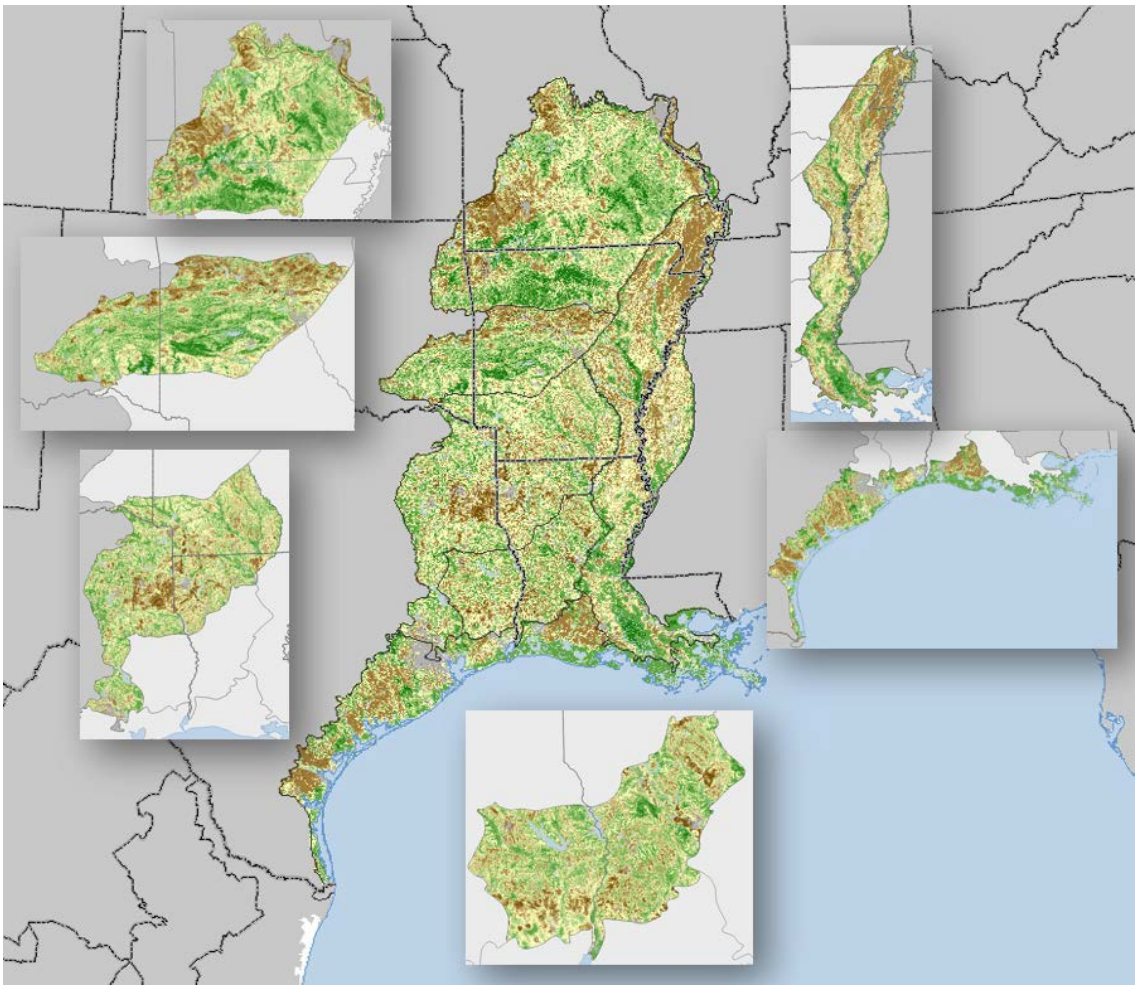
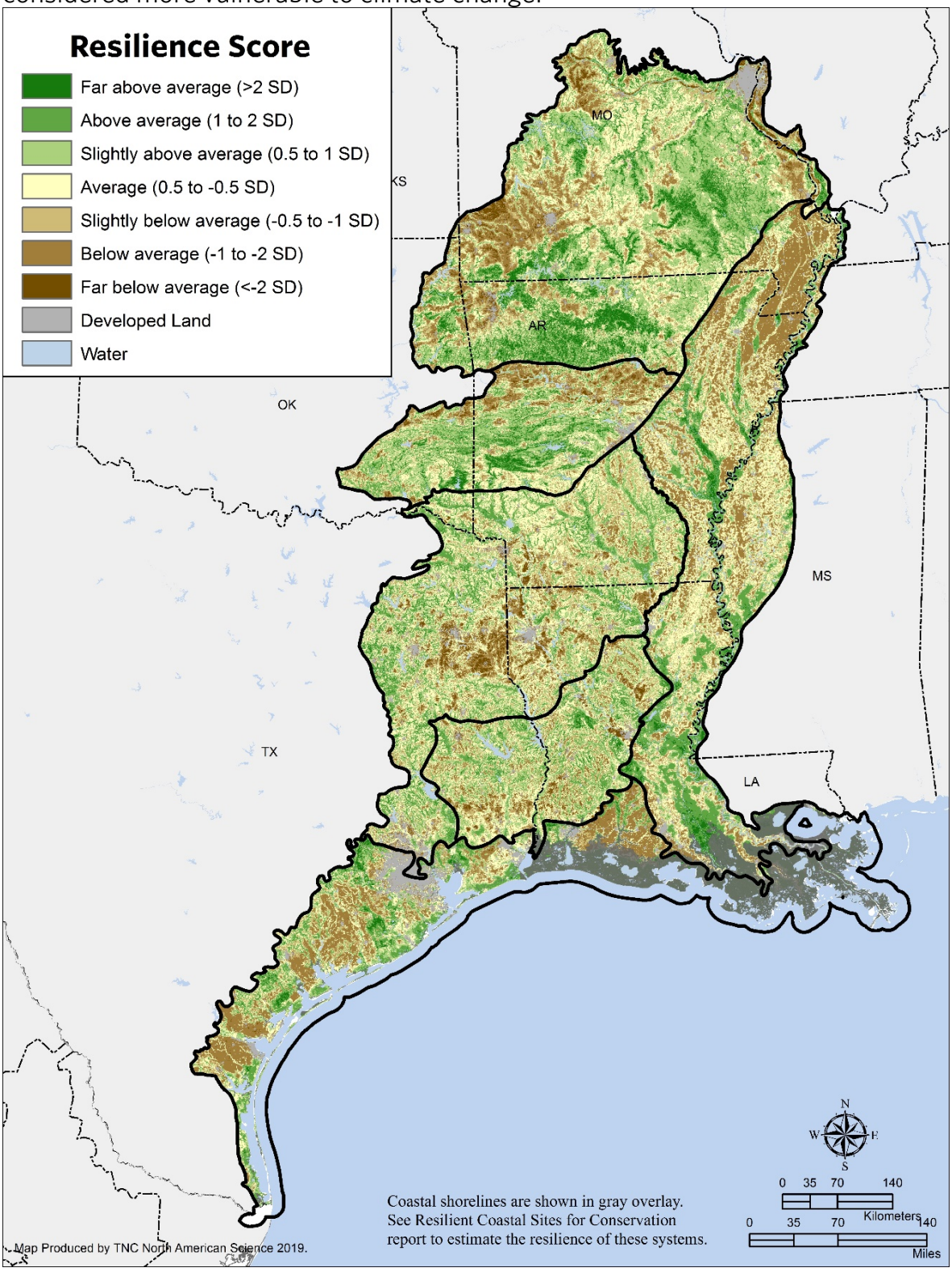


Figure 5.2: Final Regional Site Resilience Map. Areas in green score above average and are estimated to be more resilient to climate change relative to comparable geophysical settings in the same ecoregion. Areas in brown are below average and are considered more vulnerable to climate change.



To develop effective conservation strategies, it can be informative to examine the resilience scores across various scales, and the datasets we have developed allow for extensive exploration. The final regional site resilience map (Figure 5.2) incorporates the results from three queries, which are mapped in Figures 5.3-5.5.

Site resilience relative to Setting and Ecoregion (Figure 5.3). This map shows the resilience scores for each geophysical setting within each ecoregion. This is the composite (or "roll up") map of the site resilience maps for each ecoregion that includes the high resilience value sites for each setting from Chapter 4 without the application of the regional override.

Site resilience relative to Ecoregion only (Figure 5.4). This map shows the resilience scores for each ecoregion, displaying the score without the influence of the geophysical settings. In most ecoregions, the highest-scoring areas are bedrock settings, as they typically have more topographic variation (higher landform diversity) and are less fragmented than deep soil settings along rivers or valley bottoms.

Site resilience relative to Region only (Figure 5.5) This map shows the highest-scoring sites in the entire study region. We used this query to create the regional override in the final regional map by selecting all cells greater than 1 SD above the regional mean. The highest scoring sites in the study area are in the Ozark and Ouachita Mountain ecoregions.

Resilience at Multiple Scales (Figure 5.6). This map shows the highest scoring sites across all three scales—region, ecoregion, setting—in all combinations. Two combinations identify sites that are resilient at multiple scales: the dark green areas show places with high site resilience scores at every scale, and the purple areas show sites with the highest scores at the two smaller scales, the ecoregion and the setting.

It is also useful to look at the individual components of resilience—landscape diversity and local connectedness—at the scale of the whole region. Like the final regional map, we created component maps that were composites of the individual ecoregions. The landscape diversity map (Figure 5.7) shows the areas within each ecoregion that have the most microclimates relative to the various geophysical settings. The local connectedness map (Figure 5.8) highlights the areas in each ecoregion that are the most intact and connected by natural land cover relative to each geophysical setting. Although we gave the two components equal value (weight) in the resilience score, depending on location, either component may have a stronger influence (Figure 5.9).

Figure 5.3: Site Resilience Relative to Setting and Ecoregion (no regional override).

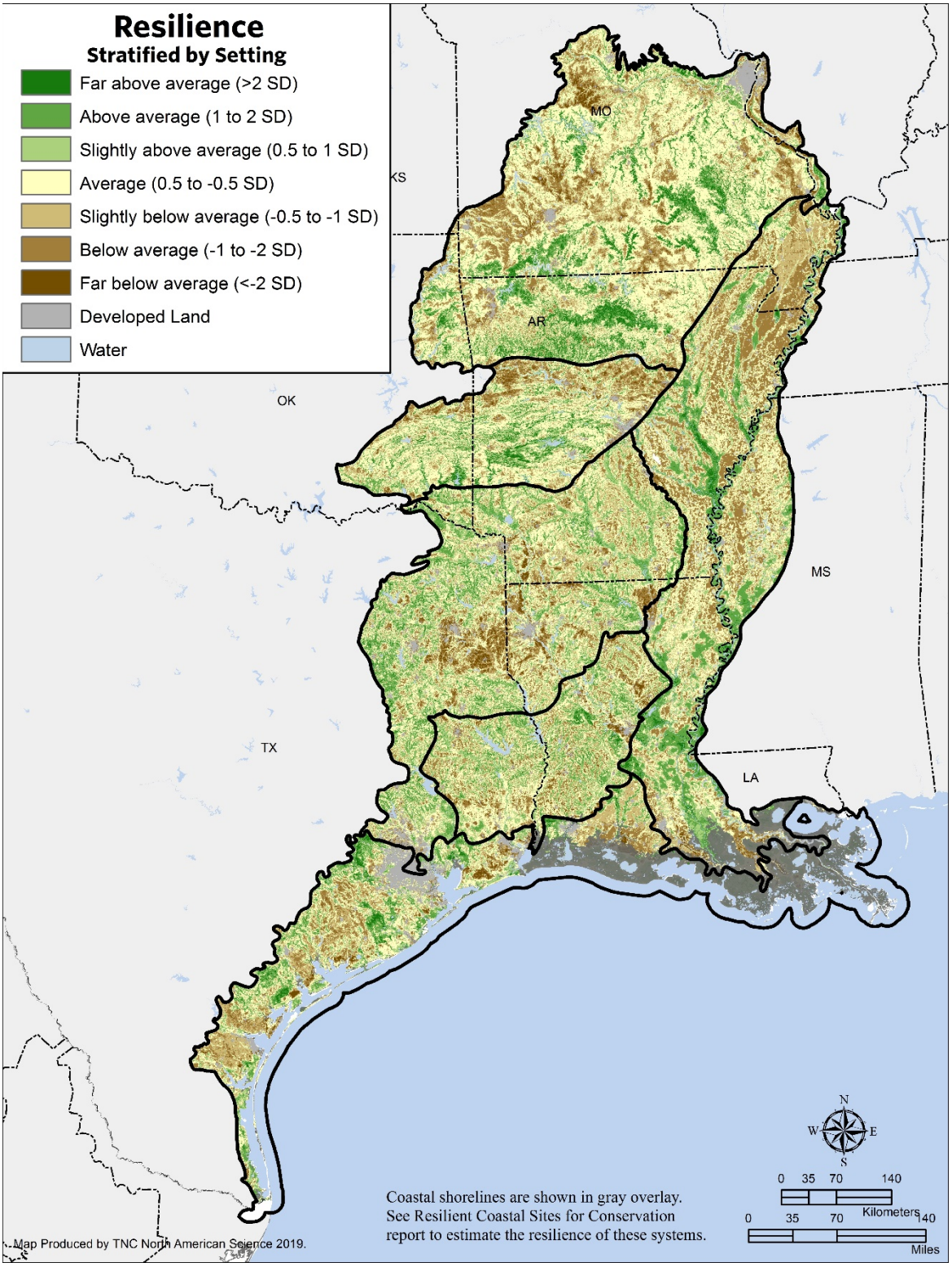


Figure 5.4: Site Resilience Relative to Ecoregion only (no settings and no regional override).

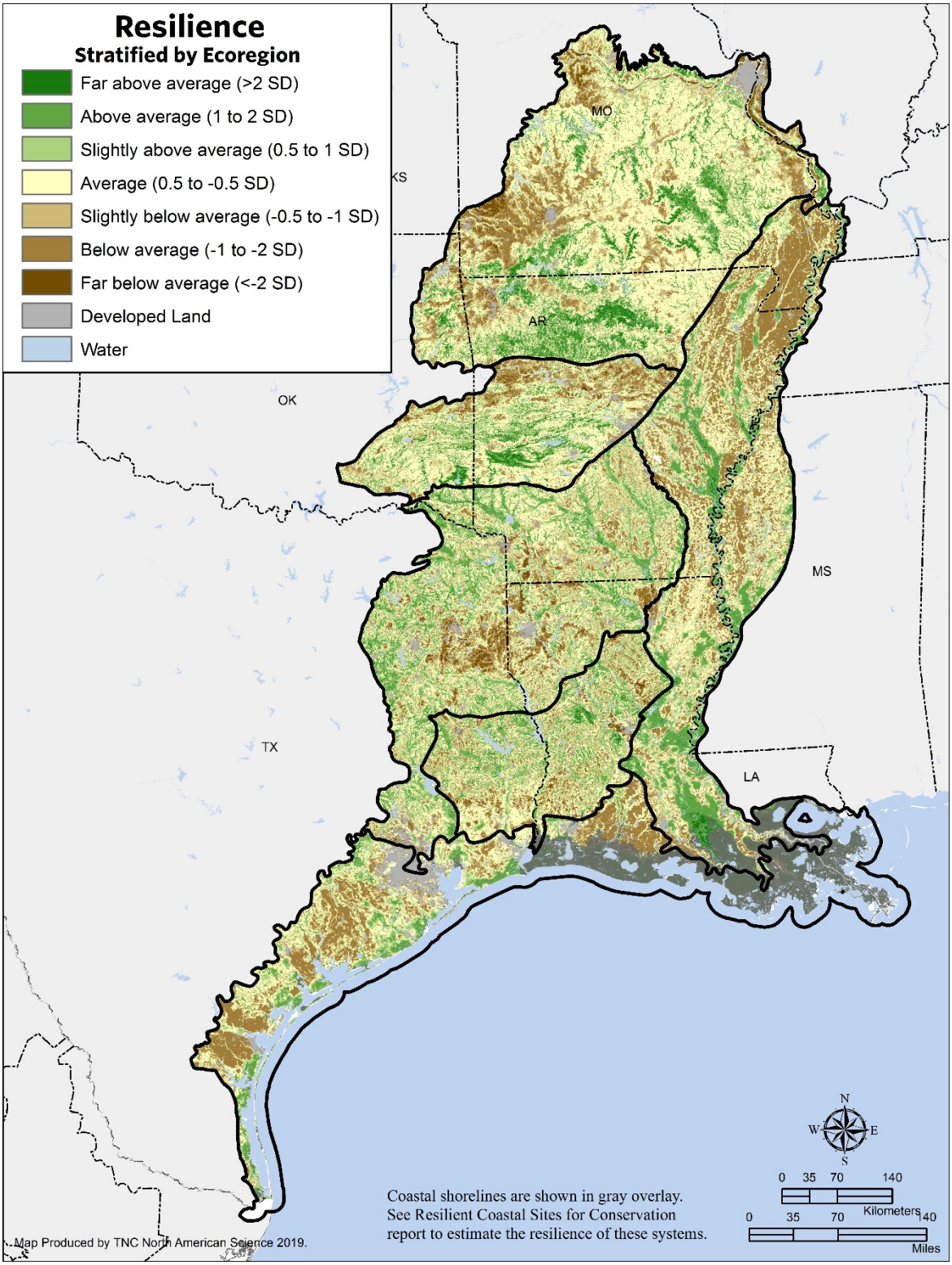


Figure 5.5: Site Resilience Relative to Region only (no settings or ecoregions).

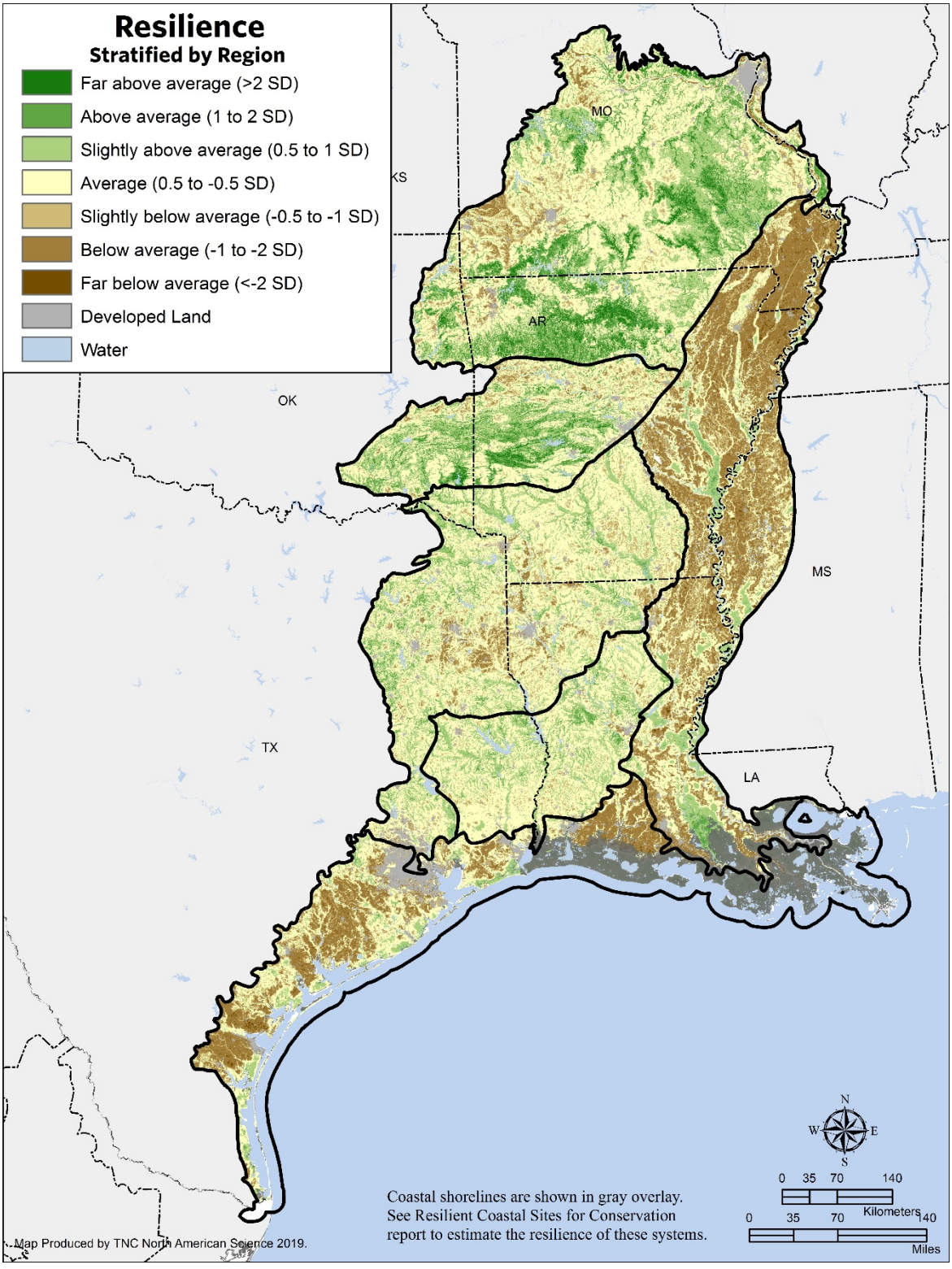


Figure 5.6: Site Resilience at Multiple Scales. This map shows the above average (>0.5 SD) scoring sites across all three scales—region, ecoregion, setting—in all combinations.

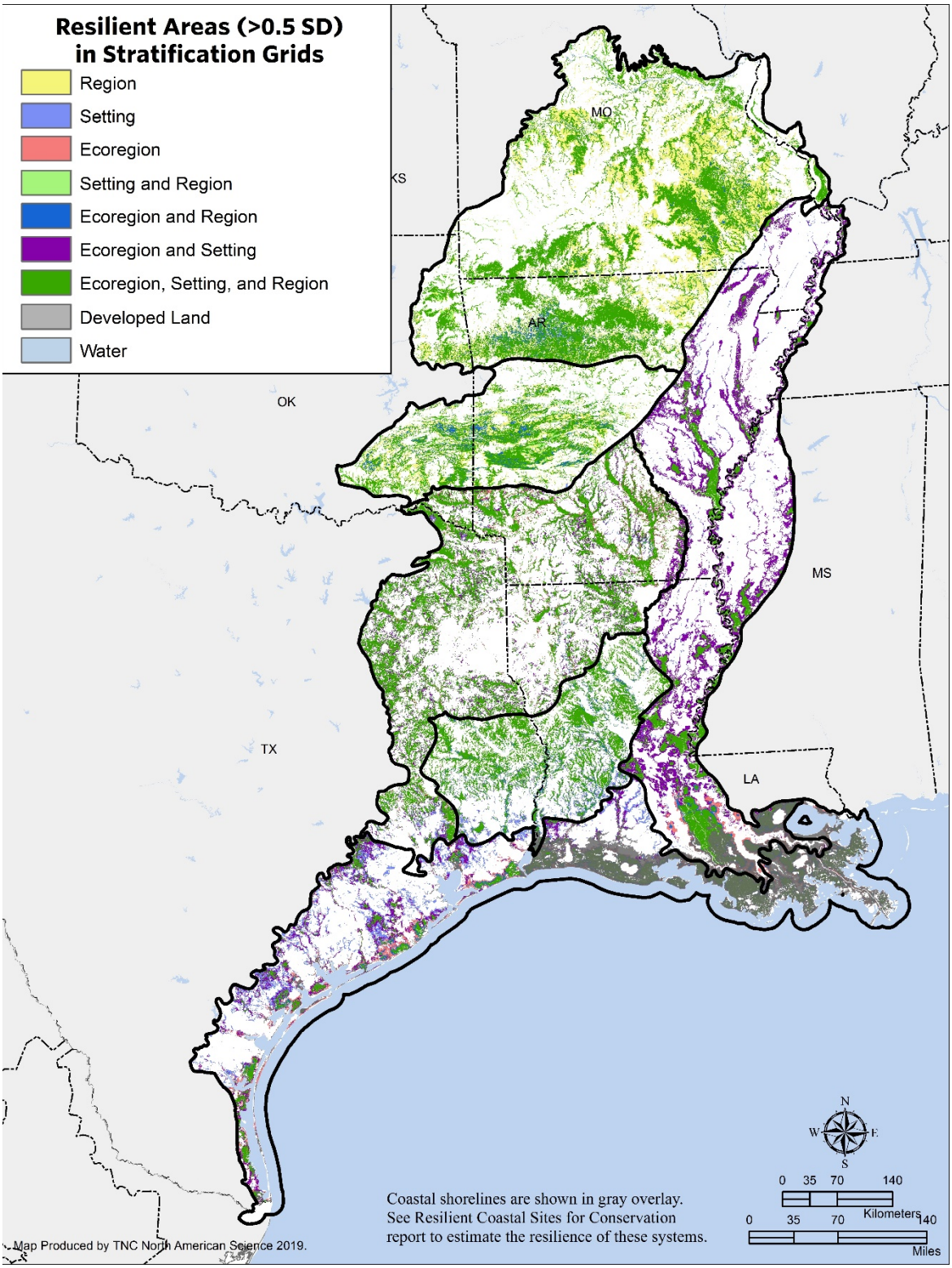


Figure 5.7: Landscape Diversity by Ecoregion and Setting with Overrides.

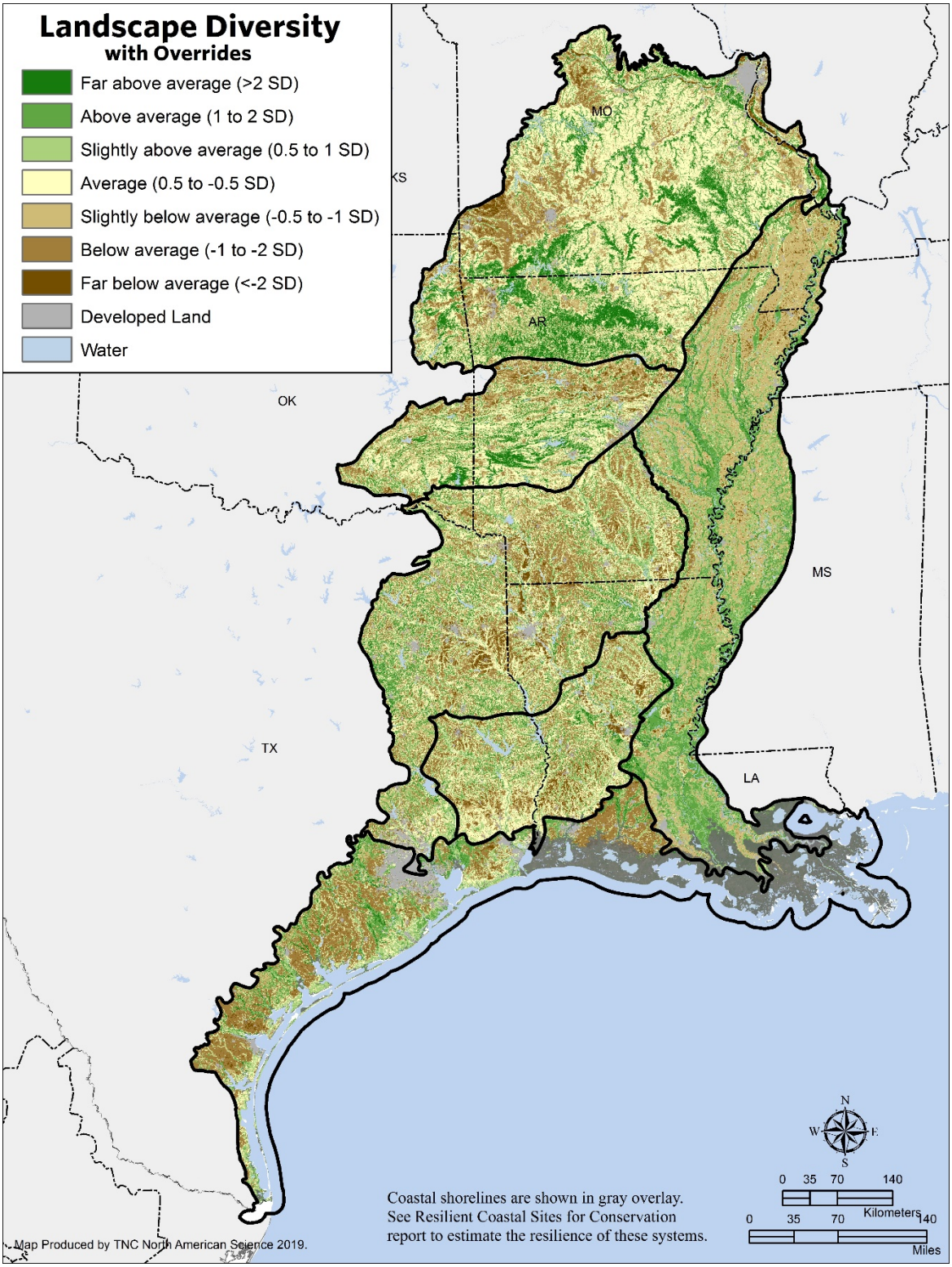


Figure 5.8: Local Connectedness by Ecoregion and Setting with Overrides.

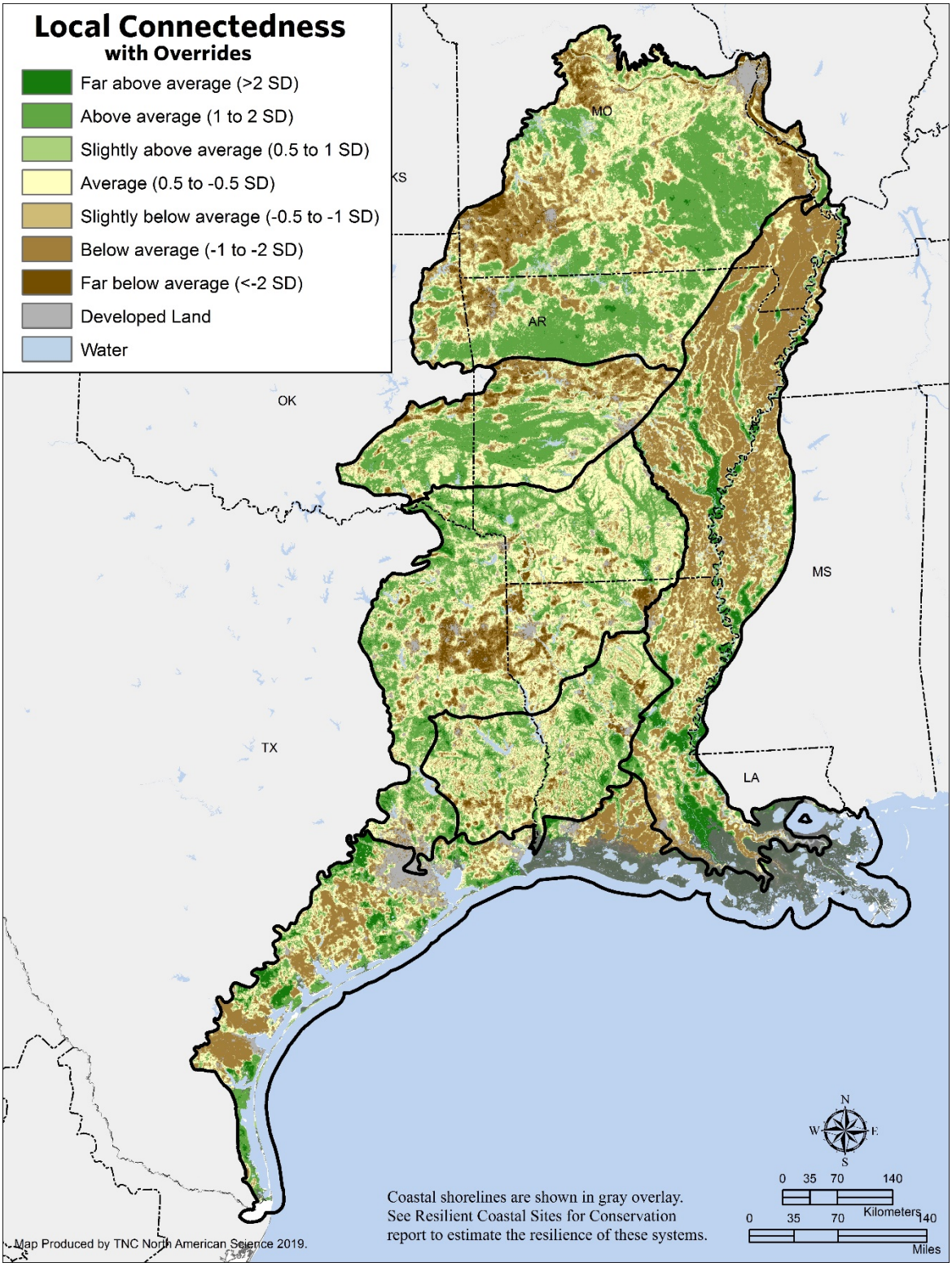
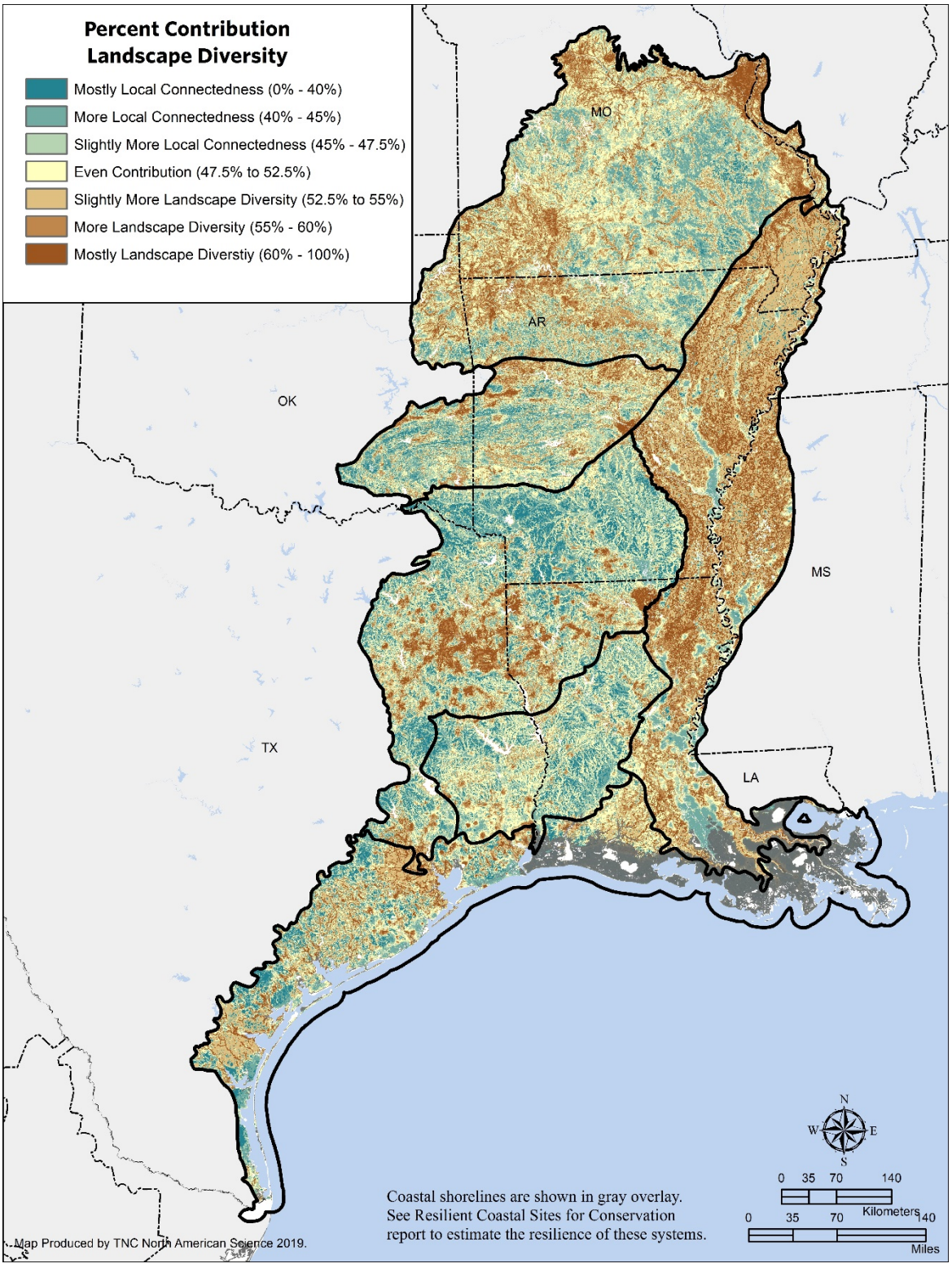


Figure 5.9: Comparision of Score Contribution. Resilience scores for sites (cells) shown in blue were more influenced by local connectedness, while scores for sites shown in brown were more influenced by landscape diversity.



Methods for Creating the Regional Resilience Map

The final regional resilience map (Figure 5.2) is a composite of the ecoregion maps (illustrated in Figure 5.1) to which we have applied an override that maintains high resilience values for the highest-scoring places in the full study area. This map was created using a set of stratification grids and by applying a smoothing algorithm to address sharp distinctions in ecoregion boundaries. The details behind these override, stratification, and smoothing steps are described here.

First, we created a grid of the raw (absolute) site resilience scores for the entire study area and stratified it by ecoregion. Stratifying the score means we calculated the mean and variance for each ecoregion, then transformed the values to Z-scores for each ecoregion, which are units of standard deviations relative to the ecoregional mean. For example, a cell with a score of +2 SD in West Gulf Coastal Plain means the cell is two standard deviations above the mean resilience score for the West Gulf Coastal Plain.

Second, we repeated the process, this time stratifying the raw resilience score by geophysical setting within ecoregion and calculating the mean score for each setting within each ecoregion. For example, a cell with a score of +2 SD for silt in the Mississippi Alluvial Plain means the cell score was two standard deviations above the average score for all the silt cells in the Mississippi Alluvial Plain ecoregion. We compared the two scores for each cell in the ecoregion, and if the setting score was greater than +1 SD AND greater than the ecoregion score, we replaced the ecoregion score with the setting score. This step had the effect of boosting the resilience score for higher scoring sites in geophysical settings that had mean scores below the ecoregion mean score. The intent of this step is to correct biases in final scores that are caused by difference in topographic variety and connectedness inherent to different setting types. Without this correction, bedrock settings, with their typical high relief and low land conversion rates, would almost always score higher than surficial settings like loess or loam that typically have gentler topography and more conversion.

Third, we repeated the review process one more time, this time focusing on the mean and distribution of raw resilience scores at the scale of the entire study region. We compared the regional site resilience score (Figure 5.5) cell-by-cell with both the ecoregion (Figure 5.4) and the setting by ecoregion score (Figure 5.3), and if the regional score was greater than +1 SD and greater than the other scores, we used that value for the regional score in the final map. This had the effect of boosting the score in places where the regional score was higher than the ecoregional or setting mean.

Smoothing the Ecoregion Boundaries

To create a more cohesive final map, we corrected sharp edge effects that occurred when adjacent ecoregions and settings had wide differences between their means, leading to strong differences in resilience scores. These strong differences in neighboring scores typically occurred in situations where two adjacent ecoregions had relatively strong differences in mean landform complexity or local connectedness values. In these cases, cells on either side of an ecoregional boundary often had roughly equivalent raw resilience scores, but after the values were stratified by

ecoregion and setting, the relativized scores were quite different due to differences across the ecoregions. This appearance of a high contrast in scores was artificial because ecoregional boundaries are gradual in nature and do not change exactly at the edge of a 30-m cell. To reduce this effect in our maps, we developed a method to create a gradual transition around the boundary line which we called an "ecoregional fade." The ecoregional fade uses a distance-weighted average of the cell values near the ecoregion boundary, so that the scores of cells near the boundary reflect the relative scales of both ecoregions in proportion to the distance of the cell from the boundary for the same geophysical setting. For instance, a cell directly on the boundary receives 50% of its score from each ecoregion, but a cell closer to the center of one ecoregion receives a higher proportion of its relativized score from that ecoregion.

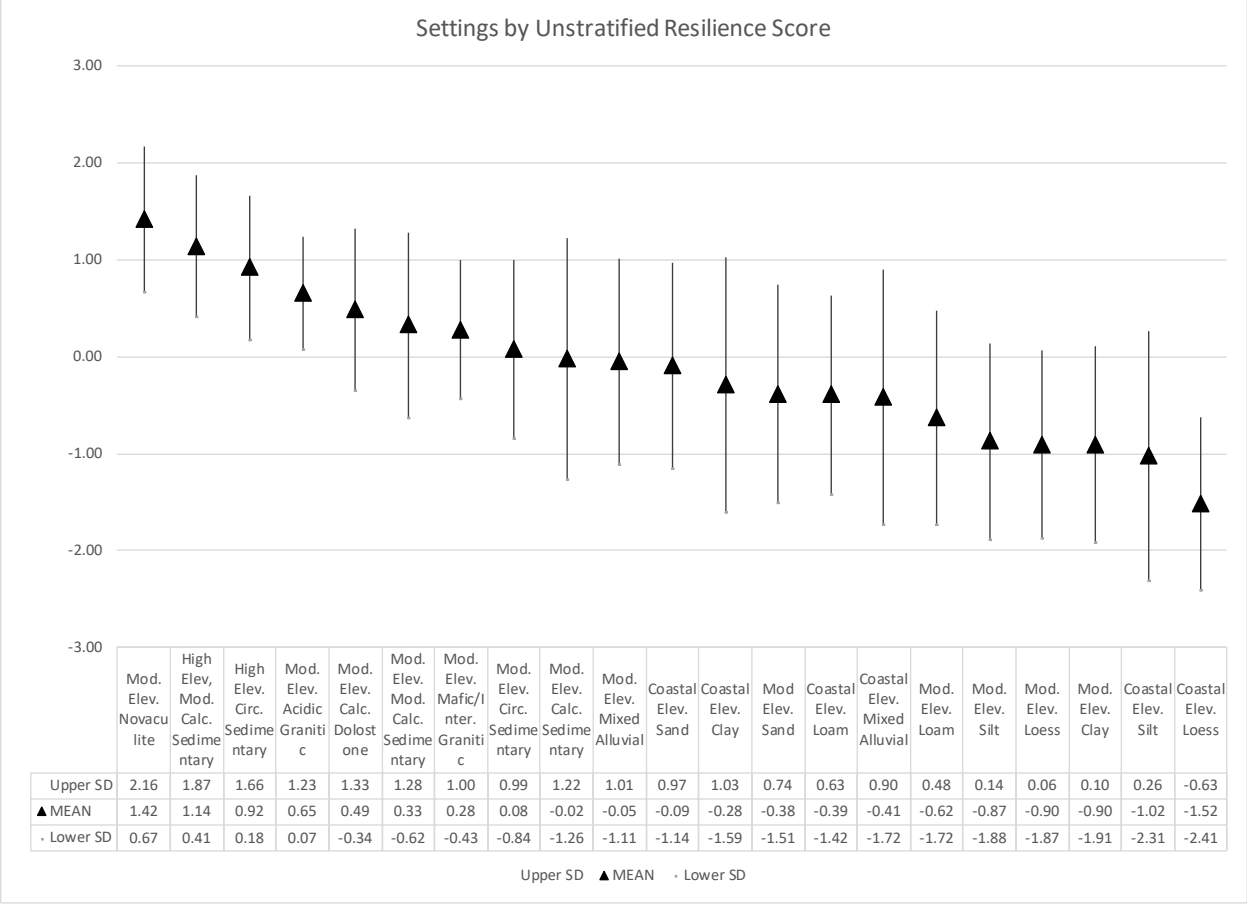
The GIS script was applied within a 20-km buffer around each ecoregional boundary. We examined other buffer distances to verify that the smoothing effect was limited to the buffer area and did not affect scores for areas more than 20 km from ecoregional boundaries. To ensure that the component maps added up to the final resilience score, we implemented the ecoregional fade three times, once for landscape diversity, once for local connectivity, and then for the final resilience map. Some sharp contrasts still remain in the map at the borders between geophysical setting, especially bedrock to surficial sediments (silt, loam, alluvial) such as the border between the Mississippi River Alluvial Plain ecoregion and Ozark Mountains.

Resilience by Geophysical Setting

Differences among geophysical settings in relationship to soil fertility, structural properties of bedrock, and the hydrologic cycle of groundwater flow have been recognized for centuries. Most human settlement has occurred in gentle landscapes with productive soils, and not surprisingly, most conservation areas are located on poor soils with steep slopes (Anderson et al. 2014b). As a result, fertile settings like this region's fine sediment and mixed alluvial sediments are not only less topographically complex, but also more fragmented by human use. This pattern is reflected in the overall means of the regional resilience scores (i.e., z-scores calculated for the entire study region, Figure 5.5). For example, bedrock settings, like novaculite, limestone, and granite associated with rough topography, remote locations, and thin soils, have the highest mean resilience score. In contrast and the fertile loess, clay, silt, loams and mixed alluvial settings have the lowest mean resilience in the region (Figure 5.10).

Ensuring that we identified high resilience sites for every geophysical setting is an essential part of sustaining diversity, allowing us to represent the full spectrum of biodiversity in conservation lands. However, due to the inherent differences across settings, maintaining and restoring resilience in some settings will take more effort and attention than in other settings, even when working at sites with the highest resilience.

Figure 5.10: Regional Resilience Scores by Geophysical Settings. The average regional resilience score for each geophysical setting (>1m elevation land) in standard normal units (z-scores). For example, the average score for the novaculite setting is +1.4 SD higher than the regional mean.



	Mod. Elev. Novaculite	High Elev, Mod. Calc. Sedimentary	High Elev. Circ. Sedimentary	Mod. Elev. Acidic Granitic	Mod. Elev. Calc. Dolostone	Mod. Elev. Mod. Calc. Sedimentary	Mod. Elev. Mafic/Inter. Granitic	Mod. Elev. Circ. Sedimentary	Mod. Elev. Calc. Sedimentary	Mod. Elev. Mixed Alluvial	Coastal Elev. Sand	Coastal Elev. Clay	Mod Elev. Sand	Coastal Elev. Loam	Coastal Elev. Mixed Alluvial	Mod. Elev. Loam	Mod. Elev. Silt	Mod. Elev. Loess	Mod. Elev. Clay	Coastal Elev. Silt	Coastal Elev. Loess
Upper SD	2.16	1.87	1.66	1.23	1.33	1.28	1.00	0.99	1.22	1.01	0.97	1.03	0.74	0.63	0.90	0.48	0.14	0.06	0.10	0.26	-0.63
▲MEAN	1.42	1.14	0.92	0.65	0.49	0.33	0.28	0.08	-0.02	-0.05	-0.09	-0.28	-0.38	-0.39	-0.41	-0.62	-0.87	-0.90	-0.90	-1.02	-1.52
Lower SD	0.67	0.41	0.18	0.07	-0.34	-0.62	-0.43	-0.84	-1.26	-1.11	-1.14	-1.59	-1.51	-1.42	-1.72	-1.72	-1.88	-1.87	-1.91	-2.31	-2.41

Resilience and Conservation Lands

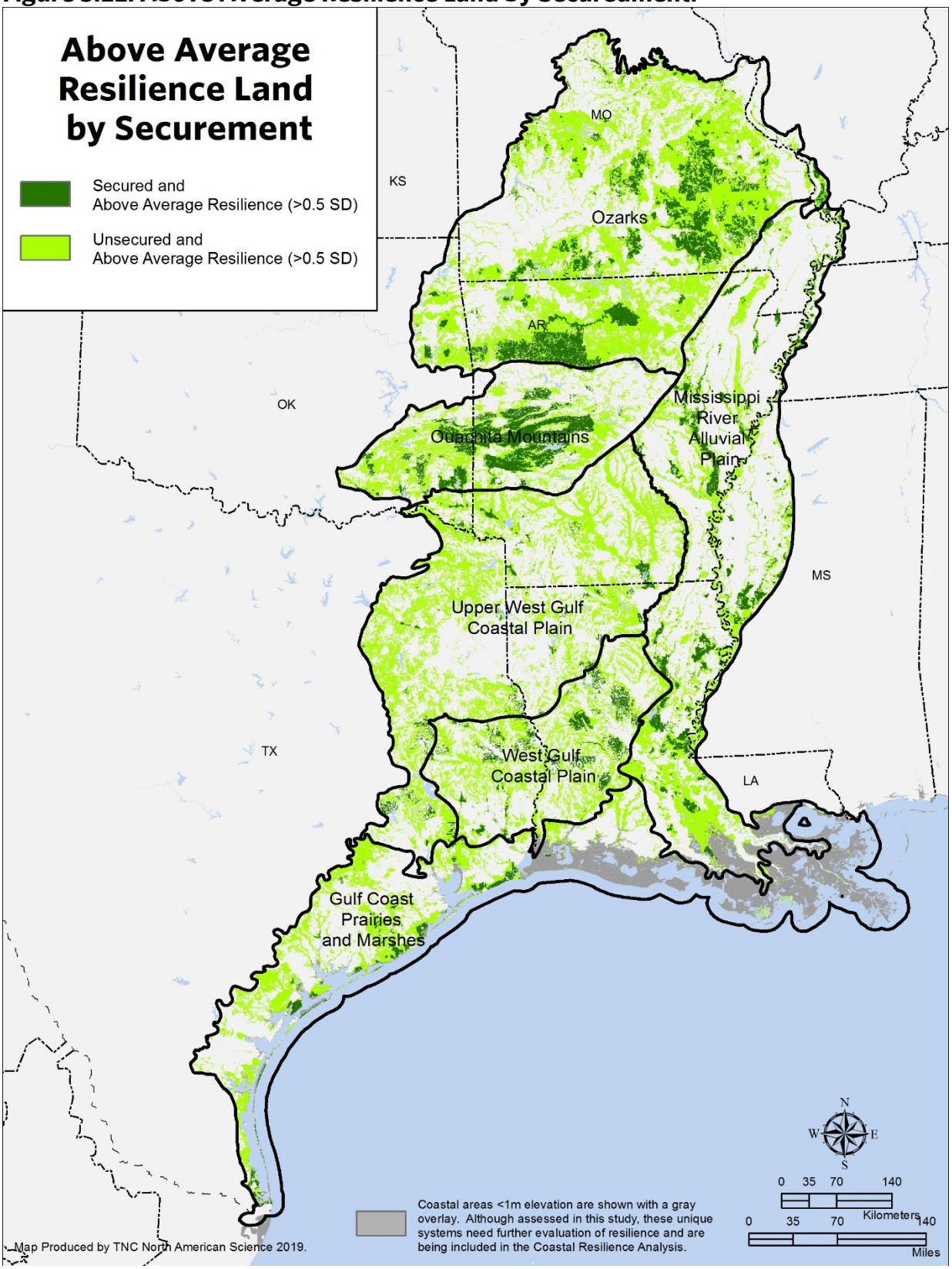
Overall, only 9% of the land in this region is permanently secured against conversion, and 30% is converted to development or agriculture (Figures 1.1, 1.2). Land securement is highest in the Ouachita Mountain ecoregions (21%), moderate in the Ozark (11%) and West Gulf Coastal Plain (11%), while quite low in the remaining ecoregions (4-9%). Of the above-average resilient land, 19% is secured from conversion and 81% is unsecured. The level of securement of above-average resilient land ranges by ecoregion from a high of 38% in the Ouachita Mountains to a low of 6% in the Upper West Gulf Coastal Plain.

Table 5.2: Securement of Above Average Resilience Land. Summary by ecoregion of the acres and percent of above average land secured or unsecured from conversion.

	Vulnerable Acres (Avg or Below)					Resilient Acres (Above Average)					Grand Total	
Ecoregion	Secured (GAP 1-3)	%	Not Secured	%	Total	Secured (GAP 1-3)	%	Not Secured	%	Total		% Resilient
Gulf Coast Prairies And Marshes	79,102	1%	7,995,079	63%	8,074,181	470,688	4%	4,092,213	32%	4,562,900	12,637,082	36%
Mississippi River Alluvial Plain	328,404	1%	16,306,711	67%	16,635,115	1,738,711	7%	6,127,178	25%	7,865,888	24,501,003	32%
Ouachita Mountains	266,475	2%	5,529,235	49%	5,795,710	2,032,522	18%	3,357,844	30%	5,390,366	11,186,076	48%
Ozarks	335,893	1%	16,829,487	50%	17,165,379	3,420,160	10%	13,118,901	39%	16,539,061	33,704,440	49%
Upper West Gulf Coastal Plain	385,510	2%	15,572,836	62%	15,958,346	531,037	2%	8,814,553	35%	9,345,590	25,303,936	37%
West Gulf Coastal Plain	432,786	4%	5,746,501	55%	6,179,287	720,589	7%	3,581,385	34%	4,301,974	10,481,261	41%
Grand Total	1,828,169	2%	67,979,849	58%	69,808,018	8,913,707	8%	39,092,072	33%	48,005,779	117,813,797	41%

Patterns in land securement and conversion are useful for understanding which geophysical settings are well-protected, and which settings are underrepresented in the current set of conservation areas. We evaluated this discrepancy by overlaying the compiled dataset of lands permanently secured against conversion (PADUS Version 2. 2018, TNC 2019) on the resilience and geophysical setting layers. Land securement corresponds closely with soil type. The fertile silts, clays, and loess are all over 30% converted, predominantly over 50% converted. These same soils at low to moderate elevation have very low rates of securement, with most less than 10% secured. In contrast, the thinner bedrock soils at higher elevations are much less converted and have higher rates of securement (Table 5.2 and 5.3).

Figure 5.11: Above Average Resilience Land by Securedment.

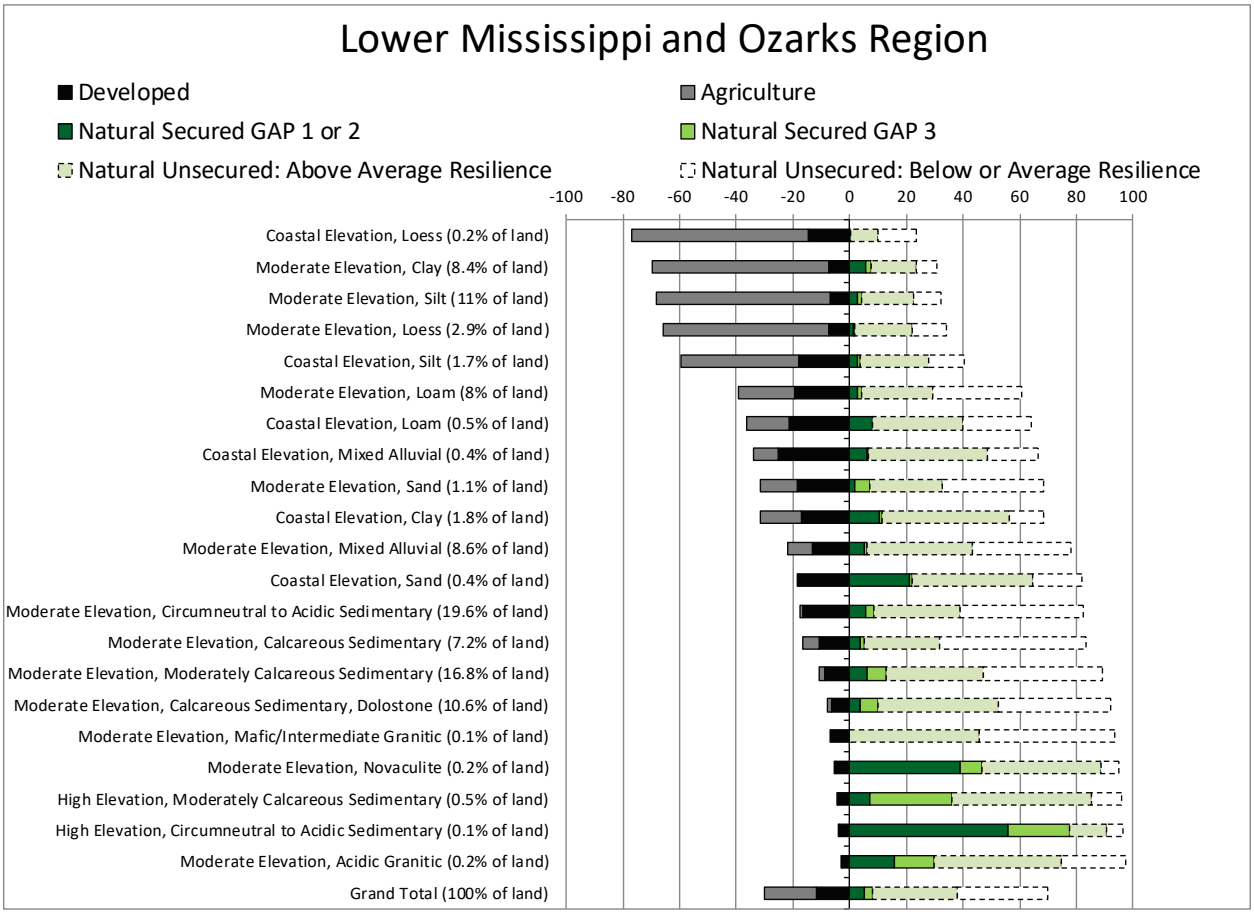


The ratio of conversion to securement—the conservation risk index—can provide an idea of the relative vulnerability of a setting to the threat of conversion. Deep loess, at coastal or moderate elevations had the highest risk of conversion with ratios ranging from 34 to 382 acres converted for every 1 acre secured. Moderate elevations silt was also at risk with 17 acres converted for every 1 acre secures. An unusual mafic bedrock type, also had high rates of conversion to securement with a ratio of 97 acres converted for every 1 secured (only a 0.1% of the setting was secured). Overall, settings with relatively fertile soils (e.g., deep loess, clay/silt, calcareous loam) had the highest risk, while bedrock settings (e.g. acidic granitic, acidic sedimentary, moderately calcareous sedimentary) were less converted and more secured. By studying the locations of resilient unsecured lands, conservation practitioners can focus attention on at-risk settings and begin to address disparities in conservation coverage.

Table 5.3: Geophysical Settings: Conversion and Securement. Summary for each geophysical setting of the total number of acres (area of land and water >1m elevation), percent converted to either development or agriculture and percent "secured" in protected status. The table is sorted by descending % Acres Converted.

Geophysical Settings	Total Acres	% of Acres Converted	% of Acres Secured	Ratio Converted to Secured Acres	% of region
Coastal Elevation, Loess	178,623	76.7	0.2	382.8	0.2
Moderate Elevation, Clay	9,848,486	69.5	7.7	9.0	8.4
Moderate Elevation, Silt	12,995,187	68.0	4.0	16.8	11.0
Moderate Elevation, Loess	3,442,392	65.9	1.9	33.9	2.9
Coastal Elevation, Silt	2,000,427	59.5	3.9	15.1	1.7
Moderate Elevation, Loam	9,432,830	39.5	4.0	9.9	8.0
Coastal Elevation, Loam	600,163	36.2	8.1	4.5	0.5
Coastal Elevation, Mixed Alluvial	456,251	33.7	6.7	5.0	0.4
Moderate Elevation, Sand	1,248,474	31.5	7.0	4.5	1.1
Coastal Elevation, Clay	2,116,694	31.4	11.7	2.7	1.8
Moderate Elevation, Mixed Alluvial	10,129,970	21.8	6.2	3.5	8.6
Coastal Elevation, Sand	523,021	18.0	21.8	0.8	0.4
Moderate Elevation, Circumneutral to Acidic Sedimentary	23,049,659	17.5	8.5	2.1	19.6
Moderate Elevation, Calcareous Sedimentary	8,427,750	16.7	4.9	3.4	7.2
Moderate Elevation, Moderately Calcareous Sedimentary	19,780,231	10.7	12.9	0.8	16.8
Moderate Elevation, Calcareous Sedimentary, Dolostone	12,465,271	7.7	9.9	0.8	10.6
Moderate Elevation, Mafic/Intermediate Granitic	74,503	6.5	0.1	97.9	0.1
Moderate Elevation, Novaculite	221,674	4.8	46.7	0.1	0.2
High Elevation, Moderately Calcareous Sedimentary	541,662	4.2	36.1	0.1	0.5
High Elevation, Circumneutral to Acidic Sedimentary	73,802	3.4	77.5	0.0	0.1
Moderate Elevation, Acidic Granitic	238,861	2.6	29.7	0.1	0.2

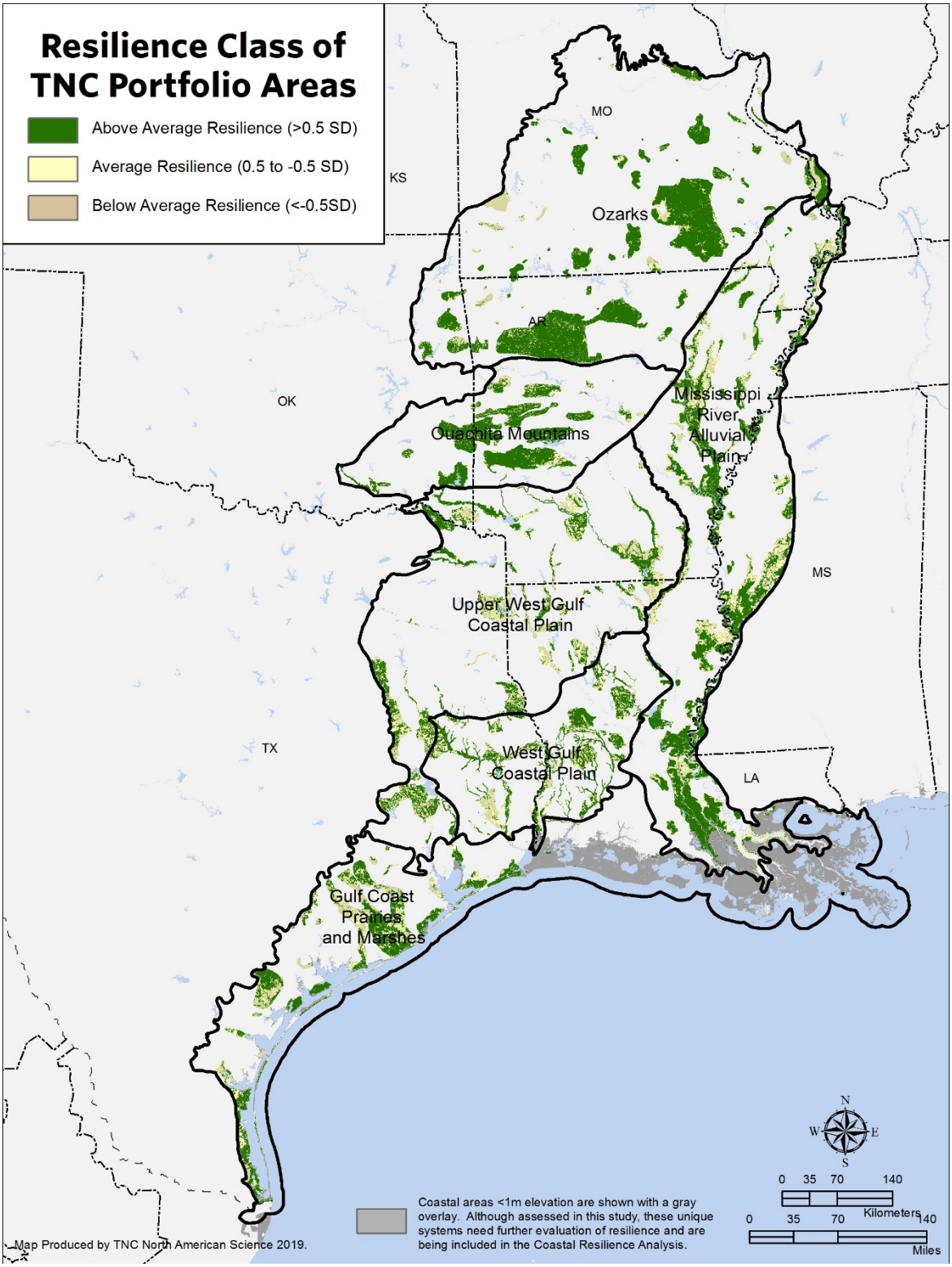
Figure 5.12: Conservation Risk Index of each Geophysical Setting. The proportion of conversion to securement for each setting, further divided by the type of conversion and the resilience score of the remaining unsecured natural land. The charts is sorted in descending order of percent converted.



Resilience and the Nature Conservancy Portfolio

The Nature Conservancy maintains information on critical sites for biodiversity conservation that was first developed through ecoregional assessments. The assessments identify conservation targets that represent viable rare species populations, exemplary natural communities, or intact vegetation types, and map a portfolio of sites that if conserved would protect multiple representative examples of each target. For the most part, climate change was not considered in TNC's ecoregional assessment process, which focused largely on the size and quality of the target occurrences. Here we compare the spatial correspondence between the TNC portfolio (TNC Rollup 2012, Southeast Portfolio Rollup 2013) and the regional resilience map to highlight place that score high both for resilience and current biodiversity (Figure 5.13). Results indicate that 84% of the TNC portfolio occurs on land that scores average or above for resilience, including 66% that scores above-average and 18% that scores average (-0.5 to +0.5 SD). 15% of the portfolio occurs on vulnerable land that scores below average for resilience (<-0.5 SD).

Figure 5.13. Resilient Areas and Existing TNC Conservation Portfolio. (Data Source: TNC Ecoregional Rollup, 2012)



Discussion

This project assessed the Lower Mississippi and Ozark Mountain region of the US to identify the areas with the highest estimated resilience relative to each of 6 ecoregions and 21 geophysical settings (life zones and substrate types). Our analysis was based on estimates of microclimate diversity and local connectedness, two attributes that appear to be predictive of site resilience to climate change, and that could be mapped at a regional scale. By balancing our protection efforts across the full spectrum of geophysical settings and using site resilience criteria to select places for conservation action, conservationists can make sound decisions about where to commit the resources needed to sustain diversity under a changing climate, even as species distributions change and ecological communities reorganize.

Our emphasis on enduring land characteristics that influence the distribution of the biota and their sustaining resources implies a long-term perspective. These tools are thus well-suited for informing choices on where to invest in land protection or implement restoration strategies. They can also help inform site-scale adaptation strategies where variation in a site's resilience factors suggest higher or lower vulnerability, which can be addressed through specific management tactics and monitoring plans. Further, the maps and assessments in this report allowed us to see the sites and landscapes we seek to protect through a new lens, expanding our focus from the many readily-apparent drivers of current species loss to envisioning how we can help nature adjust to a rapidly changing world - with a goal of sustaining a dynamic and diverse natural world capable of adapting to continued climate change.

An advantage of our approach is that it is robust to the uncertainty inherent in predictions of climate change based on regional scale models. Climate models are invaluable for understanding the general direction and magnitude of change. However, the ability of most climate models to forecast fine-scale species responses has been critiqued because they do not account for biotic interactions, dispersal limits, topographic influence, or the large variation around each estimate of temperature or precipitation (Beal et al. 2008, Araujo and Peterson 2012). Instead of selecting places for conservation based on predicted climate exposure or a future scenario derived from an ensemble of climate models as in most climate vulnerability studies, we identified places that would be resilient to many different climate scenarios because of the temperature and moisture variability inherent in the physical structure of the sites. Landscape-based climatic variation has been demonstrated to be on par with or larger than expected regional changes over the next century and is more relevant to plants and animals that experience climate at very local scales (Chapter 3).

We place a considerable emphasis on the role of microclimates in sustaining local biodiversity, the evidence for which is substantial and growing (Chapter 3). Understanding microclimates, topoclimates and climatic microrefugia is now a hot-topic of research, and some suggest it may revolutionize climate change biology (Hannah et al. 2014). Species populations use microclimates in multiple ways: to persist for a limited time under deteriorating climatic conditions (holdouts), to facilitate range shifts (stepping stones) or to persist through a long period of unfavorable climates (microrefugia). Conservation strategies built around holdouts and

stepping stones make logical sense under a rapidly changing climate (Hannah et al. 2014), although microrefugia have clearly played a needed role in past climatic events (Rull 2009, Keppel and Wardell-Johnson 2015). From the perspective of sites, areas with high microclimate diversity may serve all these functions, but more studies quantifying the climatic differences among microclimates, and how species exploit these differences, would greatly improve our ability to predict site resilience.

Current research is also reinforcing the value of connectivity in facilitating adaptation and has strong historical evidence and widespread agreement among the scientific community (Chapter 3). Improving the local connectedness of a site is an achievable strategy in many places, and much more feasible than increasing topographic diversity at a meaningful scale. The final maps and datasets of local connectedness and landscape diversity may prove useful for conservationists investigating the independent influence of each of these factors on a site. For example, users of this analysis can identify places where increasing local connectivity could significantly improve the current resilience score or areas where the resilience score is more limited by the inherent low landscape diversity.

It is also important to remember that the type of species and system that have evolved to occupy sites differ, even across sites with similar topography. Our approach does not consider these differences, but deserts and native grasslands that have evolved under extreme ranges of climate variability found in the Southwest are likely to be much more climate-resilient **ecological systems** than most, a fact that should be considered when these maps are used as part of a toolbox for identifying conservation and protection strategies. Along with these patterns of ecological system resilience and vulnerability, we suggest users also consider other aspects of condition such as past or current land uses, and incorporate their own local information, such as fine scale species studies, habitat quality information, or assessments of risk and feasibility, when using this analysis to make decisions.

It is worth repeating that this study does not predict what the future will look like in terms of vegetation structure or species composition. The places identified will likely be important strongholds for diversity in the future because of their enduring geophysical characteristics, and they can provide the framework for a network of conservation lands aimed at sustaining diversity and ecological services. However, sustaining the natural diversity of this region will require many other actions, and elements of this work may help inform a variety of current conservation activities. For example, land managers seeking to prioritize areas for restoration could use the resilience and landscape diversity maps to determine what areas would be most likely to benefit from increased connectivity, or where these activities could favor potential grassland expansion into more topographically diverse areas.

With the help of our steering committee, we tried to make our analysis as transparent, consistent, and verifiable as possible. However, we necessarily approached site resilience as a relative concept because there are no known absolute thresholds. Within an ecoregion, we could confidently say that one area had more topographic variation and was more connected than another area, but how completely those characteristics buffer the site from climate change is likely to vary greatly across ecoregions. Notably, some ecoregions had very high proportions of natural landcover,

and other ecoregions had only fragments of natural landcover left (see Chapter 4). Due to our practice of presenting relative scores, a "high resilience" site in the more converted ecoregion may be less resilient and need more management than a site with an equivalent score in a very intact ecoregion. This relativity was necessary because we were as interested in conserving prairies and playas as we were in conserving forests and canyons, but these natural systems occurred in fundamentally different ecological and human-land use contexts. Thus, the resilient areas may provide the best physical sites for sustaining biodiversity and ecological functions, but in some ecoregions, they will still require considerable management and restoration to sustain the desired properties.

As with previous studies in other geographies we found a high correspondence between sites identified for climate resilience based on their geophysical characteristics and those selected for the high quality of their biodiversity features in The Nature Conservancy ecoregional portfolio. Portfolio sites overlapped 61% with above-average and 21% with average site resilience cells, but these sites are not all protected. We also found strong biases in the conservation lands, with the ratio of conversion to securement (conservation risk index) strongly skewed against fertile settings. These settings were also among the lowest in raw resilience score (Figure 5.10). Because our method identified relatively resilient sites for every geophysical setting, this study identifies places for future conservation that could correct the bias in current secured lands. We encourage conservationists to explore opportunities to expand protection in these underrepresented settings.

This report is a revision and integration of five previous studies on identifying resilient sites for terrestrial conservation in the Northeast (Anderson et al. 2012), Southeast (Anderson et al. 2014a), Great Lakes and Tallgrass Prairie (Anderson et al. 2018a), Great Plains (Anderson et al. 2018b) and the Pacific Northwest (Buttrick et al 2015). This new study combines and (we hope) improves on methods to make a unified map for the United States. We received extensive feedback on previous versions, and most of it came from conservationists thoughtfully applying the results to places that they knew well. This ground testing was largely reassuring, but it also revealed important ecological variations that we had missed, or problems in the datasets. We also recognize that there are still many uncertainties with respect to how any system will respond to climate change, and expect that the relative role of site-based factors like those we have mapped here, in comparison to the inherent capacity of current ecosystems to persist as climate changes, will vary geographically, which could mean over time our methods will need to vary more as well.

We tried to incorporate all the good suggestions from our steering committee into this latest study, but certainly there will still be discrepancies and areas for improvement. Our intention is to continue to work with our steering committee members to develop additional outreach products and examples that facilitate exploration of these rich data products, and we encourage feedback and suggestions from our peers on how we can continue to improve the approach and can correct specific problems.

DATA SOURCES

Secured Lands:

NCED. National Conservation Easement Database. National Conservation Easement Database. August 15, 2017. URL: https://www.conservationeasement.us/downloads/ Date Downloaded: February 12, 2018

PADUS – Conservation Biology Institute. Conservation Biology Institute. September 1, 2016. Protected Areas Database of the US, PAD-US (CBI Edition), version 2.1. URL: https://consbio.org/products/projects/pad-us-cbi-edition. Date Downloaded: February 12, 2018

TNC Lands. The Nature Conservancy. TNC Lands. 2018. URL: http://www.lands.tnc.org/ Date Downloaded: January 30, 2018

CHAPTER

6

A RESILIENT AND CONNECTED NETWORK

In the second half of this report we describe our methods to map a resilient and connected network of sites that, if conserved, could sustain biological diversity and ecosystem services while allowing species to move and adapt to change.

In previous chapters we describe how we mapped sites across the study area and identified the ones with the most microclimates and the highest local connectedness (i.e. the most resilient sites) with respect to ecoregion and setting. In the next four chapters we describe how we expanded on the site resilience analysis to look at connections between sites, and at the habitats, species, and communities that currently inhabit the sites. We use this information to construct a network.

We defined resilient sites as places more likely to maintain biological diversity and ecological function as the climate changes. These "biodiversity strongholds" are more variable in topography, and more locally connected by natural landcover, than other sites with similar soils/underlying bedrock. By identifying resilient sites across all types of bedrock and soil in a region, we hoped to create a blueprint for conserving ecosystem health over the long term, even as the specific character, species assemblages, and ecosystem structure at those sites changes over time. A map of resilient sites that represent the full range of geophysical settings can guide our investments in protection and management and increase the odds that plants and wildlife will be able to find sites that meet their requirements as conditions change.

By itself, conserving the resilient sites would go a long way towards sustaining the biological diversity of the study region, but it is not enough. If nature thrives in these sites, then the inhabitants (trees to salamanders) will produce offspring and these offspring will disperse to find new resilient sites to establish in, and over time the landscape will change. The objective of our network is to facilitate these dynamics, to ensure that plants and animals are thriving, to ensure that the landscape remains permeable to movement, and to ensure that dispersing species have a place to go.

This has happened before. In past eras of climate change, plants and animals shifted their distributions by colonizing and establishing in new territory, finding suitable microclimates that allowed them to persist and producing offspring to continue the process. The problem is that this takes time – generations - but the climate is changing faster than at any time in recorded history, and the landscape is fragmented by roads,

intensive agriculture, dams, development, and other barriers to movement. The idea of conserving moving targets, and sustaining the capacity for adaptation in place, requires that we update our thinking about where to invest in land protection.

Sustaining biological diversity and ecological processes across the region is more likely if the resilient sites are embedded in a larger network of connected natural areas that allow for dispersal and movement between sites. In the next sections of this report, we examine the pattern of land use and barriers across the landscape, and we evaluate where dispersal and other movements are most likely. We recognize that the character of the landscape varies widely and that the options and character of movement corridors shift with different land use patterns and natural barriers. In our work to map connectivity across this landscape, we recognize both broad areas of unrestricted flow zones, and more constrained areas where small corridors play essential roles in supporting species movements. Our assessment method also gives additional weight to connections that are likely to traverse climate gradients, such as northward trajectories, and movements toward cooler riparian areas.

In our integration of the resilient sites with the patterns of landscape connectivity, we identify resilient sites that also play a role in supporting either broad flow patterns or high rates of flow through narrow corridors. In this process, we maintain a focus on representation of different geophysical settings, as connectivity is only an advantage if it provides access to necessary site conditions.

Our final step in designing a network is to integrate known strongholds for biodiversity – if we know a place supports important biodiversity elements now, that increases our confidence that it will support important biodiversity in the future. Further, the current biodiversity is the source of the future biodiversity, and the source of the dispersing species. We recognize that a site may be topographically diverse and in a relatively natural landscape but may still have lost species diversity due to some stressor, such as a reduction in natural processes like fire or grazing. At the scale with which we are conducting these analyses, we are not able to make site-by-site comparisons of current condition and diversity. However, we can incorporate known sites of biodiversity as mapped in other assessments like the TNC ecoregional plans or the State Wildlife Action Plans. Our intent in incorporating these datasets is to identify resilient sites more likely to have long term biodiversity value in part due to adaptation in place and in part as sources of dispersal and movement to other sites.

This work to integrate site resilience, landscape connectivity, and biodiversity is described in the following chapters:

Chapters 1-5. Site Resilience: These chapters describe the concepts and metrics for estimating the relative resilience of a site and evaluate the status of protected lands in the region with respect to representation of geophysical settings and site resilience.

Chapter 7. Landscape Permeability: This chapter describes our efforts to understand and map the permeability of the landscape and identify patterns of flow and connectivity across it. It begins with a review of the literature on species range shifts, highlighting key results and response patterns that guide our approach. The methods section describes our continuous ("wall-to-wall") method for quantifying and mapping

the potential of areas across these landscapes to support species movement based on landcover in combination with anthropogenic and natural barriers. Next, we describe our methods for incorporating response to climate change (i.e., favoring movement pathways that follow climate gradients) into the connectivity models.

Chapter 8. Biodiversity: This section describes our methods for prioritizing resilient areas that contain rare species, or have been identified as a priority by ecoregional, regional, or state conservation planning efforts.

Chapter 9. Resilient and Connected Conservation Networks: This section integrates resilience, flow, and diversity to develop a connected network of sites that both represents the full suite of geophysical settings and has the configuration and connections necessary to support the continued rearrangement of species in response to change.

CHAPTER 7

LANDSCAPE PERMEABILITY

Maintaining a landscape that facilitates range shifts for terrestrial species

Objective and Background

Maintaining a connected landscape is the most widely cited strategy in the scientific literature for building climate change resilience (Heller & Zavaleta 2009). While it makes intuitive sense that species must have the ability to move in order to adjust to a changing climate, it is less clear how we design a network that facilitates change and adaptation over time while conserving the full range of biodiversity. The interplay between range shifts, local persistence, changing habitat suitability, and evolving populations are poorly understood despite a large amount of research on these topics.

The goal of this section is to describe the mechanisms by which climate change leads to species range shifts and understand how those shifts are influenced by the condition of the landscape through which species must move. The information is used to inform a spatially-explicit assessment of relative permeability across the Western U.S. and to develop conservation priorities and strategies aimed at maintaining a landscape that facilitates range shifts for terrestrial species.

Introduction

The history of the Earth has been characterized by dramatic shifts in climate leading to radical shifts in the range of species. At the dawn of the Eocene 55 million years ago, as global temperatures rose 5-6^0 C, cypress trees and alligators had moved as far as the high Arctic (Krosby et al. 2010). More recently, much of North America and Eurasia were repeatedly ice-covered during more than 2 million years of glacial cycles causing species to continually shift their ranges. While they did so at different rates and in different directions, all the species that currently occur in these areas expanded their

ranges north to occupy their current ranges in the last 12,000 years. In all that change of the last glacial period, there were remarkably few known extinctions (Botkin et al. 2007).

We are now facing a period of even more rapid climate change where temperatures are changing at roughly ten times the average rate seen during recovery from historical ice ages. We assume many species will again respond by shifting their distributions to respond to changing conditions. Indeed, in response to present climate change, species' ranges are already shifting northward at rates of 10-20 km per decade and upslope at rates of 11 m per decade (Chen et al. 2011). However, our world is very different than it was 10,000 years ago. Human development has radically altered the landscape, causing fragmentation of natural land and creating obstacles to dispersal (Fischer & Lindenmayer 2007, Haddad et al. 2015).

How do conservationists ensure that the landscape remains permeable enough to allow such large-scale movements, particularly by species that disperse slowly or may be hindered by a variety of factors?

In this report, we address this question for terrestrial landscapes in the US.

Climate Change and Range Shifts

Range Shifts

Species respond to changes in climatic conditions in several ways: 1*) individuals adapt* their behaviors or habitat niches while staying in the same location, perhaps choosing shadier nesting sites or spending more time in riparian areas or spending less time active in the day; 2) *populations evolve* new climate tolerances to adapt to changed conditions through natural selection. We often think of evolution as happening very slowly, but as was demonstrated by studies of the Galapagos Island finches (Weiner 1995, Visser 2008), they can do so rapidly in response to dramatic changes in climatic pattern. Furthermore, many species, from trees to corals, have genetic differences in their populations related to differences in climate experienced across the species range (Davis and Shaw 2001). Such genetic differences at the population level may facilitate rapid adaptation as a way of responding to climate changes.

The other way that species may respond to climate changes is that 3) *populations and species shift their distributions*. This can occur when climate change leads to previously unsuitable habitat becoming suitable for population persistence allowing colonization of new habitat patches outside of the current range of a species. It can also result from differential survival of individuals at the range edge leading to a more gradual redistribution, for instance individual propagules surviving preferentially in shadier or moister areas causing a local population to shift in elevation or to a more shaded aspect. It is likely that components of all three mechanisms occur for most species.

Range shifts may be essential for species with narrow climatic tolerances experiencing rapid and extreme climatic changes in their current ranges, or for species that depend on naturally patchy landscape features, such as amphibians that breed in isolated wetlands.

The term "range shift" refers to the permanent colonization and subsequent spread into a new geography by a species through dispersing juveniles, propagules, seeds, eggs, adults, or other life history stage. The pressure to disperse is driven by the number of source populations and the abundance of reproducing individuals within them. The probability of reaching the new habitat is partially a function of dispersal pressure and partially of the permeability of the landscape through which the species must disperse. Additionally, a successful colonization requires that enough propagules arrive, establish, and reproduce in a suitable new area to persist for more than one generation. Thus, range shifts are a population process that occurs over generations and are sensitive to variation in three factors: dispersal pressure and vagility, the permeability of the landscape, and the suitability of the receiving habitat for the species in question.

A range shift may be accompanied by permanent extirpation in some other parts of the range, with the resulting range retraction reflecting locally failed recruitment due to unsuitable habitat, barriers, or lack of dispersal pressure. If at the same time, new and climatically suitable areas remain remote from current distributions due to the loss and fragmentation of habitats, and beyond the dispersal capacity of many species, then the concern is that species with low adaptability or dispersal capacity will be caught by the dilemma of climate-forced range change and low likelihood of finding distant habitats to colonize, ultimately resulting in increased extinction rates (Walther et al. 2002). This has been found to be the case globally for some bumblebee species no longer found in the southern part of their historic ranges but not yet expanding their ranges northward (Kerr et al. 2015). Indeed, the modeled dispersal ability of a range of taxa including North American trees (Loarie et al. 2009 quoted in Iverson and McKenzie. 2013) and mammals (Schloss et al. 2012) suggests that many species are unlikely to be able to keep pace with predicted rates of shifts in the distribution of suitable climate. However, to date, few examples of this extinction phenomenon have been documented and some evidence suggests that, at least in the short term, communities are tolerating climatic variation and/or incorporating new species without necessarily losing their current species (Roth et al. 2014). For example, alpine areas which are demonstrably sensitive to climate change (Walter 2016) and offer resident species little potential for upslope or northward movements, have yet to show any local extinctions apparently due to the abundance of local microclimates (Roth et al. 2014).

Dispersal and Dispersal Pressure

Whether species arrive in a new location that may be suitable for colonization depends on the population size and the build-up of dispersal pressure, their dispersal ability, and the proximity, relative abundance, and size of patches of suitable habitat (Primack & Miao, 2002). Research has shown that dispersal limitation is often more important than recruitment limitations for forest plant species (Honnay et al. 2002). Some animals are capable of long-distance dispersal in a single generation such as migratory birds and large mammals. Smaller mammals and herptiles are more likely to be restricted to shorter dispersal distances and therefore dependent on adjacent and proximal suitable habitats. However, smaller-bodied animals tend to reach sexual maturity earlier and often have higher fecundity. Assuming dispersing individuals can successfully establish in new habitat patches, these attributes allow the population to rapidly produce the next generation of dispersers for further expansion. Plants have evolved a host of mechanisms for dispersing their propagules: wind and water, hooks that hitchhike on feathers and fur, or seeds consumed by birds, ants, and small mammals. Bryophytes, ferns, and orchids have tiny wind-dispersed propagules that can effectively disperse over long distances and thus make up a greater proportion of the non-endemic flora in remote locations such as New Zealand (Meurk et al. 1995). Some species are particularly dependent on rare and inherently stochastic events for long-distance dispersal, whether by natural vectors, or inadvertently assisted by ubiquitous and constant human movement - in the mud of car tires or dust on freight trains or the cargo of ships (Higgins et al. 2003). Snails, for instance, are normally very short-distance dispersers, but can extend their ranges great distances when their larvae are caught in the tarsi of birds.

The greater the number of propagules, and the greater the number of vectors (in the case of chance long-distance dispersal), then the greater the likelihood of *some* successful dispersals leading to successful colonization (Rouget & Richardson 2003). High levels of dispersal pressure facilitate geographic spread regardless of biological traits, although the latter play a role in establishment and colonization (Pysek et al. 2009). Because the abundance of propagules is typically dependent upon the number, size, and demographic characteristics (such as density, age structure, and fecundity) of local source populations, these attributes are essential ingredients influencing successful dispersal and ultimate range shifts. Populations not producing surplus juveniles are unlikely to move, and thus, facilitating range shifts is directly tied to traditional conservation practices aimed at maintaining robust populations and source areas of breeding habitat with adequate resources for successful population growth.

Landscape Permeability

The Influence of the medium through which species are dispersing

Successful dispersal and colonization is a numbers game, a question of enough dispersers beating the odds to get to new habitat, and thus for terrestrial dispersers a key factor in determining the likelihood of a range shift to an unoccupied territory is the nature of the intervening landscape. If the goal was simply to maintain genetic connectivity among populations, a few individuals occasionally reaching the new area might be enough, as even a few new genes can make a difference in an isolated population (Soule & Simberloff 1986). However, range shifts to places not yet occupied by the species are often dependent on many more successes, with sufficient individuals dispersing to initially establish a population, followed by continued arrivals of new dispersers over time to prevent stochastic extinction. Under these circumstances, the extent to which the intervening landscape facilitates or impedes successful dispersal can be critical in determining whether a range shift occurs.

The relationship between specific landscape characteristics (e.g., land use, land cover, elevation, or landform) and the likelihood of dispersal is often quantified on a species-specific or taxa-specific basis through the concept of *resistance*. Resistance refers to the degree to which specific landscape features facilitate or impede the movement of a species. It can be thought of as the willingness of an organism to cross the habitat type combined with the likelihood of surviving such a crossing.

The resistance of a landscape to successful dispersal may be due to anthropogenic changes in land use. Satellite images of the Atlantic Seaboard or California's Central Valley make it obvious that human land use changes have created "islands" of native habitat, similar to forests in the East now surrounded by development, or patches of grassland in the Midwest surrounded by intensive agriculture. It seems intuitive that species in these native habitat patches may have difficulty successfully crossing a landscape of development or agriculture or be reluctant to cross due to increased exposure to risk or higher mortality from predators or traffic collisions. Indeed, many studies have confirmed that movements among patches of habitat are influenced by, or dependent on, the characteristics of the intervening matrix (Ricketts 2001, Hokit et al. 1999, Haddad et al. 2015). For instance, Richard and Armstrong (2010) tracked radio-tagged forest passerines (*Petroica longipes*, in New Zealand) in a fragmented agricultural landscape and found that juveniles move preferentially through native forest, followed by plantation forest, then shrubland, then pasture, with a marked hesitancy to cross the latter. Observations such as these have given rise to a plethora of "landscape resistance" models that simulate species movement through a landscape based on the degree of resistance expected from different land use/land cover types relative to the preferred type. In these GIS models, resistance values are assigned to individual cells in a raster layer based on the cell's land cover type and the expected degree of resistance. Such a GIS resistance model, discussed later in this document,

forms the basis of the continuous permeability models we used to model potential range shifts.

The resistance of a landscape to successful dispersal may also be ecological, i.e. a function of natural discontinuities in the landscape. The most obvious is dispersals of terrestrial species across ocean. The emergence of the Beringia Land Bridge during the Ice Age allowed dispersal of species (including *Homo sapiens*) to the Americas. The emergence of the Panamanian Isthmus allowed North American species to expand their ranges to South America. Large-scale landscape features that are highly contrasting habitat with surrounding land, such as deserts surrounding mountains, can also create "sky islands." This phenomenon has led to marked diversification of species on the mountains of the Basin and Range country of America's West (McCormack et al. 2009). On a smaller scale, some species dependent on moist conditions such as prairie potholes or riparian areas likely find the surrounding dry prairie landscape resistant to dispersal. On the other hand, the pattern of high red maple genetic variation, even in northern parts of its range, suggests that the northern Appalachian Mountains were not a significant barrier in the most recent post-glacial climate warming. Rather, it is likely that the contemporary range of red maple is the result of a combination of frequent long-distance dispersal events, only minor topographic obstacles, and diffuse northern refugia near the ice sheet (Gugger et al. 2008). Of course, some features of the landscape may facilitate more frequent successful dispersals, both ecological, such as river valleys or long mountain ridges, and anthropogenic, such as roadside verges. For example, purple loosestrife dispersed north along ditches of the I-95 corridor (Stuckey 1980), and New England cottontail populations in Maine remain connected via roadside verges and power line right-of-ways.

Any feature that facilitates or impedes movement is likely to have different impacts on different species; however, long-term studies on the effect of anthropogenic fragmentation have shown remarkably consistent negative effects across many taxonomic groups. Haddad et al. (2015) synthesizing the results of fragmentation experiments spanning multiple biomes, multiple scales, five continents, and 35 years, demonstrated that habitat fragmentation reduces biodiversity by 13% to 75% and impairs key ecosystem functions. Across all studies, they found generally consistent decreases in the abundance of birds, mammals, insects and plants, and reduced species richness of arthropods, birds, butterflies and plants and this accumulated over time as a fragment became more ecologically isolated (i.e., there was marked resistance to species moving between fragments resulting in both local extinctions and immigration lags). This overall pattern emerged despite complex patterns of increases or declines in abundance of individual species with various proximate causes such as release from competition or predation, shifts in disturbance regimes, or alteration of abiotic factors. Haddad et al. (2015) conclude that although the effects of fragmentation are mediated by variation in traits across species (e.g., rarity, trophic level, dispersal mode, reproductive mode, movement behavior), this primarily helped

to interpret variation around the overarching pattern of consistent reductions in richness and abundances across many species. If there is a positive side to these findings it is that the effects of fragmentation can be reversed by restoring the appropriate natural cover and adding a corridor which can produce up to 50% more movement (Gilber-Norton et al. 2005).

Establishment and Colonization

Successful range shifts are also reliant on the conditions found in the new unoccupied patches of suitable habitat available for colonization. In addition to the factors influencing the number of dispersers arriving as described in preceding paragraphs, whether species successfully colonize a new location depends on the breadth of their habitat tolerances, the rapidity with which they can reproduce, their success in competing with or escaping predation by native fauna or flora, and the amount of available habitat. In general, successful establishment is more likely for rapidly reproducing habitat generalists (including many of our "weedy" species) that can quickly establish and are more tolerant of spatial and temporal variation in the environment.

The more specific, uncommon, and distant the appropriate habitat is for any given species, the lower the frequency of chance dispersal into such habitats. It is easier to imagine that the arctic flora and fauna of dispersed mountaintops is a relic of a glacial period when such habitats were much more widespread than of long-distance dispersals since deglaciation. Furthermore, some specialist species have evolved lower dispersal abilities, thus stacking the odds against being stranded or landing in inhospitable habitat. The evolution of flightlessness in island-inhabiting birds is a familiar but not unique example. Likewise, although aerial ballooning is a common means of passive dispersal for many spiders, habitat specialist spiders in fragmented landscapes are much less likely to balloon (Bonte et al. 2003). Nevertheless, decades of inventory by botanists, have shown a remarkable consistency of flora on apparently isolated small-patch habitats like alkaline fens, shale slopes, serpentine outcrops, and limestone cliffs that, because of the discontinuousness of the underlying geology, are difficult to explain as remnants of once widespread populations.

The Evidence for Range Shifts in Response to Climate Change

For a range shift to be attributed to climate change it must occur when dispersing species gain access to suitable habitat that had previously been unavailable due to climatic conditions. This can happen directly through changes in mean temperature or short-term climate extremes that allow a population to expand northward, or through climate-mediated interactions with other species that remove competitive barriers. However, understanding and predicting climate-driven range shifts is complex, in part because species tolerances are not fixed. Davis and Shaw (2001) reviewed tree taxa shifts in latitude or elevation in response to changes in Quaternary climate and stressed the complexity of climate changes. Summer and winter temperature,

seasonality, and the distribution and amount of precipitation, all changed in different ways that produced new combinations of climate, not simply geographic displacements of the same climate. Although range shifts clearly occur, they questioned the assumption that taxa disperse seed and establish in new regions more readily than they evolve a new range of climate tolerances, or even that the tolerance range for a species remains temporally stable given wide intraspecific variation.

The evidence is clear that rapid periods of climate change in the Quaternary saw many shifts in species distributions. As the climate cooled, the distribution of tree species such as red spruce in North America and Scots pine in Europe shifted south, and as the ice sheet receded, they moved north again 150 km/century (Davis & Shaw 2001). Considering that much of the northern third of the US was covered by ice miles thick for millennia multiple times, every species that now lives in this region had to arrive in the last 12,000 years by shifting their ranges northward. The fact that there were so few extinctions associated with all these massive displacements of species over broad areas of North America has been dubbed the Quaternary conundrum. A hypothesis put forward to explain this for North America is that the landscape remained highly connected by natural cover allowing species distributions to track the climate (Botkin et al. 2007). It may also be that the north-south trending mountain ranges and lack of major landscape impedances to northward movement facilitated these shifts, which is consistent with the assumed mechanism of differential extinction and colonization rates at northern versus southern range edges (Honnay et al. 2002). There is some evidence that northern Europe has been slower to recover its former species diversity in part because of the obstacles posed by east-west mountain ranges such as the Pyrenees and the Alps (Adams & Woodward 1989).

Evidence for contemporary range shifts in response to climate has now been documented for over 1000 species as populations shift their geographic distributions in one of four ways: 1) upslope toward higher elevations, 2) northward toward cooler latitudes, 3) downslope towards moist riparian areas, and 4) locally toward suitable microclimates. The evidence for upslope and northward movements is strong and consistent across many taxa groups and across several continents (Table 7.1, Walther 2002, Chen et al. 2011) and there are increasing indications of the other responses as well. As we review the evidence for these four responses, it is helpful to remember that a variety of ecological factors may create variation in a species response to climate: competitive release, habitat modification, or changes in amounts and patterns of precipitation, snow cover duration, water balance, or seasonality (Groffman et al. 2012). Any of these may cause range shifts to differ substantially from straightforward poleward or upslope movement largely driven by temperature (Garcia et al. 2014). These factors, coupled with relatively gradual rates of temperature change with latitude in the tropics, mean that detecting and predicting range shift patterns in the tropics will be much more difficult. In this paper we focus on temperate regions.

Table 7.1. Summary of elevational and latitudinal observed range shifts from 30 studies (modified from Chen et al. 2011). ORS = observed range shift, SE = standard error. "Margin" refers to whether the studies focused on changes in the upper leading margin or average distribution. The list of sources for Chen et al. 2011 are located at http://www.sciencemag.org/content/333/6045/1024/suppl/DC1

Observed Elevational Range Shifts									
Taxa group	**# of Species**	**Margin (Upper / Avg.)**	**Duration (yrs.)**	**Mean ORS (m)**	**Min ORS (m)**	**Max ORS (m)**	**SE of ORS (m)**	**Temp change (C)**	**# Studies**
Invertebrate	554	U/A	20-42	37.7	7.4	108.6	12.3	0.62	5
Fish	15	U	25	32.7	32.7	32.7	12.7	0.65	1
Herptiles	30	A	10	65.3	65.3	65.3	24	0.24	1
Birds	326	A/U	11-25	-4.75	-19.3	7.6	9.3	0.795	4
Mammals	37	U/A	25-88	50	31	69	71.6	3.05	2
Plants	495	U/A	22-94	62.4	21	89	16.2	0.97	7
Observed Latitudinal Range Shifts									
Taxa group	**# of Species**	**Margin**	**Duration (yrs.)**	**Mean ORS (m)**	**Min ORS (m)**	**Max ORS (m)**	**SE of ORS (m)**	**Temp change (C)**	**# Studies**
Invertebrate	332	U	8-25	59.1	7.9	104.2	15.9	0.6	3
Fish	15	U	25	47.2	47.2	47.2	15.4	0.65	1
Birds	361	U/A	12-31	24.2	3.6	46	19	0.49	4
Mammals	9	U	25	22.4	22.4	22.4	38.4	0.45	1
Algae	37	A	50	61.4	61.4	61.4	31.6	0.74	1

Upslope Movement: A recent meta-analysis of over 51 studies detected upslope elevational range shifts for five taxonomic groups with magnitudes ranging from 6.1 m to 11.0 m per decade and this was consistent with other studies (Chen et al. 2011, Parmesan & Yohe 2003, Lenoir et al. 2008). Upslope movement appears to be greatest among plants and herptiles, followed by mammals, invertebrates, and fish (Table 7.1). Responses by birds have been inconsistent (Tingley et al. 2012) although an eight-year monitoring study in Switzerland found significant upslope shifts in communities of birds (42 m), butterflies (38 m) and vascular plants (8 m), with rates of community changes decreasing with altitude in plants and butterflies (Roth et al. 2014). For immediate climate relief, moving upslope is more efficient than moving latitudinally. For example, in the tropics there is a 5.2°C to 6.5°C decrease in temperature per 1000 m elevation, nearly 1000 times as much as the latitudinal rate of decrease (Colwell et al. 2008). Although evidence for upslope movement seems overwhelming (Lenoir et al. 2010) and it may be the dominant way in which most species are accommodating climate change in the short term, there are obvious limitations to it as a long-term

strategy for all species. First, it only works for species where upslope movement of suitable habitat is an option, which includes many plants, invertebrates, birds, and mammals, but not for those where a lowland physiographic setting is required for suitable habitat such as many wetland-associated species or plants that need deep, moist, nutrient-rich soils. Second, the extent of available upslope habitat is limited in many regions where the slopes are either so gentle or so distant that they offer little practical climate relief to most species, or the hills are so small that their summits are rapidly reached.

Northward Expansions: Northward movements are also well documented for 754 species across five taxa groups, and they appear to be ubiquitous across the northern hemisphere (Table 7.1, Chen et al. 2011). Studies have found latitudinal range shifts to range from 6.1 km to 16.9 km northward per decade (Chen et al. 2011, Parmesan & Yohe 2003, Lenoir et al. 2008). It is likely that latitudinal expansions will be the predominant long-term strategy of most species in response to climate change, and this is largely concordant with the evidence of historic range shifts in response to previous periods of rapid climatic change. Despite fears and reports that many species will lag behind, Chen et al. (2011) found that nearly as many studies of observed latitudinal changes fell above as below the expected rate suggesting that mean latitudinal shifts are not consistently lagging behind the climate.

Downslope Movements: Upslope and northward movements correlate with temperature change, but many species are more limited by moisture availability than temperature. Downslope regions collect moisture and feature microclimates that may be significantly cooler and more humid than immediately surrounding areas (Olsen et al. 2007). A recent study examining the response of eastern trees to climate change found changes in moisture availability had significantly stronger near-term impacts on vegetation dynamics than changes in temperature (Fei et al. 2018). Species seeking moisture tend to move downslope towards the water-collecting regions at the base of slopes or into moist riparian areas.

Species showing downslope shifts have been well documented (Archaux 2004, Popy et al. 2010). A survey of such range shift studies suggests that while roughly 65% of species have shifted their ranges upslope, 25% have shifted their ranges downslope, and 10% have not changed their mid-range positions (Lenoir et al. 2010). Similarly, a global review of the literature (Parmesan & Yohe 2003) suggests that about 20% of species have adjusted their ranges towards lower elevations. Long-term downhill shifts in the optimal elevations of plant species has been shown for California, apparently in response to decreased climatic water deficit (Crimmins et al. 2011). Our own spatially-explicit climate resilience analysis (Anderson et al. 2013) based on microclimates and connectedness identified many slope bases and riparian corridors as key landscape features because of the many climate options they provide, especially in relatively flat landscapes.

Moisture and temperature differences between riparian areas and their surrounding landscapes may be substantial, with riparian areas being 5-20^0 C cooler and 10-15% higher in soil moisture (Yeakley et al. 2008, Bennie et al. 2008). Thus, they are expected to provide microclimatic refugia from warming and drought for many species, particularly those that tolerate wet conditions (Seavy et al. 2009). Additionally, riparian areas naturally connect many landscape features, and this unique attribute make them logical and perhaps vital elements in any conservation network designed to maintain landscape resilience and facilitate range shifts. It is not surprising that the use of riverine corridors in a riparian connectivity network has been proposed as a strategy for maintaining climate resilience (Fremier et al. 2015). Although they comprise a minor proportion of the landscape, riparian areas are structurally diverse and more productive in plant and animal biomass than adjacent upland areas, suppling food, cover, and water for a large diversity of animals. Riparian areas sometimes serve as migration routes and connectors between habitats for a variety of wildlife (Manci 1989), particularly within highly modified landscapes (Hilty & Merenlender 2004).

Riparian areas that span climatic gradients might provide natural corridors that species could use to track shifting areas of climatic suitability and have been called riparian climate corridors (Krosby et al. 2014). In the Northeast; however, the temperature gradients *within* most riparian or floodplain corridors was found to be very small (Anderson et al. 2015), averaging 0.14^0 C on the Coastal Plain to a high of 1.3^0 C in the Central Appalachians. This suggests that although there is ample incentive for species to move into downslope or riparian areas, there may be less climatic reason to move directionally along the corridor.

The numerous studies documenting preferential use of naturally vegetated riparian zones by a wide range of species of terrestrial wildlife (e.g., Hilty & Merenlender 2004) do not necessarily demonstrate the use of such areas for long-distance dispersal. For example, a study of riparian zones as dispersal corridors for herptiles found that for many species dispersal along the riparian zone was likely impeded by species-specific habitat needs such as inundation patterns, appropriate adjacent upland habitats, or fishless pools (Burbrink et al. 1998). However, riparian habitat tends to include a higher density of wetlands in comparison to upland areas and thus on average will provide suitable breeding sites in closer proximity to one another, leading to an increased probability of successful dispersal of wetland fauna in riparian areas over time. Additionally, the rivers, themselves, clearly play a role in dispersal of fish and other aquatic species, and in the passive dispersal of plants in riparian zones whose propagules survive inundation (Jansson et al. 2005). Such dispersal is, of course, driven by the movement of the water downhill so could not be expected to contribute much if any to dispersal upslope or poleward in response to increasing temperatures, except on rivers that flow north.

Where intact riparian areas or bottomland floodplains occur in developed or converted landscapes it may be difficult to separate questions of the preferential use of riparian zones for movement from the use of strips of natural landscapes. In the Southeast Coastal Plain, for example, extensive, intact, large river floodplains contrast strikingly with the surrounding landscape providing both habitat and natural movement corridors. Radio-tracking studies have documented the use of these riparian areas for movement of large mammals in Georgia (Cook 2007) and it seems likely that many wildlife species would use a riparian corridor for dispersal if that is the only safe natural cover in the wider landscape (Fremier et al. 2015). Such corridors may allow multi-generational dispersal to occur between larger heterogeneous areas of protected habitat if the corridors include appropriate breeding habitat, and this may be particularly important for species with limited dispersal abilities. Further, it is postulated that ensuring riparian corridors right up to headwaters can provide critical over-the-ridge links for dispersal across watersheds (Olson & Burnett 2013). It is less clear in a landscape were the riparian areas occur within intact natural land cover whether upland terrestrial species would preferentially disperse along a river valley rather than along ridge lines or contour lines that have their preferred cover or food sources.

Microclimates and Rates of Change: The fourth and perhaps most common alternative for species is to find suitable habitat nearby, moving a small distance to take advantage of a local microclimate. Species experience climate at extremely local scales (cm to meters) and the available moisture and temperature in the near-ground "boundary layer" can differ greatly from the local average (Geiger et al. 2009). Thus, a topographically diverse landscape is experienced by its resident species as a heterogeneous mix of microclimates many of which might be suitable for persistence even where the average background climate appears unsuitable. Landscape-based climatic variation can be substantial, on par with or greater than the 1.5^{o}C warming expected for the future. Studies where climate data loggers are placed across gradients of slope, aspect and elevation have found maximum temperature differences over 20^{0} C (Surgett et al. 2010, Dobkin et al. 1987) and 15-20 % fractional soil moisture differences (Yeakley et al. 1998, Bennie et al. 2008). In Southern Appalachian watersheds, topography explains 40% to 72% of the variation in near-surface soil moisture (Yeakley et al. 1998). Even microscale patches of suitable climate may allow persistence of species over long periods and serve as a source for recolonization or further dispersal. For example, Roth et al. (2012) found that although lowland plants in Switzerland were moving upslope, alpine plants were persisting in place, finding suitable habitat within a few meters due to the highly varied surface of the landscape. It is probable that both lowland and alpine plants were taking advantage of all suitable microclimates, and that the apparent difference in response was due to the difference in availability of upslope microclimates.

The examples above support the idea that stable refugia, effectively decoupled from the regional climate, may offer longer-term respite in a climatically variable regional landscape. Proximity to such refugia seems to have helped some species survive the last glaciers and then served as dispersal points for populations post glaciation (Provan & Bennett 2008). Besides the better studied refugia of southern and eastern Europe, it now appears there were also cryptic refugia in northern Europe in areas of sheltered topography with stable microclimates (Steward & Lister 2001). Mapping the distribution of microclimates has been the basis of a study by The Nature Conservancy to identify climate resilient sites (Anderson et al. 2014), and some of the areas identified as microclimate concentrations (e.g., the Piedmont-Coastal Plain Fall Line), correspond to areas where the ranges of plant species have expanded and contracted in historic periods of climate change (Weakley pers. com. 2015).

Some types of cool climate refuges occur at scales larger than the topographic microclimate, such as orogenic rain shadows, lake effects, cold air pooling, or maritime cooling. In the short term, ephemeral climate refuges that offer the coolest maximum temperatures when regional temperatures are relatively high may provide relief to transient species or even populations (Gollan et al. 2014). In eastern North America there is evidence of a refugium along the coast of Maine where the maritime influence allowed spruce to survive even when the relatively dry and warm climate of the hypsithermal prevented spruce survival inland (Schauffler & Jacobson 2002). These populations were likely the source of the rapid expansion and dominance of spruce through the rest of the state about 1000 years ago during a region-wide shift to cooler and moister conditions.

The localized movement of populations to utilize microclimates is so restricted that it probably does not qualify as a range shift unless accumulated small movements add up to a directional change (i.e., upslope). However, utilization of microclimates may explain how poor dispersers can track the changing climate within larger-scale range expansions. Chen et al. (2014) hypothesized that the real and apparent lags in species response to climate may reflect the topographic and microclimatic complexity of mountainous terrain, and they emphasized the need for finer-resolution analyses with additional topographic and geological detail if we are to understand the actual climates that species are tracking. Loarie et al. (2009) noted that owing to topographic effects, the velocity of temperature change varies spatially, and is lowest in mountainous areas, which may effectively shelter many species into the next century. Coarse-scale climate models are mapping something distinctly different from very local climates experienced by species on the ground, and this can lead to erroneous conclusions about extinction rates or the rates of dispersal needed to track climate change (Willis and Bhagwat 2009). This is good news because the rates of change in species distributions documented in recent decades as well as in the last post-glacial period do not come close to the estimated rate of range shift that would be necessary to keep up with predicted climate changes (e.g., 300-500 km/century as per Anderson and Shaw

2001, or one to two orders of magnitude faster as per Honnay et al. 2002). There are probably limits to the buffering effect of microclimates as the only precisely dated extinction of a tree species, *Picea critchfieldii*, during the Quaternary coincided with the exceptionally rapid warming during the transition from the Last Glacial maximum to the Holocene about 15,000 years ago. What is surprising, however, is that this example seems to be singular.

The evidence for contemporary range shifts provides support for the four types of responses discussed above, but the studies are unavoidably focused on cumulative short distance dispersals and leave many unanswered questions about long distance jumps to suitable habitat, or responses to broad-scale episodic extreme disturbances. It is likely that we simply do not understand enough about the actual dispersal of most species, particularly the low frequency but long-distance dispersals that could explain dispersal rates during the last post-glacial period (possibly aided by hurricanes or large migrating herbivores) being much higher than what is being observed or modeled currently. In plants especially, observed average seed dispersal distances cannot account for the rapid northward migration that occurred in many species (Reid's Paradox; Clark et al. 1998). In fact, Cain et al. (1998), modeling the seed dispersal curve for *Asarum canadense*, a woodland herb dispersed by ants, concluded that an empirically calibrated diffusion model would show that since glaciation *A. canadense* should only have traveled 10-11 km from its glacial refugia, but in fact it moved hundreds of kilometers during this time. They conclude that most woodland herbs and many other plant species have such limited dispersal capabilities that occasional extreme dispersal events and mechanisms are the only explanation for their documented migration. Griffin and Barret (2004) concurred after using a genetic analysis to study the range expansion of the woodland herb *Trillium grandiflorum*, finding that it likely survived in two refugia in the southeastern US during the last glaciation and that post-glacial recolonization of northern areas was characterized by long-distance dispersal beyond what the plant appears capable. Higgins et al. (2003) suggest that long-distance dispersal events in plants are usually caused by non-standard means of dispersal, that is, a plant seed adapted to wind dissemination may get lodged in the feathers of a bird and transported much farther than wind would take it. Although such infrequent long-distance dispersal events are likely to allow some species to move much further and faster than evidenced by their typical form of dispersal, it is important to recognize that for many taxa, especially specialist species, for such events to result in locating and establishing on a patch of uncommon habitat is highly improbable without animal or human intervention.

Habitat Fragmentation and Climate Change

Current species' responses to climate change may differ from historic responses because humans have modified the landscape, fragmenting habitats and disrupting natural movements. Fragmentation of the landscape has been shown to slow dispersal and hamper the successful colonization of new habitat by creating resistance to population movement through the intervening matrix. Above, we reviewed the 35-year synthesis by Haddad et al. (2014) of the world's largest and longest running fragmentation experiments, which clearly demonstrate a resistance to movement, and/or high mortality rates, for all major taxa groups when crossing contrasting or unfamiliar land cover. Further, colonization and radio-tagged movement studies reinforce these observations with respect to tree species (Honnay et al. 2002), forest passerines (Richard & Armstrong 2010), and many other taxa. Climate change does not appear to fundamentally alter the effects of fragmentation other than to intensify the need for species to move in response to directional changes in climate and to concentrate those movements on upslope or northward gradients, or downslope into local riparian areas. We assume that the responses to fragmentation are equally applicable to these features, and that even the dispersal of species to nearby suitable microclimates is facilitated by a connected landscape through which organisms can move easily.

Implications for Conservation

This review of the mechanisms for range shifts in response to climate change highlights several points. Range shifts are a well-documented species response to past episodes of climate change and there is abundant evidence that they are already occurring in response to current climate change. The latter are detectable as expansions upslope and northward, as downslope movement into riparian areas, or as very local movements to take advantage of proximate microclimates. The magnitude and pattern of the current response is likely to differ from historic responses because humans have modified the landscape, fragmenting habitats and disrupting natural movements. These modifications create resistance that may prevent species from colonizing new habitat, instead creating range constrictions.

The conservation implications of this review guide the work presented in the rest of this report. Some of the findings reinforce well-known conservation design principles while others call for new mapping and integration methods to identify the spatial implications of climate-driven range shifts. These are organized below as ten key points with the first three focused on facilitating dispersal, and the next seven on facilitating dispersal under climate change. When appropriate, we link the points directly to the resilience analysis (Anderson et al. 2016, 2018 a & b).

1. It all starts with dispersal pressure. It is essential that there are source areas for all species to produce enough propagules to ensure a high probability of successful

dispersal. To function well as source areas, sites need to have the requisite size and optimal breeding conditions for that species. For many species, we believe sites that are above-average in local connectedness and landscape condition as defined by the resilience analysis (Anderson et al. 2016) are likely to correspond with source areas.

2. The quality of the landscape through which species disperse can impede the movement of species and there is strong and consistent evidence for this across all taxa. There is good justification for using resistance-based models to identify potentially important linkages and pinch points and solid evidence to support conservation efforts aimed at facilitating movement by maintaining or restoring suitable natural cover. This can often be accomplished through compatible land management over broad areas in conjunction with high natural cover in specific areas.

3. All species, especially habitat specialists, need sufficient suitable habitat to meet their specialized needs both now and in the future. This argues for the importance of the representation of all geophysical settings in a variety of climate zones as part of the resilient portfolio concept. For specialists, the uncertainties of occasional long-distance range expansions make the need for refugia even more important.

4. Upslope range shifts in response to climate are already widespread and are likely important for short-term reprieve, particularly in landscapes with low topographic relief. Mapping, prioritizing, and conserving connections to available upslope features are important when designing a local landscape for climate resilience.

5. Northward range extensions have been detected in over 500 species. Mapping permeability across north-south gradients should highlight areas for explicit conservation focus. This may include pinch-points that play a disproportionally important role in facilitating range shifts, diffuse areas that offer many options for movement, or low-flow areas that could be improved through restoration.

6. Downslope areas and riparian corridors are unique in that they offer cool, moist microclimates and also connect many features on the landscape. Wherever possible they should be used to connect resilient sites or already conserved land. Prioritizing downslope regions based on their degree of permeability and flow should identify areas that likely play an essential role in facilitating range shifts because they are cooler, wetter and more intact.

7. Microclimate refugia can play a role in promoting long-term persistence and slowing the velocity of climate change. In the short term, a species may find refuge by moving upslope or to another aspect of a hillside or valley or to a rock and soil type that holds more or less moisture. Such opportunities are more likely in areas with higher landscape diversity, as defined by an analysis of resilience.

8. Over the longer term, some geographies are likely to play an essential role as longer-term refugia. Some of these can be predicted based on microtopography or attributes that make their climates intrinsically more stable. Others may be harder to predict in advance, but this argues for ensuring a portfolio of conservation sites that includes geographic distribution, stratification by ecoregion, and geophysical representation.

9. Absolute contiguity of appropriate habitats may not be necessary and is in many cases impossible for most species, but proximity helps increase the odds of successful dispersal. The stepping stone concept makes sense. Even if we do not know and cannot model how occasional long-term dispersal events occur, the evidence shows that after glaciation many specialist species with poor dispersal prospects somehow relocated to pockets of suitable substrate and climate.

10. Given the apparent importance of infrequent long-distance dispersal in accounting for the pace of past range shifts, we should not discount the importance of sites that are distant and seemingly disconnected from additional habitat if they are robust source areas for multiple species, especially for uncommon habitat specialists. Integrating known sites with confirmed rare taxa or high-quality examples of unique communities should provide the best starting point for the latter.

Regional Flow: Mapping Landscape Permeability

The Nature Conservancy's analysis of site resilience sites addresses many of the recommendations summarized in the previous section, including recommendations to:

1) identify potential source habitat for species;
2) represent all geophysical settings in a variety of climate zones;
3) identify microclimate refugia in areas with higher landscape diversity;
4) ensure a portfolio of conservation sites includes representation and geographic distribution of all geophysical settings within ecoregions.

The resilience studies stop short, however, of identifying a connected network of sites that includes the linkages and confirmed biodiversity features needed to facilitate range shifts. This report is designed to address that issue. Specifically, we develop methods to map the permeability of the landscape in relation to anthropogenic uses and barriers, we examine where needed latitudinal or slope movements are likely to concentrate, and we locate sites with confirmed biodiversity elements such as rare species or exemplary communities. Finally, we integrate these components into a connected network designed to sustain diversity under climate change.

Introduction

The permeability of a landscape is a function of the resistance of its major elements and their spatial arrangement: the types and penetrability of barriers, the connectedness of natural cover, and the configuration of land uses. It is defined as the degree to which a landscape, encompassing a variety of natural, semi-natural, and developed land cover types, will sustain ecological processes and be conducive to the movement of many types of organisms (Meiklejohn et al. 2010). Consequently, our goal was to map landscape permeability as a continuous surface, not as a set of discrete cores and linkages as might be used to map an individual species' movement between areas of suitable habitat (Fischer & Lindenmayer 2006, Beier et al. 2011).

Several approaches have been developed to create a continuous model of landscape permeability: moving window (McRae in prep), centrality (Theobald et al. 2012), resistant kernel (Compton et al. 2007), and wall-to-wall (Clark in Anderson et al. 2012 and Pellatier et al. 2014). The wall-to-wall approach is particularly suitable for modeling potential range shifts because it allows for the creation of multidirectional and omnidirectional connectivity maps illustrating flow paths and variations in the ease of movement across large regions. The results provide a continuous view of connectivity across a study area at the full original resolution of the data and highlight pinch points, blockages, essential corridors and flow zones (Pelletier et al. 2014).

The mapping of permeability as a wall-to-wall surface has only recently become possible through the use of the software Circuitscape (McRae & Shah 2009), an innovative program that models species and population movements as if they were electric current flowing through a landscape of variable resistance. Circuit modeling is conceptually aligned with the concept of landscape permeability because it recognizes that movement through a landscape is affected by a variety of impediments, and it quantifies the degree and the directional outcomes of the compounding effects. One output is a "flow" map that shows the behavior of directional flows and highlights concentration areas and pinch-points. The results identify locally and regionally significant places where species range shifts are likely to be impeded by anthropogenic resistance, and that may warrant conservation.

"Flow" in an ecological sense refers to the gradual movement of plant and animal populations across the landscape over time. Populations expand when they produce a surplus of juveniles which disperse and colonize new habitat at a distance from their source point. Juvenile animals can walk, climb, fly, float, swim, glide, crawl or burrow their way to new locations, and plants have evolved a host of mechanisms for dispersing their propagules by taking advantage of many dispersal vectors such as wind, water, animals, and people. If the current habitat becomes unsuitable, but available suitable habitat exists nearby, a flow of dispersers helps ensure that the new habitat will be discovered and colonized.

Population responses to current climate change differ from historic responses because humans have modified the landscape, fragmenting habitats, and disrupting natural movements. Such modifications can create barriers that prevent species from colonizing new habitat, and may result in range constrictions in areas where range expansions were historically possible. Alternatively, the configuration of land uses can serve to channel population flow through a narrow corridor, increasing the importance of that corridor to maintaining flow. To detect and quantify these patterns within the study area we modeled how species populations will likely migrate and disperse through the anthropogenically modified landscape, and used the results to identify critical pinch points, blockages, or broad flow zones.

In a previous pilot study (Anderson et al 2016), we compared the results of regional scale flow modeling in Eastern North America against 58 smaller scale studies. The results can be found in the section titled called "Comparisons and Confirmation" and more completely in Appendix 1. We found that in spite of scale and methological differences between the studies, many showed similar results, particularly in modified landscapes where there were fewer available choices for movement through natural cover. Comparisons between the regional flow models and species based movement studies were the most similar, giving us confidence that species were likely to utilize the flow concentration areas. Results were least similar between studies that

connected predeterminded habitat blocks, particularly when the connections between blocks did not follow the natural flow patters. This observation suggested that prioritizing habitat blocks that are located within the existing natural flow patterns might be the most effective way of maintining adaptive movement. We will come back to this point in the later section on integration of flow, diversity and resilience.

Initially we modeled flow based soleley on anthropogenic resistance which we refer to as 'regional flow." This model estimates population movement patterns based on the arrangment of human-modified barriers such as roads, development and energy infrastucture. Our next step was to incorporate the influence and response to climate change directly into the model. This is presented in the susequent section entiled "Climate Flow." Using evidence on how species are already responding to climate change, the climate flow model is a modified version of the regional flow model with more weight given to flow pathways that provided cooler temperatures (upslope and northward) or higher moisture (downslope, riparian).

Circuitscape Model

All modeling of landscape permeability and regional flow was done using Circuitscape (McRae & Shah 2009). Circuit modeling recognizes that movement through a landscape is affected by a variety of impediments (resistances) and quantifies the degree to which these impediments will affect movement and the directional outcomes of the compounding effects.

The Circuitscape program calculates the amount of "current" moving directionally across a landscape based on an input grid of cells with values indicating their degree of "resistance." One output of the program, a current map, shows the behavior of directional flows, analogous to electric current flowing across a surface with varying levels of resistance. Like water moving across an uneven watershed, the flow of current over the resistance surface results in patterns of high and low concentrations very similar to the streams, gullies, eddies, and braided channels associated with the overland flow of water. The program's ability to highlight flow concentration areas and pinch-points makes it particularly useful for identifying key linkages for permeability. Flow concentration areas are easily recognized in the Circuitscape output by their high current density.

In the Circuitscape program, the landscape is converted into a graph, with every cell in the landscape represented by a node (or a vertex) in the graph and connections between cells represented as edges in the graph with edge weights based on the average resistance of the two cells being connected (Shah & McRae 2008). The program performs a series of combinatorial and numerical operations to compute resistance-based connectivity metrics, calculating net passage probabilities for random walkers passing through nodes or across edges. Unlike a least cost path

approach, Circuitscape incorporates effects of multiple pathways, which can be helpful in identifying critical linkages where alternative pathways do not exist (McRae & Beier 2007). More detail about the model, its parameterization, and potential applications in ecology, evolution, and conservation planning can be found in McRae and Beier (2007) and McRae and Shah (2009).

Anthropogenic Resistance Grid

In a Circuitscape analysis, the current flows across the landscape through a resistance grid, with lower resistance being more permeable and higher resistance less permeable. The base grid we used for anthropogenic resistance was land cover, but in theory resistance can be any factor that impedes movement (in later climate flow models we use slope and land position as well). When based on land cover, obstructions to species movement are assigned high resistance scores based on the degree to which they impede species population movements.

Our assumption was that the resistance between cells increases with their contrast to natural land. Elements that contrast strongly with natural land, such as high intensity development, were considered less permeable because of differences in structure, surface texture, chemistry, temperature, or exposure. In this model dispersing wildlife and plant propagules can cross any landscape elements, but the sharper the contrast (for example "forest" adjacent to "high-density development") the stronger the decrease in movement. Even if it is possible to cross developed land, a forest animal may prefer to avoid the risk inherent in crossing the more exposed habitat or a forest plant may fail to establish in the new environment.

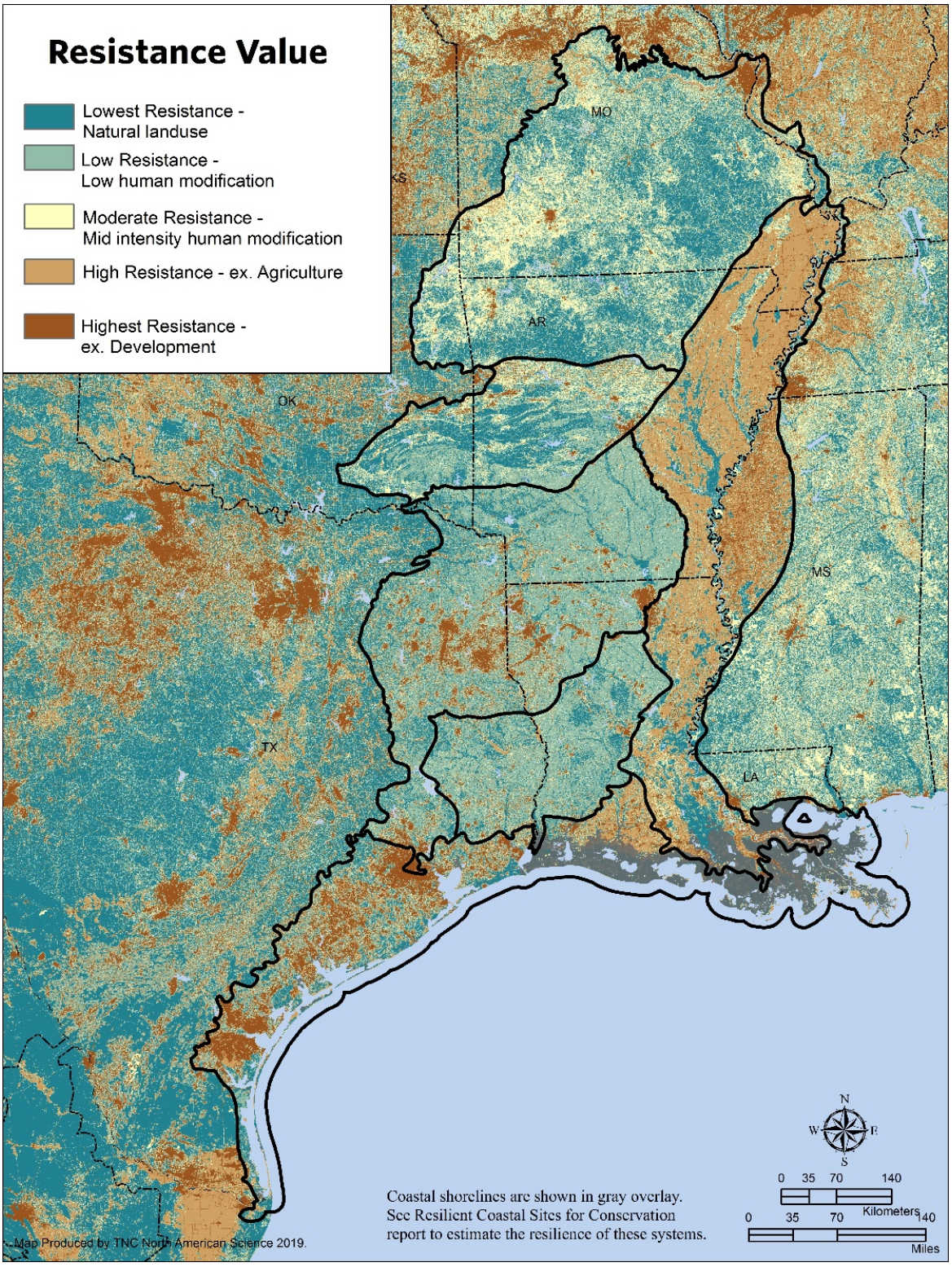
We used the same anthropogenic resistance grid that was created for local connectedness analysis (Chapter 3, Figure 7.1). Our basic elements were as follows:

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

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

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

Figure 7.1. Anthropogenic resistance grid used in the Circuitscape analysis. The figure shows the improved and integrated land cover map with each cell reclassified to its assigned resistance score.



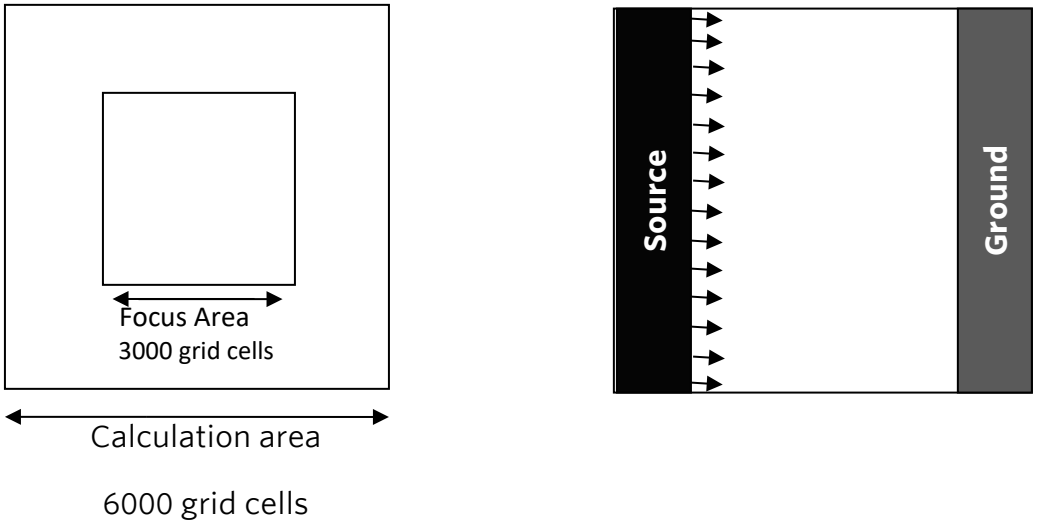
Mapping Regional Flow

Circuitscape was originally designed to measure point-to-point connectivity, calculating resistance-based connectivity metrics from one discrete patch to another. The point-to-point approach has been widely used in conservation planning to measure the connections between two patches of suitable breeding habitat as defined by the precise needs of a species (Beier et al. 2011). However, using a point-to-point approach can limit the utility of assessing connectivity over very large areas, or in evaluating the response of populations to climate change where there are so many habitat patches of interest that assessing connectivity among all possible combinations is prohibitive. Additionally, the point-to-point method is sensitive to the location of the starting points and may produce different results across the same landscape if different starting points are used. To overcome these conceptual and practical limitations, we used a minor adaptation of the Circuitscape model that allows for the "point free" creation of omnidirectional connectivity maps illustrating flow paths across large study areas. Our methods have been developed and refined over several years and were originally described in Anderson et al. (2013) and Pelletier et al. (2014).

Briefly, to obtain a multi-directional and wall-to-wall coverage of the region we ran the model in gridded landscape tiles where one whole side of the tile was assigned to be "source" and the other side to be "ground." Next, "current" was injected along the entire source side and allowed to flow across the landscape resistance surface towards the ground side. As the current flows it reveals the various flow pathways and highlights where flow gets blocked or concentrated. Because current seeks the path of least resistance from the source cells to any grid cell on the ground side, a run with the west edge as source and the east side as ground will not produce the same current map as a run with the east edge as source and west edge as ground. Runs were thus repeated in each of four directions: east to west, west to east, north to south, south to north, and summed across all directions. Lastly, we clipped out the central quarter of each tile (Figure 7.2, focus area) and joined it to the central regions of all the other tiles. This last step was done because testing had shown that the central quarter gave stable, repeatable, and consistent results regardless of the size of the calculation area. In contrast, the outer margins of the tile had considerable noise in the results created by the tile's exact boundaries. All calculations were performed using the latest version of Circuitscape (5.0) with a cell size of 180 meters.

To run the analysis, we developed a systematic processing method and then used Python scripting to automate the process. First, the study area was divided into 16 tiles - calculation areas - comprised of 6000 cells by 6000 cells or roughly 1.16 million square kilometers. Each tile was intersected with the resistance map and the analysis was run as described above. All tiles with land cover information were included except for those that were 100% water (ocean).

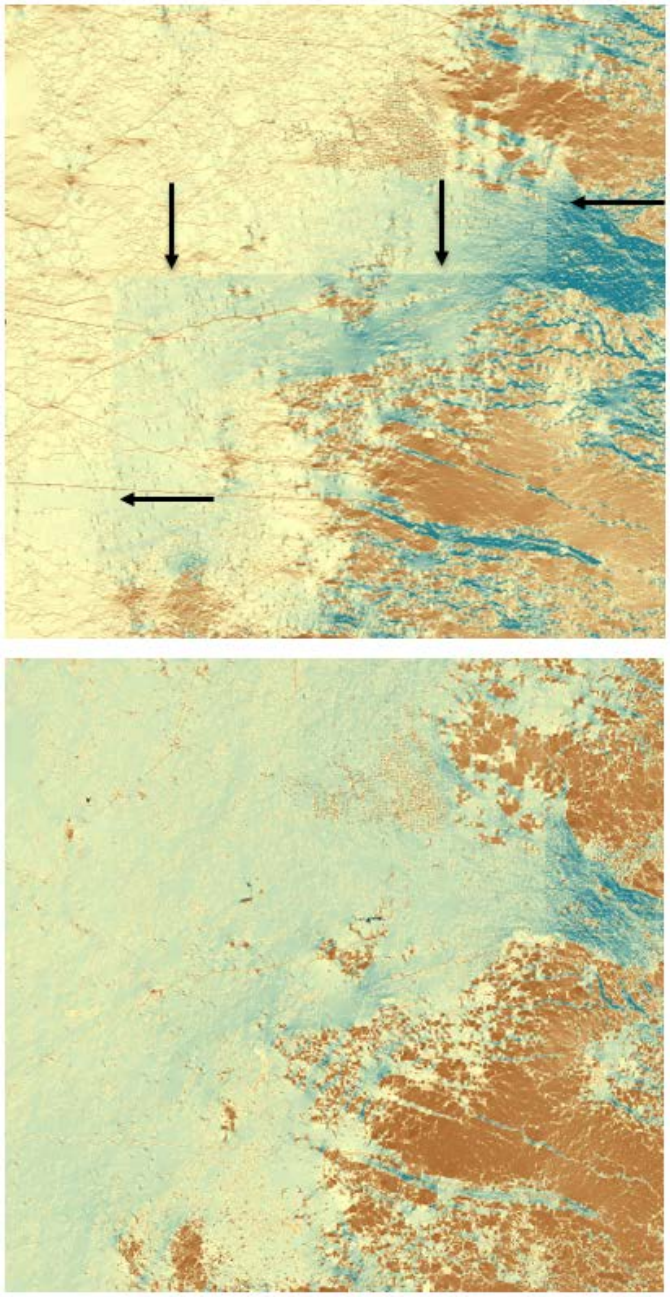
Figure 7.2. Diagram of tiles used in the Circuitscape analysis.
The image on the left shows the focus area in comparison to the calculation area. The image on the right shows how current is injected from every cell on the source (on the left) and can flow to any cell in the ground (right).



To inject current in the tile with coastal regions, where a proportion of the tile was filled by ocean or Great Lake, we used a method developed by Jeff Cardille of McGill University (personal communication, December 2015) to fill in the surface. We created a random raster with the same mean and standard deviation as the land resistance and replaced the large waterbodies with this random raster on the resistance grid. When current is injected along the "water" side of the tile it runs equally along the grid until it encounters a shoreline, allowing for equal current flow potential for coastal areas.

Lastly, the focus area was clipped out of each tile and joined together to create a single continuous coverage for the region. To standardize the scores across tiles, a cell of overlap was retained between all adjacent focus areas. Theoretically the scores within the overlap area should be the same between two adjacent tiles since they are the same area. To enforce this, the neighboring cell's score was adjusted so the overlapping areas had the same mean score as the starting tile, and this was repeated for all cells starting at the center and working outward in a starburst pattern. This created a more seamless surface than our previous method (Anderson et al. 2013) of using a standard normal transformation (Z-scores) to convert focus areas to the same scale and then joining the focus areas together (Figure 7.3). That method had minimized differences between areas that had very different mean scores such as a largely agricultural focal area adjacent to a largely natural focal area.

Figure 7.3. Edge mapping overlap. The figure on the top shows the artifacts of tiling on the middle bottom tile. The bottom figure shows the same tile with the edge artifacts smoothed out.



Regional Flow Results and Patterns

The map of wall-to-wall regional flow applied to the anthropogenic resistance grid highlights areas of highest flow in dark blue, areas of moderate flow in medium blue, and areas of blocked or low flow in brown (Figures 7.4 & 7.5).

A particularly useful feature of the wall-to-wall results is that they reveal spatial patterns in current flow that reflect how the human-modified landscape is configured (Figure 7.6). The results allow you to identify where population movements and potential range shifts may become concentrated or where they are well dispersed, and it is possbile to quantify the importance of an area by measuring how much flow passes through it and how concentrated that flow is. The four prevalent flow types found here each suggest a different conservation strategy:

- Diffuse flow: areas that are extremely intact and consequently facilitate high levels of dispersed flow that spreads out to follow many different and alternative pathways. A conservation aim might be to keep these areas intact and prevent the flow from becoming concentrated. This might be achievable through land management or broad-scale conservation easements.
- Concentrated flow: areas where large quantities of flow are concentrated through a narrow area. Because of their importance in maintaining flow across a larger network, these pinch points are good candidates for land conservation.
- Constrained flow: areas of low flow that are neither concentrated nor fully blocked but instead move across the landscape in a weak reticulated network. These areas present large conservation challanges. In some cases restoring a riparian network might end up concentrating the flow and creating a linkage that will be easier to maintain over time.
- Blocked/Low flow: areas where little flow gets through and is consequently deflected around these features. Some of these might be important restoration areas where restoring native vegetation or altering road infrastructure might reestablish a historic connection.

Figure 7.4. Results of the wall-to-wall Circuitscape model applied to the anthropogenic resistance grid. Brown indicates areas with low permeability. Medium blue indicates areas of moderate flow; often highly natural settings were species movements are diffuse. Dark blue indicates areas of concentrated flow where movements will accumulate or be channeled.

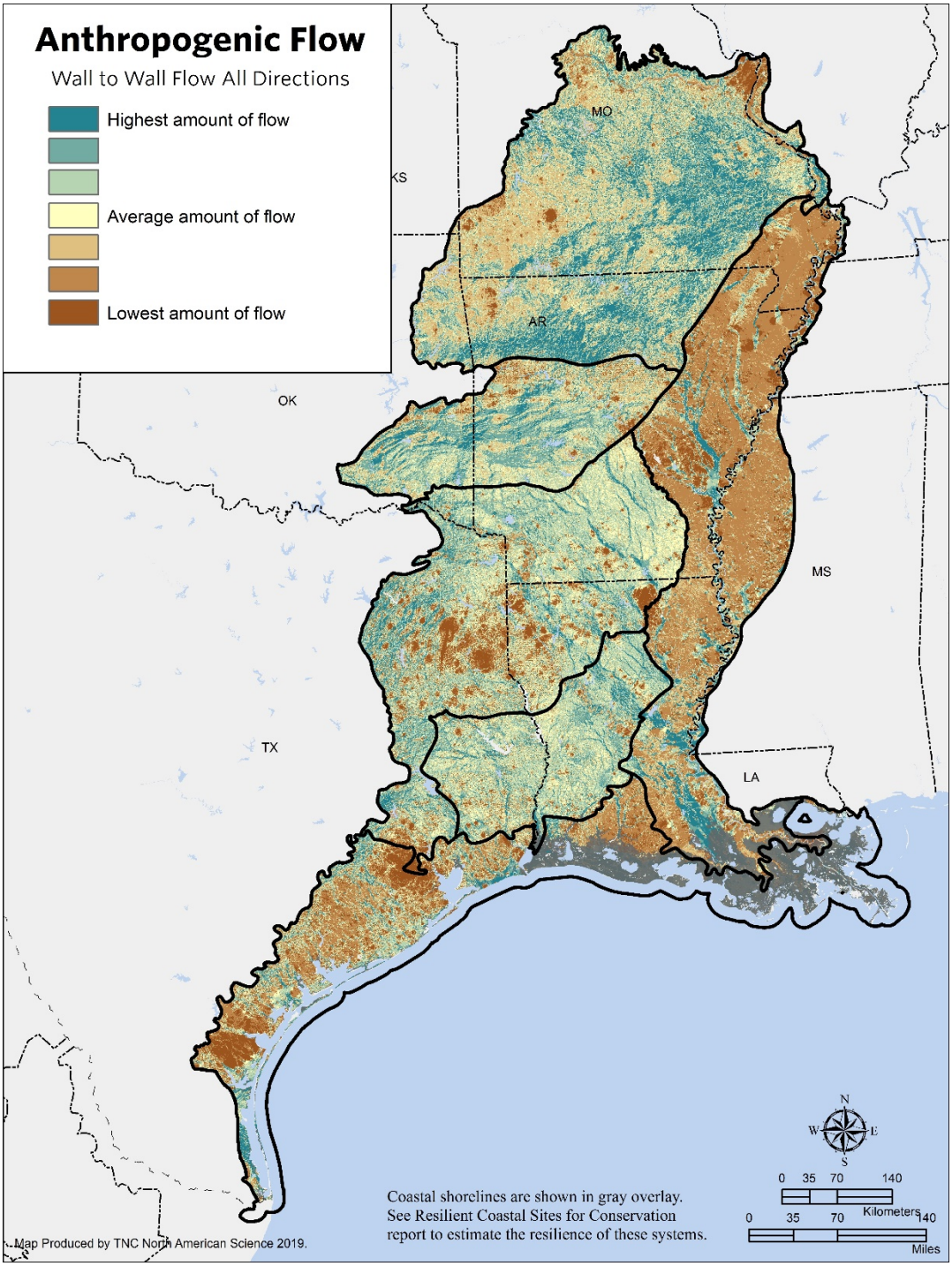


Figure 7.5. Regional Context around the wall-to-wall Circuitscape Results. The legend is the same as for Figure 7.4, but this shows the results for the surrounding area.

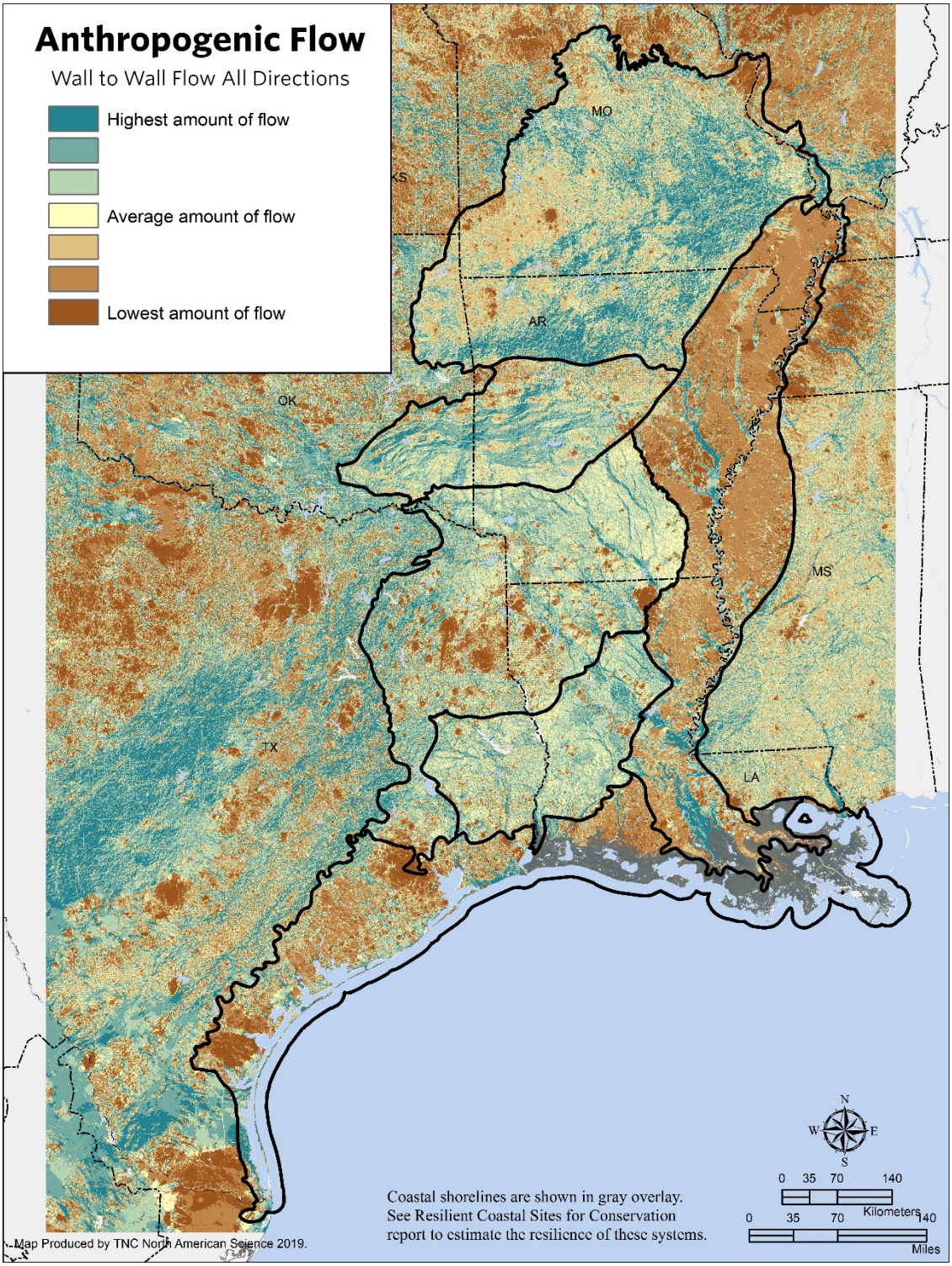
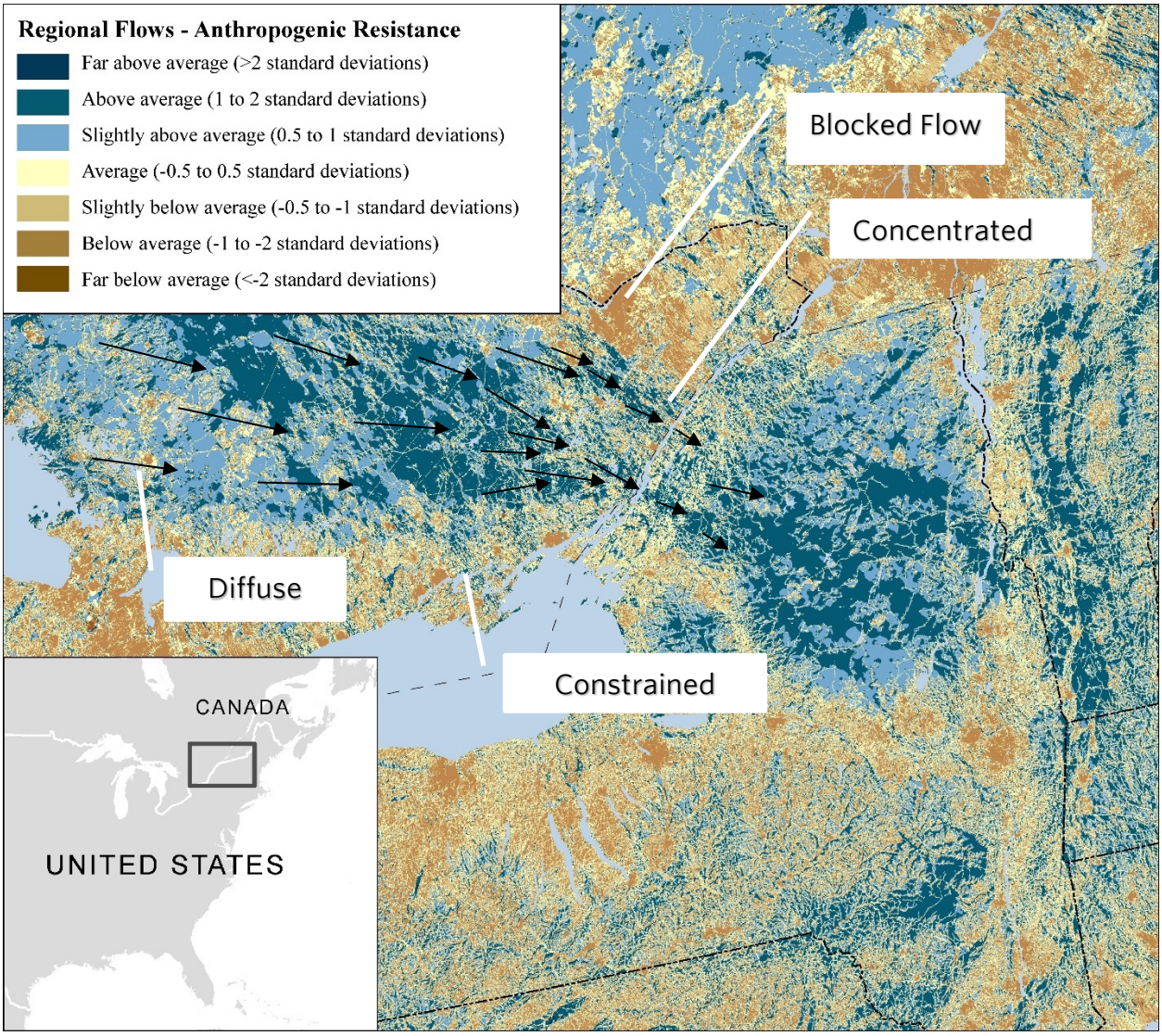


Figure 7.6. Flow types. This figure shows how the four flow types reflect the dynamics of a moving population over time. Location: St Lawrence Valley between the Algonquins and the Adirondaks.



To create a categorical classification of flow pattern, we applied the following method. First, we calculated the amount and the variation of flow in every local neighborhood (1000 acres) around every cell (The size of the neighborhood was determined by testing a variety of distances and picking the one that best captured flow pattern and still retained local detail). Next, within each neighborhood we calculated the mean amount of flow, and the variation in flow as indicated by the standard deviation. Areas that had high flow and a high standard deviation were considered "concentrated" because they not only channel a large amount of flow but are different from their surrounding cells. Areas that had above-average flow and low standard deviation were considered "diffuse" because they move a lot of flow but are similar to their neighboring cells. We divided the mean and standard deviation into 7 quantiles classes by area and analyzed the combinations to classify the wall-to-wall continuous grid (Figures 7.7 and 7.8).

Figure 7.7. Diagram illustrating catagorization from wall-to-wall map to catagorized results . Orange areas are concentrated flow that have high flow (high mean) and are different from their neighbors (high standard deviations). Blue areas are diffuse areas that have high flow (high mean) and are like their neighbors (low to medium standard deviations). Gray areas have average flow (average mean) and are different from their neighbors (high standard deviation). Areas not shown (lightest gray in the diagram or whit on the map have average or below average flow and are considered blocked flow.

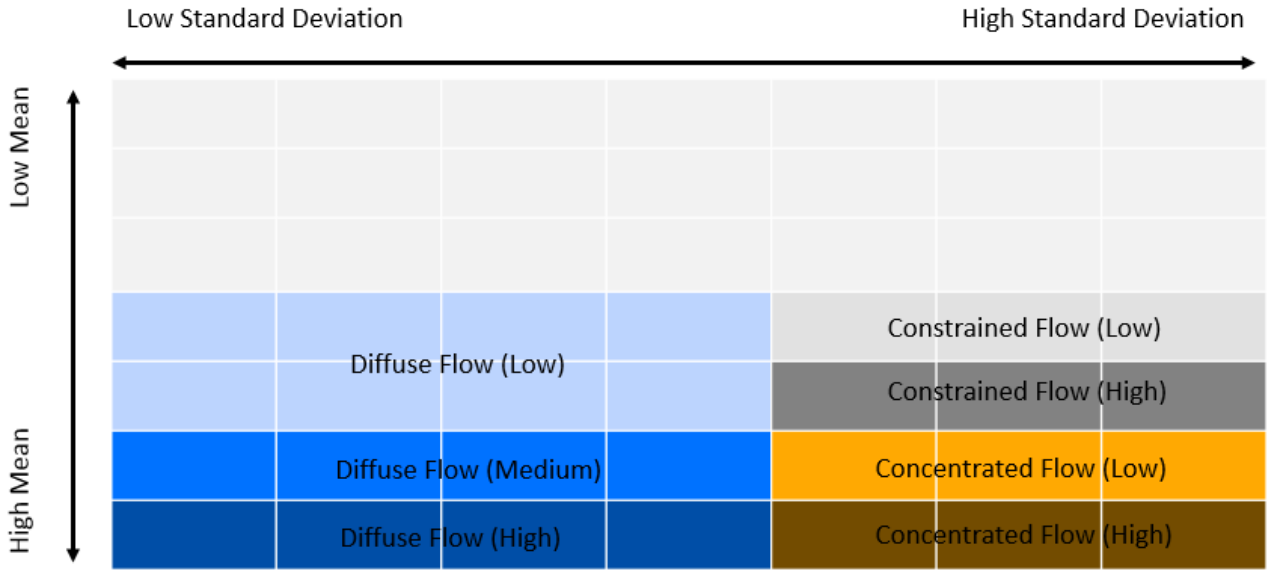
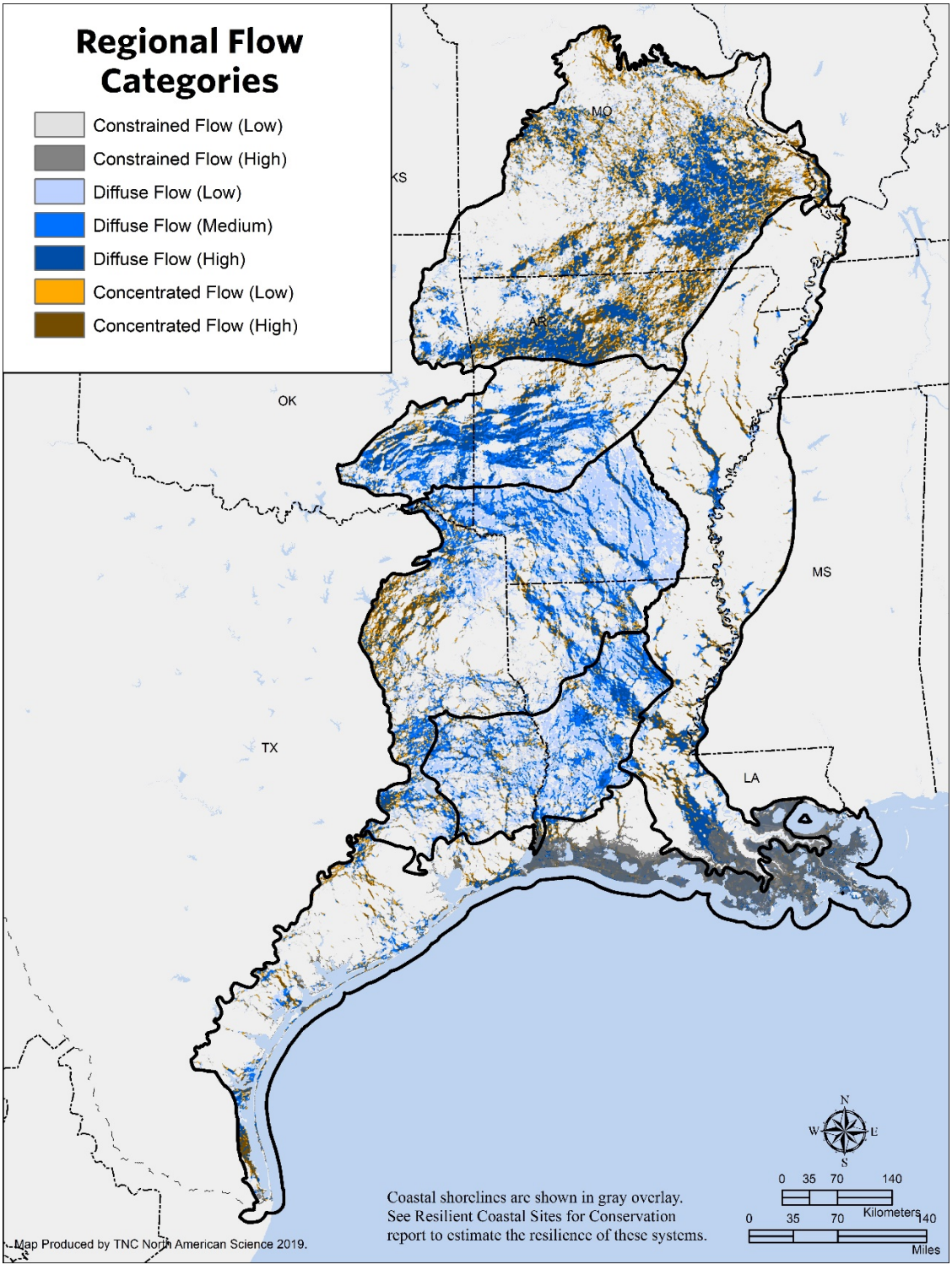


Figure 7.8. Categorized results of the wall-to-wall Circuitscape model applied to the anthropogenic resistance grid. Grey indicates areas with low permeability where movement is blocked. Green indicates areas of moderate flow; often highly natural settings where species movements are diffuse. Blue indicates areas of concentrated flow where movements will accumulate or be channeled through a pinch point.



Climate Flow

This section descriped how we modified the regional flow model to specifically highlight connections that provide climate relief. Paleoecological studies show that movement was a near universal response to past changes in climate (Pardi and Smith 2012), but not every directional movement provides equivalent climate relief. Although all parts of the landscape are important in allowing and maintaining population movements, current evidence suggest that areas that offer cooler temperatures or higher moisture are particularly critical in providing local relief from a warming climate. Our goal was to evaluate how these features are arranged on the landscape and whether access to them is limited or prevented by fragmentation, or conversely enhanced by the contours of the topography. We refer to the regional flow analysis informed by features with strong climatic gradients: **climate flow**. In the previous section we defined "regional flow" as the gradual movement of populations tracking a set of changing conditions over time, and here we define the term "climate flow" to refer to specific directional movements in response to temperature and moisture changes.

A variety of approaches to incorporating climate gradients into connectivity models have been developed. The most straightforward are models that directly connect temperature gradients based on global or national climate data (see McGuire et al. 2016). The climate gradient approach is logical and promising but is currently hindered for our purposes by the coarse scale of the temperature models (typically 1 km or larger). The issue is that these models don't contain the fine-scale topography and microclimate relief that create the local climate environments experienced by most species. Here, we explore climate gradients at a finer scale, and in lieu of fine-scale climate data, we tie the models directly to local landscape features and observed evidence.

In response to climate change, populations are already moving at impressive rates: 3.6 ft. upslope per year and 1.1 miles northward per year in US metrics (Chen et al. 2011, Table 7.1). A recent study of eastern trees using US Forest Inventory data found many common species have shifted significantly in range just over the last 30 years: Paper birch (16 miles northward), Black Oak (13 miles northward), Red Oak (10 miles northward). Evidence for contemporary range shifts in response to climate has now been documented for over 1000 species, and can provide insight into the structure and direction of these movements. In response to temperature, the evidence for upslope and northward movements is strong and consistent across many taxa groups and across several continents. In response to moisture and precipitation changes there is rapildy growing evidence for the important role of downslope basins and riparian areas, as well as for eastward movements in some parts of the US. We summarized this evidence at the start of this chapter, and following the findings in the research

litererature we focused our attention on four well documented responses of species movment to climate change:

Directional

1) **Upslope** toward higher elevations,
2) **Downslope** toward moist basins or riparian areas
3) **Northward** toward cooler latitudes,

Non-directional

4) **Locally** toward suitable microclimates.

In this section, we model the movement patterns expected from these responses and integrate them into the regional flow map. As with the regional flow map, we incorporate the arrangement and resistance of fragmentation and other human modifications into each model to explore the implications of such modifications on directional movements driven by climate change.

We integrate the directional factors into the flow map as a boost, and not as a fixed determinate of movement. Although the evidence shows that these factors are correlated with population expansions and range shifts, it is also clear that a variety of ecological factors may create variation in a species response to climate such as competitive release, habitat modification, or changes in amounts and patterns of precipitation, snow cover duration, water balance, or seasonality (Groffman et al. 2012). Our decision to give weight to these factors but not to override the other drivers acknowledges that many things might cause a range shift to differ substantially from straightforward poleward or upslope movement largely driven by temperature or moisture (Garcia et al. 2014) .

The wall-to-wall Circuitscape approach is well suited to exploring and mapping climate flow because it assumes that every cell in the region is a starting point for some species and the directional movement along elevation gradients could be conceived in terms of resistance, or latitudinal movement as source-ground flow. In the following sections we first look at 1) upslope movement primarily driven by temperature change, and 2) downslope movement primarily driven by moisture changes and 3) northward movement driven by regional temperature gradients. Finally, we integrate these factors into the regional flow model to create a map of climate flow.

Upslope Model: Local Temperature Relief

Chen et al (2001) detected upslope elevational range shifts for plants, herptiles, mammals, and invertebrates with magnitudes ranging from 6.1 m to 11.0 m per decade. Upslope movement by birds has not been consistently detected, although Tingley et al. (2012) found significant upslope shifts in communities of birds. For immediate climate relief, moving upslope is more efficient than moving latitudinally in temperate regions because there is roughly a -1.7^0 C (-3^0 F) temperature change for every 1,000′ increase in elevation. That is equivalent to a 483 km (300-mile) change northward in latitude. Upslope movement has limitations as a long-term strategy because the extent of available habitat may be restricted or the habitat itself may be unsuitable for some species because it is dryer, more exposed or may have thinner soil. Still, the evidence for upslope movement seems overwhelming (Lenoir et al. 2010).

To model upslope movement we created a 30-m continuous landform model based on each cell's relative land position and slope (Anderson 1999, Anderson et al. 2012). We converted this to a resistance grid by first isolating the relative land position value and assigning increased resistance to moving downslope and decreased resistance to moving upslope. Next, we modified the resistance score using the cell's slope value, to reflect the relative degree of effort versus gain in temperature differences (Figure 7.9, Table 7.2). For example, moving upward along a gentle slope is easy but provides little gain in temperature differences (moderate resistance), moving upward along a moderate slope provides larger gains in temperature differences for moderate effort (low resistance), moving upward along a steep slope is too difficult for most species despite the temperature gains (high resistance, Figures 3.9 and 3.10). Finally, the resistance on cooler aspects was reduced slightly with respect to warmer aspects (Table 7.2). We combined the land position and slope values into one resistance score.

Although mountainous areas may produce the largest amount of pure elevation change, species also experience temperature relief from slopes relative to their local landscape (e.g. a 10-m slope in a flat landscape may provide more relief to nearby species than a 10-m slope in an already mountainous landscape). To ensure that the model was upslope resistance grid was scaled to both local relief and larger regional relief we calculated both a regional resistance score and a local neighborhood resistance score around each cell and then integrated them. For regional relief we calculated the absolute amount of upslope resistance in a 3 km focal area around each cell and converted it to a Z-score using the mean and standard deviation for the whole region. For local relief, we used the same focal statistic algorithm to calculate the mean and standard deviations of upslope resistance for a 3 km radius around each cell and converted the flow to a Z score using only these local means and deviations. The regional and neighborhood resistance Z scores were combined by adding the two grids. We were aiming to give them equal weight, highlighting areas of both absolute upslope

flow and neighborhood upslope flow, but the distributions of the two datasets were very different such that the local neighborhood resistance score overwhelmed the regional score. To correct for this, we gave twice the weight to the regional resistance grid. The results provide a single upslope resistance grid that was a weighted combination of regional and local resistance (Figure 7.10).

Table 7.2. Resistance scores applied to the landform model. Land position ranks (LP rank) were ordered so they decrease towards higher land positions. Slope (S-rank) were ordered so that they increase at the extremes of no slope (no temperature gain) and steep slopes (too difficult to transverse) and are lowest at moderate values.

Landform	code	Slope	Position	LP rank	S rank	Sum	Weight
Steep slope	3, 4	4 High	any	NA	9	18	9
Cliff	5, 6	5 Highest	any	NA	10	20	10
Flat summit	11	1flat	highest	1	7	8	4
Slope crest	13	3mod	highest	1	1	2	1
Hilltop flat	21	1flat	high	4	7	11	5.5
Gentle slope	22	2gentle	high	4	4	8	4
NE sideslope	23	3mod	high	4	1	5	2
SW sideslope	24	3mod	high	4	1	5	2.5
Dry flat	30	1flat	low	7	7	14	7
Wet flat	31	1flat	low	7	7	14	7
Lower side	33	3mod	low	7	1	8	4
Slopebottom flat	41	1flat	lowest	10	7	17	8.5
Slopebottom	42	2gentle	lowest	10	4	14	7
N-cove	43	3 mod	lowest	10	1	11	5
S-cove	44	3 mod	lowest	10	1	11	5.5

Figure 7.9. Conceptual model: How a species population (black arrows) might move upslope and northward over five generations.

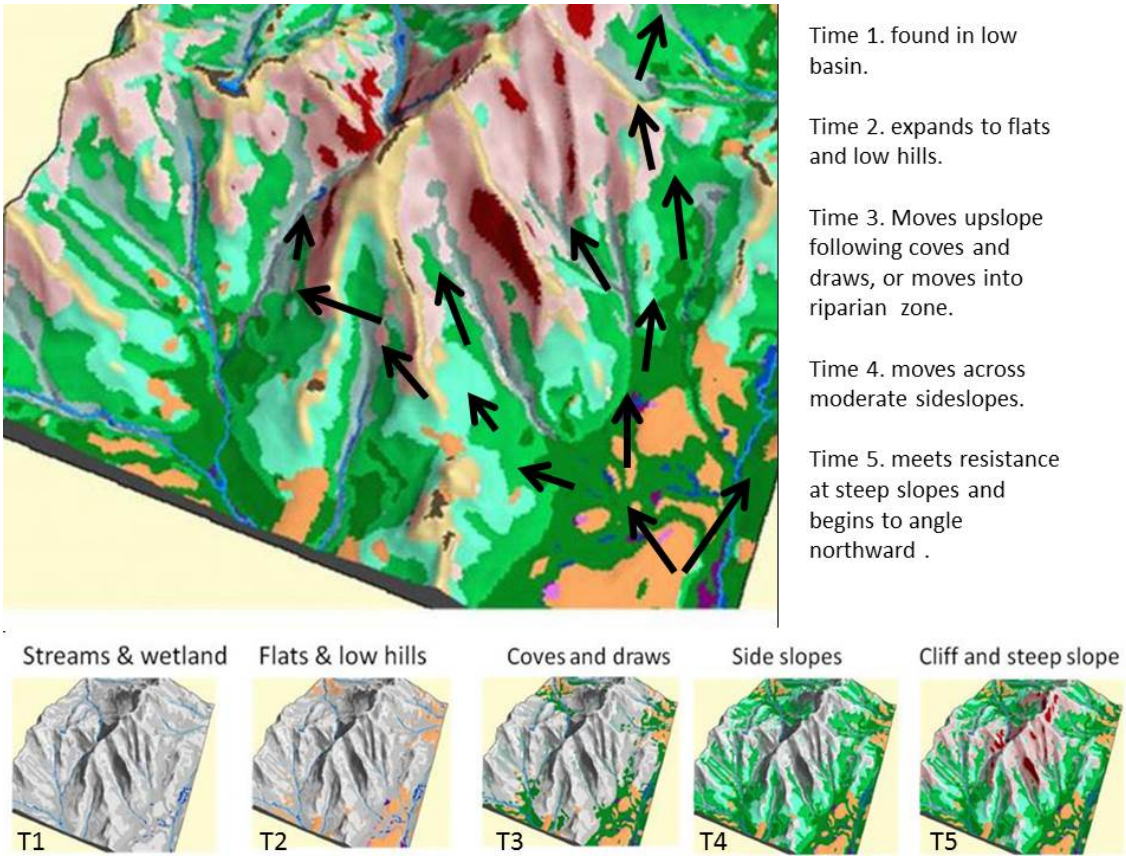
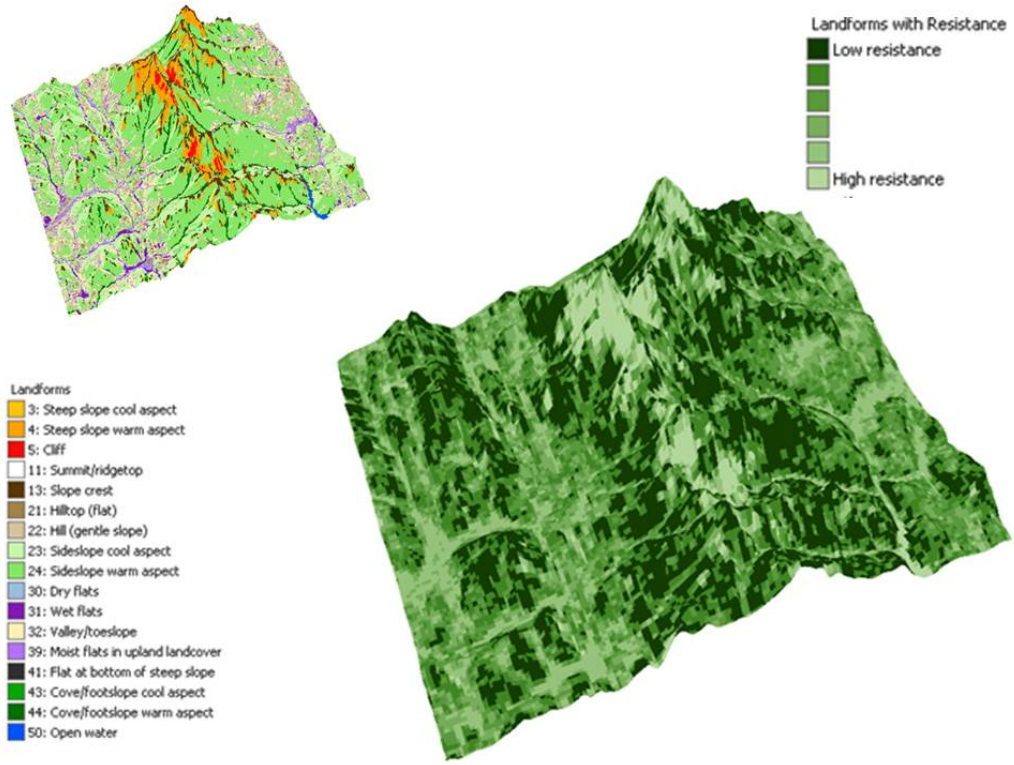


Figure 7.10. The resistance scores applied to the landform model. This picture shows a three-dimensional model of Mt Mansfield in Vermont. The left image shows the landform model. The second image shows the resistances where low resistance corresponds to areas with the most temperature gain for the least effort (moderately steep sideslopes). Flat valley bottom and steep slopes have higher resistance.



To incorporate anthropogenic resistance, we combined the upslope resistance grid with the anthropogenic resistance grid weighting the scores so that the final resistance score of each cell was 50% from the upslope resistance value and 50% from the anthropogenic resistance value. In Circuitscape, we ran current through the combined upslope/anthropogenic resistance grid in all directions (as described previously for the regional flow model) to create an output of upslope current flow incorporating anthropogenic resistance (Figure 7.11).

The upslope model highlights areas with high potential for upslope range shifts are arranged locally and across the region (Figures 7.11). The realistic effect of the local scaling is to create a much more distributed picture of where upslope movements may be available to species for local climate relief (Figure 7.12). This takes the emphasis off the mountains and highlights a wide range of moderate slopes that might play a large role in providing local climate relief (Figure 7.13).

Figure 7.11: The Upslope model applied to the study area.

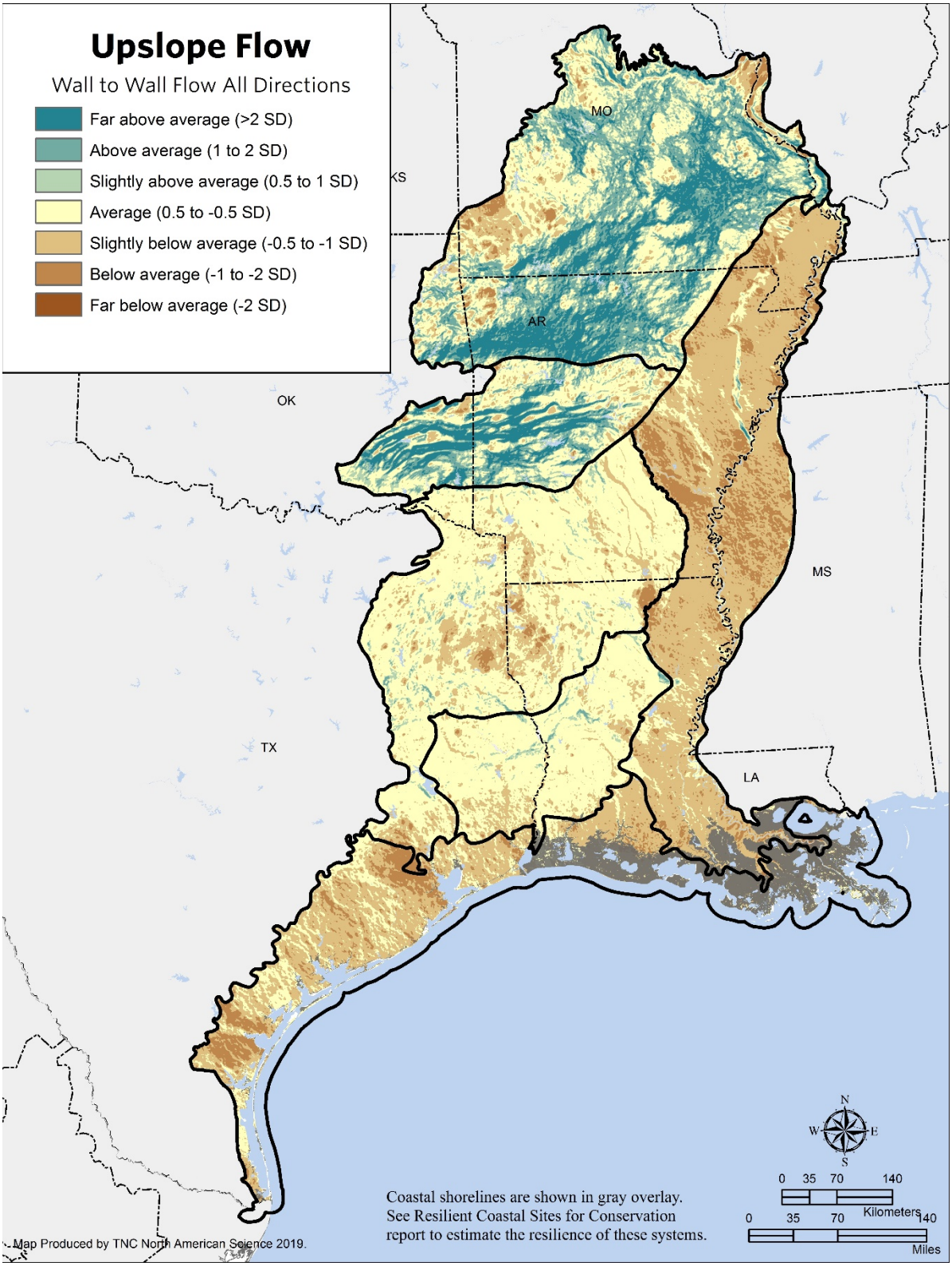


Figure 7.12: Zoom in of upslope model in Ozark Mountain ecoregion. The map shows flow going upslope into the topographically diverse eastern end of the Ozark Mountains on the left side of the map. There is low upslope flow on the right side of the map in the flat agricultural area of the Mississippi River Alluvial Plain.

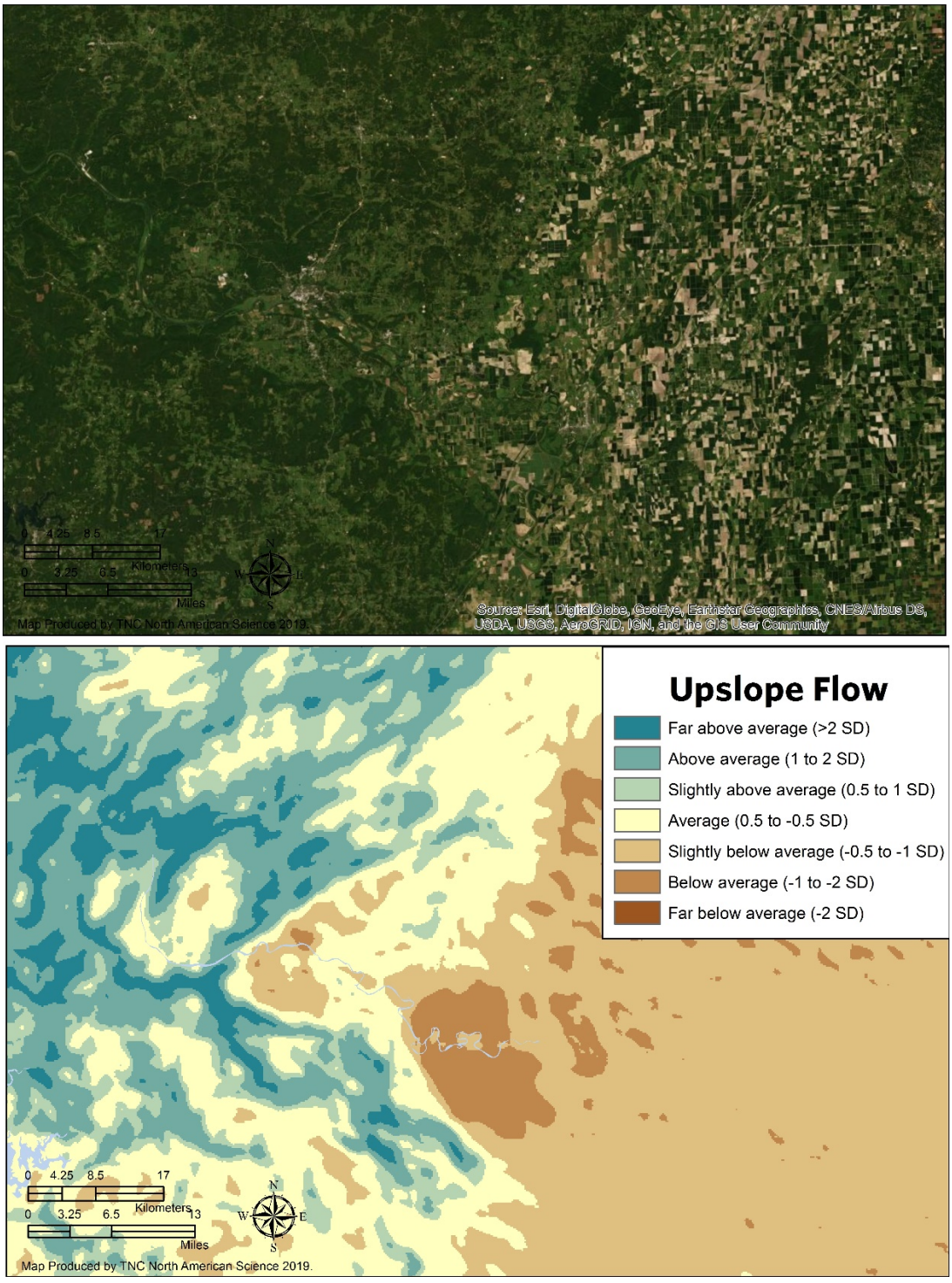
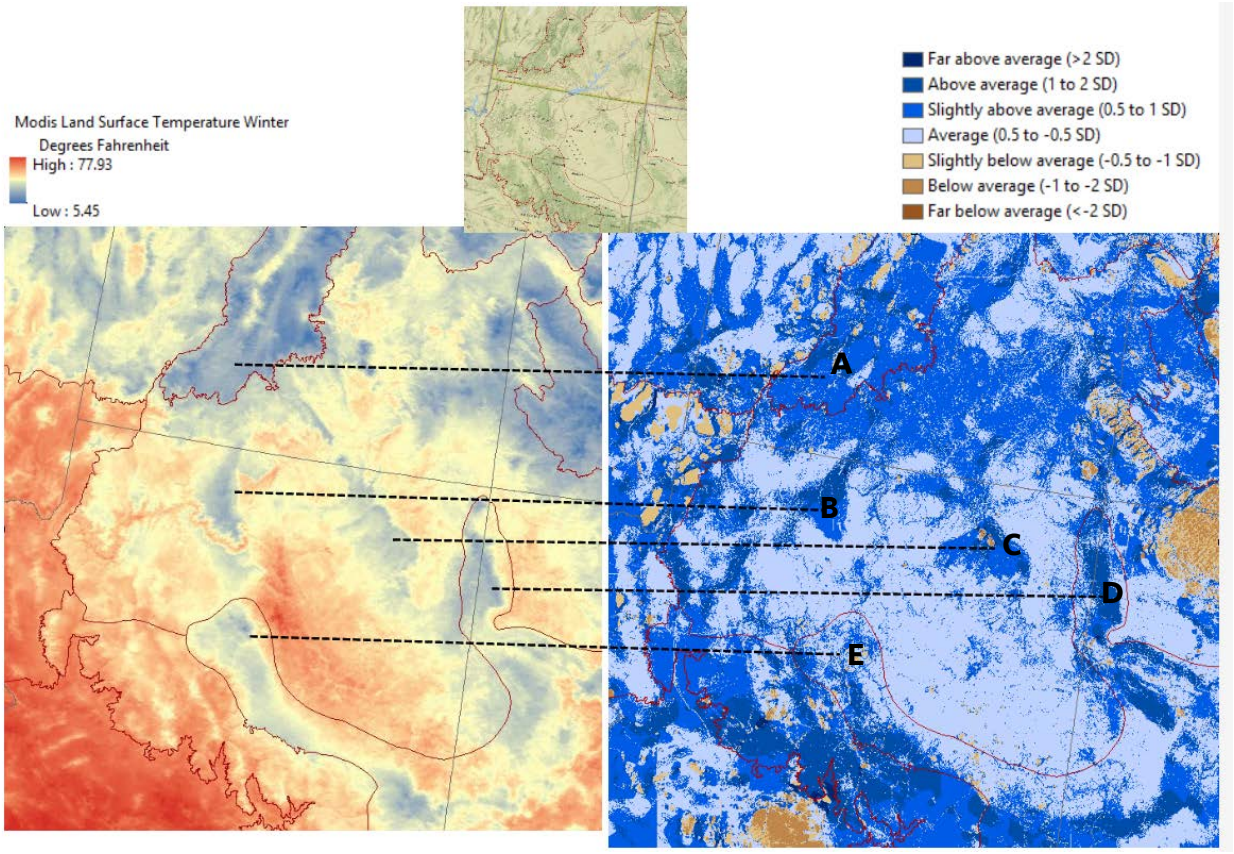


Figure 7.13. Comparison of upslope model with land surface temperature (LST) model for the Sandhills Region. This figure shows the correspondence between the topography and surface temperature in fall. The LST model is MODIS (MOD11A2.006) Terra Land Surface Temperature and Emissivity Winter mean at a 1km scale for September 2018. Although the scale of the LST model is coarse, local cool spots can be seen to correspond with the topography and the upslope model especially in: A) Sevier Plateau; B) Kaibab Plateau north of the Grand Canyon; C) Black Mesa; D) Ohuska Mountains; E) San Francisco Plateau and Peaks



Downslope Model: Access to Local Moisture

Introduction and Background

A recent study of eastern trees found changes in moisture availability had significantly stronger near-term impacts on vegetation dynamics than changes in temperature (Fei et al. 2018). Downslope areas collect water and feature microclimates that may be significantly moisture and cooler the surrounding landscape (Olsen et al. 2007).

As the climate becomes warmer and drier, species are expected to move downslope into cooler and moisture regions, and this pattern has been well documented (Archaux 2004, Popy et al. 2010). A survey of such range shift studies suggests that while roughly 65% of species have shifted their ranges upslope, 25% have shifted their ranges downslope, (Lenoir et al. 2010). Similarly, a global review of the literature suggests that about 20% of species have adjusted their ranges towards lower elevations (Parmesan & Yohe 2003). Long-term downhill shifts in the optimal elevations of plant species has been shown for California, apparently in response to decreased climatic water deficit (Crimmins et al. 2011). Our own spatially explicit climate resilience analysis (Anderson et al. 2013) which was based on microclimates and connectedness, identified many slope bases and riparian areas as critical parts of the landscape due to the presence of many microclimates.

Riparian areas, near where water collects, are usually a minor proportion of any landscape but they serve and outsize role in facilitating adaptations. Typically, they are structurally diverse and more productive than adjacent upland areas and have the unique characteristic of connecting many parts of the landscape. They serve as migration routes and connectors between habitats for a variety of wildlife, particularly within highly modified landscapes (Hilty & Merenlender 2004). In addition to their connectivity functions, riparian areas are important in mitigating nonpoint source pollution, removing excess nutrients and sediment from surface runoff and ground water. Riparian vegetation modifies the temperature conditions for aquatic plants and animals, stabilizes streambanks, mitigates flooding, and contributes to the health of adjacent freshwater habitats (Pusey & Arthington 2003).

In a previous study (Anderson et al 2013) we identified distinct riparian climate corridors (RCC) for the Eastern US and measuring a variety of characteristics about each RCC unit such as its size, length, intactness, temperature change. That work was inspired by Krosby et al. (2014) analysis for the Pacific Northwest where they identified potential riparian areas that spanned large temperature gradients, had high levels of canopy cover, were relatively wide, had low solar insolation, and low levels of human modification – characteristics expected to enhance their ability to facilitate climate-driven range shifts and provide microclimatic refugia from warming.

Here, we present a new approach that measures the potential contributions of downslope movement continuously across the whole landscape, rather than identifying individual corridors and summarizing their attributes. As with upslope movement, we evaluated where downslope movements were likely to concentrate or where they facilitate high current flow. This new approach emphasizes downslope and riparian areas as collectors of climate-driven movement from the surrounding landscape. It decreases the emphasis on directional movement within the riparian areas, although many of the resulting corridors traverse and connect large parts of the landscape and may facilitate movement for many species. We hypothesized that species could experience additional moisture, deeper soils, and local temperature relief by moving into these relatively lower areas.

Mapping Downslope Movement

To model downslope movement, we first identified areas that were down-gradient and lower in elevation than the surrounding landscape. We did this by creating a continuous 30-m dataset that assigned a relative elevation value to every cell by comparing its elevation to its neighbors within a 3 km neighborhood (the same radius used calculate upslope local flow and to calculate local connectedness in the resilience analysis). We used a focal statistic to calculate the mean and standard deviations of the elevations within a 3 km radius, and then calculated a Z-score for each cell based on the neighborhood mean and standard deviation. Values below the mean were lower than their neighborhood and values higher than the mean were higher in elevation than their neighborhood, and these values became the resistance values.

We used the Z-Scored relative elevation surface as a resistance grid in Circuitscape to force current to flow more easily into and throughout the downslope areas as they had less resistance. To give additional benefit to flow in moist areas, we integrated the landform model (described earlier in this section) into the resistance grid and further lowered the Z score within moister landforms. Areas of coves, pluvial moist flats, and wet flats were extracted from the landform dataset and their Z-Score was lowered. Coves were lowered to one quarter -0.25 standard deviations below average, pluvial landforms were lowered to one half -0.5 standard deviations below average , and wetlands were lowered to -1.0 standard deviations below average if the elevation-based Z score was not already less than theses scores. This lessened the resistance slightly in moist and wet areas allowing current to flow more easily. This moisture enhanced Z-scored resistance surface was used as the downslope resistance grid in further Circuitscape flow modeling.

We tested the model in Circuitscape by running current through it in all directions (as described for the regional flow model) to create an output of “current” flow based on the downslope and moisture-enhanced resistance surface. The output tracked

downslope moisture patterns at a fine scale, but at this point did not account for any anthropogenic modifications of the landscape.

To create an integrated final downslope model that included human uses, we combined the downslope, moisture-enhanced resistance grid with the anthropogenic resistance grid to create a resistance surface that favored moving downslope but was sensitive to anthropogenic barriers. This was achieved with a 50/50 weighting of downslope resistance and anthropogenic resistance.

The Circuitscape analysis on the resultant resistance grid shows how the areas with high potential for downslope and moist range shifts are arranged locally and across the region, and how they intersect with anthropogenic resistance (Figures 7.14 -7.15).

The downslope model has very high flow accumulations in the valleys and streambeds, but we wanted to limit the extreme values in order to highlight areas leading to these valleys and streambeds. To accomplish this, when Z-scoring the raw flow values we capped the z-score at 1.5 SD.

Figure 7.14. Downslope model. This map shows the results of the moisture-enhanced downslope model with anthropogenic resistance weighted at 50% and downslope flow weighted at 50%.

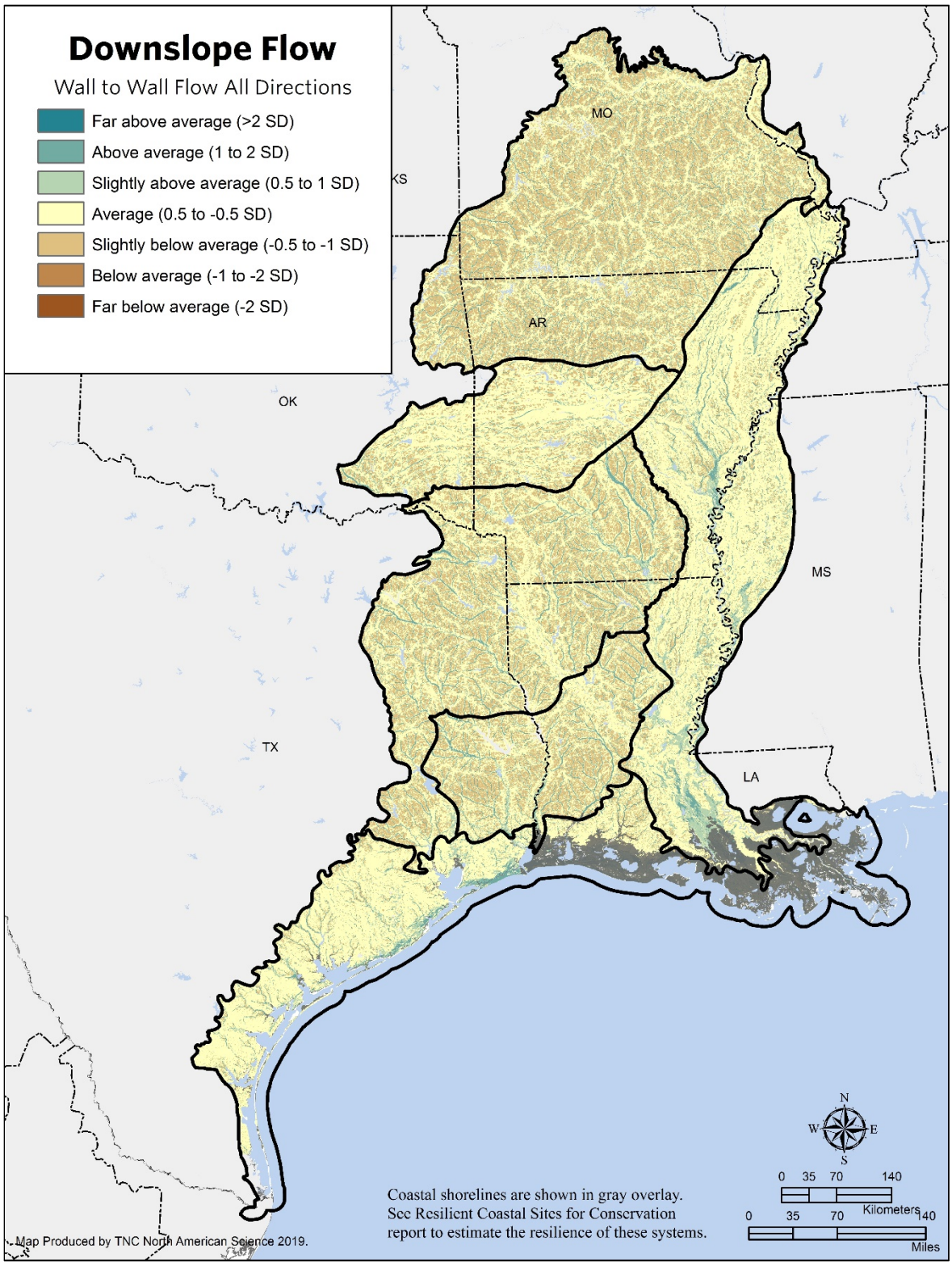
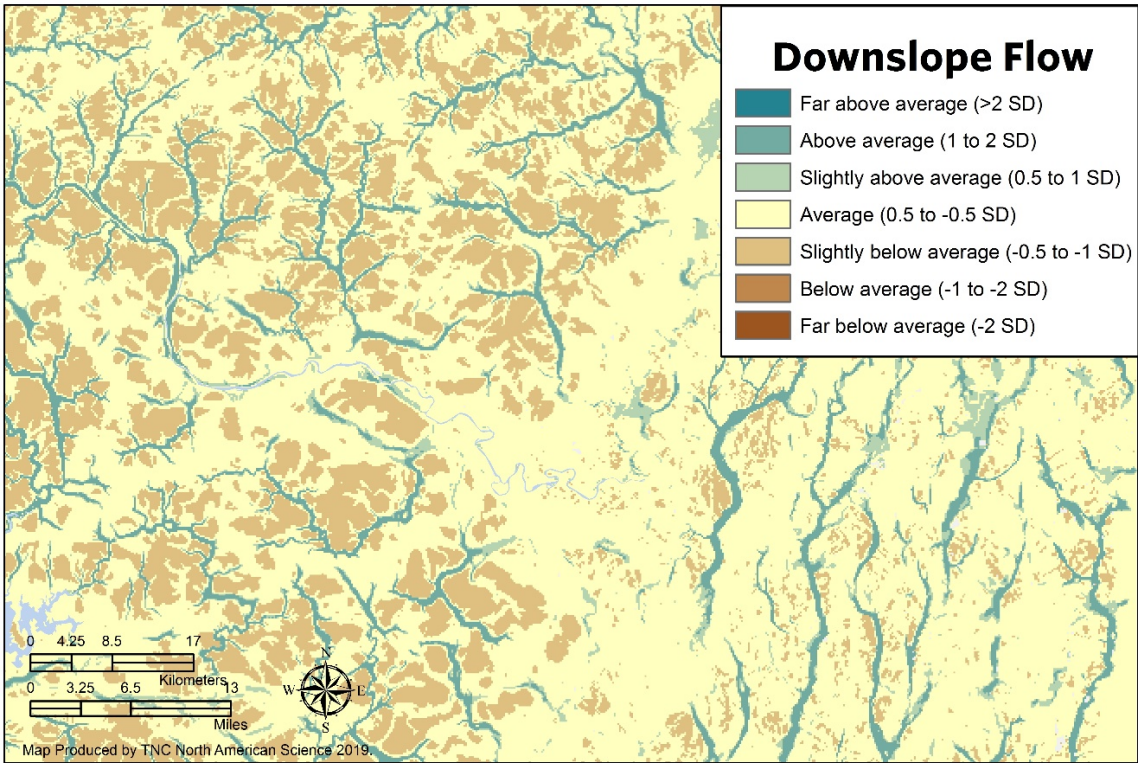


Figure 7.15. Zoom in of the Downslope Model. This map shows a zoom in of the same area as 7.12. Downslope flow clearly tracks valley slopes and bottoms in the Ozark Mountains on the right side of the aerial photo/map. On the left, in the flat Mississippi River Alluvial Plain, downslope flow concentrates along riparian corridors.





Northward Model: Regional Temperature Relief

Northward movements in response to climate change have been documented for over 800 species across five taxa groups, and they appear to be ubiquitous across the northern hemisphere. Studies have found latitudinal range shifts to range from 6.1 km to 16.9 km northward per decade (Chen et al 2011) with extremes of 21-64 km for some Oaks (Fei et al 2018). It is likely that latitudinal expansions will be the predominant long-term strategy of most species in response to climate change, and this is largely concordant with the evidence of historic range shifts in response to previous periods of rapid climatic change. Despite fears and reports that many species will lag behind, Chen et al. (2011) found that nearly as many studies of observed latitudinal changes fell above as below the expected rate suggesting that mean latitudinal shifts are not consistently lagging behind the climate.

We added latitudinal direction into the climate flow model to simulate long-term climate relief for populations that expand or shift northward. We did this by modifying the four directional runs we used to develop the regional flow model (i.e., north to south, south to north, east to west, and west to east, see previous section for details) to emphasize the northward flows. We did this by combining the four individual runs so the north-south runs contributed 66% of the flow value and east-west runs contributed 33 % of the flow value (Figures 7.16 & 7.17).

Figure 7.16: Northward model for study area. This map shows regional flow model with north-south movements weighted 66% and east-west movements weighted 33%.

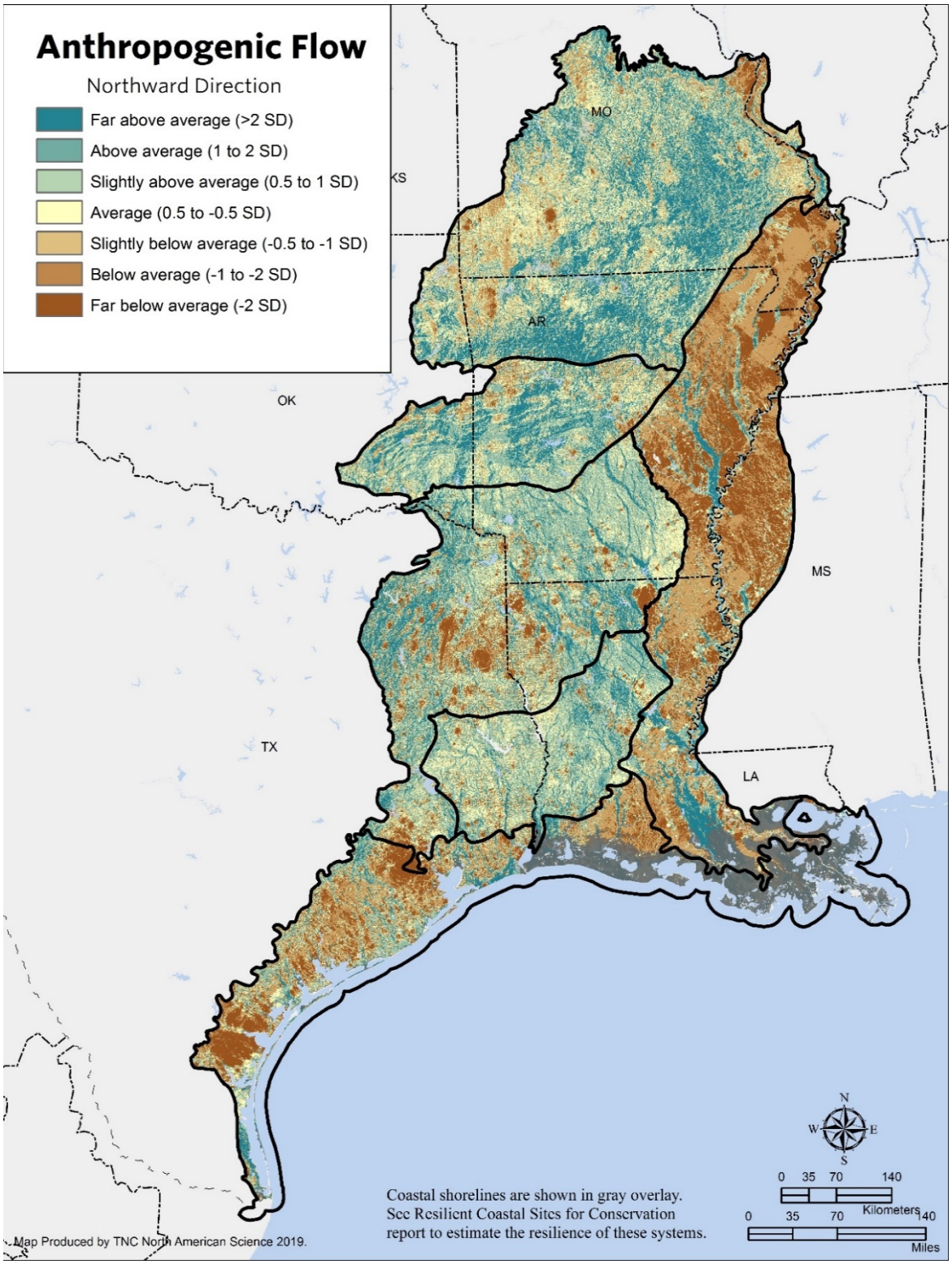
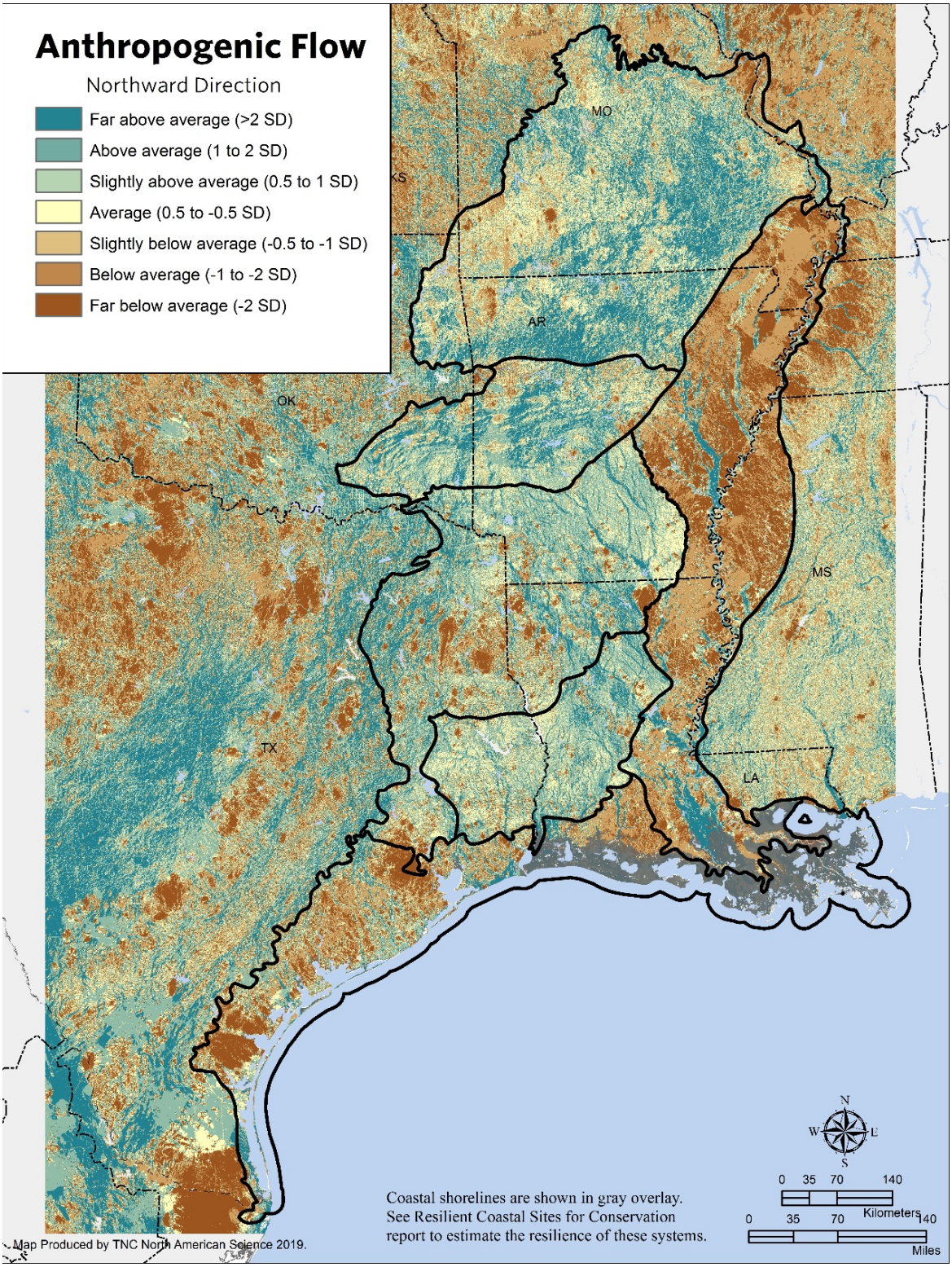


Figure 7.17: Northward model for region. This map shows regional flow model with north-south movements weighted 66% and east-west movements weighted 33%.



Final Climate Flow Model: Integration of Slope and Latitude

For our final model, we weighted the regional flow model with the upslope, downslope and northward models to simulate species populations could flow through the natural landscape finding climate refuge both by moving up or down slopes and mostly in a northward direction. The goal was to approximate a species population expanding locally then northward as allowed by the anthropogenic resistance within its neighborhood.

When combining the factors, a challenge was how to weight the influence of each factor in a way that most closely approximates the real world. We wanted to keep the emphasis on the areas that are important for regional flow, while boosting slightly the areas that channel slope-based and northward movements. We accomplished this by using the northward regional flow map as our based dataset and boosted the score of cells if they were important for upslope or downslope movement. For each of the two factors we took the areas that were above-average with respect to their factor.
We overlaid each factor on the regional flow map and replaced the cell score if the cell score for the factor was higher. For example, a cell score of 1.2 for Upslope would replace a Northward Regional Flow score of 1.0, giving a slight bump-up to the cell reflecting its slope. If both factors had scores higher than the northward regional flow score, we replaced the latter with the highest score. This had the effect of raising the scores in areas with above-average current flow for upslope, downslope movement but still retaining the northward regional flow score, and thus not penalizing areas for not having slopes (Figures 7.18).

Classified Version of the Climate Flow Map

We created categorical classification of the climate flow patterns, using the similar method described previously for the regional flow. The amount of flow was calculated by looking at the mean flow within a 1000-acre circle of each cell (Figure 7.19 & Figure 7.20). We used the anthropogenic regional flow weighted towards northward movement (66%) as the base map and added in the areas of upslope and downslope flow wherever those areas had higher flow than the base flow. The outcome looks superficially like the regional flow map but has higher flow along gradients important for temperature and moisture relief. This allowed us to parse out more levels of diffuse and concentrated flow and identify key climate pathways.

Figure 7.18: Climate Flow model for study area. The results of a Circuitscape analysis applied to the regional flow grid and weighted for above-average upslope flow, downslope flow or northward flow

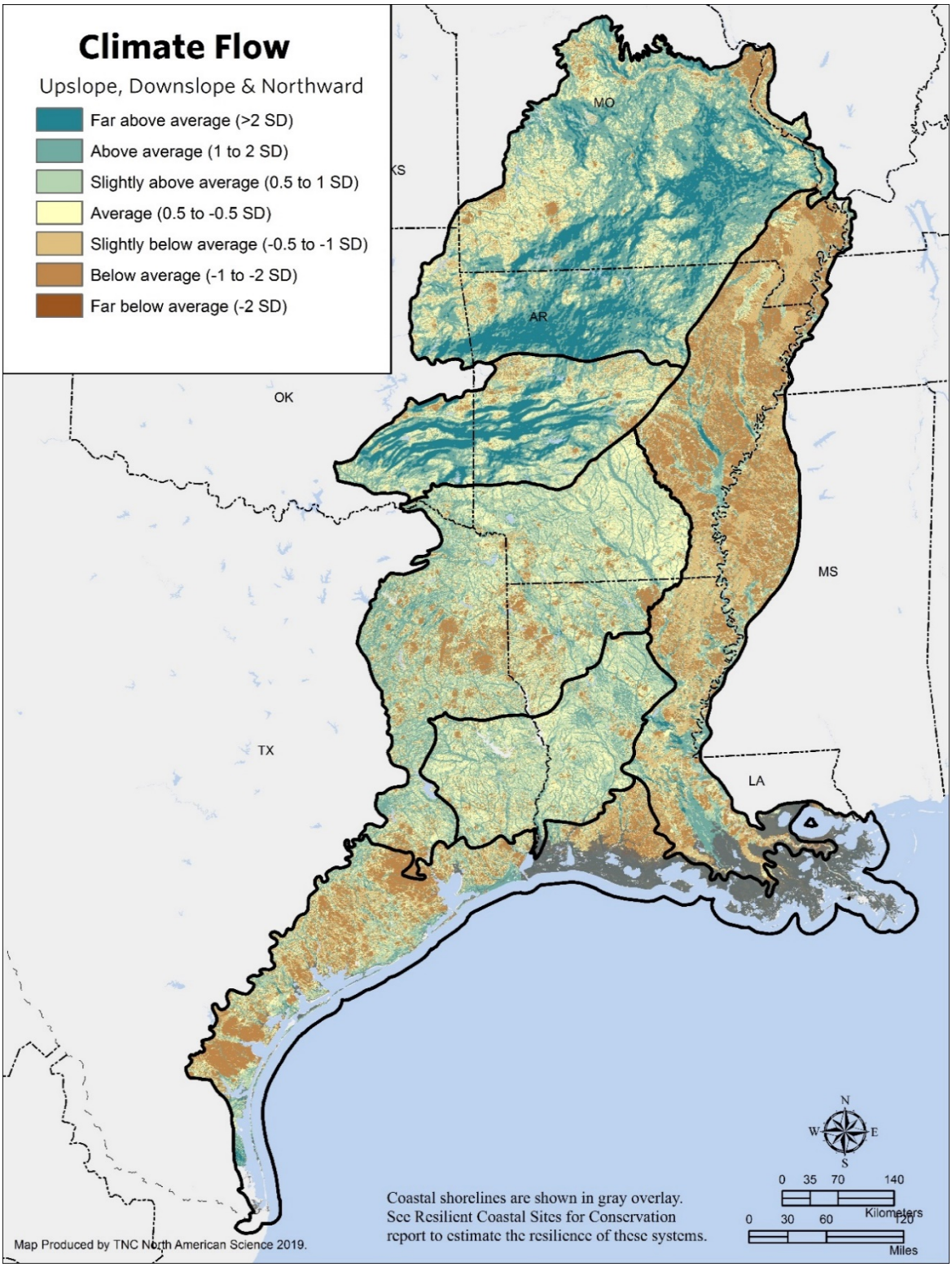


Figure 7.19: Comparision of flow results. These maps for the Canyonlands region of Utah compare the Circuitscape results for Regional Flow based on anthropogenic resistance only, with the enhanced versions that include upslope flow, downslope flow, northward flow and the integrated Climate Flow.

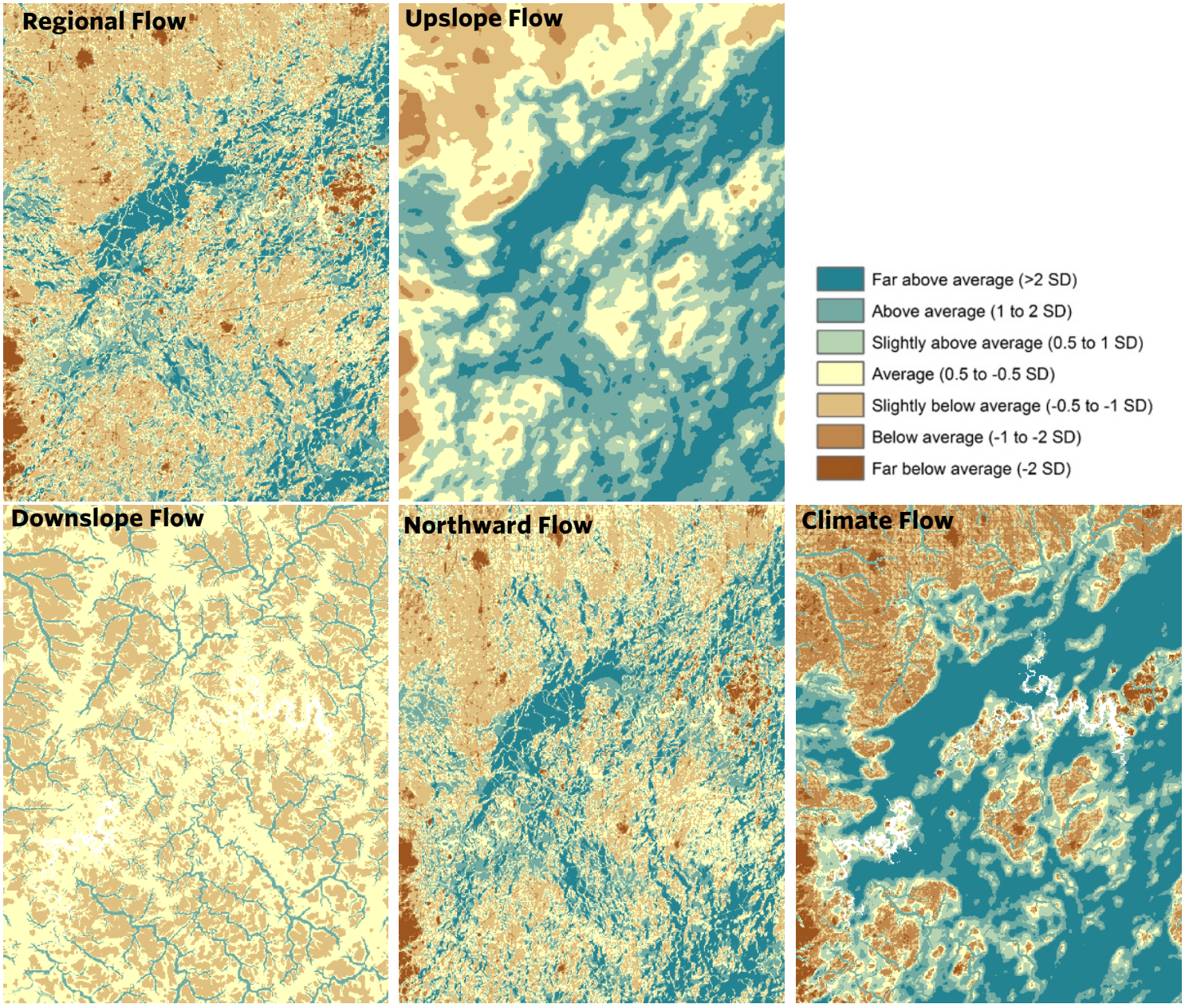
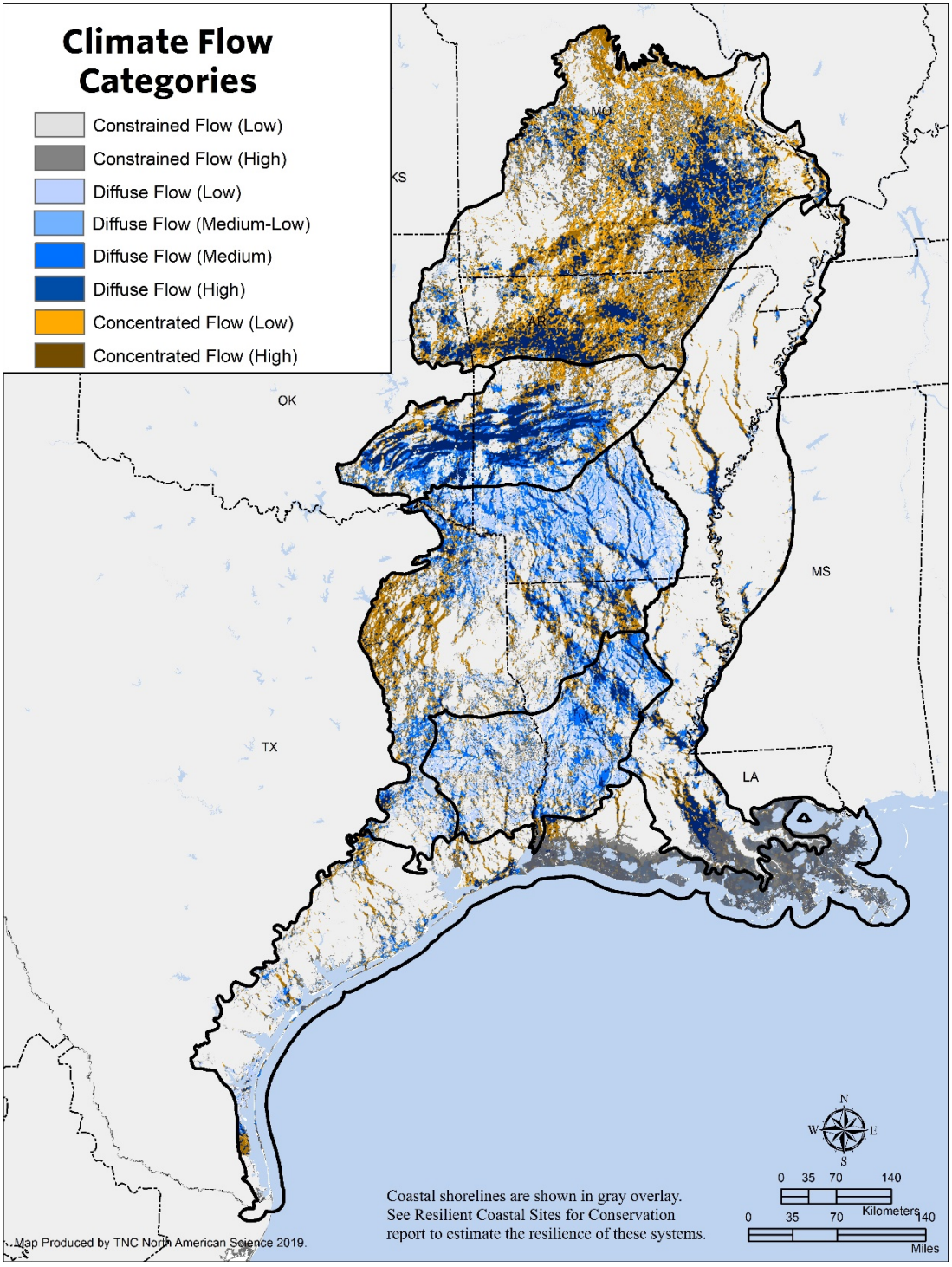


Figure 7.20: Classified Climate flow for Study Area. The results of classifying the climate flow map into 7 categories of flow density and spread.



Access to Local Microclimates

We introduced this section with evidence for contemporary range shifts, and we suggested that population movement responses to climate change could be grouped into four main patterns: upslope toward higher elevations, northward toward cooler latitudes, downslope toward moist riparian areas, and locally toward suitable microclimates. The former three have been discussed previously and represent larger scale responses. The latter is a very small-scale response where a population shifts slightly over time to take advantage of a moist spot or cool microclimate and thus persist at a site.

Local microclimates may be the primary mechanism for species persistence under a changing climate for most organisms. Species experience climate at extremely local scales and the available moisture and temperature in the near-ground "boundary layer" can differ greatly from the local average (Geiger et al. 2009). Thus, a topographically diverse landscape is experienced by its resident species as a heterogeneous mix of microclimates, many of which might be suitable for persistence even where the average background climate appears unsuitable. Landscape-based climatic variation can be substantial, on par with or greater than a 1.5°C warming.

The focus of this report has been on mapping larger scale, between-site responses to climate change, and because mapping the distribution of microclimates is the basis of the climate resilient site analysis (Anderson et al. 2018a&b), we do not address it further here. However, microclimates are an important part of how species respond to climate change. Further, areas of high microclimate diversity are an important part of the upcoming chapter "Resilient and Connected Landscapes" because they are integrated into the resilient sites which form the base of the connected networks.

CHAPTER
8

BIODIVERSITY

Confirmed Areas for Biological Diversity

The central idea of a conserving-the-stage approach to conservation is that rather than trying to protect biodiversity one species at a time, the key is to conserve the geophysical "stages" that create diversity in the first place at local and regional scales (Hunter et al. 1988, Beier & Brost 2010, Lawler et al. 2014). Species ranges are not fixed, and the world has always experienced some measure of climate change. Thus, protecting the full spectrum of physical environments that provide habitat for distinct sets of species offers a way to conserve diversity under both current and future climates (Anderson & Ferree 2010). Toward that end, we performed a separate analysis of resilient sites (Chapters 1-5) and identified resilient examples of each distinct geophysical setting but we did not consider the habitats, communities or species populations present at each location. Here we now integrate information on the biota with the physically based resilience map.

To identify a network of sites that could likely sustain biological diversity into the future, we wanted the network to be composed of climate resilience sites that contained the maximum amount of current biodiversity. Thus, in this section, we prioritized sites that scored high for resilience and contained viable rare species populations, exemplary natural communities, or served as critical migratory stopover. To identify areas of high biodiversity value we compiled the results of two sets of intensive, multi-year studies on the locations of exemplary habitats and rare species populations: TNC's Ecoregional Plans, and Conservation Opportunity Area maps or related map products developed as part of State Wildlife Action Plans (SWAPs).

The Nature Conservancy's Ecoregional Portfolios

From 1998 to 2006, The Nature Conservancy implemented a series of biodiversity assessments across each of the United States' 81 terrestrial ecoregions. The goal of each assessment was to identify a portfolio of sites that, if conserved, would collectively protect multiple viable examples of a set of focal conservation targets - species and communities characteristic of, or unique to, each ecoregion. Although the assessments were performed independently by ecoregion, the data are relatively consistent because the teams followed a similar methodology and applied a standard

set of criteria (Groves et al. 2000, Anderson et al. 1999). Viability criteria were based on the size, condition, and landscape context of each biodiversity element (EO), and the results were reviewed by local experts familiar with the species and communities of the ecoregion. The assessments were performed and evaluated by teams of scientists from both TNC and other NGOs or agencies. The final selection of sites was based on the viability of each target occurrence combined with a set of numeric distribution and representation goals set for each target. In most regions, "sites" were drawn around clusters of viable targets using roads, property boundaries, or some other delineating feature. In addition to describing the targets, assessment process, and final portfolios, the reports detail the extent to which the portfolio met the stated goals for each conservation target. In some cases, lack of data, low numbers of occurrences, or poor target viability were important constraints to identifying a robust portfolio. Published versions of each report were compiled for this study (Table 8.1) and we obtained the national "roll-up" version of the TNC ecoregional portfolios (TNC 2012). The ecoregional assessments are publicly available on TNC's Conservation Gateway along with many of the supporting datasets: http://www.conservationgateway.org/ConservationPlanning/SettingPriorities/EcoregionalReports/Pages/EastData.aspx

Table 8.1: Ecoregional Assessments compiled for this study.

TNC Ecoregional Assessments
The Nature Conservancy, Ozarks Ecoregional Assessment Team. 2003. Ozarks Ecoregional Conservation Assessment. Minneapolis, MN: The Nature Conservancy Midwestern Resource Office. USA.
The Nature Conservancy. 2003. Ouachita Mountains Ecoregional Assessment. Ouachita Ecoregional Assessment Team. The Nature Conservancy, Little Rock, AR. Tulsa, OK. USA.
The Nature Conservancy. 2002. Upper West Gulf Coastal Plain Ecoregional Plan. Final Implementation Draft Prepared by Dave Gosse, Russell McDowell, Rob Evans and the UWGCP Technical and Planning Teams.
The Nature Conservancy. 2003. The West Gulf Coastal Plain Ecoregional Conservation Plan. Wesst Gulf Coastal Plain Ecoregional Planning Team, The Nature Conservancy, San Antonio, TX, USA.
The Nature Conservancy. 2002. The Gulf Coast Prairies and Marshes Ecoregional Conservation Plan. Gulf Coast Prairies and Marshes Ecoregional Planning Team, The Nature Conservancy, San Antonio, TX, USA.
The Nature Conservancy. 2002. Conservation Planning in the Mississippi River Alluvial Plain. The Nature Conservancy. Baton Rouge, LA, USA.

To identify areas of resilient confirmed biodiversity value, we selected the portion of each portfolio site that scored above-average for resilience. This amounted to 66% of the TNC portfolio with 18% scoring "average" and 15% "below-average.

In a previous study (Anderson et al 2018 c), we had tested whether the locations of biodiversity elements were concentrated in the resilient portion of the TNC portfolio sites. We overlaid the individual locations of species and communities in states where we had relatively comprehensive data on the locations of biodiversity element occurrences (EO). We found that 76% of the EO locations in the Great Lakes and Tallgrass Prairie ecoregions and 70% of the EO locations in the Great Plains ecoregions were located on the above-average resilience portion of the portfolio roll-up. Additionally, the pattern of the majority of EOs occurring on above-average resilience sites was consistent across taxonomic groups: 65-75% of animal, 81-86% of plant, and 73-76% of community EOs were on resilient sites depending on the ecoregion. This gave us confidence that identifying the resilient portion of each portfolio site did a reasonably good job of capturing biodiversity elements across the region, thus allowing us to incorporate resilient portfolio sites an indicator of known biodiversity.

State Wildlife Action Plans

We supplemented the TNC ecoregional portfolio data with datasets and priority maps developed by the states as part of their State Wildlife Action Plans (SWAPs). The SWAPs were created by each state's Fish and Wildlife agency (or equivalent), in collaboration with academic and agency scientists, conservation practitioners, private landowners, and other stakeholders, with the goal of providing resource assessments and blueprints for conserving the state's fish and wildlife. To be approved by the US Fish and Wildlife Service (USFWS), each plan had to address eight requirements laid out by the US Congress. USFWS approval is required for states to be eligible to receive funding through the State and Tribal Wildlife Grants program. First iterations of the plans were completed in 2005, and they were updated in or by 2015, with some pursuing additional revisions. To develop the plan, the assessment teams identify "Species of Greatest Conservation Need" (SGCN) and then assess habitats, risks, and actions needed. States vary in their approach for developing these lists –all include mammal, bird and fish species, and many also include insects and other invertebrates, and some include rare plants or habitats.

Many plans from our focal regions developed a map of "Conservation Opportunity Areas," which incorporate key locations for focal species, and are similar in concept to TNCs ecoregional plans, though COAs may be prioritized based on other factors, such as partnerships that are already in place, or available funding. In many states, TNC's ecoregional plans were important inputs to the assessment process. The methods for developing COAs varied, with some states creating detailed maps of terrestrial and

aquatic biodiversity, and others working primarily with existing prioritizations from partners and stakeholders.

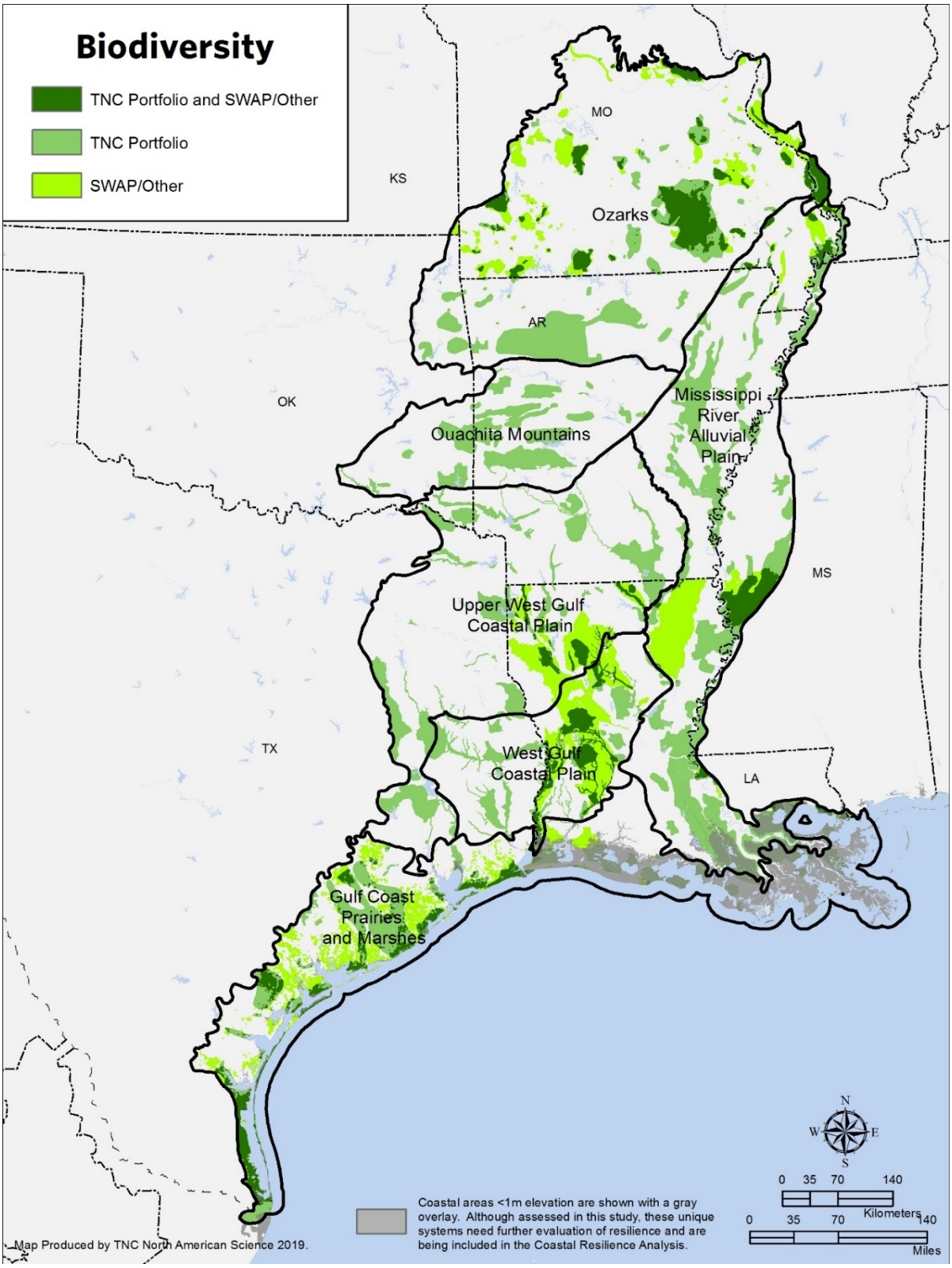
With assistance from our Steering Committee, we reached out to SWAP coordinators to obtain the SWAP COA spatial dataset, and/or other spatial data that represented the distribution of wildlife/biodiversity priorities in their state. In cases where there were multiple data layers available and it was not clear which was most equivalent to the TNC biodiversity portfolio, we talked with the developers via phone or Web Ex to understand the intricacies of the data. In all, we obtained spatial data for all states except Oklahoma and Arkansas, which do not currently have a COA or similar map (Table 8.2).

Collectively the biodiversity data identified land with intact habitat, viable species populations, or unique communities. The SWAP lands added an additional 9 million acres beyond the TNC Portfolio Lands as confirmed biodiversity areas (Figure 8.1).

Table 8.2. Spatial data from State Wildlife Action Plan (SWAP).

State & plan date, Title of map	Comments & link to the plan and dataset if publicly posted
Arkansas	None
Oklahoma	None
Louisiana	LA Wildlife & Fisheries. Conservation Opportunity Areas COAS April 2019
Missouri (2015): 2015 Conservation Opportunity Areas separated by habitat systems	In the MO SWAP, COAs were divided by type (grassland, forest, river, etc.) and each had a different set of scoring criteria. For grasslands, the criteria include a pre-settlement prairie layer, current land condition from NLCD, and community records from the Heritage Program database. We used just the terrestrial system COAs. https://mdc.mo.gov/sites/default/files/downloads/SWAPopt.pdf
Texas (2012, revising now):	Texas in in the process of revising their plan and has two types of assessments that were appropriate for this application, but only one was complete at the time of our compilation. We have incorporated an assessment a CHAT product, which incorporates SCGN distributions, but is primarily intended to identify sensitive resources and direct development away from them. This map draws information from an aggregated biodiversity value metric that is not yet complete for the state. The CHAT map uses these terrestrial maps as input, prioritizing areas that have confirmed presence and high-quality habitats. These "in progress" products were shared directly by the plan developers and are not in the current SWAP.
Mississippi	Mississippi Conservation Opportunity Areas: Geospatial Data Presentation Form: vector digital data https://www.sciencebase.gov/catalog/item/5849874be4b06d80b7b094fa

Figure 8.1: Confirmed biodiversity areas. Areas recognized for their biodiversity value in TNC ecoregional portfolios and State Wildlife Action Plans.



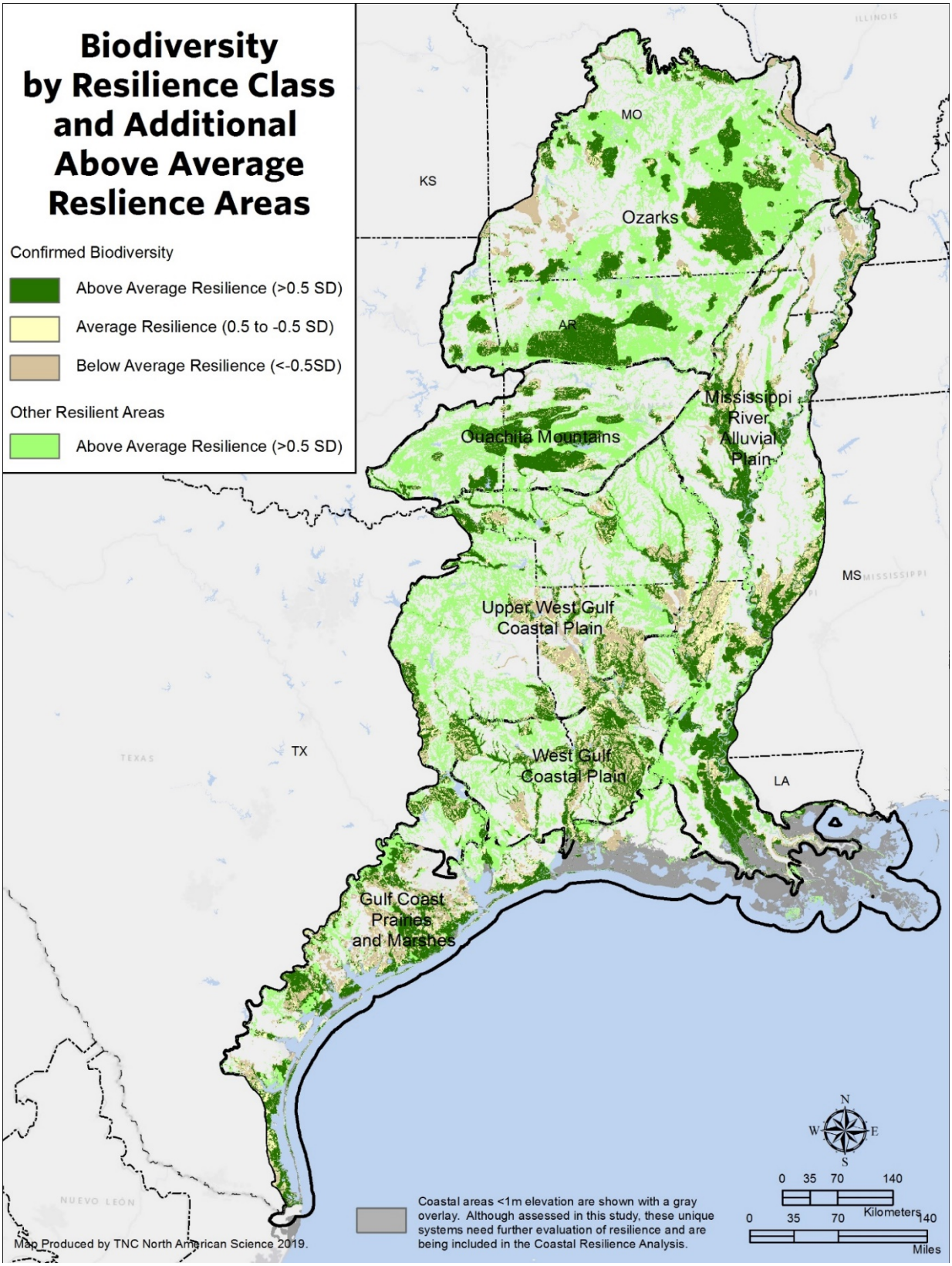
Biodiversity and Resilience

The biodiversity areas were intersected with the resilience classes (Figure 8.2) to estimate the amount of resilient land confirmed with biodiversity. The amount of resilient land with confirmed biodiversity varied widely by ecoregion and ranged from a low of 27% in the Upper West Gulf Coastal Plain to a high of 63% in the Mississippi River Alluvial Plain. Over the entire study area, the confirmed biodiversity areas comprised 42% of the resilient area and 29% of the total land assessed (Table 8.3).

Table 8.3. Percent overlap of confirmed biodiversity sites with resilient areas. The final column is the proportion of resilient land identified as having confirmed biodiversity value. % Resilient area indicated the amount of the ecoregion land area that scored above-average for resilience. % Biodiversity indicated the amount of the ecoregion land area that was confirmed for biodiversity by our biodiversity sources.

Ecoregion	Land Area (acres) >1m in elevation	% Resilient	% Biodiversity	% Resilient Land that is Confirmed Biodiveristy
Mississippi River Alluvial Plain	24,521,915	32%	36%	63%
Gulf Coast Prairies And Marshes	12,640,253	36%	43%	58%
West Gulf Coastal Plain	10,481,261	41%	41%	51%
Ouachita Mountains	11,187,324	48%	22%	37%
Ozarks	33,710,142	49%	24%	35%
Upper West Gulf Coastal Plain	25,305,451	37%	22%	27%
Grand Total	117,846,346	41%	29%	42%

Figure 8.2: Resilient Biodiversity Areas. This map show areas which have high site resilience and are also recognized for their high biodiversity value (dark green)



RESILIENT AND CONNECTED CONSERVATION NETWORKS

CHAPTER 9

The goal of this section was to identify a network of resilient sites that if adequately managed or conserved would sustain the diversity of the region under a dynamically changing climate. Our approach to mapping such a network was to first combine the wall-to-wall resilience and flow datasets into a single coverage and then to overlay the confirmed diversity areas. We used this integrated coverage to identify a connected network of resilient sites which maximized resilience, diversity, and flow.

The resilient site analysis in the first five chapters highlights a relatively fixed portion (approx. 33-38%) of each of the region's geophysical settings based on the distribution of microclimates and degree of local connectedness. Our use of a statistical distribution to calculate the average resilience score for each geophysical setting and identify the places that score above-average guarantees perfect representation of each setting within each ecoregion. The regional override adds additional areas that are among the highest scoring for the whole region (>1 SD for the region). These tend to be biased towards certain settings, but because it is relatively restricted to a few areas it does not greatly bias the representation.

In this section we prioritize among that resilient sites based on biodiversity and flow, to identify the places most essential for conserving and sustaining diversity under a changing climate.

One approach to prioritizing sites is to use a higher resilience score threshold. For example, selecting sites that score far above-average for resilience (> 1 SD instead of > 0.5 SD). That approach will identify the top scoring sites based solely on their resilience characteristics and will maintain perfect representation of the geophysical settings. An alternative approach, and the one that we used here, is to explicitly address the spatial configuration needed to produce an ecologically coherent network that allows for adaptation and change. Implementing the latter required that we study how the natural flow patterns are arranged across the region, where the rare species and exemplary natural communities are currently located, which riparian corridors

naturally connect critical features, and where a stepping stone pattern will have to be relied upon because there is no realistic way to functionally connect the sites. By incorporating these characteristics into the network design, we hoped to strengthen its collective long-term ability to sustain diversity while allowing for range shifts and adaptation.

Go with the flow:

Our approach to creating a network differs from similar studies in that we did not first identify sites and then try to connect them, instead we used the natural flow patterns as a spatial template and integrated the resilient and confirmed biodiversity areas with the flow pattern. In effect, we prioritized resilient sites that were aligned with the natural flow patterns and contained high quality biodiversity. By ensuring that resilient source areas representing the region's diverse species and environments are situated in places that naturally intercept and transmit population movements, we can facilitate the adaptation and persistence of nature's diversity.

We prioritized the study area based on three themes – resilience, biodiversity, and flow. Resilience criteria were based on microclimates and local connectedness applied to each geophysical setting as described in previous chapters. The goal of the resilience criteria was to ensure that the network was designed around representative areas of every habitat were species could persist in to the future due to the climatic variability and connectedness of the site. Diversity criteria were based on the TNC and SWAP portfolios of critical sites for biodiversity. The goal of the diversity criteria was to include confirmed features in the network that were particularly hard to capture by random chance, and thus ensure that the network contained the full spectrum of biodiversity. Flow criteria was based on an analysis of circuit flow to a landscape of variable resistance as defined by the arrangement and resistance of land uses, weighted by key upslope, northward and riparian corridors. The idea was to use the natural flow patterns in designing the network by selecting resilient and biodiverse sites that reinforced or enhanced those patterns.

We did not set a numeric acreage goal for this prioritization, but we aimed to identify the half of all the resilient areas that were the most connected and diverse, and by implication, the most critical to protect. In the Eastern and Central US this amounted to 23% of the region and subsequently rose to 26% when we added coastal sites. The prioritization reveals how the resilient sites interweave and are juxtaposed with the flow and diversity patterns. The prioritization is not necessarily intended as an estimate of how much conservation is needed to sustain diversity over time but rather to provide a starting point for focusing conservation on the most critical network of sites and linkages.

The resilient and connected network developed in the next chapters can be thought of as the landscape's skeleton and vital organs, critical but not enough to perform all the functions of nature that life depends on. If all the above-average resilient areas were

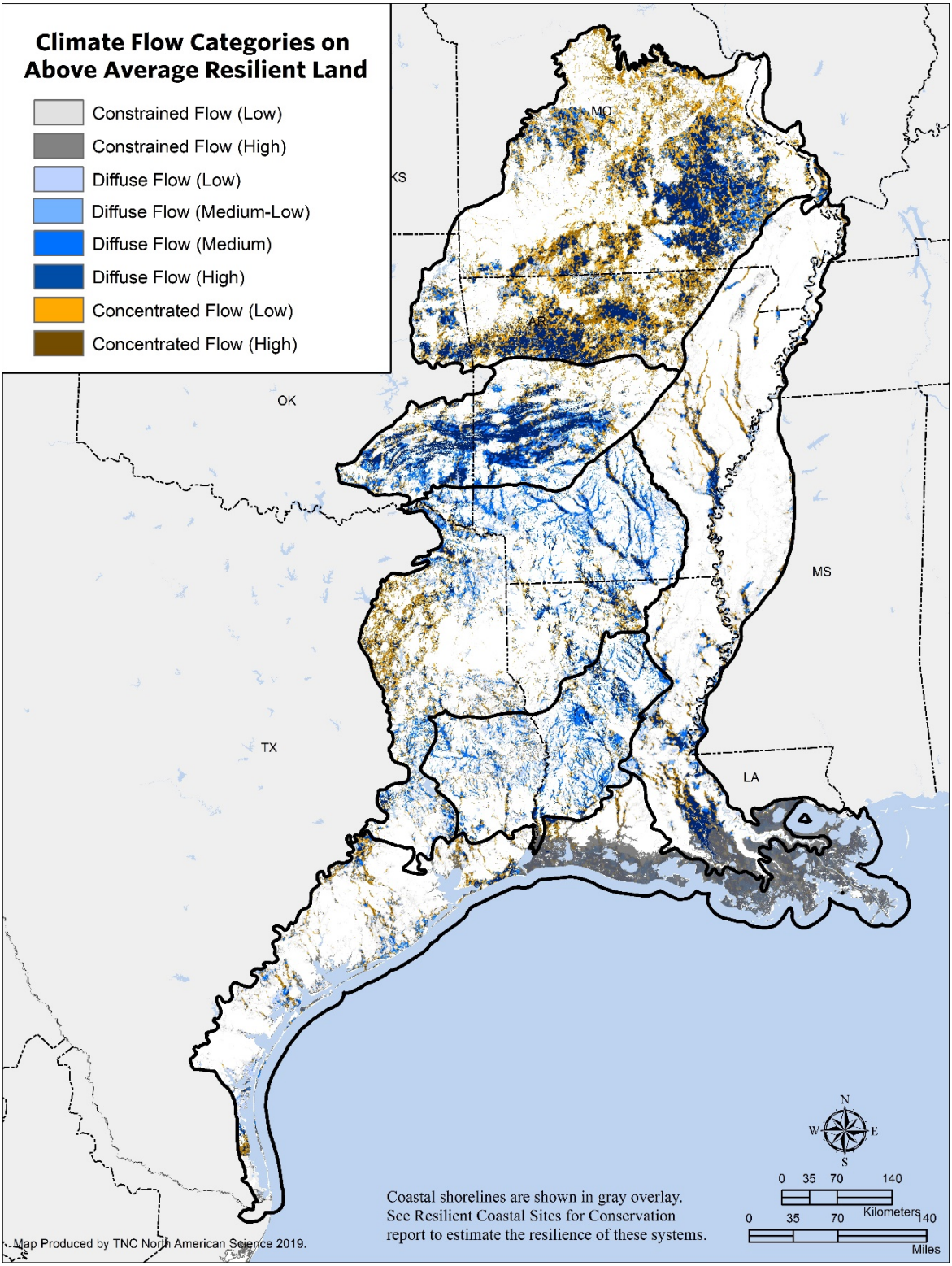
protected in totality it would amount to over 38% of the area and encompass the whole network. This approaches EO Wilson's Half Earth goal (Wilson 2016) and is probably closer to the actual area that we need to be concerned about if we want to maintain all the natural benefits and services we derive from nature. Currently only 8% of the Lower Mississippi Ozarks region is in some form of permanent conservation, so it will be a challenge to protect, or sustainably manage, the network even in its minimalist form.

Site Prioritization: Resilience, Flow, and Diversity

Resilience and Climate Flow

The resilience analysis and flow analysis are both continuous and geographically comprehensive. To identify an ecologically coherent network, we first combined these two datasets in their categorical forms. This allowed us to study for example the above average resilience areas by the flow class (Figure 9.1). Using the categorical climate flow map (Figure 7.22), we selected places that met the criteria of above-average resilience and concentrated (high and low) or diffuse flow (high, medium, and medium-low), thus selecting the places that maximized geophysical representation, resilience, and flow. We included the medium-low diffuse flow in the network because it highlighted potentially important areas of moderate upslope or downslope flow within the relatively intact landscape. Collectively the selected areas covered 31% of the region and delineated the structure, outline, and extent of the network.

Figure 9.1. Resilience and Climate Flow. This map shows the areas that met the criteria for above-average resilience by the various flow categories.



Biodiversity

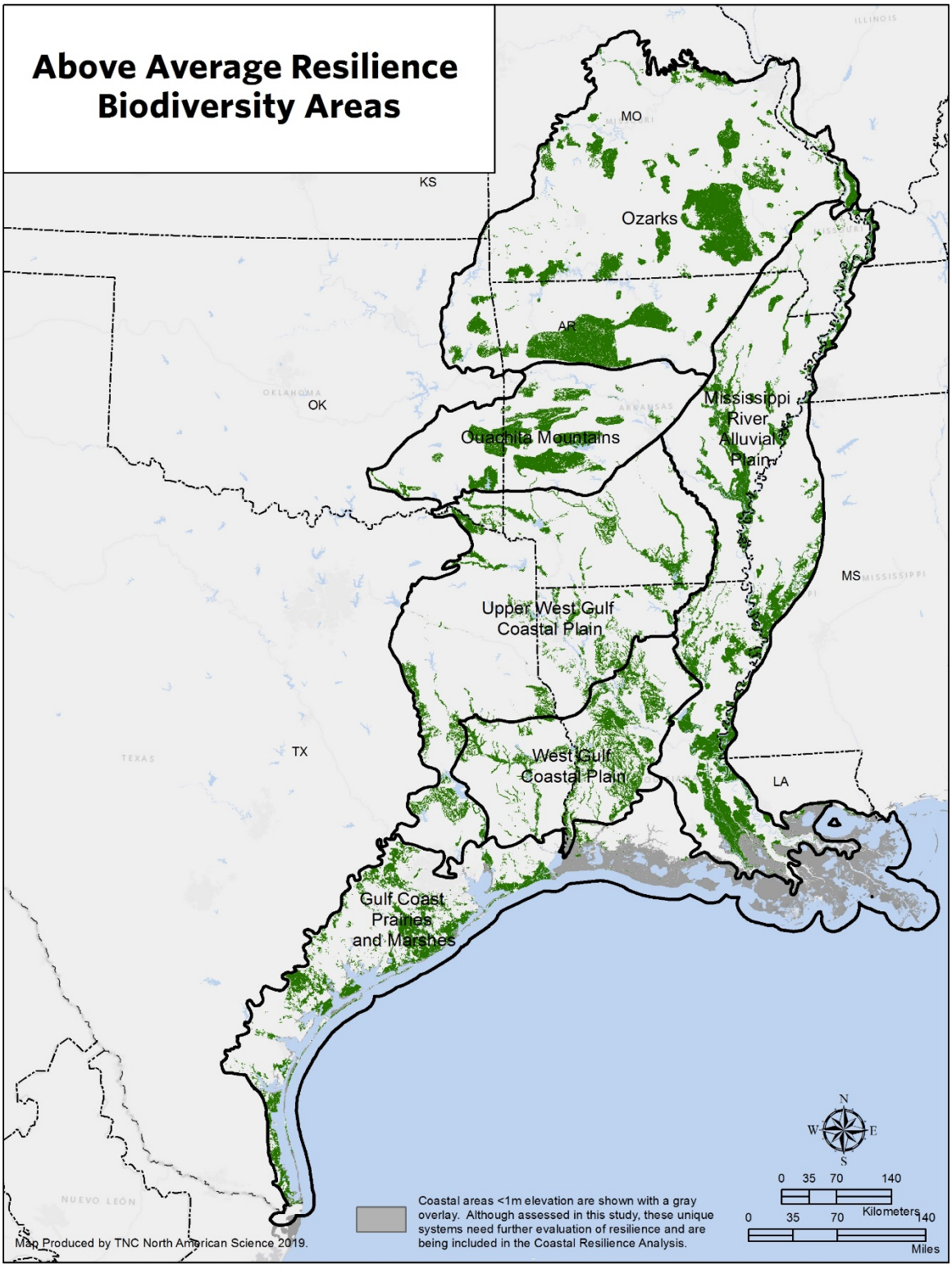
The biodiversity criteria identified the resilient portions of sites that have been recognized for their biodiversity value by other independent studies, namely the TNC ecoregional portfolio sites or the State Wildlife Action Plan sites (Figure 9.2). In total, the resilient biodiversity sites covered 17% of the study region, with most of them (12%) also overlapping with the flow network. The remaining 5% was identified as resilient land with confirmed biodiversity.

The goal of the confirmed diversity criteria was to ensure that the prioritized resilient areas contained as many known rare species populations or high-quality natural community examples as possible. Unlike common species which are relatively easy to represent in a wide variety of configurations, rare species, because of their small populations, are difficult to pick up based on random chance. Building them into the prioritization ensured that we selected the sites where they are most likely to persist and that have the characteristics to support similar species as the composition changes.

The criteria also ensured that the network was capturing high-quality natural communities in good condition, or species populations that were thriving. As the resilience analysis was based on enduring features alone, this was the first time that finer-scale criteria on the structure and composition of the vegetated communities or size of the population was brought into the analysis. Although we expect the communities to rearrange and the species to move over time, this gives us confidence that the starting materials, the soils, topography, and existing vegetation, are likely to be in suitable condition.

We emphasize that the although the recognized biodiversity sites give us high confidence in the current value of these places, other resilient areas might have high-quality natural communities or rare species on them. We simply have no information about to confirm that, and they have not been recognized in any of the studies we compiled.

Figure 9.2. Recognized Biodiversity. This map shows the distribution of sites that 1) were identified for their biodiversity features in a TNC ecoregional portfolio or a State Wildlife Action Plan, and 2) also met the criteria for above-average resilience.



Integration: Resilient and Connected Landscapes

We combined the sites and linkages identified by the combination of resilience, flow, and biodiversity into a single network. The network is designed to represent resilient examples all the characteristic environments of the region while maximizing amount of diversity contained within in them and the natural flow that connects them. By building the network around the natural flows and pathways that allow species populations to shift and expand and then identifying representative resilient sites situated within those pathways, the network is specifically configured to sustain biological diversity while allowing nature to adapt and change.

The results delineate a resilient and connected network that covers 31% (36.4 million acres) plus another 10% (11.6 million acres) of resilient land. Just over a third of the network (36%) met all three criteria: flow, confirmed diversity and resilience. The rest of the area met at least two criteria: flow and resilience (44%) or confirmed diversity and resilience (19%). Only 1% of the RCN met the resilient only and secured criteria. The breakdown of the network compared to the total land area of the region was as follows:

- **Resilient and Connected Network** **31%**
  - Climate Corridor 6.5%
  - Climate Corridor with Confirmed Biodiversity 3.5%
  - Climate Flow Zone 7.0%
  - Climate Flow Zone with Confirmed Biodiversity 7.5%
  - Resilient w Confirmed Biodiversity 6.0%
  - Resilient Secured 0.3%

- **Resilient Only (not in Network)** 10%

In total, the network represents: resilient examples of all geophysical settings, contains the resilient portions of 20 M acres of sites identified by TNC/SWAP portfolios for biodiversity, and includes over 29 million acres of climate corridor and flow zones. (Table 9.1, Figures 9.3–9.6).

Table 9.1. Percentages of Resilient and Connected Network by Ecoregion

This table shows the amount of each ecoregion's land identified by the respective network classes. The resilient and connected network averaged 31% of the region and ranged from a high of 42% in the Ozark Mountains to a low of 23% in the Mississippi River Alluvial Plain. Note: water (8% of region) is excluded.

	Outside of Network			Resilient and Connected Network							
Ecoregion	Developed	Average or Vulnerable	Resilient Only	Climate Corridor	Climate Corridor with Confirmed Diversity	Climate Flow Zone	Climate Flow Zone with Confirmed Diversity	Resilient Confirmed Diversity	Resilient Secured	Total Network	Total Land Acres
Gulf Coast Prairies And Marshes	1,297,403	6,776,778	1,411,332	272,001	465,905	199,821	421,066	1,773,639	19,135	3,151,568	12,637,082
Mississippi River Alluvial Plain	753,063	15,882,052	2,350,747	241,712	833,826	166,928	1,311,234	2,818,926	142,515	5,515,141	24,501,003
Ouachita Mountains	281,836	5,513,874	885,697	576,889	175,445	1,907,971	1,621,728	179,468	43,167	4,504,668	11,186,076
Ozarks	1,000,246	16,165,134	2,369,045	5,153,199	2,079,954	3,205,134	3,173,550	501,987	56,192	14,170,016	33,704,440
Upper West Gulf Coastal Plain	1,090,970	14,867,375	3,239,005	1,305,714	376,440	2,213,724	1,170,283	1,009,239	31,185	6,106,585	25,303,936
West Gulf Coastal Plain	271,108	5,908,179	1,265,442	165,079	250,286	601,608	1,190,555	757,842	71,161	3,036,532	10,481,261
Grand Total	4,694,627	65,113,392	11,521,268	7,714,594	4,181,856	8,295,187	8,888,416	7,041,102	363,355	36,484,510	117,813,797

	Outside of Network			Resilient and Connected Network							
Ecoregion	Developed	Average or Vulnerable	Resilient Only	Climate Corridor	Climate Corridor with Confirmed Diversity	Climate Flow Zone	Climate Flow Zone with Confirmed Diversity	Resilient Confirmed Diversity	Resilient Secured	% RCN	Total Land Acres
Gulf Coast Prairies And Marshes	10%	54%	11%	2%	4%	2%	3%	14%	0%	25%	100%
Mississippi River Alluvial Plain	3%	65%	10%	1%	3%	1%	5%	12%	1%	23%	100%
Ouachita Mountains	3%	49%	8%	5%	2%	17%	14%	2%	0%	40%	100%
Ozarks	3%	48%	7%	15%	6%	10%	9%	1%	0%	42%	100%
Upper West Gulf Coastal Plain	4%	59%	13%	5%	1%	9%	5%	4%	0%	24%	100%
West Gulf Coastal Plain	3%	56%	12%	2%	2%	6%	11%	7%	1%	29%	100%
Grand Total	4%	55%	10%	7%	4%	7%	8%	6%	0%	31%	100%

Figure 9.3. Resilient and Connected Network. This map shows the resilient areas that met criteria for confirmed biodiversity, climate flow or both. The network covers 31% of the region and captures 80% of all the resilient sites.

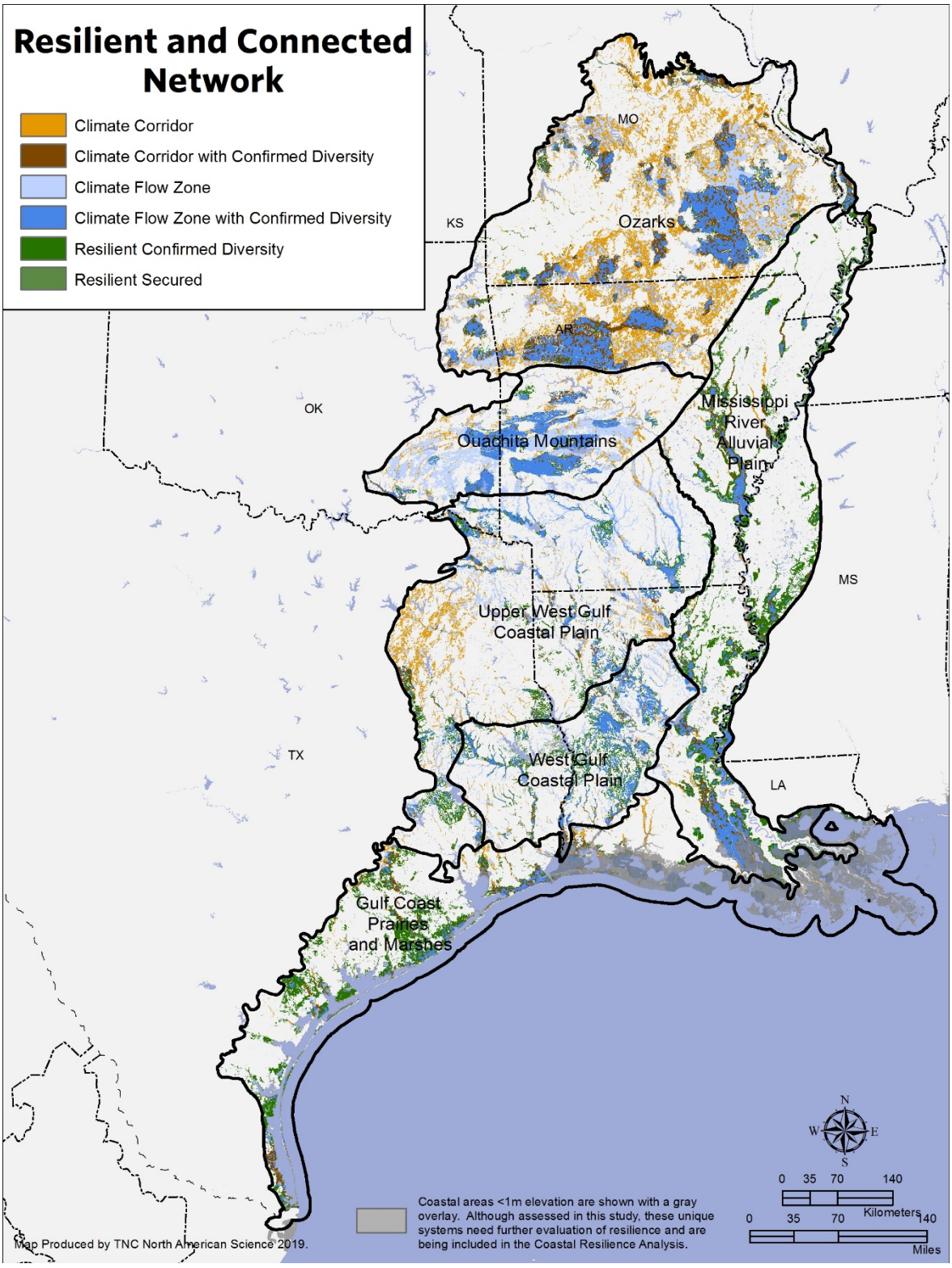


Figure 9.4. Resilient and Connected Network plus Other Resilient Land. This map shows the resilient and connected network (31%) plus other resilient areas (10%) that did not meet the criteria for confirmed biodiversity or climate flow.

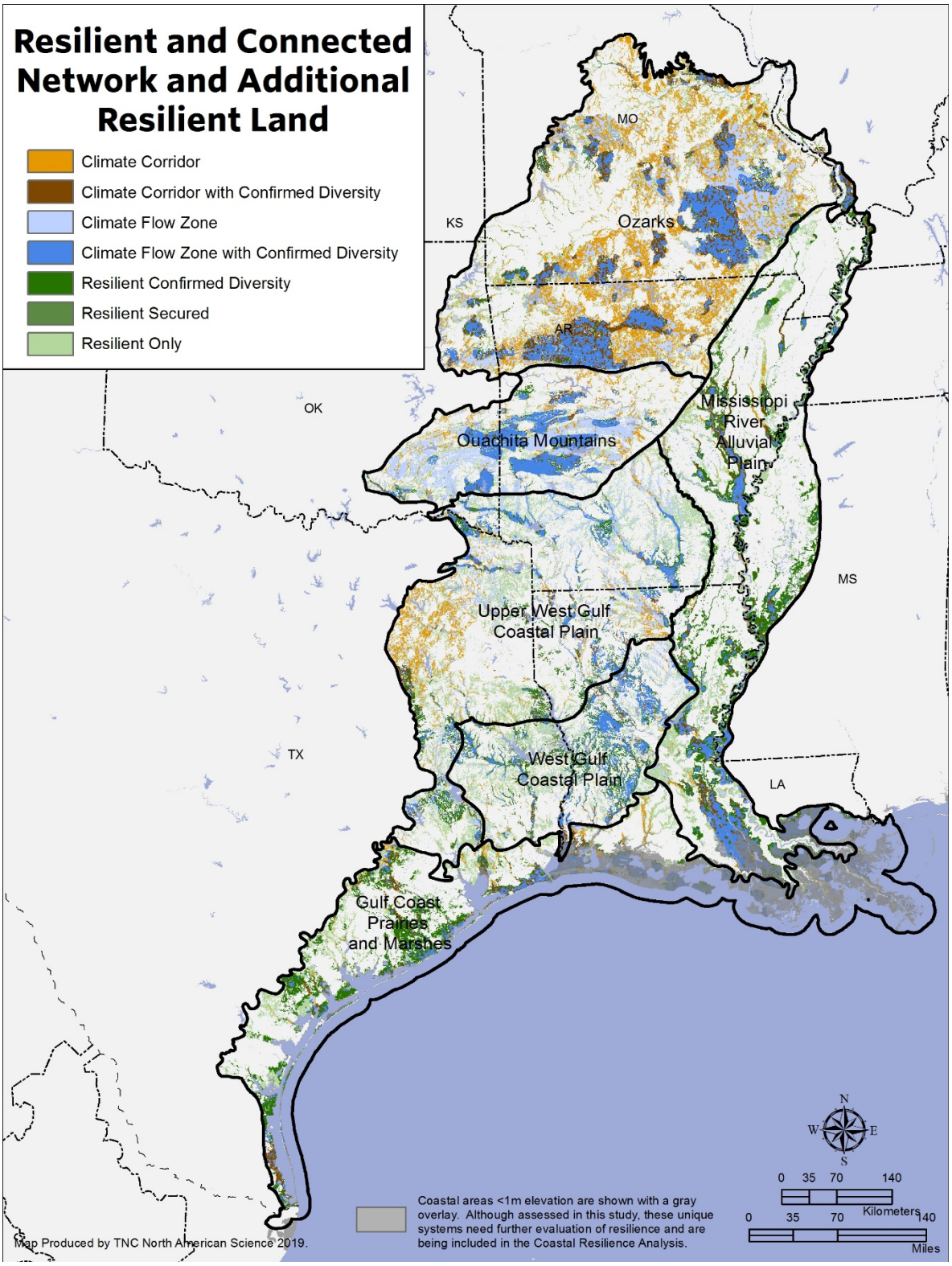


Figure 9.5. Continuous Map of Resilient and Connected Sites. This wall-to-wall map shows the resilient and connected network (31%), plus all other resilient sites (10%), plus all other categories of average, vulnerable or developed land (59%).

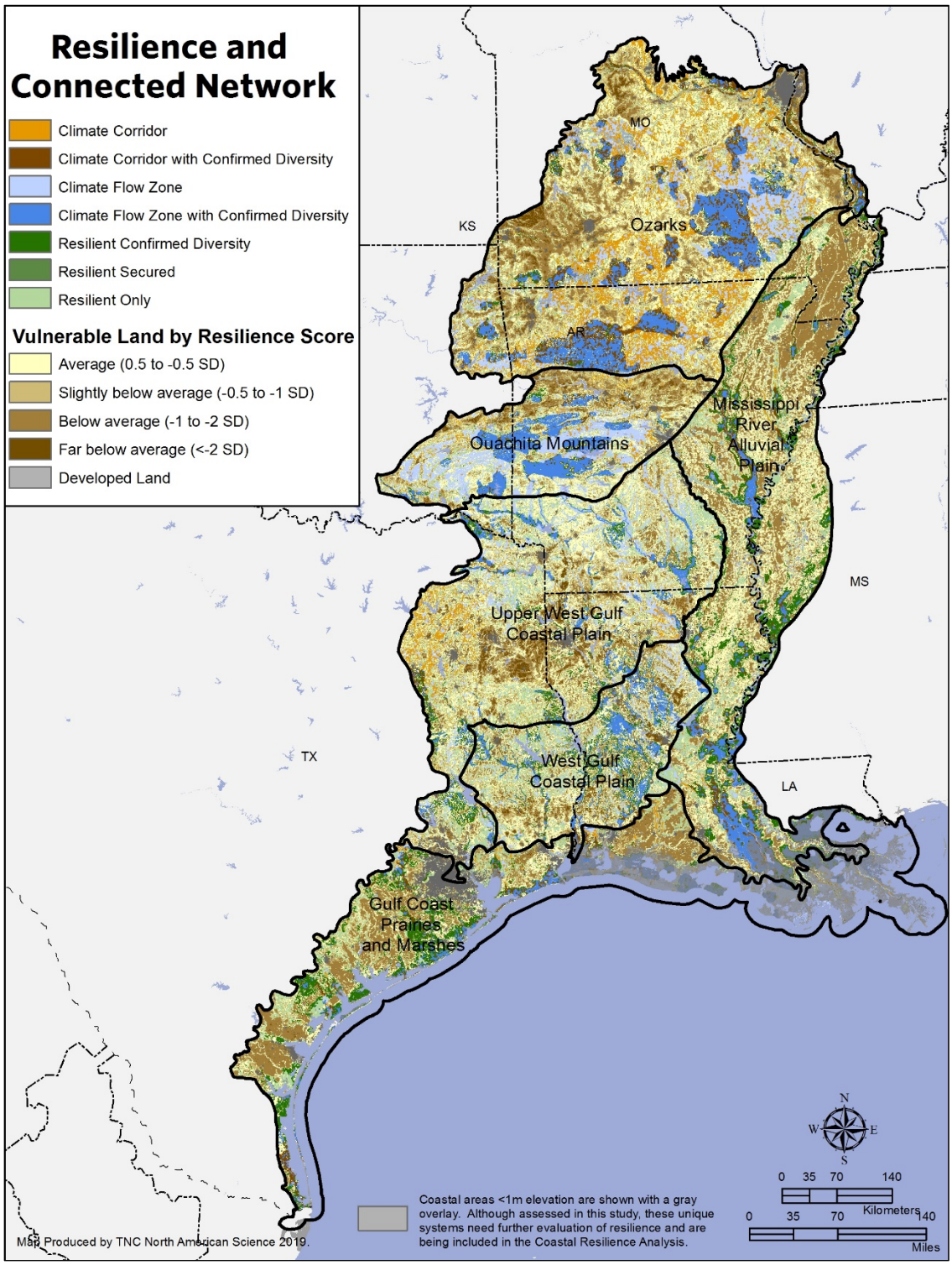
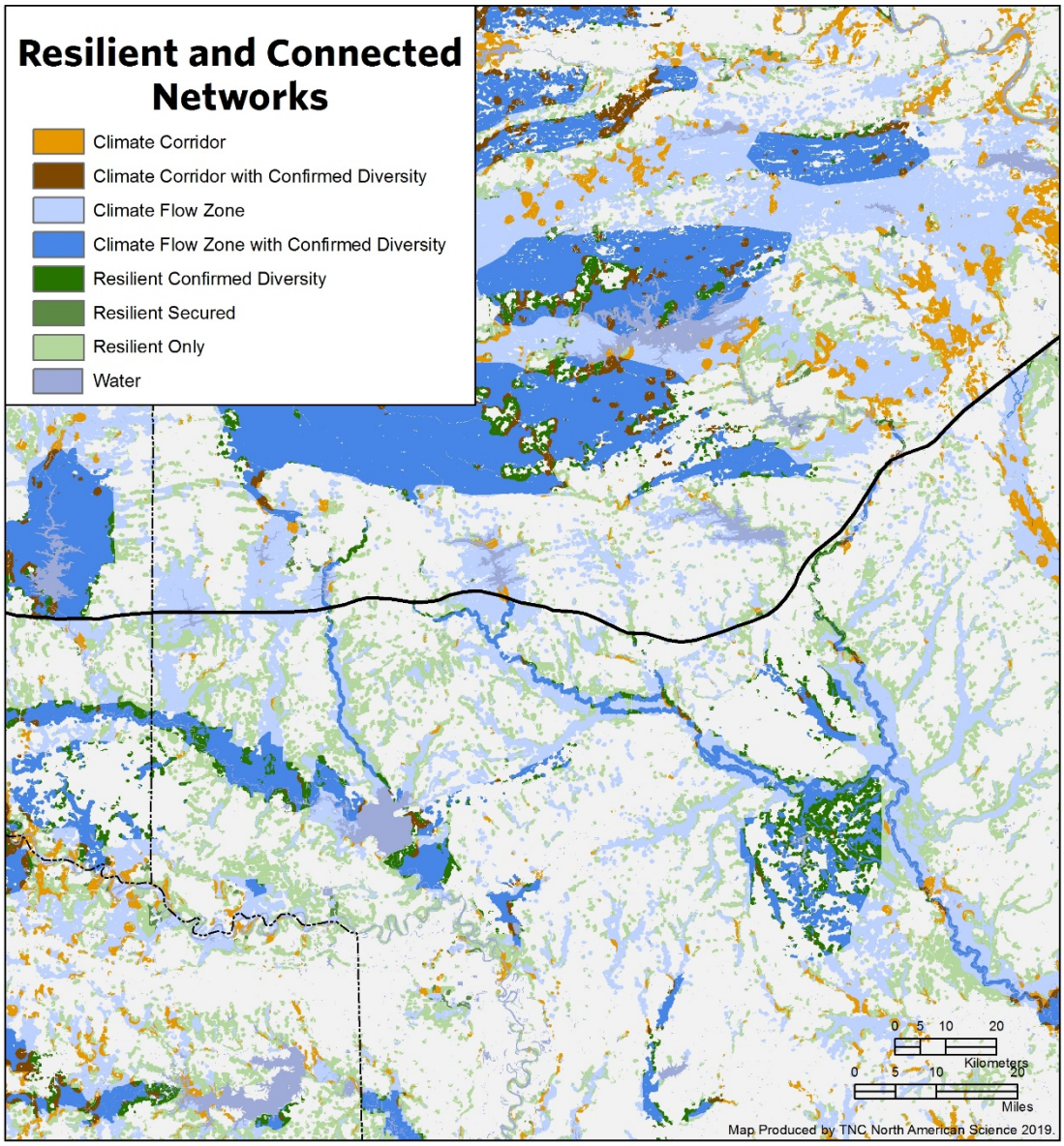


Figure 9.6. Zoom-in Border of Ouachita Mountains Upper West Gulf Coastal Plain. This map shows the resilient and connected network including seven categories of resilient sites. Climate corridors and flow zones with confirmed diversity are in darker colors.



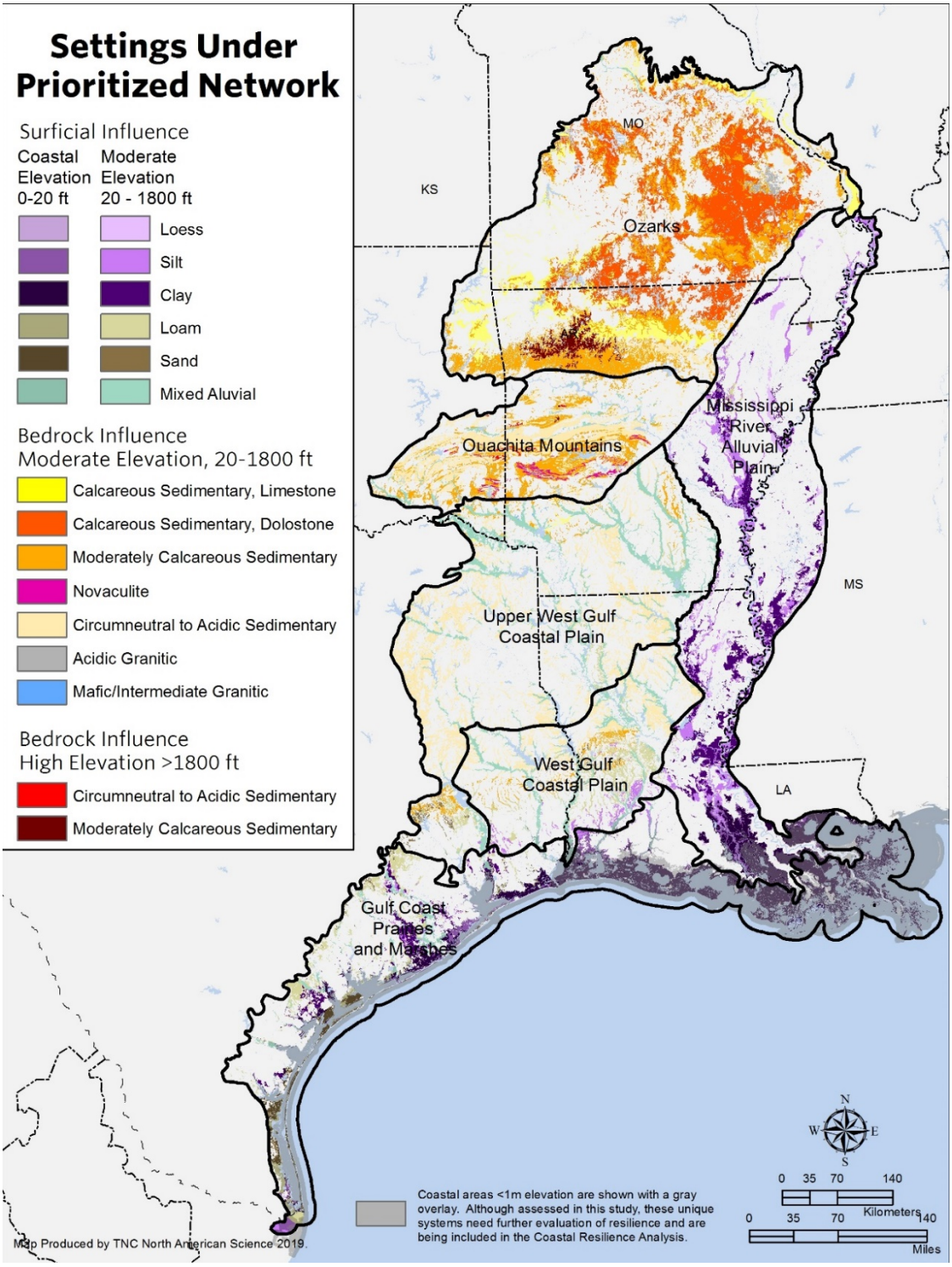
Representation of Geophysical Settings

The resilient and connected network represents all geophysical settings in the region, but because we used connectivity as prioritization criteria, we were concerned that the network might be biased towards more acidic settings that tend to be more intact. An assessment showed that high elevation areas are well represented (80%-85%) while loess is underrepresented (Table 9.2, Figure 9.7). The latter may require restoration and sustained management to ensure that it retains its natural diversity into the future.

Table 9.2. Representation of Geophysical Settings in Network.
This table is arranged by the % representation of the setting in the resilient and connected network (RCN). Settings below 20% may be considered under-represented in the network and may need restoration and management. Water was excluded.

Geological Setting	RCN		Distribution Across RCN						Not in RCN		
	Acres	%	Climate Corridor	Climate Corridor with Confirmed Diversity	Climate Flow Zone	Climate Flow Zone with Confirmed Diversity	Resilient Confirmed Diversity	Resilient Secured	Resilient Only	Average or Vulnerable	Developed
High Elevation	**519,048**										
Moderately Calcareous Sedimentary	460,033	85%	10%	29%	5%	39%	2%	0%	2%	13%	1%
Circumneutral/Acidic Sedimentary	59,015	80%	1%	2%	11%	66%	0%	0%	0%	19%	1%
Moderate Elevation	**33,589,889**										
Novaculite	190,358	86%	6%	2%	20%	57%	1%	0%	6%	7%	1%
Acidic Granitic	157,540	66%	3%	11%	5%	42%	5%	0%	3%	30%	0%
Calcareous: Dolostone	5,893,600	47%	19%	6%	13%	8%	1%	0%	7%	44%	1%
Moderately Calcareous	7,654,175	39%	10%	4%	11%	11%	2%	0%	10%	49%	3%
Mixed Alluvial	3,542,211	35%	4%	4%	9%	11%	6%	0%	10%	52%	3%
Circumneutral/Acidic Sedimentary	6,477,048	28%	6%	1%	11%	7%	3%	0%	11%	58%	3%
Calcareous: Limestone/Other	2,163,510	26%	9%	5%	5%	5%	2%	0%	7%	61%	6%
Clay	2,381,379	24%	1%	3%	1%	5%	13%	1%	7%	65%	4%
Sand	252,969	20%	3%	2%	3%	4%	8%	0%	13%	60%	7%
Silt	2,599,640	20%	1%	3%	1%	3%	11%	0%	11%	64%	4%
Loam	1,829,261	19%	2%	2%	3%	4%	10%	0%	12%	61%	7%
Mafic/Intermediate Granitic	10,516	14%	2%	0%	10%	1%	1%	0%	34%	50%	2%
Loess	437,682	13%	1%	2%	0%	2%	8%	0%	16%	66%	5%
Coastal Elevation	**2,375,574**										
Sand	311,014	59%	1%	8%	1%	11%	39%	0%	5%	28%	7%
Clay	1,118,985	53%	2%	9%	4%	21%	17%	0%	8%	31%	8%
Mixed Alluvial	205,035	45%	7%	9%	2%	8%	19%	1%	8%	37%	9%
Loam	242,829	40%	1%	12%	0%	5%	23%	0%	4%	50%	5%
Silt	491,835	25%	2%	5%	1%	8%	9%	0%	8%	55%	13%
Loess	5,876	3%	0%	0%	0%	0%	3%	0%	14%	70%	12%
Grand Total	**36,484,510**	**31%**	**7%**	**4%**	**7%**	**8%**	**6%**	**0%**	**10%**	**55%**	**4%**

Figure 9.7. Geophysical Representation of the Resiilent and Connected Network.
This map shows geophysical settings that underlie the RCN (Table 9.2)



Secured Lands

We compiled information on tracts of secured conservation land defined as "land that is permanently secured against conversion to development" (Figure 9.8). The process to compile and classify secured land is described in Chapter 1. Briefly, the definition was developed by an international group of scientists to differentiate "secured land" from the International Union for Conservation of Nature (IUCN) term "protected areas" which refers to land with a formal government designation of conservation value (Dudley 2008). Thus, this dataset includes tracts of land with no formal designation but with permanent protection and substantial conservation value, such as reserves held by TNC. Each parcel was classified to one of three GAP status values:

GAP 1 Intent: *Nature conservation with little human interference*
Areas having permanent protection from conversion of natural land cover and a mandated management plan to maintain a natural state within which disturbance events can proceed without interference or are mimicked through management.

GAP 2 Intent: *Nature conservation with extensive management where needed*.
Areas having permanent protection from conversion of natural land cover and a management plan in operation to maintain a primarily natural state, but which may receive uses or management practices that degrade the quality of existing natural communities, including suppression of natural disturbance.

GAP 3 Intent: *Multiple uses, typically resource extraction, recreation and conservation*
Areas having permanent protection from conversion of natural land cover for most of the area, but subject to extractive uses of either a broad, low-intensity type (e.g., logging) or localized intense type (e.g., mining).

We intersected the secured lands dataset with the resilient and connected network (Table 9.3, Figure 9.9)

Table 9.3. Land Securement across the Resilient and Connected network.

RCN Categories	Acres	% Secured	% GAP 1	% GAP 2	% GAP 3
Climate Corridor	7,714,594	6%	0%	3%	2%
Climate Corridor with Confirmed Diversity	4,181,856	29%	2%	15%	13%
Climate Flow Zone	8,295,187	15%	0%	9%	6%
Climate Flow Zone with Confirmed Diversity	8,888,416	51%	4%	28%	19%
Resilient Confirmed Diversity	7,041,102	16%	2%	11%	4%
Resilient Secured	363,355	100%	4%	65%	30%
Total Resilient and Connected Network	36,484,510	24%	2%	14%	9%
Resilient Only	11,521,268	0%	0%	0%	0%
Average or Vulnerable	65,113,392	3%	0%	2%	1%
Developed	4,694,627	1%	0%	0%	0%
Total Land	**117,813,797**	**9%**	**1%**	**5%**	**3%**

Figure 9.8. Secured lands. This map shows the secured lands in the region by Gap status. In total 9% of the study area is secured against conversion (Table 9.3)

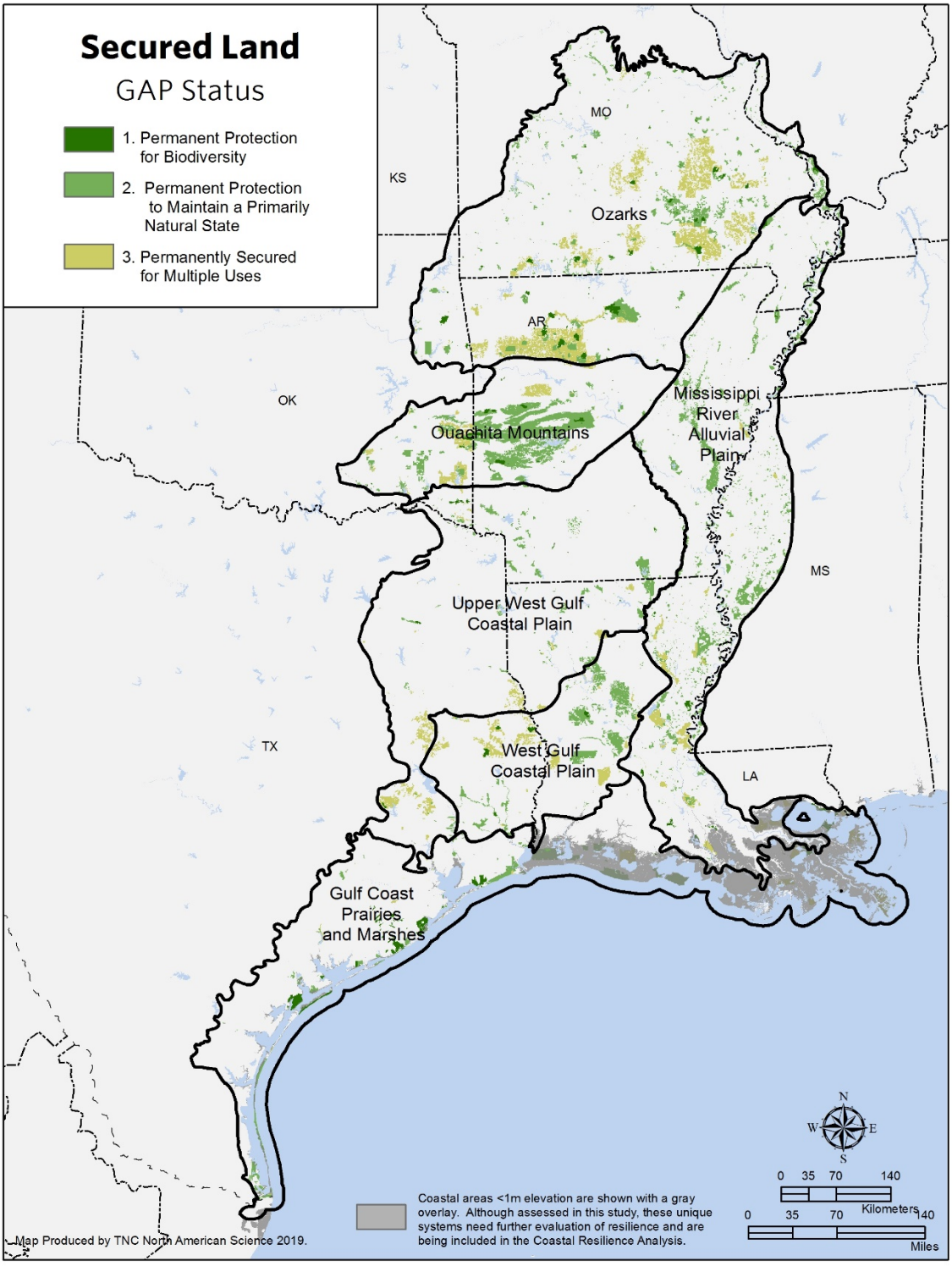
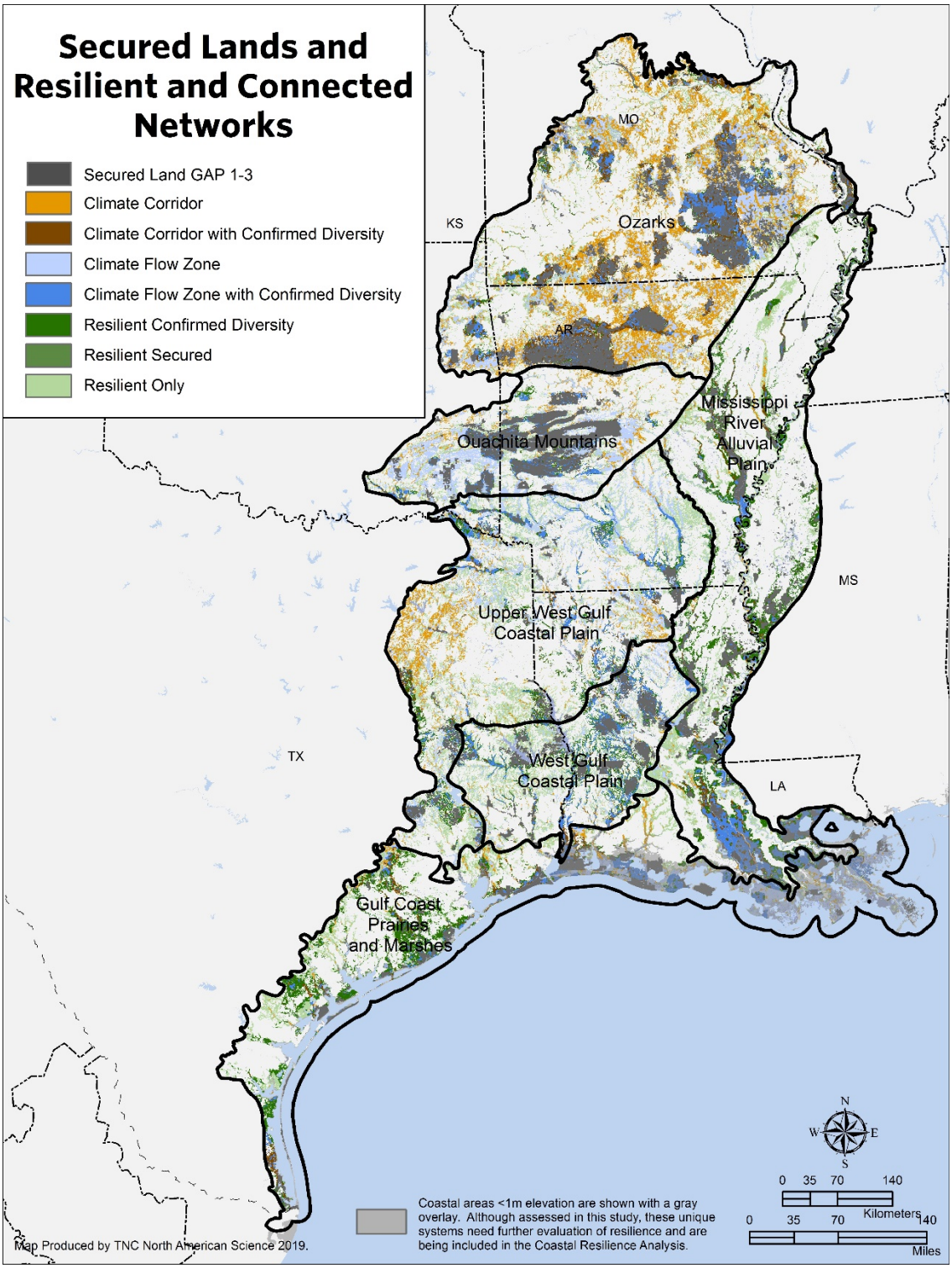


Figure 9.9. Secured land with the resilient and connected network . The map shows the secured lands in gray on top of the resilient and connected network. In sum the network is 24% secured by conservation land in Gap 1-3 status.



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