Resilient Sites & Connected Landscapes

For Terrestrial Conservation in the Rocky Mountain and Southwest Desert Region

Mark Anderson, Melissa Clark, Arlene Olivero, and John Prince

The Nature Conservancy

Resilient Sites and Connected Landscapes for Terrestrial Conservation in the Rocky Mountain and Southwest Desert Region.

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The Nature Conservancy, Eastern Conservation Science
Eastern Regional Office
99 Bedford St, 5th Floor
Boston, MA 02111
eScience@tnc.org

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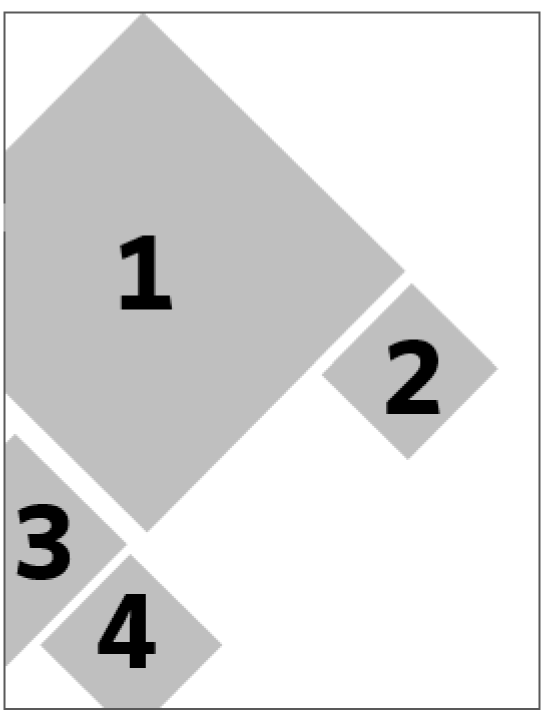

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CHAPTER 1

INTRODUCTION

This report presents the results of a 1-year project to identify and map climate resilient sites across the **Rocky Mountain–Southwest Desert region** of the U.S. This work was made possible by a grant from the Doris Duke Charitable Foundation, 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 U.S.

Project History and Scope

TNC has been working for over ten years with support from the Doris Duke Charitible Foundation to identify climate resilient sites in theU.S. The Conserving Nature's Stage (CNS) approach has been applied to the U.S. 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). Each of these geographies were analyzed using CNS methods pioneered by TNC'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 Rocky Mountain and Southwest Desert 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 of organisms and natural communities. 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 ten states (Figure 1.1). The region is defined by the boundaries of 12 TNC ecoregions, and encompasses portions of Montana, Idaho, Wyoming, Nevada, Utah, Colorado, California, Arizona, New Mexico, and Texas. This analysis does not include portions of ecoregions that cross into Mexico.

The Rocky Mountain-Southwest Desert study area encompassed the following ecoregions:

Mountains:

1. Arizona-New Mexico Mountains
2. Southern Rocky Mountains
3. Utah High Plateaus
4. Utah-Wyoming Rocky Mountains

Cold Deserts:

5. Colorado Plateau
6. Great Basin
7. Wyoming Basins

Warm Deserts:

8. Apache Highlands
9. Chihuahuan Desert
10. Mojave Desert
11. Sonoran Desert
12. Tamaulipan Thorn Scrub

Scientists and conservation planners from these states 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 12 TNC ecoregions comprising the Rocky Mountain-Southwest Desert study area (in colors) as well as the ten states fully or partially included. Mexico was not included in this analysis.

Figure 1.2: Land Use in the Rocky Mountain-Southwest Deserts. The region is dominated by natural grasslands, shrubland, and deserts in the south and forested mountains in the north.

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 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 USFW 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.

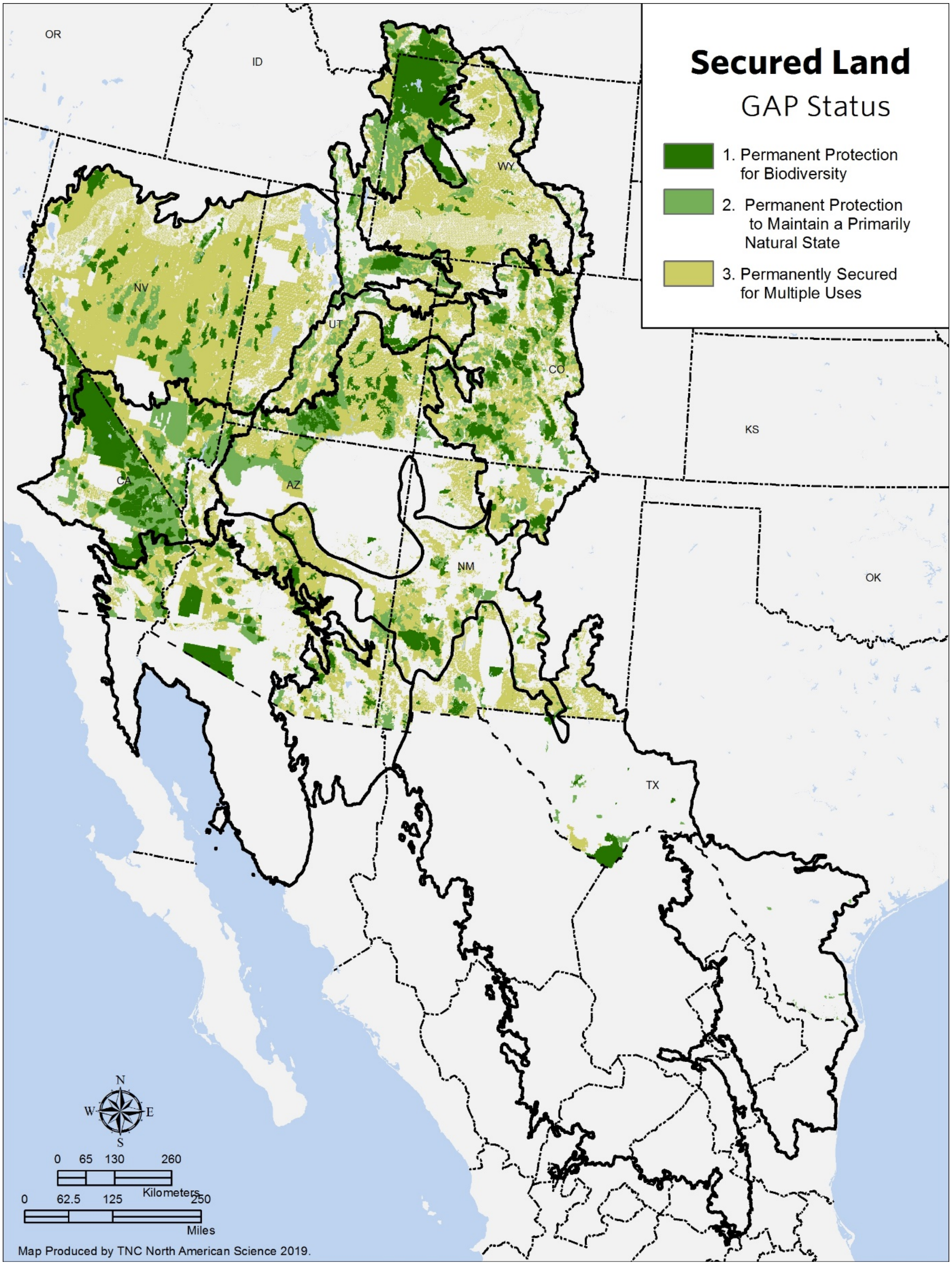
TNC GAP is a land classification system and it does not necessarily describe how protected the contained conservation targets are within a secured area (Table 1.1). For example, a species breeding on a secured parcel may be only partially conserved if their conservation calls for securement of multiple 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 70 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 TNC 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 Rocky Mountain-Southwest Deserts, 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 with the Steering Committee 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 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).

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 (Holling 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 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).

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 Rocky Mountain-Southwest Deserts 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 than 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 as 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 12 ecoregions, and the regional map is a composite of the individual ecoregion maps.

DATA SOURCES

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 Rocky Mountain-Southwest Desert 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 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 our 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,
(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 (Bailey 1995). 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) and the Canadian Provinces (Ecological Stratification Working Group 1995). 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 grouped the ecoregions into three major regions, Mountains, Cold Deserts, and Warm Deserts to represent major differences in climate and physiography of the ecoregions (Figure 2.1). The Tamaulipan Thorn Scrub was placed in a separate Tropical Lowland and Coastal group.

Mountains:

1. Arizona-New Mexico Mountains
2. Southern Rocky Mountains
3. Utah High Plateaus
4. Utah-Wyoming Rocky Mountains

Cold Deserts:

5. Colorado Plateau
6. Great Basin
7. Wyoming Basins

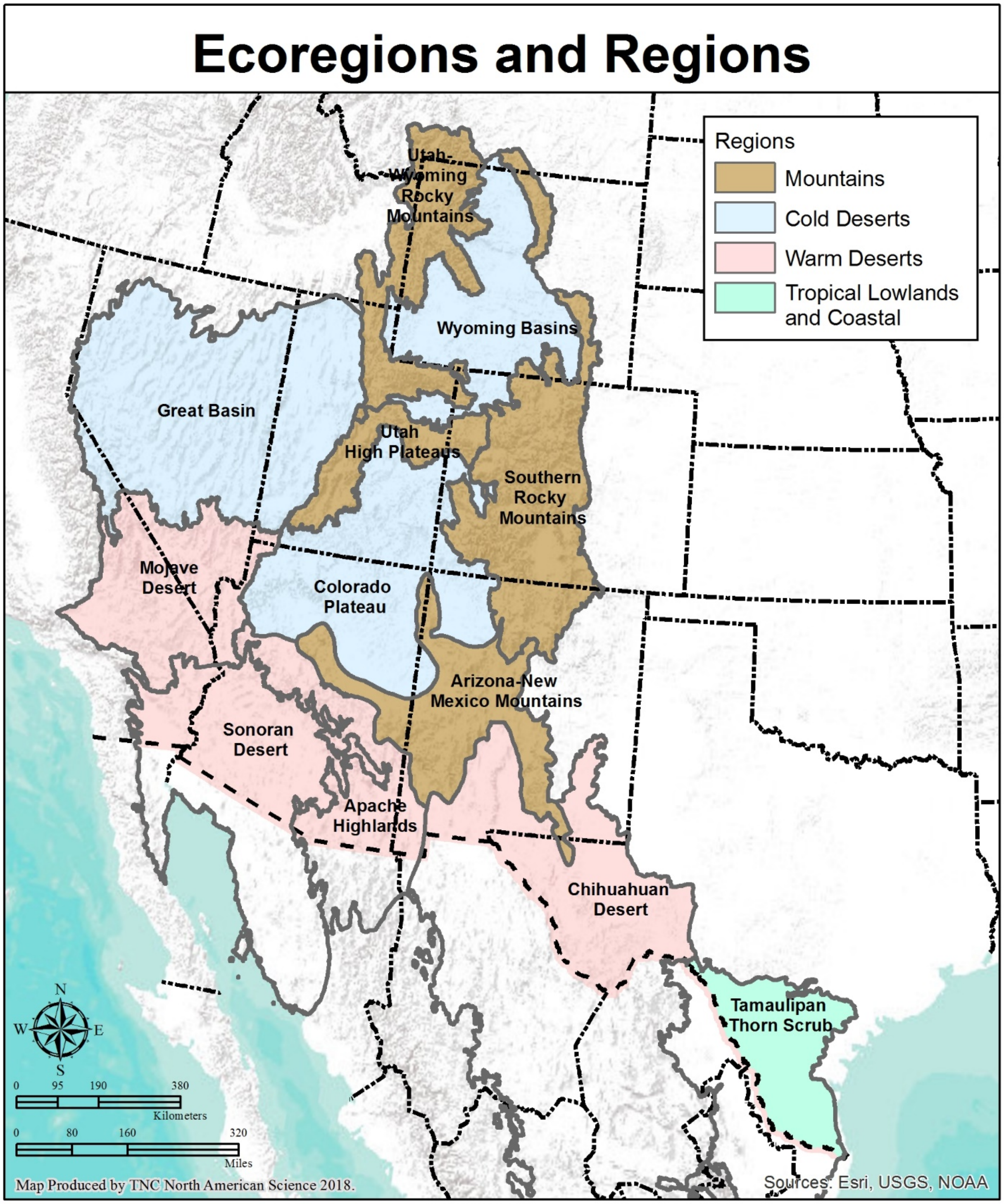
Warm Deserts:

8. Apache Highlands
9. Chihuahuan Desert
10. Mojave Desert
11. Sonoran Desert

Tropical Lowland and Coastal

12. Tamaulipan Thorn Scrub

Figure 2.1: Ecoregions and Regions. Ecoregions and Regions in the study area.



Geophysical Settings

The geophysical settings were developed using bedrock, surficial soils, and elevation data. The section on delineating settings is divided into six parts:

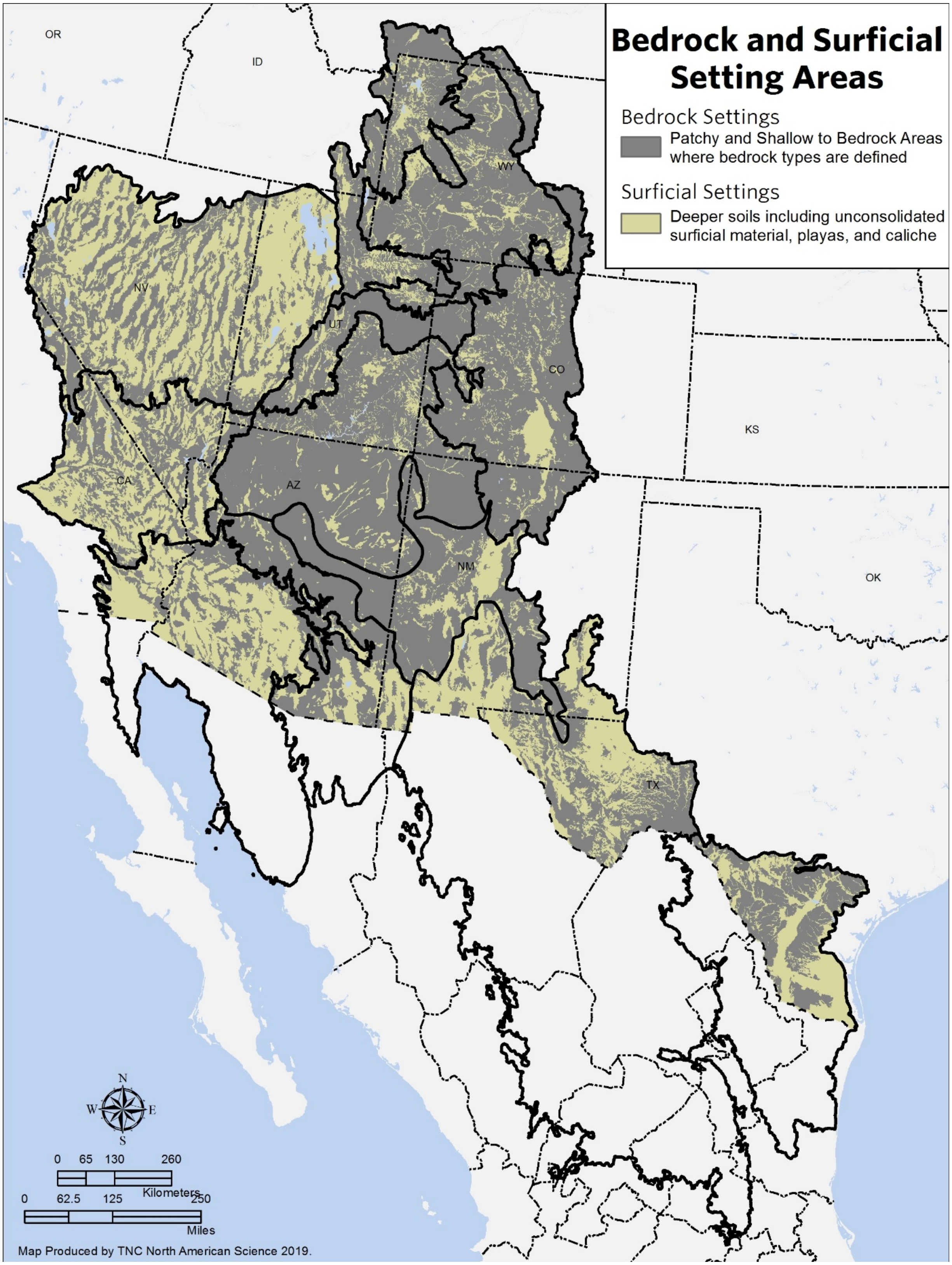
1. Delineating Surficial and Bedrock Zones
2. Classifying and Mapping the Bedrock Geology
3. Classifying and Mapping the Surficial Sediments
4. Integrating Bedrock Geology and Soil Texture
5. Integrating Life Zones and Elevation
6. Associated Natural Communities and Species

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 vs. areas of shallow bedrock-dominated land. The natural communities, associated species, and ecological processes differ markedly between these two environments, which separate the deep soil in valleys and flatter plains from the areas of bedrock outcrops, bluffs, glades, and slope-based natural 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 coarser in scale than the state bedrock datasets, Soller's categorical assignment of areas as discontinuous or patchy (defined as map units where sediments are patchy and bedrock is exposed at land surface) matched very closely the areas mapped as bedrock in the finer-resolution mapped geology datasets (Horton et al. 2017). Given the spatial agreement, we selected the state bedrock data polygons as the base for delineating a bedrock vs. surficial zone. Areas that were mapped with some named bedrock type in the state data were separated from those areas mapped in the state datasets as unconsolidated, sand, clay, or silt (Figure 2.2).

Figure 2.2: Bedrock vs. Surficial Influence Zones based on Horton et al. 2017.



Classifying and Mapping the Bedrock Geology

We placed the bedrock classes from US Geological Survey State Geologic Mapping Compilation (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, the source polygon dataset had multiple (up to six) rock type assignments in their major and minor class codes. In these cases, we resolved the assignment of geologic taxonomic types by studying the units ecologically relevant properties (chemistry, erodability, texture) and/or spatial agreement with adjacent formations, landforms, and known natural communities. Particularly helpful in this process was the SGS GAP Analysis Program unpublished "1:500,000 Scale Geology for the Southwestern U.S. (SWGEO.)" This was a seamless geologic coverage for the states of Arizona, Colorado, Nevada, New Mexico, and Utah, compiled and edge matched from five existing digital versions of the 1:500,000 scale state geologic maps. In SWGEO the correlation and merging of units along state boundaries was based on similar age and characteristics of units.

Although the SWGEO mapping was coarser than Horton et al. (2017) it was useful in highlighting calcareous substrates that were otherwise obscured in the state geology mapping compilation by multiple names. For example, when a unit had two major classes and one was assigned to limestone and another to sandstone, we overlaid the SWGEO dataset and assigned the state bedrock polygon to our calcareous class if >50% of the polygon was covered by SWGEO carbonate polygon. Similarly, when rock types were classified differently on either side of a state or country boundaries, we resolved the difference using SWGEO or other supplemental information from a variety of sources to smooth and join polygons across the border. We also consulted and used an overlay of SWGEO to inform unclear state "mixed geology" polygons and correct errors pointed out by our steering committee review. Given the different scales of the source bedrock data, perfection was not always possible and we allowed certain formations to end at state borders if they were more finely mapped in a particular state as we had no information on how they continued across the border.

The resultant classes of bedrock included (Figure 2.3):

SEDIMENTARY ROCK

<u>1. Calcareous Sedimentary</u>: alkaline sedimentary or metasedimentary rock with high calcium content such as limestone, dolostone, marlstone, calcarenite, carbonite, chalk, coquina, marble, and marl.

<u>2. Moderately Calcareous Sedimentary</u>: moderately alkaline sedimentary or meta-sedimentary rock with some calcium but less than rocks in the calcareous rock class. Calcareous shales, mixed sedimentary rocks with calcareous components, calcium-silicate, and calcium-silicate schist rocks, usually in the minor components of the rock.

Note, in the data set any mixed bedrock with one of the three major components in the dataset listed as limestone or dolostone was assigned here.

3. Sandstones and Mixed Sedimentary: sandstones, arenite, arkose, conglomerate, or sandstone mixed with mudstone, claystone, shale, siltstone.

4. Shale and other Fine Grained Sedimentary: shale, siltstone, mudstone, claystone, bentonite, politic schist, argillite, phyllite (slightly metamorphosed shale), black shale or oil shale, marlstone with shale.

5. Novaculite: microcrystalline to cryptocrystalline rock 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.

IGNEOUS ROCK

EXTRUSIVE: Extrusive igneous rocks with small or poorly formed crystals.

6.Volcanic, Felsic: volcanic rocks rich in feldspar and quartz. Includes rhyolite, trachyte, basanite.

7.Volcanic, Mafic and undifferentiated Rocks rich in magnesium and iron. Includes basalt, andesite, mafic volcanic, alkali volcanic.

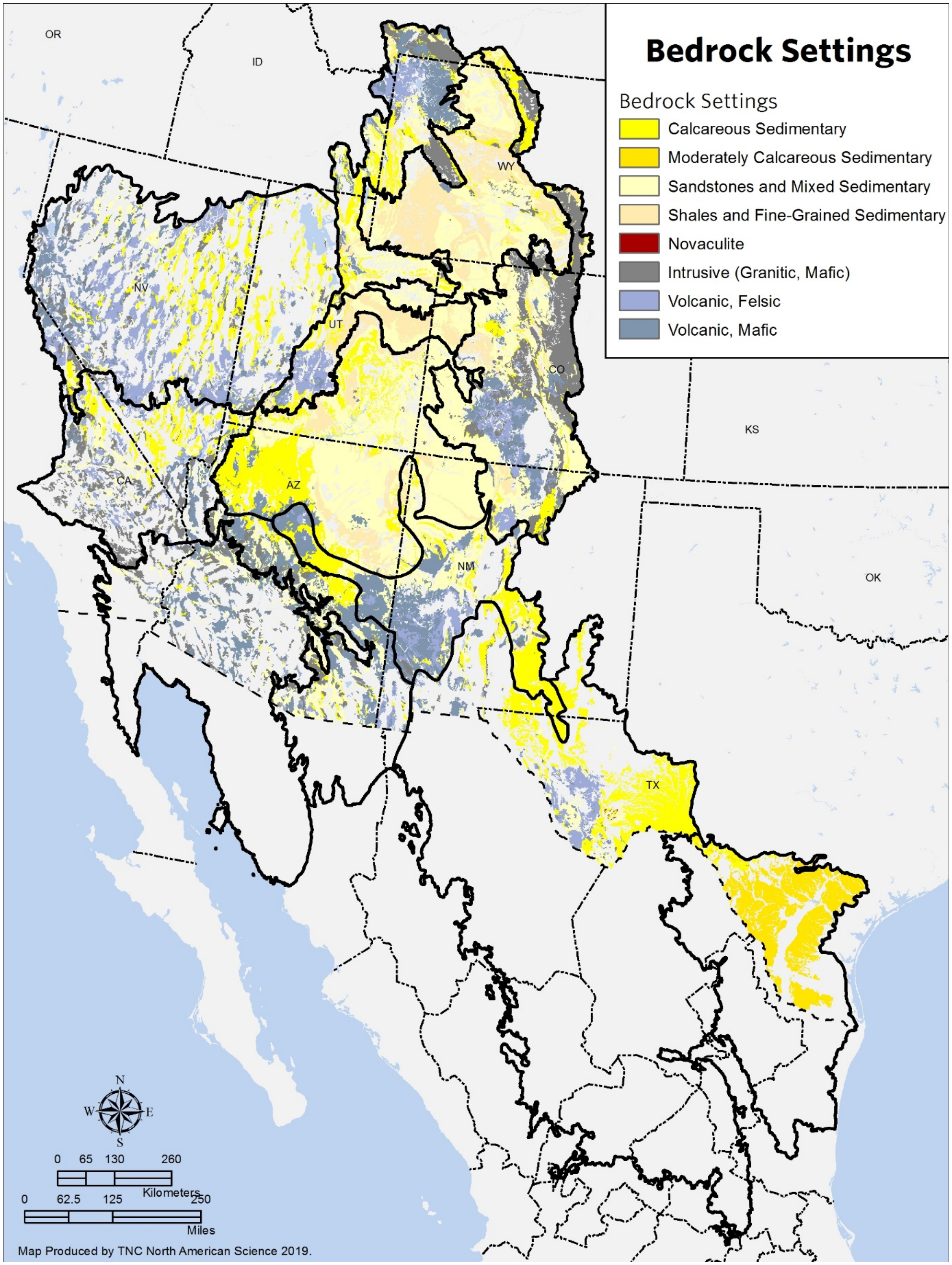
INTRUSIVE: *Intrusive igneous rocks with large interlocking crystals.*

8.Intrusive (Granitic, Mafic): The following rock types were included in this category

Granitic/Felsic: quartz-rich: resistant igneous and meta-igneous or meta-sedimentary rock. Granite, granodiorite, gneiss, tonalite, migmatite, quartzite, mylonite, latite, dacite.

Mafic/Intermediate: Quartz-poor alkaline to slightly acidic igneous and meta-igneous rock. Syenite, diorite, gabbro, anorthosite, migmatite, syenite, tectonite, hornfels, amphibolite, monzonite , amphibole schist, dioritic, and monzodiorite. Ultramafic rocks that were extremely rare in this region, such as magnesium-rich alkaline igneous and meta-igneous rock, serpentine, and peridotites.

Figure 2.3: Bedrock Geology. Results of the compilation and classification of state-based geology datasets into a single regional map.



Classifying and Mapping the Surficial Sediments

We created a spatially comprehensive regional dataset of surficial texture using data from POLARIS (Chaney et al. 2016) a gridded soil dataset created by the Program in Atmospheric and Oceanic Sciences Lab at Princeton University. This new dataset of soil series probabilities was produced for the contiguous U.S. 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 provides a spatially continuous, internally consistent, quantitative prediction of soil series that fixes some of the problems in SSURGO. Namely: 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 the coarse polygons.

We focused on the texture classes within the upper 30-m of soil by creating a weighted average of the available near-surface depths to calculate percent sand, silt, and clay for every pixel. Using these percentages, we assigned each 30-m pixel to one of the 12 USDA Soil Triangle Categories. These 12 detailed USDA soil types were then placed into three major categories based on their water storing capacity and feedback from our review team regarding their influence on ecological expressions:

- Sand: Sand, Loamy Sand
- Loam: Loam, Silty Loam, Sandy Loam, Sandy Clay Loam
- Fine: Silt, Clay, Silt Clay, Clay Loam, Silty Clay Loam, Playa

The soil texture data was further smoothed using a circular 100-acre focal maximum function to 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 areas into larger units.

These three soil texture categories covered most of the region, but we also integrated additional surficial data sources to better map surficial gypsum, caliche, and fine-sediment playas. These sources and methods are described below under the resultant surficial setting types (Figure 2.4).

<u>1. Sand</u>: Sand, Loamy 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.

<u>2. Loam</u>: Loam, Silty Loam, Sandy Loam, Sandy Clay Loam

Loam is a relatively fertile soil reflecting a mixture of sand, silt and clay. It yields the highest availability of water to plants.

3. Fines and Playas: Silt, Clay, Silt Clay, Clay Loam, Silty Clay Loam, Playa

Silts are fine-grained substrates of a size between sand and clay. Silts typically transported by water and are deposited during evaporation. Soils with a high silt content have an increased nutrient and water holding capacity and are often poorly drained. Mapped playas from *USGS Surficial Materials in the Conterminous United States* (Soller et al. 2009) were also added to augment and given better spatial representation to playa formations which are dominated by fine sediments in the arid west.

4. Gypsum and Evaporites:

Surficial mineral deposits formed primarily in the lakebeds of evaporating water bodies. This class includes unspecified evaporites, anhydrites, surficial gypsum and salt deposits. We mapped this category off the bedrock dataset (Horton et al. 2017) where the major component geologic type was listed as gypsum or evaporites, or where the major type was listed as unconsolidated and the minor component listed gypsum or evaporite. Because this class was inconsistently mapped across states, especially TX and NV, we augmented it in these states with SSURGO gypsum areas defined as >25% gypsum in the 0-100cm layer and STATSGO defined as >50% gypsum in the surficial layer. This filled in some well-known gypsum areas in the Mojave and Chihuanan Desert.

5. Caliche:

This surficial setting of caliche hardpan was restricted to Chihuahuan ecoregion. Although it may occur in other ecoregions in small patches, it could not be accurately mapped outside the Chihuahuan ecoregion where we had polygons in Horton et al. (2017) that denoted "caliche" as their major geologic type. State review highlighted that these areas were correct but not the full extent of this setting in the ecoregion.

To add additional areas of caliche in the Chihuahuan ecoregion we built a simple predictive model using the confirmed caliche polygons to estimate the larger extent. To do this, we queried the POLARIS data for areas less than 110 cm depth to a restrictive layer. We smoothed the resulting cells in GIS using focal statistics to remove speckles and consolidate the data to the coarser resolution of the dominant settings. In the consolidated data, areas with >=60 % in the shallow depth zone corresponded to the known caliche and highlighted some new areas as well. We then selected other 1000-acre patches and added them to the dataset. Some hand editing was necessary to remove patches adjacent to mountains or slopes where the shallow restrictive layer was likely due to bedrock not caliche.

Figure 2.4: Surficial Settings.

Integrating Bedrock Geology and Surficial Substrates

To create the final geology setting map for the study area, we combined the surficial classes and the bedrock classes to fully cover the study area with the appropriate bedrock or surficial settings (Figure 2.5).

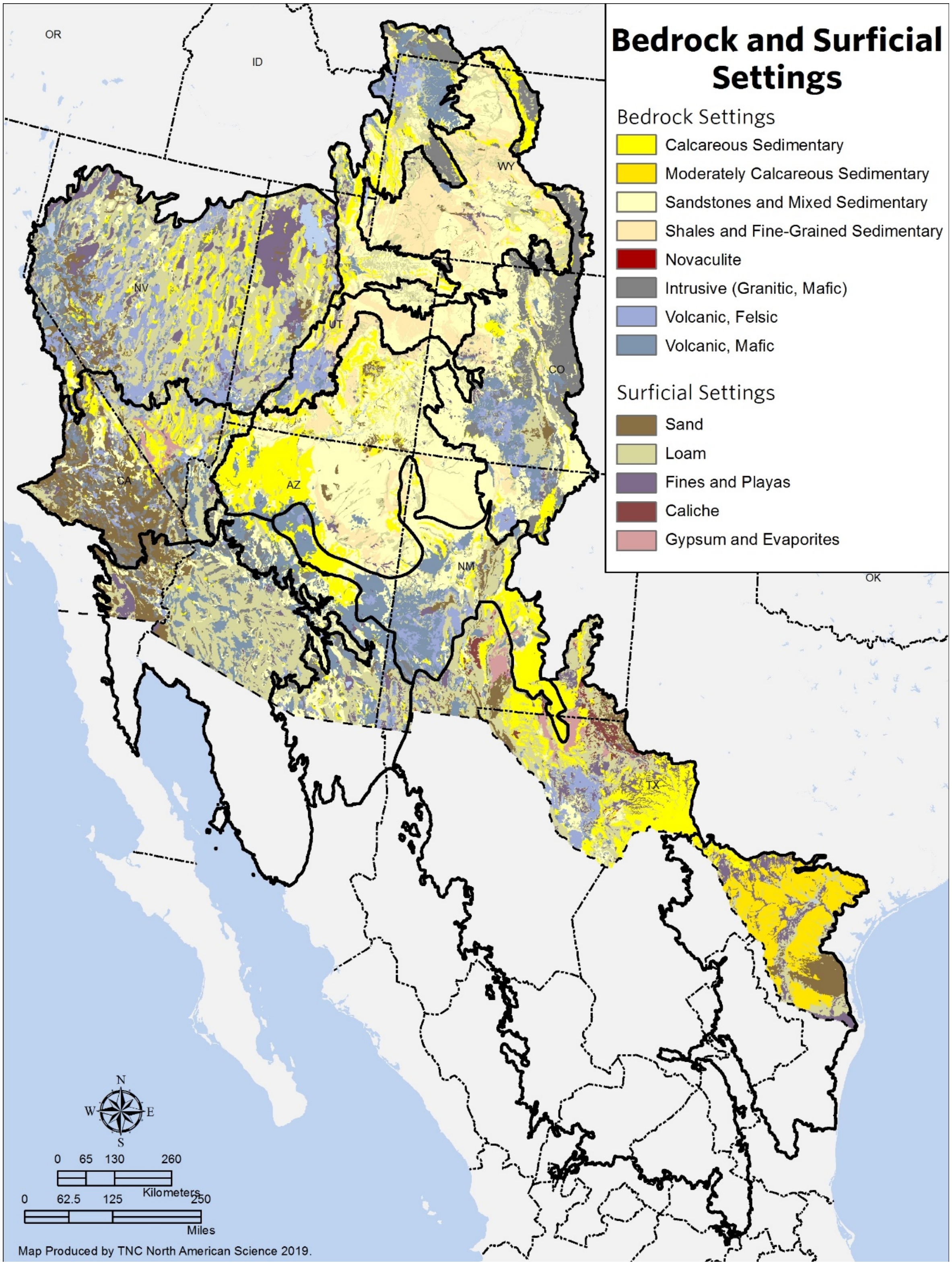
We smoothed the results by eliminating small occurrences of individual setting polygons less than 1000 acres in size. We used a combination of the "Eliminate function" and the Euclidean "nibble" function in ArcGIS to replace small areas with the closest adjacent bedrock or surficial setting type. Small patches or outcrops of geology may be nested within the dominant settings, but we were aiming for patches likely to support the representative suite of flora and fauna typical of the setting.

The bedrock settings represent 64% of the study area and the surficial settings represent 36% of the study area (Table 2.1). The two most common bedrock settings are Sandstones (21%) and Calcareous (12%) sedimentary rock. The two most common surficial settings are Loams (25%).

Table 2.1: Acres of each Bedrock and Surficial Setting

	Substrate	Land Acres	Water Acres	Total Acres	Percent
Bedrock	Calcareous Sedimentary	47,561,972	38,192	47,600,164	11.9
	Moderately Calcareous Sedimentary	9,856,124	30,042	9,886,167	2.5
	Sandstones and Mixed Sedimentary	84,604,481	117,503	84,721,984	21.1
	Shale and Fine-Grained Sedimentary	24,257,995	40,622	24,298,617	6.1
	Novaculite	23,586	0	23,586	0.0
	Intrusives (Granitic, Mafic)	28,890,307	67,983	28,958,290	7.2
	Volcanic, Felsic	24,745,364	11,083	24,756,448	6.2
	Volcanic, Mafic	34,214,927	28,324	34,243,251	8.5
Surficial	Sand	21,634,851	140,788	21,775,640	5.4
	Loams	97,307,641	1,203,239	98,510,880	24.6
	Fines and Playas	20,812,509	931,663	21,744,172	5.4
	Gypsum and Evaporite	2,682,921	1,256	2,684,177	0.7
	Caliche	1,726,182	725	1,726,907	0.4
	Grand Total	398,318,862	2,611,420	400,930,282	100.0

Figure 2.5: Bedrock and Surficial Settings. The 12 major geology settings in the Rocky Mountain–Southwest Desert study area.



Life Zones

We defined four high elevation-based life zones: **Alpine, Subalpine, Upper Montane, and Lower Montane** and four low elevation zones: **Cold Desert Lowlands**, **Warm Desert Lowlands**, **Mountain Lowlands**, and **Coastal/Tropical Lowlands**.

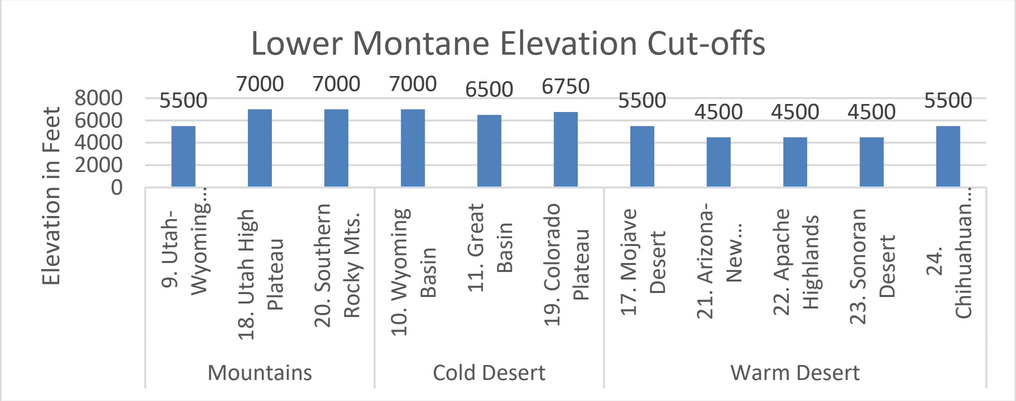
The four high elevation zones were mapped using Landfire Biophysical System Model dataset as the base data (LANDFIRE 2014: bps5b.tif 5/14/2019 Comer et al.). LANDFIRE's Biophysical Settings represents the vegetation that may have been dominant on the landscape prior to Euro-American settlement and is based on both the current biophysical environment and an approximation of the historical disturbance regime. Map units are based on NatureServe's Ecological Systems classification and represent the natural plant communities that may have been present during the reference period. A table relating the Biophysical System Name to life zone was provided by Pat Comer (per comm. Pat Comer 8/12/2019). This grouping placed the hundreds of named biophysical systems into general life zone categories and we mapped the collective distribution of all the biophysical systems in each life zone to create the life zone map (Table 2.2).

Table 2.2. Example of Biophysical Settings in each Life Zone.

Life Zone	Examples of LANDFIRE Biophysical Settings in each zone
Alpine	Rocky Mountain Alpine Bedrock and Scree, Rocky Mountain Alpine Turf
Subalpine	Rocky Mountain Subalpine Dry-Mesic Spruce-Fir Forest and Woodland, Rocky Mountain Lodgepole Pine Forest
Upper Montane	Rocky Mountain Aspen Forest and Woodland, Northern Rocky Mountain, Madrean Upper Montane Conifer-Oak Forest and Woodland
Lower Montane	Southern Rocky Mountain Dry-Mesic Montane Mixed Conifer Forest and Woodland, Southern Rocky Mountain Ponderosa Pine Woodland, Colorado Plateau Pinyon-Juniper Woodland

Steering committee review of the map suggested that the approach worked well, but highlighted errors at low elevations. To refine the map and correct errors in these life zones, we applied the same smoothing as for the bedrock and soils (a circular 100-acre focal maximum function) to remove isolated or small groups of pixels. We then applied elevation thresholds within each ecoregion to restrict the lowest elevational point at which each life zone areas could extend (Figure 2.7). We also filled holes in the LANDFIRE data using elevation rules to estimate classes for unassigned land area by assigning it to the most likely lifezone. With these modifications, the life zone map appeared to be quite accurate (Figure 2.6).

Figure 2.7. Elevation limit for Lower Montane Life Zone by Ecoregion.



Lower elevation life zones (elevations below the Lower Montane) were assigned to one of four geographic zones types to match their ecoregion and region as described in Chapter 1: Cold Desert Lowlands, Warm Desert Lowlands, Mountain Lowlands, and Coastal/Tropical Lowlands.

As with geology and soils, we applied the same 1000-acre minimum smoothing (100 acres for Alpine) to ensure that mapped life zone patches were large enough to contain their typical flora and fauna (Table 2.3).

Table 2.3: Acres of each Life Zone

Life Zone	Land Acres	Water Acres	Total Acres	Percent
Alpine	4,089,464	21,593	4,111,057	1.0
Subalpine	17,215,654	64,788	17,280,442	4.3
Upper Montane	6,883,586	39,387	6,922,974	1.7
Lower Montane	50,919,086	133,013	51,052,099	12.7
Mountain Lower Basin	41,120,316	220,874	41,341,190	10.3
Warm Desert Basin	115,197,825	478,701	115,676,527	28.9
Cold Desert Basin	143,390,207	1,510,361	144,900,567	36.1
Tropical Lowland	19,502,724	142,703	19,645,427	4.9
Grand Total	398,318,862	2,611,420	400,930,282	100.0

Integrating Life Zones and Geology into Geophysical Settings

The 13 geology or surficial types were combined with the 8 life zones for the final geophysical settings. This combination yielded 73 actual combinations with acreage >1000 acres (Table 2.4).

Figure 2.6: Life Zones. The major life zones in the study area. The four high elevation zones make up 20% of the study area while 80% of the region is in one of the lowland basins.

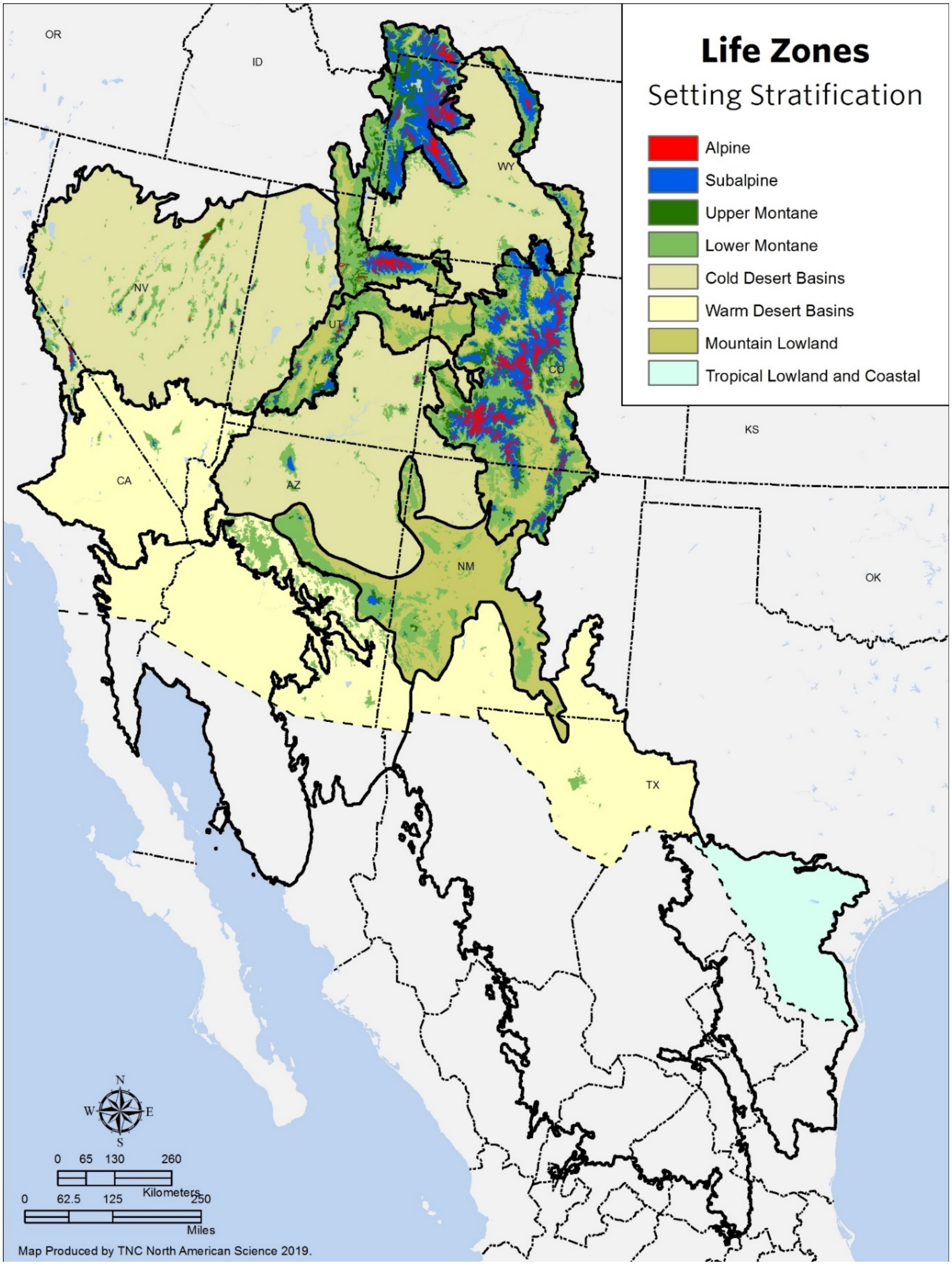


Figure 2.7: Geophysical Settings. The geophysical settings are a combination of life zones and bedrock/surficial geology.

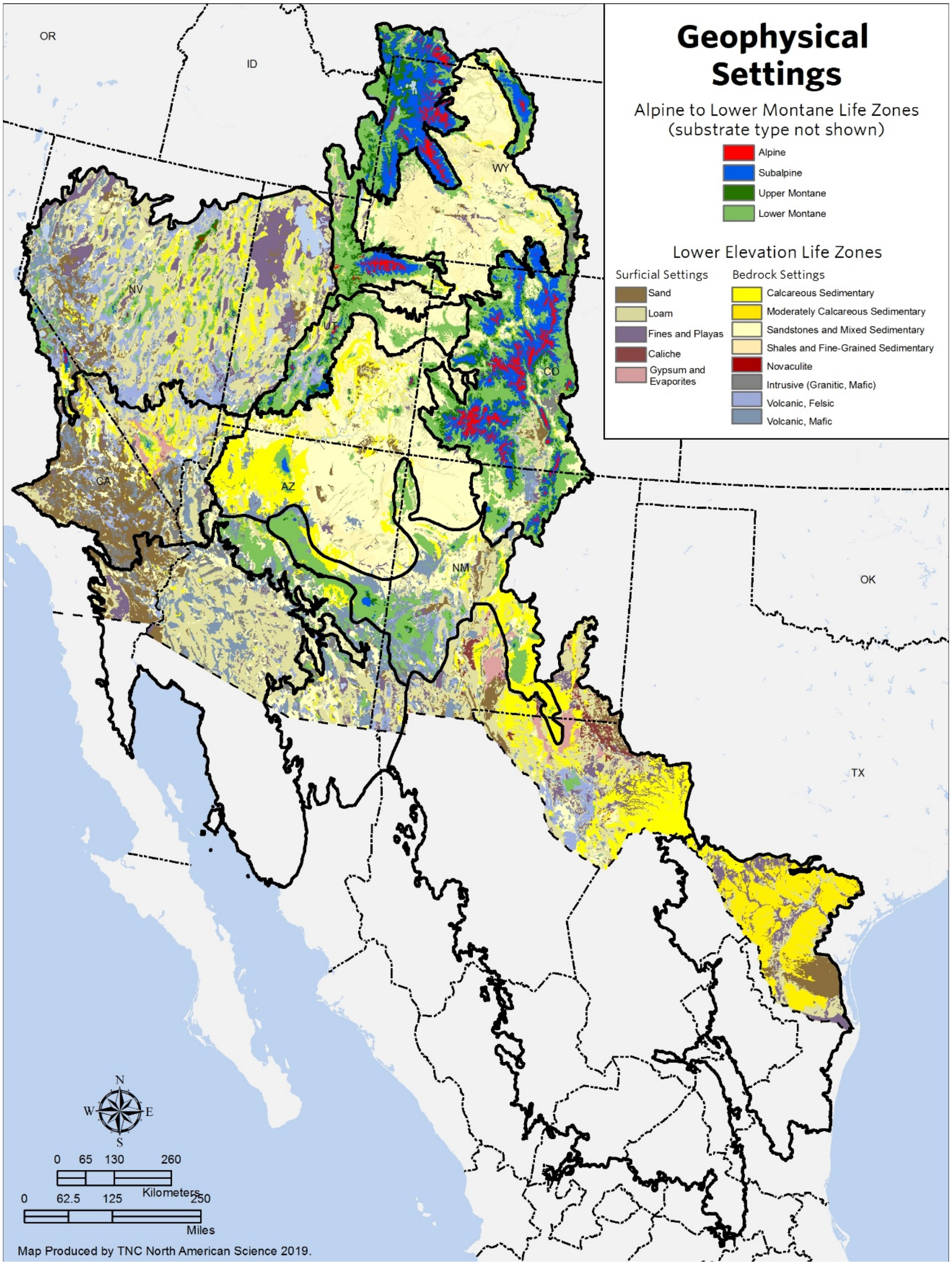


Table 2.4: Acres of each Setting. The different types of geologic settings within the upper elevation life zones were collapsed in this summary table given their small acreages.

Setting	Land Acres	Water Acres	Total Acres	Percent
Alpine	4,089,464	21,593	4,111,057	1.0
Subalpine	17,215,654	64,788	17,280,442	4.3
Upper Montane	6,883,586	39,387	6,922,974	1.7
Lower Montane	50,919,086	133,013	51,052,099	12.7
Mountain Lower Basin: Calcareous Sedimentary	5,620,813	4,058	5,624,871	1.4
Mountain Lower Basin: Fines and Playas	937,180	10,958	948,138	0.2
Mountain Lower Basin: Gypsum and Evaporite	99,386	13	99,399	0.0
Mountain Lower Basin: Intrusives (Granitic, Mafic)	1,899,492	4,555	1,904,047	0.5
Mountain Lower Basin: Loams	7,810,291	158,802	7,969,093	2.0
Mountain Lower Basin: Sand	937,979	1,301	939,281	0.2
Mountain Lower Basin: Sandstones and Mixed Sedimentary	12,943,135	23,232	12,966,367	3.2
Mountain Lower Basin: Shale and Fine-Grained Sedimentary	3,399,845	13,927	3,413,773	0.9
Mountain Lower Basin: Volcanic, Felsic	2,014,048	1,192	2,015,241	0.5
Mountain Lower Basin: Volcanic, Mafic	5,458,147	2,834	5,460,981	1.4
Warm Desert Basin: Calcareous Sedimentary	14,270,402	5,046	14,275,449	3.6
Warm Desert Basin: Caliche	1,726,182	725	1,726,907	0.4
Warm Desert Basin: Fines and Playas	6,090,831	161,082	6,251,913	1.6
Warm Desert Basin: Gypsum and Evaporite	2,583,535	1,243	2,584,778	0.6
Warm Desert Basin: Intrusives (Granitic, Mafic)	9,729,764	8,220	9,737,984	2.4
Warm Desert Basin: Loams	39,660,835	243,172	39,904,007	10.0
Warm Desert Basin: Moderately Calcareous Sedimentary	15,763		15,763	0.0
Warm Desert Basin: Novaculite	23,586		23,586	0.0
Warm Desert Basin: Sand	13,990,402	34,809	14,025,211	3.5
Warm Desert Basin: Sandstones and Mixed Sedimentary	10,831,426	12,174	10,843,601	2.7
Warm Desert Basin: Shale and Fine-Grained Sedimentary	2,731		2,731	0.0
Warm Desert Basin: Volcanic, Felsic	6,009,626	1,555	6,011,181	1.5
Warm Desert Basin: Volcanic, Mafic	10,262,742	10,675	10,273,417	2.6
Cold Desert Basin: Calcareous Sedimentary	15,469,852	20,797	15,490,649	3.9
Cold Desert Basin: Fines and Playas	10,056,212	709,505	10,765,716	2.7
Cold Desert Basin: Intrusives (Granitic, Mafic)	2,639,782	1,619	2,641,401	0.7
Cold Desert Basin: Loams	38,272,075	588,801	38,860,876	9.7
Cold Desert Basin: Sand	4,429,621	100,171	4,529,793	1.1
Cold Desert Basin: Sandstones and Mixed Sedimentary	40,706,720	61,397	40,768,118	10.2
Cold Desert Basin: Shale and Fine-Grained Sedimentary	15,779,490	23,274	15,802,764	3.9
Cold Desert Basin: Volcanic, Felsic	9,690,243	1,027	9,691,270	2.4
Cold Desert Basin: Volcanic, Mafic	6,346,211	3,769	6,349,980	1.6
Tropical Lowland: Calcareous Sedimentary	844,975	2,993	847,968	0.2
Tropical Lowland: Fines and Playas	3,124,150	47,348	3,171,497	0.8
Tropical Lowland: Loams	3,394,761	57,813	3,452,574	0.9
Tropical Lowland: Moderately Calcareous Sedimentary	9,840,361	30,042	9,870,403	2.5
Tropical Lowland: Sand	2,226,289	4,405	2,230,694	0.6
Tropical Lowland: Sandstones and Mixed Sedimentary	69,343	99	69,441	0.0
Tropical Lowland: Volcanic, Mafic	2,846	3	2,849	0.0
Grand Total	398,318,862	2,611,420	400,930,282	100.0

Characterizing the Geophysical Settings

Geophysical Settings and their Current Biota

The land's physical setting influences the type and diversity of natural communities occurring on a site. While we do not know exactly how the communities will rearrange, evidence from other climate zones suggests 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 distinct alkaline-tolerant flora, as well as fine-filter targets like cave-adapted species. These differ from the drought and fire-adapted species more common in sand (Kruckeberg 2004, Anderson and Ferree 2010, Beier and Brost 2010).

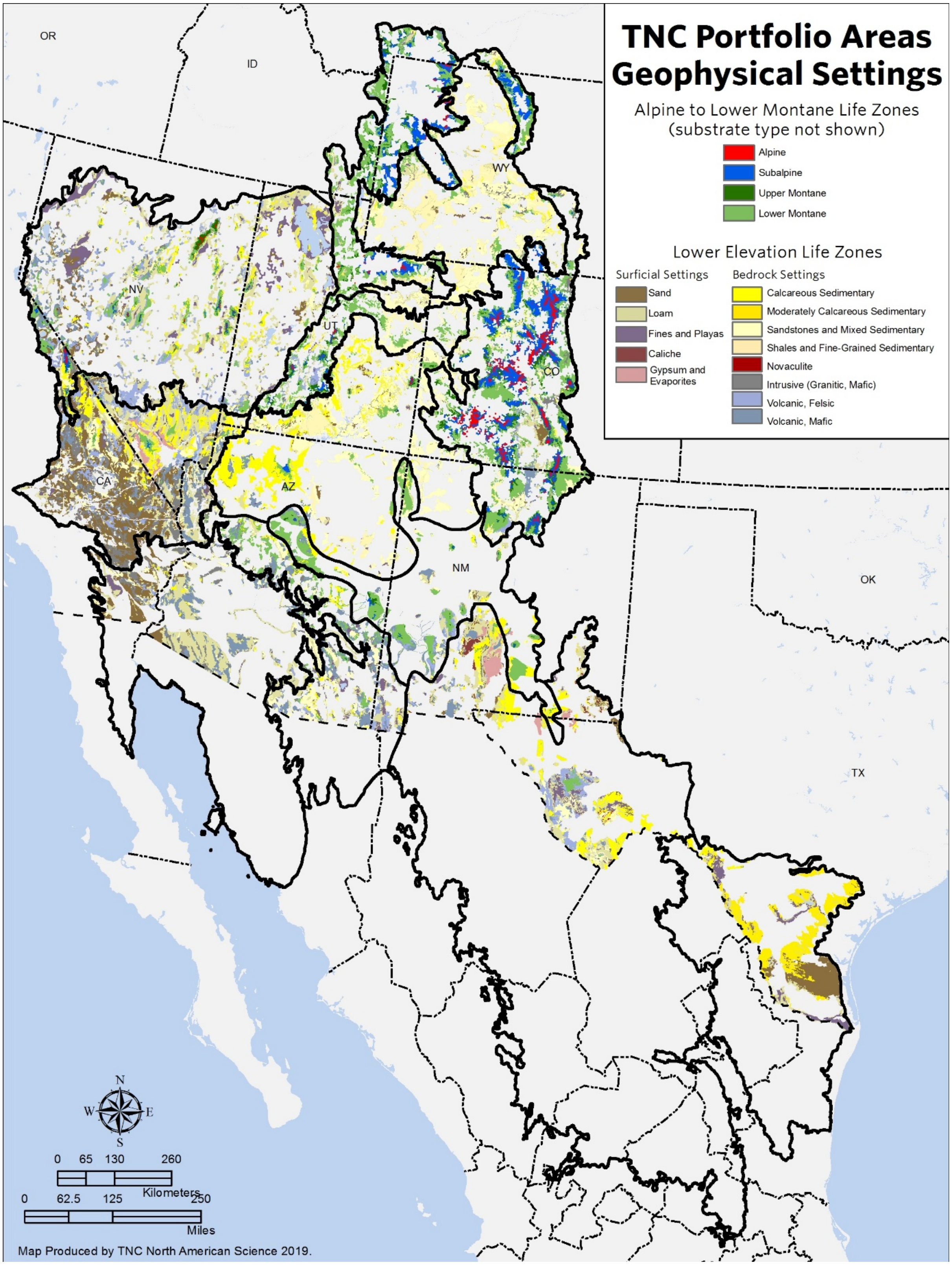
To characterize the dominant vegetation of each lifezone we overlaid the LANDFIRE Biophysical Settings (vegetation that may have been dominant on the landscape prior to Euro-American settlement) and Existing Vegetation Types (complexes of *current* plant communities) on the settings map (LANDFIRE 2014). We summarized the dominant types that had an extent over one million acres plus a few smaller types that seemed particularly characteristic.

To assess the associations between the current biota and each geophysical setting we overlaid the TNC ecoregional portfolio sites on the geophysical setting data. TNC portfolio sites are areas with intact habitat, viable rare species populations, or unique communities characteristic of their ecoregion (see full description in Chapter 8). For each portfolio site we tabulated the type and amount of each life zone and geological class (Figure 2.8). After characterizing the physical characteristic of each portfolio site, we assigned the site's dominant life zone and geological class to all the conservation targets listed for the site. The target lists were based on Natural Heritage Program element occurrences and consisted of verified examples of viable rare species population, intact habitats, or representative examples of natural communities that were on the site.

We queried the data set for species that were associated with each life zone or geological class. First, we identified a subset of portfolio sites that were predominantly (>50%) within a single life zone or geological class and then looked across site to identify birds, mammals, herptiles and plant that were predominantly (> 50%) within a single life zone or geological class. We ignored communities or species where we only had one sample except in those cases where the data was very sparse (e.g., Novaculite, Gypsum, etc.)

The TNC portfolio targets were comprised of representative vegetation types and populations of rare species. 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.

Figure 2.8: TNC Portfolio Areas by Geophysical Setting. Distribution of Species and Natural Community Element Occurrences within TNC Portfolio Areas was summarized by Geophysical Setting



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. Species data are more complete for vertebrates and vascular plants but include selected species of invertebrates from groups such as beetles, snails, and butterflies.

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). It appears that only Colorado and Texas systematically tracks natural community occurrences, other states tend to use vegetation maps as their base community data.

The results are summarized below to give readers 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. Familiar ecosystem and community types may be present in some form in the future but their specific composition and structure could vary widely from their current expression.

In some parts of the study we also had access to the current Natural Heritage data and these were used largely to confirm accuracy of geologic datasets assembled for this project. The sample was limited in distribution to four states in the eastern portion of the study area provided by Nature Serve: MN, WY, CO, and TX. These were distributed across the four regions as follows: Mountains (21,615 EOs), Cold Deserts (29,888 EOs), Warm Deserts (1717 EOs), Tropical Lowland (200 EOs). Total 53,420 EOs.

Current Biota by Geophysical Setting

ALPINE and SUBALPINE

High elevation areas, generally over 11,000 feet with a distinctive biota shaped by cold and high winds. These two life zones are concentrated in the mountain ecoregions, but small amounts occur in the Great Basin, Colorado Plateau, Mojave Desert and Chihuahuan Desert. In total, Alpine and Subalpine life zones cover 21 million acres, 5.3 % of the study area (Figure 2.6).

Alpine Communities

Alpine dry tundra & wet meadow
Alpine fellfields
Alpine meadows
Alpine scrub
Alpine snowbed
Alpine substrate - ice field
Alpine tundra - dwarf shrub & fell field
Alpine wetland
Alpine willow scrub
Dry alpine meadows
Mesic alpine meadows
Rocky Mountain Alpine Turf
Rocky Mountain Alpine Dwarf-Shrubland
Rocky Mountain Alpine Bedrock and Scree, Rocky Mountain Alpine Turf
Snow-Ice

Subalpine Communities

Inter-Mountain Basins Subalpine Limber-Bristlecone Pine Woodland
Northern Rocky Mountain Subalpine Deciduous Shrubland
Northern Rocky Mountain Subalpine Woodland and Parkland
Northern Rocky Mountain Subalpine-Upper Montane Grassland
Rocky Mountain Subalpine Dry-Mesic Spruce-Fir Forest and Woodland
Rocky Mountain Lodgepole Pine Forest
Rocky Mountain Subalpine Mesic-Wet Spruce-Fir Forest and Woodland
Rocky Mountain Subalpine/Upper Montane Riparian Forest and Woodland
Rocky Mountain Subalpine/Upper Montane Riparian Shrubland
Rocky Mountain Subalpine-Montane Mesic Meadow
Southern Rocky Mountain Montane-Subalpine Grassland
Subalpine Douglas-fir Forest

Species (Alpine or Subalpine)

This data is from TNC portfolio sites which tend encompass both alpine and subalpine environments which commonly co-occur on the landscape. These species were found in one or the other or both.

Birds

Brown-capped Rosy-Finch *(Leucosticte australis)*
Common Loon *(Gavia immer)*
Western Screech-Owl *(Megascops kennicottii)*
White-winged Crossbill *(Loxia leucoptera)*

Mammals

Pygmy Shrew *(Sorex hoyi montanus)*

Plants

Absaroka Beardtongue *(Penstemon absarokensis)*
Alpine Aster *(Aster alpinus var. vierhapperi)*
Alpine Poppy *(Papaver radicatum ssp. kluanense)*
Altai Cotton-grass *(Eriophorum altaicum)*
Angell Cinquefoil *(Potentilla angelliae)*
Aquarius Indian-paintbrush *(Castilleja aquariensis)*
Aromatic Pussytoes *(Antennaria aromatica)*
Avery Peak Twinpod *(Physaria alpina)*
Boreal Whitlow-grass *(Draba borealis)*
Colorado Cinquefoil *(Potentilla subjuga)*
Colorado Divide Whitlow-grass *(Draba streptobrachia)*
Colorado Tansy-aster *(Machaeranthera coloradoensis)*
Downy Indian-paintbrush *(Castilleja puberula)*
False Uncinia Sedge *(Carex microglochin)*
Globe Gilia *(Ipomopsis globularis)*
Grassy Slope Sedge *(Carex oreocharis)*

Gray's Peak Whitlow-grass *(Draba grayana)*
Greater Red Indian-paintbrush *(Castilleja crista-galli)*
Greenland Primrose *(Primula egaliksensis)*
Hairy False Goldenaster *(Heterotheca villosa)*
Ice Grass *(Phippsia algida)*
King's Campion *(Silene kingii)*
Kirkpatrick Ipomopsis *(Ipomopsis spicata)*
Linear-leaf Discoid Gumweed *(Ericameria discoidea var. linearis)*
Low Braya *(Braya humilis)*
Molybdenum Milkvetch *(Astragalus molybdenus)*
Mountain Bladderfern *(Cystopteris montana)*
Mountain Lousewort *(Pedicularis pulchella)*
Mountain Whitlow-grass *(Draba rectifructa)*
Nagoonberry *(Rubus arcticus ssp. acaulis)*
Naked-stemmed Wallflower *(Parrya nudicaulis)*
Nelson's Sedge *(Carex nelsonii)*
Patterson's Wormwood *(Artemisia pattersonii)*
Payson's Whitlow-grass *(Draba paysonii)*
Penland's Alpine Fen Mustard *(Eutrema penlandii)*
Pink Agoseris *(Agoseris lackschewitzii)*
Porter's Feathergrass *(Ptilagrostis porteri)*
Railhead Milkvetch *(Astragalus terminalis)*
Reflected Moonwort *(Botrychium echo)*
Rockcress Draba *(Draba globosa)*
Rocky Mountain Beardtongue *(Penstemon cyathophorus)*
Rocky Mountain Columbine *(Aquilegia saximontana)*
Rocky Mountain Nailwort *(Paronychia pulvinata)*
Rolland's Bulrush *(Trichophorum rollandii)*
Rothrock's Townsend-daisy *(Townsendia rothrockii)*
Rough Fescue *(Festuca hallii)*
Showy Whitlow-grass *(Draba spectabilis)*
Siberean Sea Thrift *(Armeria maritima ssp. sibirica)*
Single-head Pussytoes *(Antennaria monocephala)*
Slender Indian-paintbrush *(Castilleja gracillima)*
Smooth Rockcress *(Braya glabella)*
Taprooted Fleabane *(Erigeron radicatus)*
Teton Wire-lettuce *(Stephanomeria fluminea)*
Thread-branch Stitchwort *(Minuartia filiorum)*
Weber's Saw-wort *(Saussurea weberi)*
Weber's Scarlet Gilia *(Ipomopsis aggregata)*
Weber's Whitlow-grass *(Draba weberi)*
Wind River Whitlow-grass *(Draba ventosa)*
Wolf Willow *(Salix wolfii var. wolfii)*
Woolly Fleabane *(Erigeron lanatus)*

UPPER and LOWER MONTANE

Mountainous areas between 4,000 to 11,000 feet depending on the ecoregion. These two life zones are widespread and found in association with high foothills to towering mountains. Together they cover 59 million acres, 14% of the study area (Figure 2.6).

Upper Montane Communities and Vegetation Types

Rocky Mountain Aspen Forest and Woodland
Northern Rocky Mountain, Madrean Upper Montane Conifer-Oak Forest and Woodland
Northern Rocky Mountain Subalpine-Upper Montane Grassland
Rocky Mountain Subalpine/Upper Montane Riparian Forest and Woodland
Rocky Mountain Subalpine/Upper Montane Riparian Shrubland

Lower Montane Communities and Vegetation Types

California Lower Montane Blue Oak-Foothill Pine Woodland and Savanna
Great Basin Foothill and Lower Montane Riparian Woodland and Shrubland
Inter-Mountain Basins Montane Riparian Forest and Woodland
Inter-Mountain Basins Montane Sagebrush Steppe
Madrean Lower Montane Pine-Oak Forest and Woodland
Mediterranean California Foothill and Lower Montane Riparian Woodland and Shrubland
Mediterranean California Lower Montane Black Oak-Conifer Forest and Woodland
Middle Rocky Mountain Montane Douglas-fir Forest and Woodland
North American Warm Desert Lower Montane Riparian Woodland and Shrubland
Northern Rocky Mountain Lower Montane Riparian Woodland and Shrubland
Northern Rocky Mountain Lower Montane-Foothill-Valley Grassland
Northern Rocky Mountain Montane-Foothill Deciduous Shrubland
Rocky Mountain Lower Montane-Foothill Riparian Woodland and Shrubland
Rocky Mountain Lower Montane-Foothill Shrubland
Rocky Mountain Montane Riparian Forest and Woodland
Rocky Mountain Montane Riparian Shrubland
Southern Rocky Mountain Dry-Mesic Montane Mixed Conifer Forest and Woodland,
Southern Rocky Mountain Mesic Montane Mixed Conifer Forest and Woodland
Southern Rocky Mountain Ponderosa Pine Woodland,
Xeric Montane Douglas-fir Forest

Species (Upper or Lower Montane)

This data is from TNC portfolio sites which to encompass both upper and lower montane environments which commonly co-occur on the landscape. These species were found in one or the other, or both.

Birds

American Three-toed Woodpecker *(Picoides dorsalis)*
Boreal Owl *(Aegolius funereus)*
Great Gray Owl *(Strix nebulosa)*
Lazuli Bunting *(Passerina amoena)*
Sharp-tailed Grouse *(Tympanuchus phasianellus)*
Trumpeter Swan *(Cygnus buccinator-RM pop)*

Mammals

Brown bear *(Ursus arctos)*
Canada lynx *(Lynx canadensis)*
Dwarf shrew *(Sorex nanus)*
Elk *(Cervus canadensis)*
Fisher *(Martes pennanti)*
North American river otter (Lontra canadensis)
North American water vole *(Microtus richardsoni)*
Preble's meadow jumping mouse *(Zapus hudsonius preblei)*
Wolverine *(Gulo gulo)*

Herptiles

Columbia Spotted Frog *(Rana luteiventris)*
Sacramento Mountain Salamander *(Aneides hardii)*
Short-horned Lizard *(Phrynosoma hernandesi)*
Western Toad *(Bufo boreas)*

Plants

Surficial

Loam

Utah Ivesia *(Ivesia utahensis)*

Plants

Bedrock

Calcareous

Arizona Bugbane (Actaea arizonica)
Cedar Breaks Biscuitroot (Cymopterus minimus)
Cedar Breaks Goldenbush (Ericameria zionis)
King's Serpentweed (Tonestus kingii var. barnebyana)
Peterson's Catchfly (Silene petersonii)
Podunk Groundsel (Packera malmstenii)
Reveal's Indian-paintbrush (Castilleja revealii)
Rock Fleabane (Erigeron saxatilis)
Senator Mine Alumroot (Heuchera eastwoodiae)
Wyoming Townsend-daisy (Townsendia alpigena var. caelilinensis)

Sandstone / Coarse-Grained Sedimentary Bedrock

Goodrich's Blazingstar (Mentzelia goodrichii)
Mt. Bartles Buckwheat (Eriogonum brevicaule var. promiscuum)
Payson's Bladderpod (Lesquerella paysonii)
Repand Twinpod (Physaria repanda)
Untermann's Daisy (Erigeron untermannii)

Shale / Fine-Grained Sedimentary Bedrock

Canyon Sweet-vetch *(Hedysarum occidentale)*
Piceance bladderpod (*Lesquerella parviflora*)
Purpus' sullivantia *(Sullivantia hapemanii)*
Roan Cliffs blazing star *(Mentzelia rhizomata)*
Sun-loving Meadowrue *(Thalictrum heliophilum)*
Yellow Columbine *(Aquilegia flavescens)*

Granite or Volcanic Felsic

Gray Willow *(Salix glauca)*
Rocky Mountain Cinquefoil *(Potentilla rupincola)*

Volcanic / Extrusive Igneous Rocks

Arizona Willow (Salix arizonica)
Creeping Milkvetch (Astragalus troglodytus)
Many-leaf Ivesia (Ivesia multifoliolata)
Mogollon Thistle (Cirsium parryi ssp. mogollonicum)
Western Flameflower (Talinum validulum)

MOUNTAIN LOWLAND

Low elevation valleys, foothills and lowlands in the four mountainous ecoregions: Utah-Wyoming Rocky Mountains, Utah High Plateau, Southern Rocky Mountains and Arizona-New Mexico Mountains (Figure 2.6).

Communities and Vegetation Types

Colorado Plateau Pinyon-Juniper Woodland
Inter-Mountain Basins Big Sagebrush Shrubland
Inter-Mountain Basins Greasewood Flat
Inter-Mountain Basins Mixed Salt Desert Scrub
Inter-Mountain Basins Semi-Desert Grassland
Inter-Mountain Basins Semi-Desert Shrub-Steppe
Ponderosa pine forest and woodland
Riparian woodland community
Rocky mountain aspen forest and woodland
Rocky mountain juniper woodland and savanna
Rocky Mountain Lower Montane-Foothill Riparian Woodland and Shrubland
San Luis Valley Winterfat Shrub Steppe
Southern Rocky Mountain dry-mesic montane mixed conifer forest and woodland
Southern Rocky Mountain Juniper Woodland and Savanna
Southern Rocky Mountain Pinyon-Juniper Woodland
Southern Rocky Mountain Ponderosa Pine Savanna
Southern Rocky Mountain Ponderosa Pine Woodland
Winterfat shrub steppe

Birds

Band-tailed Pigeon *(Patagioenas fasciata)*
Common Grackle *(Quiscalus quiscula)*
Grace's Warbler *(Dendroica graciae)*
Greater Sandhill Crane *(Grus canadensis tabida)*
Red-faced Warbler *(Cardellina rubrifrons)*
Whip-poor-will *(Caprimulgus vociferus)*

Mammals

Botta's Pocket Gopher *(Thomomys bottae)*
Gunnison's Prairie Dog *(Cynomys gunnisoni)* Least Chipmunk*(Neotamias minimus caryi)*
Merriam's Shrew *(Sorex merriami)*
Ord's Kangaroo Rat *(Dipodomys ordii montanus)*
Silky Pocket Mouse *(Perognathus flavus sanluisi)*
Thirteen-lined Ground Squirrel *(Spermophilus tridecemlineatus blanca)*

Herptiles

Milksnake *(Lampropeltis triangulum)*
Sonoran Mountain Kingsnake *(Lampropeltis pyromelana)*

Plants
Surficial

Loam

Autumn Buttercup *(Ranunculus aestivalis)*
Many-stemmed Spider-flower *(Cleome multicaulis)*

Plants
Bedrock

Calcareous

Biennial Woolly-white *(Hymenopappus biennis)*
Cardinal Beardtongue *(Penstemon cardinalis)*
Chisos Coralroot *(Hexalectris revoluta)*
Golden Columbine *(Aquilegia chrysantha)*
Guadalupe Cliffdaisy *(Chaetopappa hersheyi)*
Guadalupe Fescue *(Festuca ligulata)*
Guadalupe Pincushion Cactus *(Escobaria guadalupensis)*
Guadalupe Valerian *(Valeriana texana)*
Lee's Pincushion Cactus *(Escobaria sneedii var. leei)*
Mckittrick Pennyroyal *(Hedeoma apiculata)*
Payson Hiddenflower *(Cryptantha paysonii)*
Rubber Rabbitbrush *(Ericameria nauseosa)*
Strong Bladderpod *(Lesquerella valida)*
Wooton's Hawthorn *(Crataegus wootoniana)*

Sandstone

Acoma Fleabane *(Erigeron acomanus)*
Barneby's Thistle *(Cirsium barnebyi)*
Dudley Bluffs Bladderpod *(Lesquerella congesta)*
Many-stem Stickleaf *(Mentzelia multicaulis var. librina)*
Piceance Twinpod *(Physaria obcordata)*
Wetherill's Milkvetch *(Astragalus wetherillii)*
White River Beardtongue *(Penstemon scariosus var. albifluvis)*

Shale

Arapien Stickleaf *(Mentzelia argillosa)*
Graham's Beardtongue *(Penstemon grahamii)*
Thrift Mock Goldenweed *(Stenotus armerioides var. gramineus)*
Toad-flax Cress *(Glaucocarpum suffrutescens)*
Uinta Basin Hookless Cactus *(Sclerocactus glaucus)*

Volcanic: Mafic

Cliff Brittlebush *(Apacheria chiricahuensis)*
Goodding's Bladderpod *(Lesquerella gooddingii)*
Porsild's Starwort *(Stellaria porsildii)*
Rock-loving Aletes *(Neoparrya lithophila)*
White Mountain Groundsel *(Packera cynthioides)*

COLD DESERT BASIN

Low elevation basins, lowlands, valleys and foothills in the three cold desert ecoregions: Great Basin, Wyoming Basin, Colorado Plateau (Figure 2.6).

Communities and Vegetation Types

Colorado Plateau Blackbrush-Mormon-tea Shrubland
Colorado Plateau Mixed Bedrock Canyon and Tableland
Colorado Plateau Pinyon-Juniper Woodland
Desert grassland and shrub-steppe
Desert riparian shrubland and woodland
Ephemeral alkaline playa lake, chloride waters
Gardner saltbush flats
Grass riparian and meadow
Greasewood shrubland
Great basin altered andesite pine woodland
Great Basin Foothill and Lower Montane Riparian
Great Basin Foothill and Lower Montane Riparian Woodland and Shrubland
Great Basin Pinyon-Juniper Woodland
Great Basin Xeric Mixed Sagebrush Shrubland
Great Basin Xeric Mixed Sagebrush Shrubland
Great Basin Xeric Mixed Sagebrush Shrubland
Inter-Mountain Basins Active and Stabilized Dune
Inter-Mountain Basins Big Sagebrush Shrubland
Inter-Mountain Basins Big Sagebrush Steppe
Inter-Mountain Basins Cliff and Canyon
Inter-Mountain Basins Greasewood Flat
Inter-Mountain Basins Mat Saltbush Shrubland
Inter-Mountain Basins Mixed Salt Desert Scrub
Inter-Mountain Basins Montane Sagebrush Steppe
Inter-Mountain Basins Playa
Inter-Mountain Basins Semi-Desert Grassland
Inter-Mountain Basins Semi-Desert Shrub-Steppe
Inter-Mountain Basins Shale Badland
Inter-Mountain Basins Sparsely Vegetated Systems
Mojave Mid-Elevation Mixed Desert Scrub
Rocky Mountain Lower Montane-Foothill Riparian Woodland and Shrubland
Southern Colorado Plateau Sand Shrubland
Southern Colorado Plateau Sand Shrubland
Wyoming basins low sagebrush shrubland

Mammals

Bighorn Sheep *(Ovis canadensis)*
Black-footed Ferret *(Mustela nigripes)*
Brazilian Free-tailed Bat *(Tadarida brasiliensis)*
Chisel-toothed Kangaroo Rat *(Dipodomys microps)*
Hoary Bat *(Lasiurus cinereus)*
Idaho Pocket Gopher *(Thomomys idahoensis)*
Pygmy Rabbit *(Brachylagus idahoensis)*
Sierra Nevada Bighorn Sheep *(Ovis canadensis)*
Silver-haired Bat *(Lasionycteris noctivagans)*
Spotted Bat *(Euderma maculatum)*
Swift Fox *(Vulpes velox)*
Uinta Ground Squirrel *(Spermophilus armatus)*
Utah Prairie Dog *(Cynomys parvidens)*
White-tailed Prairie Dog *(Cynomys leucurus)*

Birds

American White Pelican *(Pelecanus erythrorhynchos)*
Blue Grosbeak *(Passerina caerulea)*
Brewer's Sparrow *(Spizella breweri)*
Cooper's Hawk *(Accipiter cooperii)*
Ferruginous Hawk *(Buteo regalis)*
Gray Flycatcher *(Empidonax wrightii)*
Gray Vireo *(Vireo vicinior)*
Greater Sage-Grouse *(Centrocercus urophasianus)*
Horned Grebe *(Podiceps auritus)*
Juniper Titmouse *(Baeolophus ridgwayi)*
Long-billed Curlew *(Numenius americanus)*
Northern Harrier *(Circus cyaneus)*
Peregrine Falcon *(Falco peregrinus)*
Pinyon Jay *(Gymnorhinus cyanocephalus)*
Prairie Falcon *(Falco mexicanus)*
Redhead *(Aythya americana)*
Sage Sparrow *(Amphispiza belli)*
Sage Thrasher *(Oreoscoptes montanus)*
Sandhill Crane *(Grus canadensis)*
Swainson's Hawk *(Buteo swainsoni)*
Virginia's Warbler *(Vermivora virginiae)*
Western Snowy Plover *(Charadrius alexandrinus)*
White-faced Ibis *(Plegadis chihi)*
Wilson's Phalarope *(Phalaropus tricolor)*
Yellow-breasted Chat *(Icteria virens)*

Herptiles

Midget Faded Rattlesnake *(Crotalus oreganus)*
Northern Plateau Lizard *(Sceloporus undulatus)*
Smooth Green Snake *(Liochlorophis vernalis)*
Tree Lizard *(Urosaurus ornatus)*
Utah Mountain Kingsnake *(Lampropeltis pyromelana)*
Utah Night Lizard *(Xantusia vigilis utahensis)*

Plants
Surficial

Loam

Barneby's Caulanthus *(Caulanthus barnebyi)*
Blaine's Pincushion *(Sclerocactus blainei)*
Cactus Flat Gily-flower *(Gilia heterostyla)*
Callaway Milkvetch *(Astragalus callithrix)*
Candelaria Blazingstar *(Mentzelia candelariae)*
Compact Cat's-eye *(Cryptantha compacta)*
Coulter's Biscuitroot *(Cymopterus coulteri)*
Currant Milkvetch *(Astragalus uncialis)*
Desert Valley Fishhook Cactus *(Sclerocactus spinosior)*
Eastwood's Milkweed *(Asclepias eastwoodiana)*
Frisco Clover *(Trifolium friscanum)*
Ibex Wild Buckwheat *(Eriogonum ammophilum)*
Intermountain Wavewing *(Cymopterus basalticus)*
Jan's Catchfly *(Silene nachlingerae)*
Jone's Globemallow *(Sphaeralcea caespitosa)*
Limestone Wild Buckwheat *(Eriogonum eremicum)*
Low Beardtongue *(Penstemon nanus)*
Monte Neva Paintbrush *(Castilleja salsuginosa)*
One-leaflet Torrey Milkvetch *(Astragalus calycosus var. monophyllidius)*
Parish's Phacelia *(Phacelia parishii)*
Plains Wavewing *(Cymopterus acaulis var. parvus)*
Pohl's Milkvetch *(Astragalus lentiginosus var. pohlii)*
Rayless Tansy-aster *(Machaeranthera grindelioides var. depressa)*
Rock Purpusia *(Ivesia arizonica var. saxosa)*
Sand Cholla *(Opuntia pulchella)*
Snake Range Bladderpod *(Lesquerella pendula)*
Son's Wild Buckwheat *(Eriogonum natum)*
Southwestern Phacelia *(Phacelia glaberrima)*
Squalid Milkvetch *(Astragalus serenoi var. sordescens)*
Sunnyside Green-gentian *(Frasera gypsicola)*
Tunnel Springs Beardtongue *(Penstemon concinnus)*
Welsch's Cat's-eye *(Cryptantha welshii)*
White River Valley Beardtongue *(Penstemon barnebyi)*
Winged Milkvetch *(Astragalus pterocarpus)*

Fines and Playas

Lahontan Basin Buckwheat *(Eriogonum rubricaule)*

Sand

Fourwing Saltbush (Atriplex canescens)
Tonopah Milkvetch (Astragalus pseudiodanthus)

Plants
Bedrock

Calcareous Sedimentary

Branched Fleabane *(Erigeron allocotus)*
Cronquist's Phacelia *(Phacelia cronquistiana)*
Fickeisen's Hedgehog Cactus *(Pediocactus peeblesianus var. fickeiseniae)*
Grand Canyon Catchfly *(Silene rectiramea)*
Grand Canyon Flaveria *(Flaveria macdougalii)*
Grand Canyon Rose *(Rosa stellata ssp. abyssa)*
Hevron's Milkvetch *(Astragalus cremnophylaxi)*
House Range Primrose *(Primula domensis)*
Knight Rock Phacelia *(Phacelia petrosa)*
Largeleaf Spring-parsley *(Cymopterus megacephalus)*
Mt. Tumbull Beardtongue *(Penstemon distans)*
Nodding-flower Scorpionweed *(Phacelia laxiflora)*
Pennyroyal-leaf Scorpionweed *(Phacelia glechomifolia)*
Purpus' Sullivantia *(Sullivantia hapemanii)*
Sentry Milkvetch *(Astragalus cremnophylax)*
Sheep Fleabane *(Erigeron ovinus)*
Southwestern Pepper-grass *(Lepidium nanum)*
Waxflower *(Jamesia tetrapetala)*
Willow Glow-weed *(Hesperodoria salicina)*

Sandstone and other Coarse-grained Sedimentary

Alcove Rockdaisy *(Perityle specuicola)*
Altai Chickweed *(Stellaria irrigua)*
Aromatic Scurfpea *(Pediomelum aromaticum)*
Aztec Gilia *(Gilia formosa)*
Beath's Milkvetch *(Astragalus beathii)*
Caespitose Cat's-eye *(Cryptantha caespitosa)*
Canyonlands Lomatium *(Lomatium latilobum)*
Cliff Jamesia *(Jamesia americana var. zionis)*
Colorado Desert-parsley *(Lomatium concinnum)*
Debris Milkvetch *(Astragalus detritalis)*
Desert Mountain Phlox *(Phlox austromontanans)*
Devil's Gate Twinpod *(Physaria eburniflora)*
Dolores River Skeleton-plant *(Lygodesmia doloresensis)*
Duchesne Milkvetch *(Astragalus duchesnensis)*
Entrada Skeletonplant *(Lygodesmia entrada)*
Erect Cryptantha *(Cryptantha stricta)*
Fisher Milkvetch *(Astragalus piscator)*
Gibben's Beardtongue *(Penstemon gibbensii)*
Grand Junction Milkvetch *(Astragalus linifolius)*
Green River Greenthread *(Thelesperma caespitosum)*
Isely's Milkvetch *(Astragalus iselyi)*
Jane's Globemallow *(Sphaeralcea janeae)*
Jone's Cycladenia *(Cycladenia humilis var. jonesii)*
Kachina Daisy *(Erigeron kachinensis)*
Ligulate Feverfew *(Parthenium ligulatum)*
Logan Wild Buckwheat *(Eriogonum loganum)*
Mancos Milkvetch *(Astragalus humillimus)*
Mancos Saltbush *(Proatriplex pleiantha)*
Mesa Verde Cactus *(Sclerocactus mesae-verdae)*
Mojave Desert Whitethorn *(Ceanothus greggiii)*
Montrose Bladderpod *(Lesquerella vicina)*
Navajo Beardtongue *(Penstemon navajoa)*
Needleleaf Fleabane *(Erigeron nematophyllus)*
New Mexico Fishhook Cactus *(Sclerocactus cloveriae ssp. brackii)*
Paria Breadroot *(Pediomelum pariense)*
Penland's Beardtongue *(Penstemon yampaensis)*
Rocky Mountain Thistle *(Cirsium perplexans)*
San Juan Milkweed *(Asclepias sanjuanensis)*
San Juan Whitlow-grass *(Draba graminea)*
Siler Pincushion Cactus *(Pediocactus sileri)*
Smooth Woody-aster *(Xylorhiza glabriuscula)*
Uinta Basin Spring-parsley *(Cymopterus duchesnensis)*
Welsh's Bugseed *(Corispermum welshii)*
Welsh's Milkweed *(Asclepias welshii)*
Wetherill's Milkvetch *(Astragalus wetherillii)*
White River Beardtongue *(Penstemon scariosus)*
Whiting's Indigo-bush *(Psorothamnus thompsoniae)*

Shale and other Fine-grained Sedimentary

Cisco Milkvetch *(Astragalus sabulosus)*
Garrett's Beardtongue *(Penstemon scariosusi)*
Graham's Beardtongue *(Penstemon grahamii)*
Nelson's Milkvetch *(Astragalus nelsonianus)*
Opal Phlox *(Phlox opalensis)*
Payson's Beardtongue *(Penstemon paysoniorum)*
Persistent-sepal Yellowcress *(Rorippa calycina)*
Rock-tansy *(Sphaeromeria capitata)*
Rollins' Cat's-eye *(Cryptantha rollinsii)*
Sheep Creek Beardtongue *(Penstemon pachyphyllus var. mucronatus)*
Talus Spring-parsley *(Cymopterus lapidosus)*
Uinta Basin Hookless Cactus *(Sclerocactus glaucus)*

Intrusive: Granitic

Altai Cotton-grass *(Eriophorum altaicum var. neogaeum)*

Volcanics: Felsic

Beatley's Buckwheat *(Eriogonum beatleyae)*
Clustered Popcorn-flower *(Plagiobothrys glomeratus)*
Hall's Meadow Hawk's-beard *(Crepis runcinata)*
Long Valley Milkvetch *(Astragalus johannis-howellii)*
Ostler's Ivesia *(Ivesia shockleyi var. ostleri)*
Pine Valley Milkvetch *(Astragalus convallarius)*
Pink Egg Milkvetch *(Astragalus oophorus)*
Toiyabe Wild Buckwheat *(Eriogonum esmeraldense)*
Toquima Milkvetch *(Astragalus toquimanus)*

Volcanics: Mafic

Pinyon Milkvetch *(Astragalus pinonis)*
Bodie Hills Cusickiella *(Cusickiella quadricostata)*
Lavin's Egg Milkvetch *(Astragalus oophorus)*
William's Combleaf *(Polyctenium williamsiae)*
Wyoming Tansymustard *(Descurainia torulosa)*

WARM DESERT BASIN

Low elevation basins, lowlands, valleys and foothills in the three warm desert ecoregions: Mohave Desert, Sonoran Desert, Apache Highlands, Chihuahuan Desert (Figure 2.6).

Communities and Vegetation Types

Apachean Grassland and Savanna
Apachean Shrubland
Apacherian-Chihuahuan Semi-Desert Grassland and Steppe
California fan palm woodland
Chihuahuan Creosotebush Desert Scrub
Chihuahuan desert grassland
Chihuahuan desert scrub
Chihuahuan Gypsophilous Grassland and Steppe
Chihuahuan Loamy Plains Desert Grassland
Chihuahuan Mixed Desert and Thornscrub
Chihuahuan Mixed Salt Desert Scrub
Chihuahuan rocky outcrop
Chihuahuan Sandy Plains Semi-Desert Grassland
Chihuahuan Stabilized Coppice Dune and Sand Flat Scrub
Chihuahuan Succulent Desert Scrub
Chihuahuan-Sonoran Desert Bottomland and Swale Grassland
Cienega
Desert pavement
Desert spring/seep
Desert wash
Desert-willow Intermittently Flooded Shrubland Alliance
Fremont Cottonwood Riparian Woodland
Interior dunes
Interior riparian marsh
Intermittently flooded playa lake bed
Joshua tree woodland
Madrean Encinal
Madrean Pine-Oak Forest and Woodland
Madrean Pinon-Juniper and Encinal
Madrean Pinyon-Juniper Woodland
Marfa grasslands
Mescalero dunelands
Mesquite bosque
Mixed desert shrubland
Mogollon Chaparral
Mohave desert scrub
Mojave Mid-Elevation Mixed Desert Scrub
North American Warm Desert Active and Stabilized Dune
North American Warm Desert Badland
North American Warm Desert Bedrock Cliff and Outcrop
North American Warm Desert Pavement
North American Warm Desert Playa
North American Warm Desert Riparian Woodland and Shrubland
North American Warm Desert Wash
Sacaton riparian grassland
Semi-desert chaparral
Sonora-Mojave Creosotebush-White Bursage Desert Scrub
Sonora-Mojave Mixed Salt Desert Scrub
Sonoran Mid-Elevation Desert Scrub
Sonoran Paloverde-Mixed Cacti Desert Scrub
Sonoran Desert Scrub

Birds

Abert's Towhee *(Pipilo aberti)*
American Yellow Warbler *(Dendroica petechia brewsteri)*
Arizona Bell's Vireo *(Vireo bellii arizonae)*
Baird's Sparrow *(Ammodramus bairdii)*
Bell's Vireo *(Vireo bellii)*
Belted Kingfisher *(Megaceryle alcyon)*
Bendire's Thrasher *(Toxostoma bendirei)*
Black-capped Vireo *(Vireo atricapilla)*
Botteri's Sparrow *(Aimophila botterii)*
Brown-crested Flycatcher *(Myiarchus tyrannulus)*
Cactus Ferruginous Pygmy-owl *(Glaucidium brasilianum cactorum)*
California Black Rail *(Laterallus jamaicensis coturniculus)*
Common Black-Hawk *(Buteogallus anthracinus)*
Costa's Hummingbird *(Calypte costae)*
Crissal Thrasher *(Toxostoma crissale)*
Elegant Trogon *(Trogon elegans)*
Elf Owl *(Micrathene whitneyi)*
Gilded Flicker *(Colaptes chrysoides)*
Golden Eagle *(Aquila chrysaetos)*
Green Kingfisher *(Chloroceryle americana)*
Gull-billed Tern *(Gelochelidon nilotica)*
Hepatic Tanager *(Piranga flava)*
Le Conte's Thrasher *(Toxostoma lecontei)*
Least Bell's Vireo *(Vireo bellii pusillus)*
Long-eared Owl *(Asio otus)*
Lucy's Warbler *(Vermivora luciae)*
Masked Bobwhite *(Colinus virginianus ridgwayi)*
Northern Aplomado Falcon *(Falco femoralis septentrionalis)*
Northern Gray Hawk *(Buteo nitidus maxima)*
Phainopepla *(Phainopepla nitens)*
Rufous-winged Sparrow *(Aimophila carpalis)*
Scaled Quail *(Callipepla squamata)*
Scott's Oriole *(Icterus parisorum)*
Short-eared Owl *(Asio flammeus)*
Southwestern Willow Flycatcher *(Empidonax traillii extimus)*

Summer Tanager *(Piranga rubra)*
Tricolored Blackbird *(Agelaius tricolor)*
Vermilion Flycatcher *(Pyrocephalus rubinus)*
Western Burrowing Owl *(Athene cunicularia)*
Western Least Bittern *(Ixobrychus exilis hesperis)*
Western Yellow-billed Cuckoo *(Coccyzus americanus occidentalis)*
Yellow Warbler *(Dendroica petechia)*
Yuma Clapper Rail *(Rallus longirostris yumanensis)*
Zone-tailed Hawk *(Buteo albonotatus)*

Mammals

Allen's Big-eared Bat *(Idionycteris phyllotis)*
American Badger *(Taxidea taxus)*
Arizona Gray Squirrel *(Sciurus arizonensis)*
Arizona Myotis *(Myotis occultus)*
Arizona Shrew *(Sorex arizonae)*
Big Free-tailed Bat *(Nyctinomops macrotis)*
Bighorn Sheep - Peninsular Range *(Ovis canadensis)*
Black-tailed Prairie Dog *(Cynomys ludovicianus)*
Cactus Deermouse *(Peromyscus eremicus)*
California Bonneted Bat *(Eumops perotis)*
Californian Leaf-nosed Bat *(Macrotus californicus)*
Californian Myotis *(Myotis californicus)*
Cave Myotis *(Myotis velifer)*
Chihuahuan Grasshopper Mouse *(Onychomys arenicola)*
Chihuahuan Pocket Mouse *(Chaetodipus eremicus)*
Desert Bighorn Sheep *(Ovis canadensis mexicana)*
Desert Kangaroo Rat *(Dipodomys deserti)*
Desert Pocket Mouse *(Chaetodipus penicillatus)*
Fringed Myotis *(Myotis thysanodes)*
Jaguar *(Panthera onca)*
Kit Fox *(Vulpes macrotis)*
Lesser Long-nosed Bat *(Leptonycteris yerbabuenae)*
Long-eared Myotis *(Myotis evotis)*
Long-legged Myotis *(Myotis volans)*
Merriam's Deermouse *(Peromyscus merriami)*
Mexican Long-nosed Bat *(Leptonycteris nivalis)*
Mexican Long-tongued Bat *(Choeronycteris mexicana)*
Mexican Wolf *(Canis lupus baileyi)*
Mohave Ground Squirrel *(Spermophilus mohavensis)*
Nelson's Pocket Mouse *(Chaetodipus nelsoni)*
New Mexican Jumping Mouse *(Zapus hudsonius)*
Organ Mountains Chipmunk *(Neotamias quadrivittatus australis)*
Pale Lump-nosed Bat *(Corynorhinus townsendii)*
Palm Springs Round-tailed Ground Squirrel *(Spermophilus tereticaudus chlorus)*
Palmer's Chipmunk *(Neotamias palmeri)*
Panamint Kangaroo Rat *(Dipodomys panamintinus)*
Pinacate Cactus Deermouse *(Peromyscus eremicus)*
Pocketed Free-tailed Bat *(Nyctinomops femorosaccus)*
Pronghorn *(Antilocapra americana)*
Robust Cottontail *(Sylvilagus robustus)*
Sonoran Pronghorn *(Antilocapra americana)*
Southern Pocket Gopher *(Thomomys umbrinus)*
Southwestern River Otter *(Lontra canadensis)*
Texas Antelope Squirrel *(Ammospermophilus interpres)*
Underwood's Bonneted Bat *(Eumops underwoodi)*
Western Small-footed Myotis *(Myotis ciliolabrum)*
Western Yellow Bat *(Lasiurus xanthinus)*
White Sands Pocket Gopher *(Geomys arenarius)*
Yellow-faced Pocket Gopher *(Cratogeomys castanops)*
Yellow-nosed Cotton Rat *(Sigmodon ochrognathus)*

Amphibians

Arizona Toad *(Bufo microscaphus)*
Arroyo Toad *(Bufo californicus)*
California Red-legged Frog *(Rana draytonii)*
Chiricahua Leopard Frog *(Rana chiricahuensis)*
Great Plains Toad *(Bufo cognatus)*
Pacific Chorus Frog *(Pseudacris regilla)*
Plains Leopard Frog *(Rana blairi)*
Red-spotted Toad *(Bufo punctatus)*
Relict Leopard Frog *(Rana onca)*
Sonoran Green Toad *(Bufo retiformis)*
Western Barking Frog *(Eleutherodactylus augusti)*
Yavapai Leopard Frog *(Rana yavapaiensis)*

Reptiles

Arizona Ridgenose Rattlesnake *(Crotalus willardi)*
Banded Gila Monster *(Heloderma suspectum)*
Barefoot Gecko *(Coleonyx switaki)*
Brown Gartersnake *(Thamnophis eques megalops)*
California Kingsnake *(Lampropeltis getula)*
Coachella Valley Fringe-toed Lizard *(Uma inornata)*
Colorado Desert Fringe-toed Lizard *(Uma notata)*
Desert Box Turtle *(Terrapene ornata luteola)*
Desert Iguana *(Dipsosaurus dorsalis)*
Desert Night Lizard *(Xantusia vigilis)*
Desert Rosy Boa *(Lichanura trivirgata gracia)*
Desert Tortoise *(Gopherus agassizii)*
Desert Tortoise - Mohave Pop *(Gopherus agassizii)*
Desert Tortoise - Sonoran Pop *(Gopherus agassizii)*
Flat-tailed Horned Lizard *(Phrynosoma mcallii)*
Giant Spotted Whiptail *(Aspidoscelis burti stictogrammus)*
Glossy Snake *(Arizona elegans)*
Long-nosed Leopard Lizard *(Gambelia wislizenii)*
Mexican Plateau Mud Turtle *(Kinosternon hirtipes)*

Mexican Plateau Slider *(Trachemys gaigeae)*
Mohave Rattlesnake *(Crotalus scutulatus)*
Mojave Fringe-toed Lizard *(Uma scoparia)*
Mojave Patch-nosed Snake *(Salvadora hexalepis)*
Mountain Skink *(Eumeces callicephalus)*
Plateau Striped Whiptail *(Aspidoscelis velox)*
Red-backed Whiptail *(Aspidoscelis burti)*
Rosy Boa *(Lichanura trivirgata)*
Sidewinder *(Crotalus cerastes)*
Slevin's Bunchgrass Lizard *(Sceloporus slevini)*
Sonoran Lyresnake *(Trimorphodon biscutatus)*
Sonoyta Mud Turtle *(Kinosternon sonoriense)*
Southern Desert Horned Lizard *(Phrynosoma platyrhinos calidiarum)*
Southern Pacific Pond Turtle *(Actinemys marmorata)*
Speckled Rattlesnake *(Crotalus mitchellii)*
Spotted Leaf-nosed Snake *(Phyllorhynchus decurtatus)*
Striped Plateau Lizard *(Sceloporus virgatus)*
Texas Horned Lizard *(Phrynosoma cornutum)*
Trans-Pecos Black-headed Snake *(Tantilla cucullata)*
Twin-spotted Rattlesnake *(Crotalus pricei)*
Two-striped Gartersnake *(Thamnophis hammondii)*
Utah Banded Gecko *(Coleonyx variegatus utahensis)*
Western Banded Gecko *(Coleonyx variegatus)*
Western Redtail Skink *(Eumeces gilberti)*
Western Threadsnake *(Leptotyphlops humilis)*
Zebra-tailed Lizard *(Callisaurus draconoides)*

Plants
Surficial

Loam
Branching Penstemon *(Penstemon ramosus)*
Desert Night-blooming Cereus *(Peniocereus greggii)*
Desert Tree Caper *(Atamisquea emarginata)*
Dune Unicorn-plant *(Proboscidea sabulosa)*
Five-bract Fetid-marigold *(Pectis filipes)*
Giant Spanish-needle *(Palafoxia arida var. gigantea)*
Orcutt's Foxtail Cactus *(Escobaria orcuttii)*
Short Joint Beavertail *(Opuntia basilaris var. brachyclada)*

Sand
California Fan Palm *(Washingtonia filifera)*
Coachella Valley Milkvetch *(Astragalus lentiginosus)*
Harwood's Milkvetch *(Astragalus insularisi)*
Mojave Monkeyflower *(Mimulus mohavensis)*
Orcutt's Woody-aster *(Xylorhiza orcuttii)*
Peirson's Milkvetch *(Astragalus magdalenae)*
Sand Linanthus *(Linanthus arenicola)*

Gypsum
Gypsum Ground-plum *(Astragalus gypsodes)*
Scheer's Cory Cactus *(Coryphantha scheeri)*
Burgress' Broomshrub *(Lepidospartum burgessii)*
Gypsum Moonpod *(Selinocarpus lanceolatus)*
Shrubby Honeysweet *(Tidestromia suffruticosa)*
Gypsum Grama *(Bouteloua breviseta)*

Plants
Bedrock

Calcareous
Alamo Beardtongue *(Penstemon alamosensis)*
Bunched Cory Cactus *(Coryphantha ramillosa)*
Castetter's Milkvetch *(Astragalus castetteri)*
Chisos Agave *(Agave glomeruliflora)*
Chisos Mountain-brickellbush *(Flyriella parryi)*
Cliff Bedstraw *(Galium correllii)*
Cliff Thistle *(Cirsium turneri)*
Cutler's Twistflower *(Streptanthus cutleri)*
Five-flower Rockdaisy *(Perityle quinqueflora)*
Glass Mountain Coralroot *(Hexalectris nitida)*
Great Sage *(Salvia summa)*
Guadalupe Mountains Rabbitbrush *(Chrysothamnus spathulatus)*
Guadalupe Needlegrass *(Achnatherum curvifolium)*
Gypsogenus Ringstem *(Anulocaulis gypsogenus)*
Heather Leaf-flower *(Phyllanthus ericoides)*
Incense Cory Cactus *(Escobaria tuberculosa)*
Ivory Spined Agave *(Agave utahensis)*
Limestone Rockdaisy *(Perityle aglossa)*
Maravillas Milkwort *(Polygala maravillasensis)*
Marble Canyon Rockcress *(Sibara grisea)*
Mcvaugh's Bladderpod *(Lesquerella mcvaughiana)*
New Mexico Rockdaisy *(Perityle staurophylla)*
Rock Crevice Milkwort *(Polygala rimulicola)*
Royal Red Penstemon *(Penstemon cardinalis)*

Sacramento Mountain Foxtail Cactus *(Escobaria villardii)*
Sand Bear-grass *(Nolina arenicola)*
Scented Croton *(Croton suaveolens)*
Senator Mine Alumroot *(Heuchera eastwoodiae)*
Smooth-stem Skullcap *(Scutellaria laevis)*
Todsen's Pennyroyal *(Hedeoma todsenii)*
Trans Pecos Aletes *(Aletes filifolius)*
Trans Pecos False Mountain-parsley *(Pseudocymopterus longiradiatus)*
Two-spike Rockdaisy *(Perityle bisetosa)*
White Mountain False Pennyroyal *(Hedeoma pulcherrima)*
Wright's Spiderwort *(Tradescantia wrightii)*

Sandstone

Alcove Rockdaisy *(Perityle specuicola)*
Aromatic Scurfpea *(Pediomelum aromaticum)*
Desert Mountain Phlox *(Phlox austromontana)*
Dolores River Skeleton-plant *(Lygodesmia doloresensis)*
Fisher Milkvetch *(Astragalus piscator)*
Isely's Milkvetch *(Astragalus iselyi)*
Jane's Globemallow *(Sphaeralcea janeae)*
Jone's Cycladenia *(Cycladenia humilis var. jonesii)*
Mojave Desert Whitethorn *(Ceanothus greggii)*
Siler Pincushion Cactus *(Pediocactus sileri)*
Smooth Woody-aster *(Xylorhiza glabriuscula var. linearifolia)*

Granite / Intrusive

Arizona False Pennyroyal *(Hedeoma dentata)*
Lemmon's Cloakfern *(Notholaena lemmonii)*

Volcanic: Felsic

Hinckley's Brickell-bush *(Brickellia hinckleyi var. hinckleyi)*

Volcanic: Mafic

Arizona Agave *(Agave arizonica)*
Arizona Willow *(Salix arizonica)*
Blumer's Dock *(Rumex orthoneurus)*
Chaparral Goldenweed *(Ericameria brachylepis)*
Cliff Brittlebush *(Apacheria chiricahuensis)*
Creeping Milkvetch *(Astragalus troglodytus)*
Eggleaf Coral-drops *(Besseya oblongifolia)*
Goodding's Bladderpod *(Lesquerella gooddingii)*
Goodding's Onion *(Allium gooddingii)*
Hess' Fleabane *(Erigeron hessii)*
Mogoll Deathcamas *(Zigadenus mogollonensis)*
Mogollon Clover *(Trifolium neurophyllum)*
Mogollon Mountain Lousewort *(Pedicularis angustifolia)*
Mogollon Whitlowgrass *(Draba mogollonica)*
Naturita Milkvetch *(Astragalus naturitensis)*
New Mexico Groundsel *(Packera quaerens)*
Porsild's Starwort *(Stellaria porsildii)*
Shining Sandpaper-plant *(Petalonyx nitidus)*
Western Flameflower *(Talinum validulum)*
White Mountain Groundsel *(Packera cynthioides)*
White Mountains Paint Brush *(Castilleja mogollonica)*

Novaculite

Correll's Green Pitaya (Echinocereus viridiflorus)
Davis' Green Pitaya (Echinocereus viridiflorus)
Golden-spine Hedgehog Cactus (Echinocereus chloranthus var. neocapillus)
Hester's Cory Cactus (Escobaria hesteri)
Incense Cory Cactus (Escobaria tuberculosa)
Nellie Cory Cactus (Escobaria minima)
Rio Grande Butterfly-weed (Gaura boquillensis)
Straw Spine Cactus (Thelocactus bicolor)
Tall Indian-paintbrush (Castilleja elongate)
Wilkinson's Nailwort (Paronychia wilkinsonii)

Tropical Lowland and Coastal

Low elevation desert, thornscrub and coastal plain in the Tamaulipan Thornscrub ecoregion (Figure 2.6).

Communities and Vegetation Types

Central and South Texas Coastal Fringe Forest and Woodland
East-Central Texas Plains Post Oak Savanna and Woodland
South Texas Sand Sheet Grassland
Tamaulipan Calcareous Thornscrub
Tamaulipan Floodplain
Tamaulipan Mixed Deciduous Thornscrub
Tamaulipan Saline Thornscrub
Tamaulipan Savanna Grassland
Guajillo shrubland

Birds

Altamira Oriole *(Icterus gularis)*
Audubon's Oriole *(Icterus graduacauda audubonii)*
Bell's Vireo *(Vireo bellii bellii)*
Cassin's Sparrow *(Aimophila cassinii)*
Elf Owl *(Micrathene whitneyi idonea)*
Interior Least Tern *(Sternula antillarum athalassos)*
Lark Bunting *(Calamospiza melanocorys)*
Sennett's Hooded Oriole *(Icterus cucullatus sennetti)*

Mammals

Ocelot *(Leopardus pardalis)*
Strecker's Pocket Gopher *(Geomys streckeri)*

Herptiles

Black-spotted Newt *(Notophthalmus meridionalis)*
Lesser Siren (Rio Grande population) *(Siren intermedia)*

Plants

Surficial

Fine Sediment

Dwarf Nicker *(Caesalpinia drummondii)*
Gregg's Wild-buckwheat *(Eriogonum greggii)*
Large Selenia *(Selenia grandis)*
Siler's Tube-rose *(Manfreda sileri)*
Texas Palmetto *(Sabal mexicana)*
Zapata Bladderpod *(Lesquerella thamnophila)*

Loam

Arrow-leaf Milkvine *(Matelea sagittifolia)*
Correll's False Dragon-head *(Physostegia correllii)*
St. Joseph's Staff *(Manfreda longiflora)*
Star Cactus *(Astrophytum asterias)*
Texas Stonecrop *(Lenophyllum texanum)*

Sand

Amelia's Sand-verbena *(Abronia ameliae)*
Cory's Croton *(Croton coryi)*
Jones' Nailwort *(Paronychia jonesii)*
Lundell's Nailwort *(Paronychia lundelliorum)*
Yellow Alicoche *(Echinocereus papillosus)*
Sand Brazos-mint *(Brazoria arenaria)*
Small-flower Milkvine *(Matelea parviflora)*
Texas Peachbush *(Prunus texana)*
Velvet Spurge *(Euphorbia innocua)*

Plants
Bedrock

Calcareous or Moderately Calcareous
Ashy Dogweed *(Thymophylla tephroleuca)*
Burridge's Goldthread *(Thelesperma burridgeanum)*
Bushy Whitlow-wort *(Paronychia congesta)*
Correll's Bluet *(Houstonia correllii)*
Fitch's Hedgehog Cactus *(Echinocereus reichenbachii var. fitchii)*
Johnston's Frankenia *(Frankenia johnstonii)*
Peyote *(Lophophora williamsii)*
Rio Grande Bugheal *(Trichocoronis rivularis)*
Texas Almond *(Prunus minutiflora)*
Turner's Four-nerve-daisy *(Tetraneuris turneri)*
Two-flowered Stick-pea *(Calliandra biflora)*

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Appendix

Detailed rules for cleaning up the data were as follows:

1. Alpine: Anything above >11,500ft was assigned to Alpine and Landfire mapped Alpine areas were allowed down to 95,00ft.
2. SubAlpine: Anything between 10,000-11,500ft not mapped as Alpine was assigned to SubAlpine and Landfire mapped SubAlpine areas were allowed down to 8000ft
3. Upper Montane: Anything between 9,500-10,000ft not already mapped as SubAlpine plus Landfire Upper Montane areas down to 7,000.
4. Lower Montane areas: A more complex rule set was used. Areas not mapped in the above three zones were placed into Lower Montane based on elevation thresholds as follows
   a. Southern Rockies Ecoregion: Lower Montane was mapped for anything above 8,500ft if if not already mapped in upper zones
   b. Ecoregions including Great Basin, Wyoming Basin, Arizona and New Mexico Mountains, Utah High Plateau, and Utah Wyoming Mountains: Lower Montane was mapped for anything above 8,000ft if not already mapped in upper zones
   c. Coloardo Plateau Ecoregion: Lower Montane was mapped for anything above 6,750ft if not already mapped in upper zones
   d. Ecoregions of Apache Highlands and Mojave: Lower Montane was mapped for anything above 6,000ft if not already mapped in upper zones
   e. Chiuahuan Ecoregion: Lower Montane was mapped for anything above 5,757ft if not already mapped in upper zones

ESTIMATING SITE RESILIENCE

CHAPTER 3

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 under a changing climate, because individuals and populations can shift their locations locally to take advantage of the microclimate variation.

Sites with little fragmentation and many microclimates are hypothesized to have high **site resilience** because the climatic variation allows 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 change resilience factor - landscape diversity - addresses variation in topography and wetlands as indicator of microclimate variation.

Projections of future climate patterns indicate that this region is already experiencing increased temperatures, drought and fire, and these trends are likely to continue (Garfin et al. 2018 National Climate Assessment). While climate projections should inform our conservation strategies, it's important to remember that climate data is based on regional averages. However, changes in global and regional climate interact with other factors, such as topography and landform to modify local microclimate conditions in patterns that are much more predictable at local scales. Understanding and mapping these persistent 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 temperature measurements exceeding 34^0 F (Suggitt et al. 2011). In California's serpentine grasslands, microtopographic thermal climates showed a 34^0 F difference between maximum values at different slopes (Dobkin et al. 1987). In these serpentine 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 heavily forested 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 (Yeakley et al. 1998) in Appalachian forests. In grasslands, aspect alone can explain as much of 20% of the local differences in soil moisture (Bennie et al. 2006 & 2008). Studies of landscape-based climate variation continue to show how local climatic variation strongly influences 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 fully 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. 2014b).

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, elevation, moisture and wetlands. The calculation of landscape diversity scores for each pixel included integrating the following inputs:

1. Landform Variety: the variety (count) of all landform types derived from topographic position, slope, aspect, and moisture
2. Elevation Range: additional weight where elevation range was greater than expected from the number of landforms
3. Moist landforms: additional weight to pluvial flats, coves, northeast facing lower slopes, northeast facing side slopes, wetlands, springs and water
4. Wetland density: additional weight to larger wetlands or dense wetland areas

Landform

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, for example in sand prairie species diversity, 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 micro climates, 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 21 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), and use it to derive estimates of slope, aspect, and land position for each pixel in the study area. For slope, aspect, and land position, we defined thresholds that allowed us to partition values into different zones (Figure 3.1) that corresponded with recognizable distinctions in the field and had meaning relative to species distributions or ecological processes. The primary divisions in the model were based on relative land position and slope (X and Y axis in Figure 3.1). Some slope classes were then further divided by aspect, and flats were further divided by moisture (Figures 3.1-3.3).

Figure 3.1: The Underlying Slope and Land Position Model used to Map Landforms. Adapted from Fels and Matson 1997.

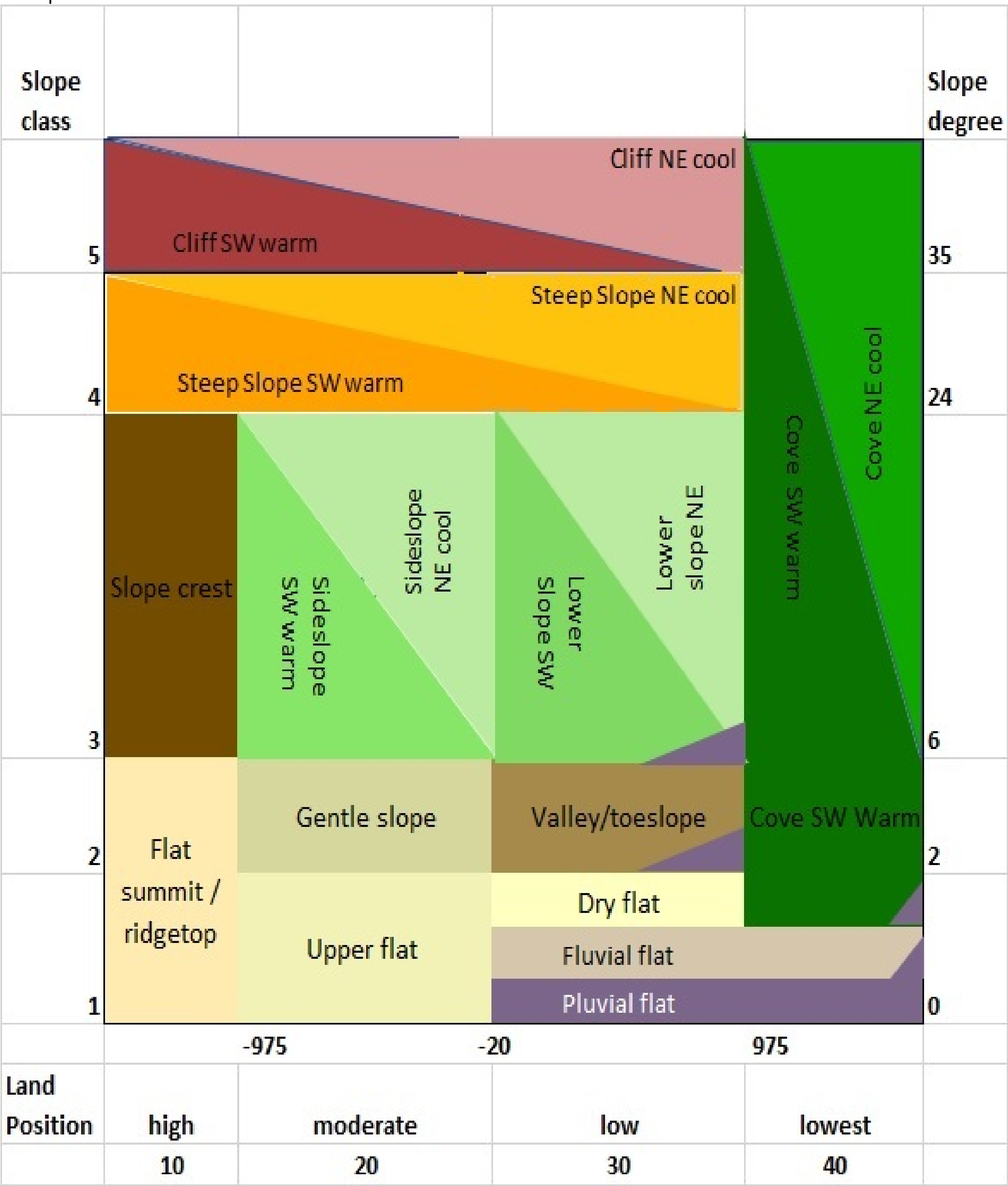
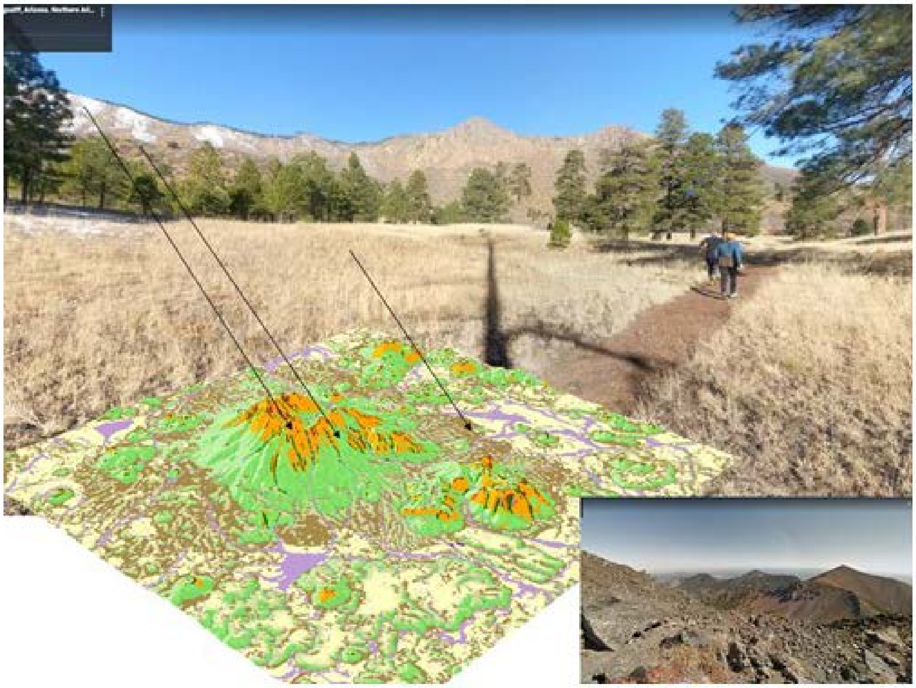


Figure 3.2. Zoom in 3D View of Landforms and Photographs, San Francisco Peak, AZ and Black Canyon, CO.

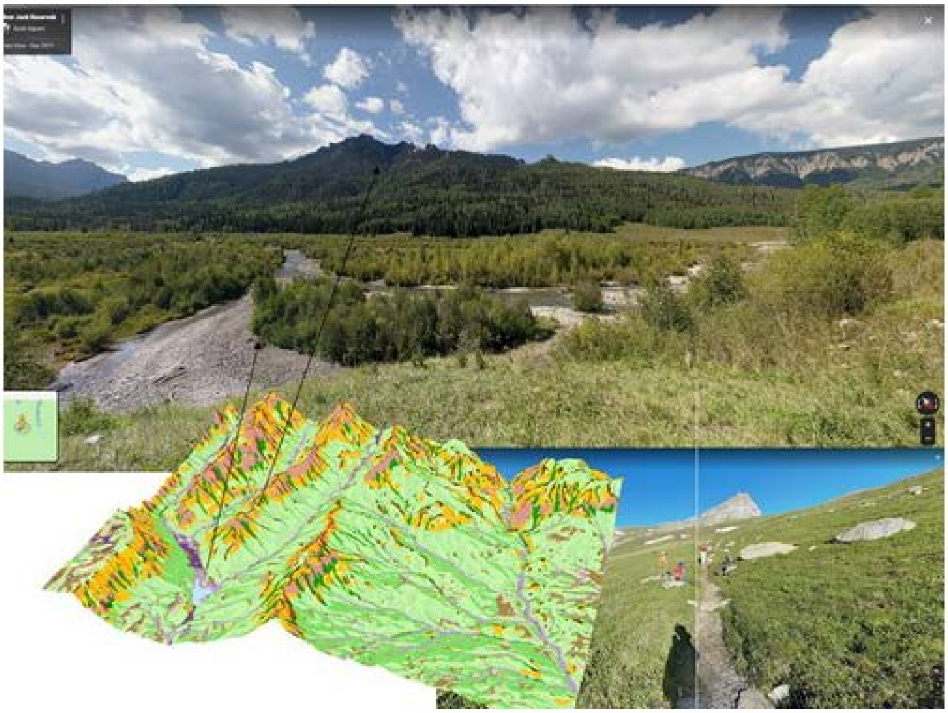
A. San Francisco Peak AZ



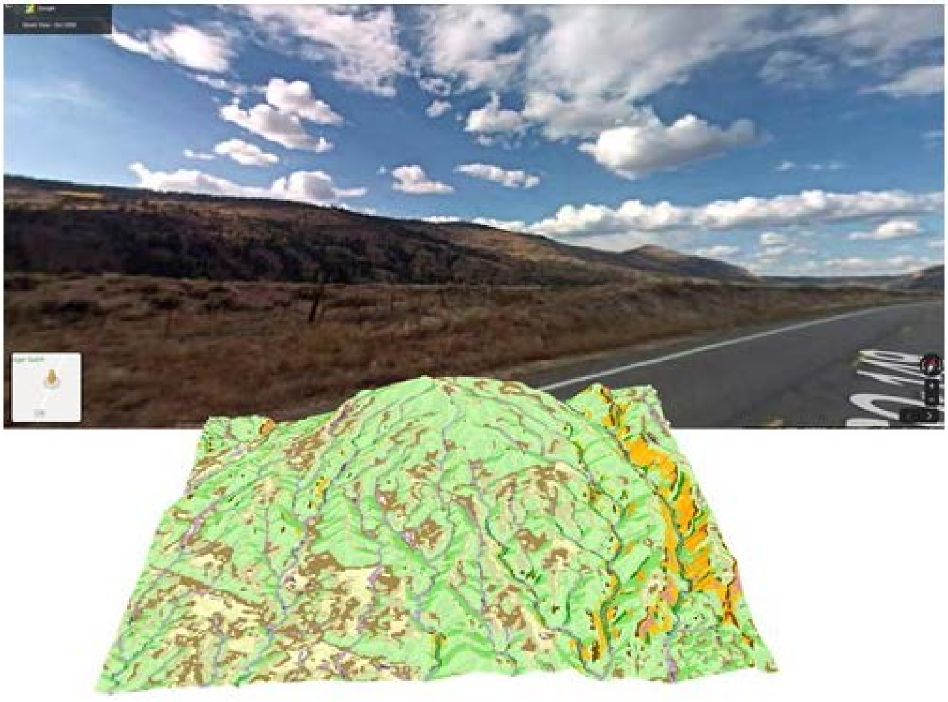
B. Black Canyon, Gunnison CO

Figure 3.3. Zoom in 3D View of Landforms and Photographs of Uncompahgre Mountains, CO and unnamed hill near Yeager Gulch CO.

C. Uncompangne Mountains, Colorado



D.



To create a basic landform model (Figure 3.4), 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 350m 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.

Combining the above three datasets using specific thresholds (Figure 3.1) allowed us to map 13 slope classes (> 2^0 slope):

- Cliffs (2 aspects),
- Steep slopes (2 aspects),
- Slope crests,
- Side slopes (2 aspects),
- Lower slopes (2 aspects),
- Coves (2 aspects)
- Gentle slopes,
- Valley/ toeslope

And 3 classes of flats (<2^0 slope)

- Flat summit
- Upper flat
- Low Flat

The Low Flat class was then further subdivided by moisture regime into: pluvial flat, fluvial flat, wet flat (wetland), spring, and water. The specific inputs for modification of the low flats by moisture regime are described below.

Pluvial flats are moist areas where periodic rainfall or snowmelt accumulates due to topographic runoff resulting in overland flow. Fluvial flats are areas where river systems overflow in to the surrounding floodplain. To map these, we used the FATHOM 2018 30m grid dataset (Wing et al.2017), a new floodplain model for the conterminous US which has separate datasets for mapping pluvial and fluvial zones. We combined them into one dataset using the natural expected 100-year flood wet zone as the extent and giving precedence to pluvial where both types were present (given pluvial has both topographic accumulation and overbank flow). Further, the periodic nature of flooding in fluvial areas is exacerbated by the fact that most western rivers have flood control structures which reduce the frequency and extent of overbank flooding. Fluvial areas from FATHOM were then restricted to areas of low and very low land position in the landform model. Pluvial areas also occurred primarily on low and very low flats but could override cells of other low-lying landforms including: cove, valley-toeslope and lower side slopes (see Figure 3.1). In effect this created the natural pattern of pluvial streams occurring in the lowest portion of a most coves or low slopes.

Small pluvial channel mapping in FATHOM was augmented using the NHD medium resolution (1:100,000) headwater and creek linework to delineate pluvial channels. This corrected for inconsistencies in FATHOM's pluvial mapping of headwaters and creek. Finally, 1-2 cell groups of isolated source FATHOM model pixels were removed to clean up some odd scatter in the source data and concentrate pluvial and fluvial mapping on larger areas.

Playas are basins or depressions that formerly contained standing surface water but are now dry in most years. Playas are a common landform in this region and to map them we extracted them from the Medium and High resolution NHD waterbody data (where they are labeled as "playa") and from a specific Nevada dataset "Lakes, Playas, and Other Water Bodies of Nevada) from Nevada Natural Heritage Program (USEPA and USGS 2012; Nevada Natural Heritage Program 2003). We added playas to our fluvial zone as like the fluvial areas they are mostly dry and flood only intermittently. Playa's appeared to be missing from the FATHOM data in flatter areas where perennial streams and rivers were absent.

Open water was mapped using a many-step process (Appendix 3.1). Our base map was the National Hydrography Dataset (NHD) Medium resolution non-intermittent waterbodies and wide river polygon areas (U.S. Geological Survey 2010). We removed all waterbodies coded as non-natural or altered (aquaculture, disposal-tailings pond, disposal-unspecified, evaporator, treatment, treatment-cooling pond). We also intersected the data set with National Wetland Inventory data and the NHD high resolution data and removed any waterbodies under 100 acres that were coded as reservoir or non-natural (excavated, farmed, diked, impounded, spoil) in either dataset (U.S. Fish and Wildlife Service 2017; U.S. Geological Survey 2017). Reservoirs over 100 acres were retained as they are unlikely to be removed and thus form a more permanent source of water. We aligned the final waterbody dataset with the NLCD 2016 representation of open water and added in any other large (>250 acre) waterbodies not in the NHD dataset.

Rivers were mapped using the NHD wide-river areas dataset augmented with perennial river linework from the NHD Medium Resolution flowlines to map any rivers with a drainage area over >518 sq.km. Rivers were then added to the "open water" class of the landform map. The combined "open water" areas were then limited to >2 acre. The resulting dataset focused on natural and/or permanent waterbodies and leaves out small non-natural waterbodies.

Springs were added from the high-resolution National Hydrography Dataset point feature class (U.S. Geological Survey 2017).

Wetland were mapped using the NLCD 2016 "emergent wetland" or "forested wetland" categories as our base wetland dataset (Yang et al.2018). Artificial, diked, and non-natural wetlands were removed using the same methods described above for "open water" with the additional step of overlaying the results with NASS Cropland Data

(USDA 2019, Cropscape) to remove crop and fallow land (Cropscape >= 5 years crop/fallow) that were mapped in NLCD as wetland.

When added to the landform dataset, wetlands were limited to appropriate landforms (Lower slopes, Coves, Flats, Valley/toeslope). Water was burned on top of wetlands and the remaining cells were grouped. Only wetland patches >2 acres were added to the landform grid.

Figure 3.4: Landforms. The Rockies and Southwest Desert region mapped as 21 landform types. These landforms are used to characterize the region's topography and to calculate the landform variety metric (30m cell mapping resolution).

Landform Variety

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 3.5) using a focal variety analysis. This search area corresponds to roughly a 350-m radius around each focal cell and was chosen because this size provides the best discrepancy between cells (highest between-cell variance). The size is also a reasonable scale for a wide range of species, in that it suggests local population movements could access a 40.4 ha neighborhood. Each landform counted for one microclimate except for cliffs where the two aspects were combined, and water and springs which were also combined in to one. This brought the total possible landforms to a maximum count of 21.

The landform variety count was then transformed into a Z-score within each of the 3 major regions so the Mountain ecoregions, Warm desert ecoregions, and Cold desert ecoregions were only compared internally against each other.

Elevation Range

Our goal in the elevation range analysis was identify areas had more elevation range than would be expected by their number of landforms. We were particularly interested in identifying long side slopes and low slopes that have been shown to offer climate relief to many species (Chen et al.2017).

Using a 30-m Digital Elevation Model (Gesch et al. 2007) we calculated the total elevation range in a 40 ha (100-acre) circle surrounding each cell using a focal range analysis (the same search area as for the landform variety analysis). We converted the results to Z-score using the mean and variance for each group of ecoregions (Mountains, Cold Deserts, Warm Deserts/Tropical). We subtracted the landform variety score from the elevation range score such that a positive difference indicated the elevation range was greater than the landform variety relative to their respective means. We then identified areas were the elevation was both 1) above the mean (>0.5 SD) and 2) the difference between the elevation and landform variety score was also above the mean (>0.5 SD) To these areas, we gave a slight boost (0.25 – 1 SD) to the landscape diversity score by proportionally recalling their scores from 500-3500 to 250-1000 and adding them to the landscape diversity score (Figure 3.6).

Figure 3.5: Landform Variety. The distribution of the counts of number of landforms in a 100-acre circle for the region. Areas with higher landform counts (more topographic variation) appear in green, and lower counts (flatter) appear brown.

Figure 3.6: Elevation Range. Areas where the elevation range score was at least 0.5 SD more than the landform variety score alone and where the raw elevation range was large, at least 0.5 SD above the mean for that region.

Moist Landform Boost

Temperature and moisture are inextricably linked in the landform model where every landform represents a distinct combination of both factors and each weighted equally. There is evidence, however, that water-collecting landforms play a disproportionally important role in sustaining site resilience and maintaining hydrologic processes, especially with changing water availability under climate change. In areas where water scarcity is a major limitation now or under future climates, hydrologic microrefugia are expected to play an increasingly greater role in species persistence and resilience (McLaughlin et al. 2017).

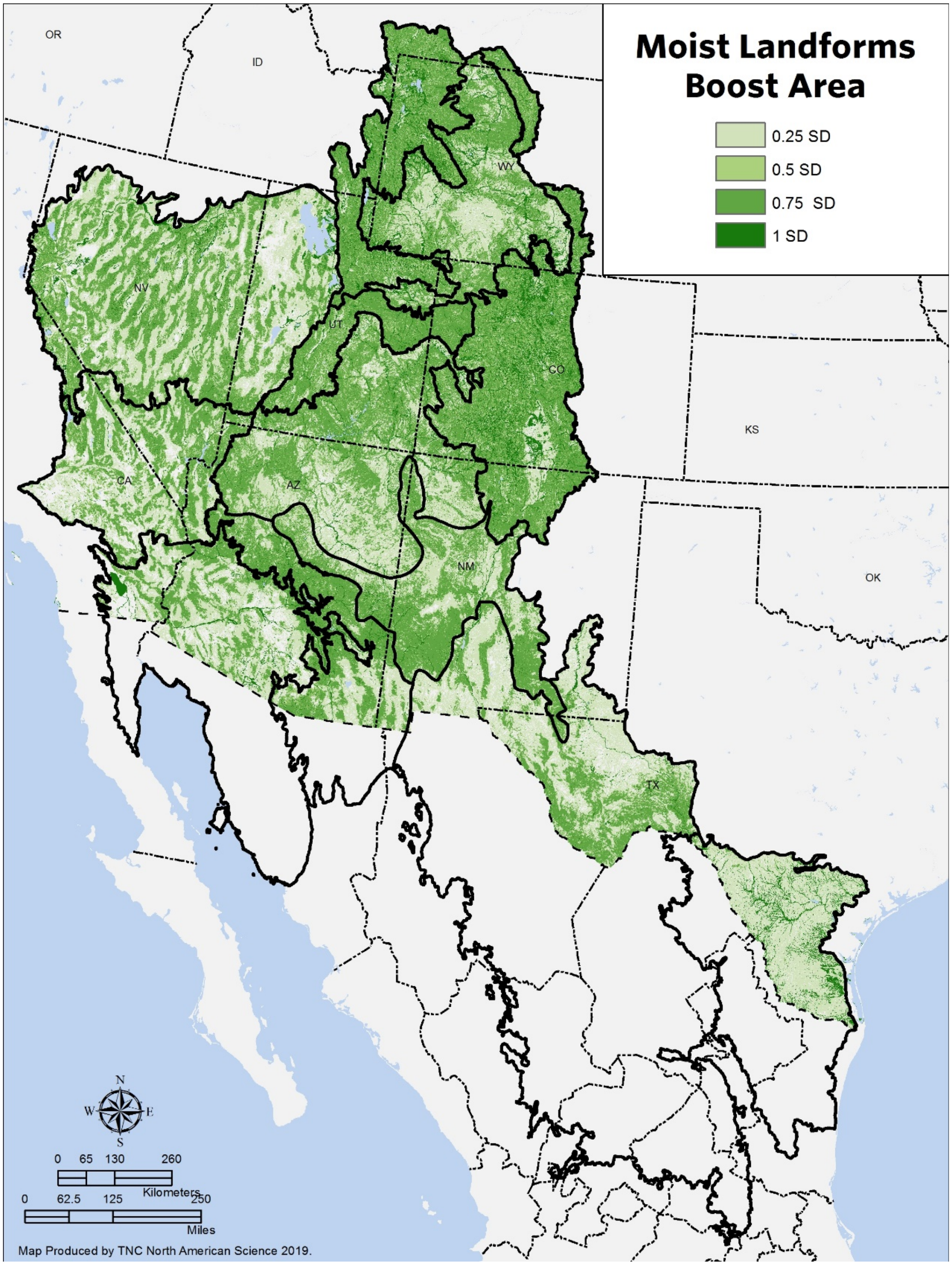
To reflect the importance of moist and wet topographic settings we increased their influence of the landscape diversity score by giving more weight to water-collecting landforms. First, we identified the set of landforms associated with moisture: coves, pluvial flat, wet flat, water and northeast facing side slopes and lower slopes. Using the same methods, we used to calculate landform variety we reran the focal count, this time counting only the total number moist landform types and noting whether water or a confirmed wetland was present.

We used the results to apply a systematic moist landform boost to the landform variety grid as follows (Figure 3.7):

- One moist landform = 0.25 SD boost
- Two moist landforms = 0.50 SD boost
- Three moist landforms = 0.750 SD boost
- Presence of any wetland or water = 1.0 SD boost

Photograph of ephemeral and intermittent stream channels connecting to a perennial reach of Cienega Creek, southeast of Tucson Arizona (Photograph: Lainie Levick/Aerial flight courtesy of Lighthawk, www.lighthawk.org)

Figure 3.7: Moist Landform Features Boost Area. Areas that have moister landforms defined as coves, sideslope northeast facing, lower slopes northeast facing, pluvial flats, wet flat, and water/springs within 100acre focal area.



Wetland Density Influence

In addition to moisture-collecting topographic settings, large wetlands or wetland concentration areas play an important role in sustaining site resilience, 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 et al. 1993, Fremier et al. 2015). We expect the current wetlands will continue to be important under variable climates even though the size and wetness of the areas are likely to change. 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 and larger wetland 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).

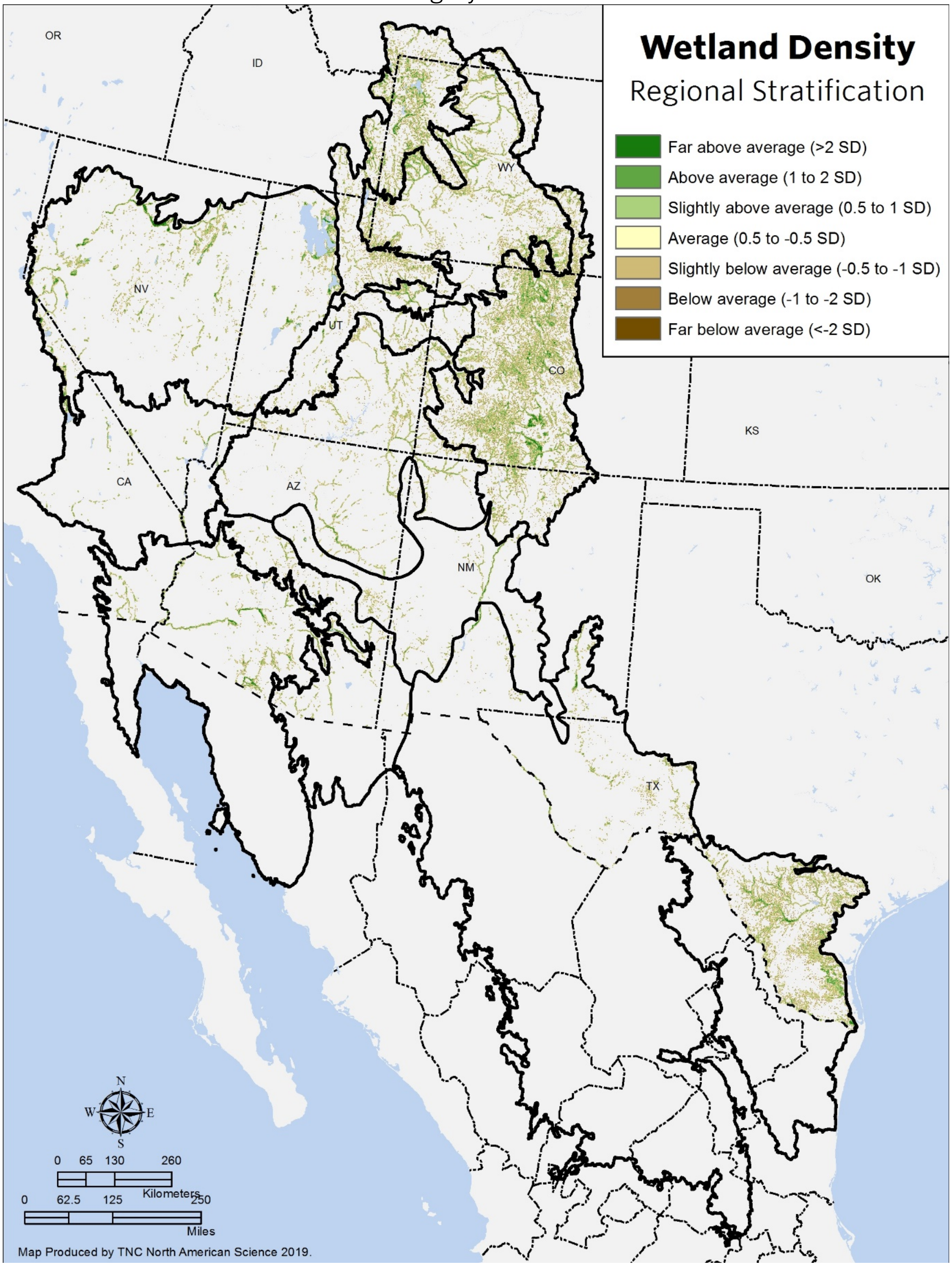
We calculated a wetland density score using the same scale as landform variety: the percentage of wetlands within a 40.4 ha (100-acre) circle centered on each 30-m cell using a focal mean function in GIS. We excluded open water from the density calculation so that density was relative to the amount of 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. Areas with a wetland density of zero were assigned a Z score of -3.5 SD (lowest number). Areas of the larger focal 1000 acres were only allowed to improve the 100-acre score (thus numerically we substituted the 100-acre score into the 1000-acre data when it was higher for our final calculations). We combined the standardized values from both search distances using the formula:

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

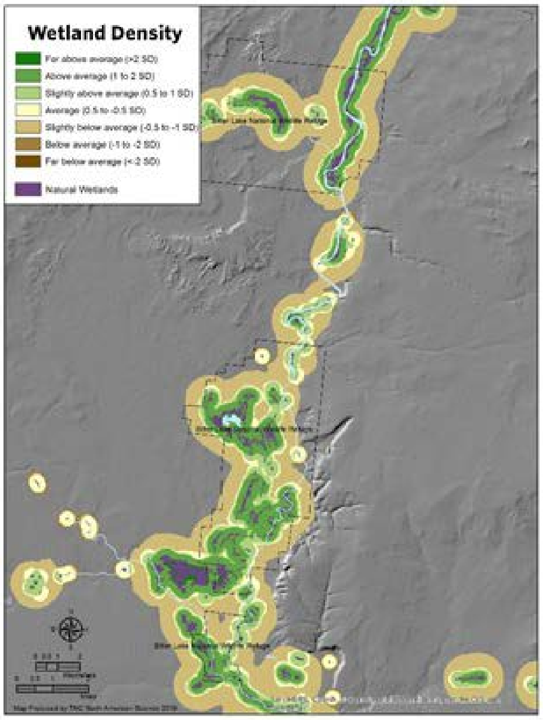
The resulting wetland density was then Z scored using the means and SD from each of the three regions, calculated from only cells which had a wetland (Figure 3.8).

Figure 3.8: Wetland Density. Weighted density of wetlands in 40- and 404-hectare circles around each central cell compared to the regional average. Areas with no wetlands within the search radius are gray.



We subtracted the landform variety score from the wetland density score such that a positive difference indicated the wetland density was greater than the landform variety relative to their respective means. We then identified areas were wetland density was both 1) above the mean (>0.5 SD) and 2) the difference between wetland density and landform variety was also above the mean (>0.5 SD) To these areas, we gave a slight boost (0.50 – 2 SD) to the landscape diversity score scaling the boost to the size of the difference (Figure 3.10).

Figure 3.9: Bitter Lake National Wildlife Refuge, New Mexico: Wetland Density and area that qualified for Wetland Density Boost.



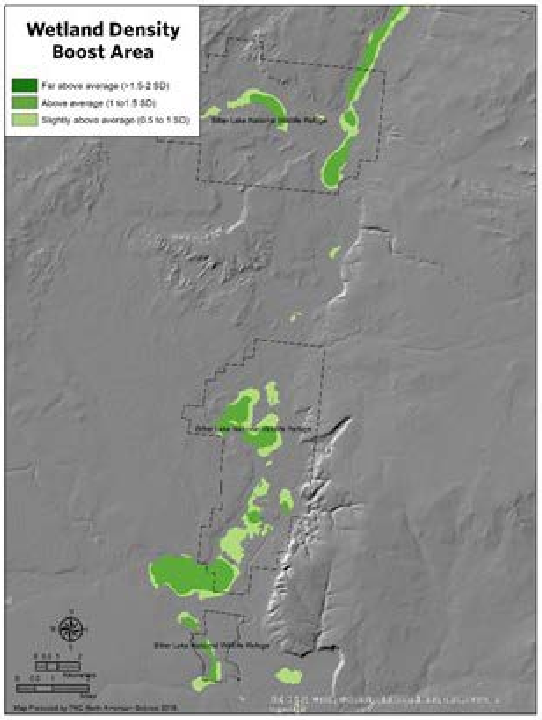


Figure 3.10: Wetland Density Boost Area. Areas where there were significant larger and dense wetland features (>.5SD wetland density) in otherwise low scoring landscape diversity areas. We spread a possible 0.5 SD to 2 SD point boost across the wetland density areas meeting these criteria.

Final Landscape Diversity Score

To create a final map of landscape diversity, we created a regional score within the 3 regions and an ecoregion score within each of the 12 ecoregions.

For each cell, base score was the landform variety Z score within the given geography (region or ecoregion). The cell scores were then increased if they were identified by any of the boosting criteria for elevation, moisture, or wetland density. The magnitude of the boost varied depending on the cell characteristics described above. Boosts varied between:

1. Elevation Range boost: 0.25-1 SD
2. Moist Landform boost: 0.25-1 SD
3. Wetland Density boost: 0.25-2 SD

The final Landscape Diversity score was equal to landscape variety score plus the sum of the boosts. This was then divided by the standard deviation of the ecoregion to appropriately spread out the distribution and approximate standard normal units (Figure 3.11, 3.12).

Figure 3.11 Components of the Landscape Diversity Score. These figures of Coconino County, AZ show areas around San Francisco Mountain in the Arizona-New Mexico Ecoregion and areas around the Little Colorado River in the Colorado Plateau Ecoregion.

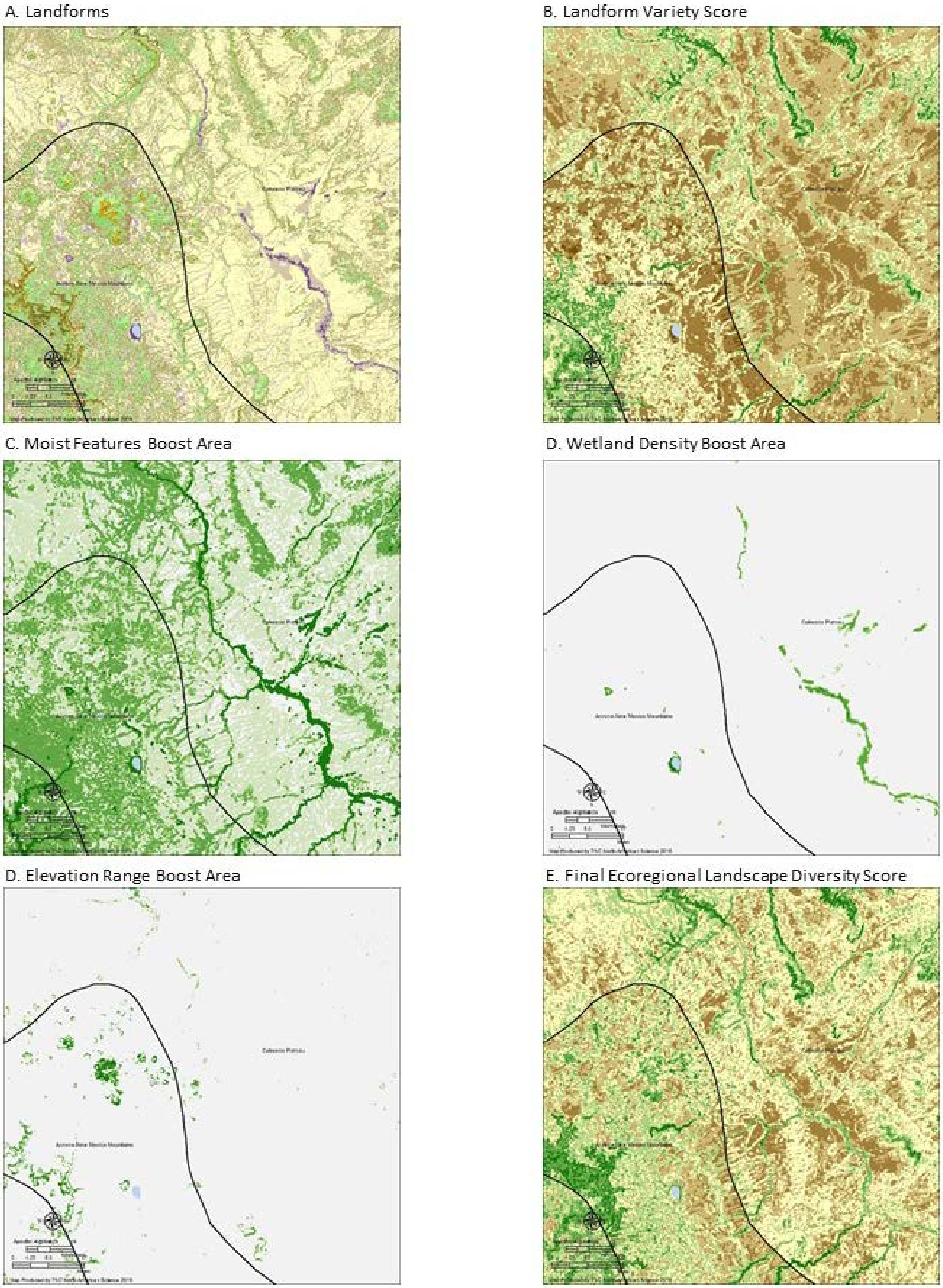


Figure 3.12: Landscape Diversity Ecoregional Score. Landscape diversity combined values of landform variety, elevation range, moisture, and wetland density influences. Values are relative within each Ecoregion.

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 sufficient 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 regions where there are few protected areas, but many large expanses of natural habitat in private ownership. Our emphasis on permeability reflects this goal of facilitating large-scale reorganization of species in response to climate change, which we suggest requires a more 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. The larger scale, or regional flow analyses is a part of the Resilient and Connected Network analysis later in this report.

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 weight 1): 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 5-7): 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 several datasets representing land cover, land use, roads, railroads and agriculture. The primary data source was the 30-m 2016 NLCD, which identifies each grid cell as belonging to one of 16 classes of land cover (Yang et al. 2019). We made several upgrades to the basic land cover data that substantially improved their performance as resistance grids, including:

1) Oil and gas development
2) Wind energy development
3) Solar Energy
4) High Intensity Developed Lands
5) Landscape Condition
6) Waterbodies
7) Roads and railroads
8) Energy transportation – pipelines and powerlines
9) Agricultural modifications
10) Building Footprints

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 study area.

Land Cover Code (NLCD)	Land Cover Description	Resistance Score	Source
21	Developed, Open Space	8	NLCD 2016
22	Developed, Low intensity	8	NLCD 2016
23	Developed, Medium Intensity	9	NLCD 2016
24	Developed, High Intensity	20	NLCD 2016
31	Barren Land, non-natural	10	NLCD 2016
32	Barren Land, natural	1	NLCD 2016
41	Deciduous Forest	1	NLCD 2016
42	Evergreen Forest	1	NLCD 2016
43	Mixed Forest	1	NLCD 2016
52	Shrub/Scrub	1	NLCD 2016
71	Grassland/Herbaceous	1	NLCD 2016
81	Hay/Pasture	1	NLCD 2016
82	Cultivated Crops	7	NLCD 2016
90	Woody Wetlands	1	NLCD 2016
95	Emergent Herbaceous Wetlands	1	NLCD 2016

Oil and Gas Development
With about 350,000 active and inactive wells, the natural areas in the Rocky Mountain and Southwest Desert region are 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.

To accurately map the spatial effects of oil and gas development, we formed an oil and gas working group within the Steering Committee to guide our analysis approach, and review results. First, we compiled oil and gas well data from all the states in the study area (Table 3.2). Next, 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 3.13).

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.

Montana 41,756 Wells	Source: http://bogc.dnrc.mt.gov/WebApps/DataMiner/MontanaMap.aspx (Emailed from Brian Martin, Montana Grasslands, Conservation Director) **Active Wells**: Status: Active Injection, Completed, Domestic, Other, PA-Approved, Producing, Shut In, Temporarily Abandoned, **Inactive Wells:** Abandoned, Abandoned Unapproved, Expired, Not released, Permitted to Drill, Permitted Injection Well, Revoked Inj. Permit, Spudded, Unknown, Water Well Completed, Water Well Released
Wyoming 55,909 wells	Wyoming Oil and Gas –Two datasets from Holly Copeland (TNC WY), WY Active Wells, WY Plugged and Abandoned **Active** and **Inactive** Wells listed in each dataset
Idaho 169 wells	Source: Idaho Oil and Gas Conservation Commission https://ogcc.idaho.gov/maps/ Idaho Geologic Survey – Historic Oil and Gas Data https://www.idahogeology.org/product/dd-3 **Active:** Producing, Shut-in, Permitted, Drilled **Inactive:** Plugged and Abandoned, Historic Wells
Colorado 114,524 wells	Source: http://cogcc.state.co.us/data2.html#/downloads **Active:** AC-Active, CM-Commingled, DG-Drilling, DM-Domestic Well, IJ-Injecting, PR-Producing, RC-Recompleted, SI-Shut In, TA-Temporarily Abandoned, WO-Waiting on Completion, XX-Permitted Location **Inactive:** AB-Abandoned, AL-Abandoned Location, CL-Closed, DA-Dry and Abandoned, PA-Plugged and Abandoned
New Mexico 117,621 wells	Source: http://www.emnrd.state.nm.us/OCD/ocdgis.html **Active:** A (Active) **Inactive:** C (cancelled APD), H (Plugged (not released)), N (New Not Drilled/Completed), P (plugged), S (Plugged Site Released), T (approved TA – Temporarily Abandoned)
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, Well, Gas Well, Horizontal Drain hole, 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, Dry Hole, Observation Well, Permitted Location, Plugged Gas Well, Plugged Oil Well, Plugged Oil/Gas Well
California 237,097 wells	Source: California Department of Natural Resources: Division of Oil, Gas, and Geothermal Resources. https://www.conservation.ca.gov/dog Active: Active, Idle, New, Inactive: Plugged, Unknown, Cancelled
Nevada	Source: Nevada Bureau of Mines and Geology: https://gisweb.unr.edu/OilGas/

1,061 Wells	Active: Producer, Shut-in, Inactive: Abandoned, cancelled, Dry and Abandoned, Never Drilled, Plugged and Abandoned
Arizona 1,107 Wells	Source: Arizona Oil and Gas Conservation Commission http://azogcc.az.gov/ **Active**: Producing Gas Well, Producing Oil Well, Shut-in Oil Well, Gas Storage (Liquified Gas), Temporarily Abandoned **Inactive:** Dry Hole, Helium well, plugged abandoned, Oil well, plugged abandoned, Stratigraphic Test, Geothermal gradient well, plugged and abandoned
Utah 36,596 Wells	Source: Utah Department of Natural Resources, Oil, Gas and Mining Division. https://gis.utah.gov/data/energy/oil-gas/ Active: Active service well (well types: WI, WD, GI, GS, WS, TW) (A), Approved Permit to Drill, Deepen, or Re-enter. (APD), Well Spudded and/or currently Drilling (DRL), Inactive service well (well types: WI, WD, GI, GS, WS, TW) (I), New Application for Permit to Drill (APD), Deepen, or Re-enter - received but not yet approved (NEW), Drilling Operations Suspended - spudded, but no drilling activity for an extended period - well not yet completed (OPS), Producing oil or gas well (OW, GW) (P), Shut-in oil or gas well (OW, GW) (S), Temporarily-Abandoned oil or gas well (TA) Inactive: Location Abandoned - Approved Permit to Drill (APD) for a NEW well - Rescinded - no site disturbance. (LA), Any well or construct permanently Plugged and Abandoned (PA), New Application for Permit to Drill (APD), Deepen, or Re-enter - Returned UNAPPROVED. (RET),

Table 3.3 Well Density Resistance Weights.

Well Density	**Resistance Weight**
0 – 1 well 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:
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 U.S. 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 U.S. There are over 7,000 wind turbines in the region.

To map the impact in the local connectedness score, we used a 1-mile kernel density with the same 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 3.14.

Table 3.4 Wind Turbine Density Resistance Weights.

Turbine Density	Resistance Weight
0 – 1 turbine per square mile	0
1-2 turbines per square mile	+ 1
2-4 turbines per square mile	+ 2
4-8 turbines per square mile	+ 3
8- 16 turbines per square mile	+ 4
16 turbines per square mile	+ 5

Figure 3.13: Oil and Gas Well Density. The density of oil and gas wells in the Rocky Mountain -Southwest Desert study area based on source data from every state.

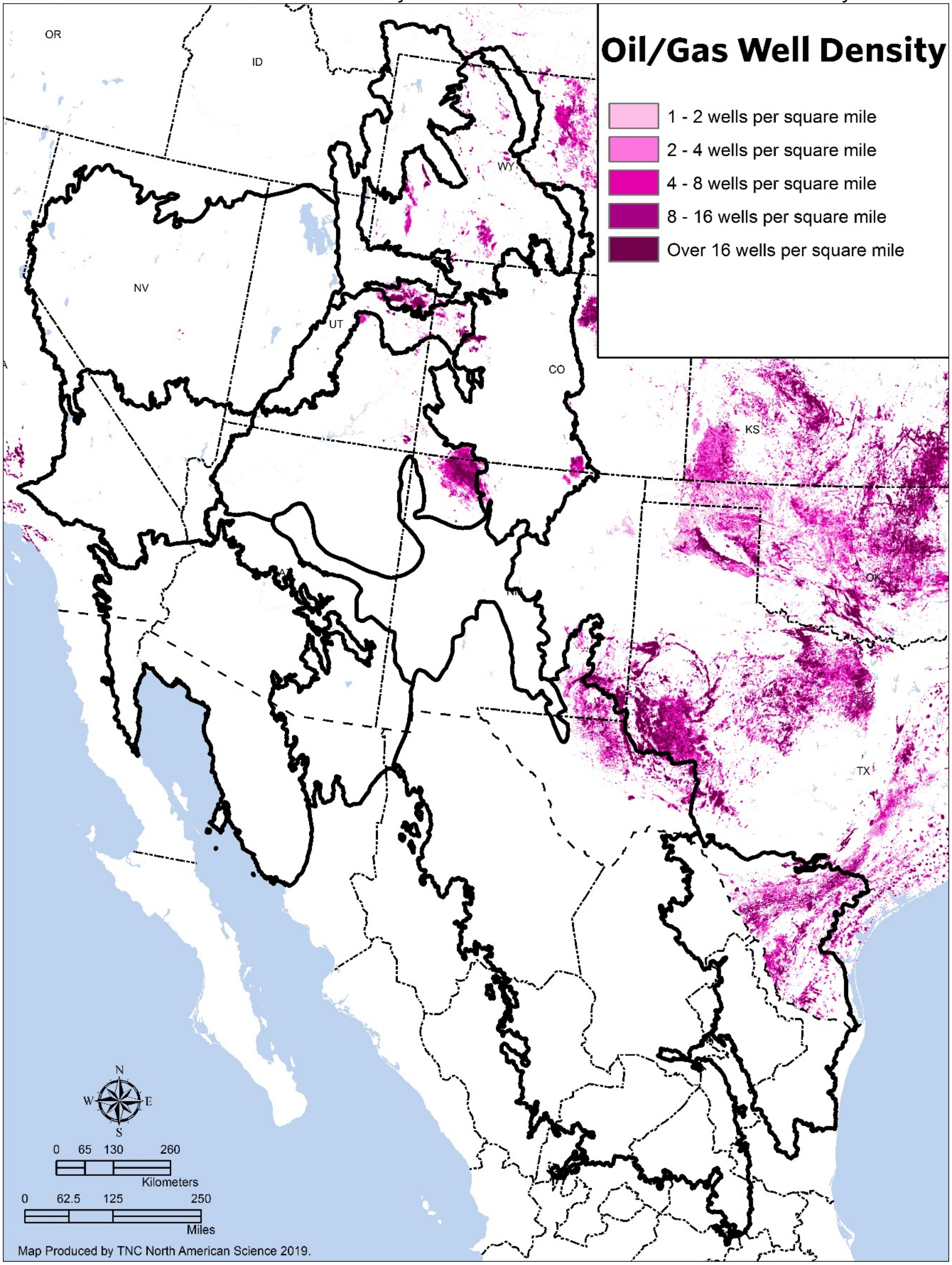


Figure 3.14: Wind Turbine Density. The density of wind turbines in the study area.

Solar Energy

Solar Energy is one of the cleanest energy sources there is, but for the actual land where the solar field is sited, there are negative effects for connectivity. The area is fenced off to prevent vandalism and damage from larger animals. Most of the surface of the land is covered with solar energy panels.

No single map of solar energy polygons for the West currently exist, but the EPA eGRID renewable energy data has latitude/longitude for all facilities across the country (US EPA 2019). We filtered this dataset for just wind energy and then hand digitized the spatial extent of the solar energy facility using National Agriculture Imagery Program (NAIP) imagery (USDA Farm Services Agency 2019).

Solar energy sites present high resistance to connectivity. We gave these areas a high resistance score of 20.

Mines and other High Intensity Developed Lands:

In the land cover datasets, the category "barrens" often mixes developed lands such as oil and gas wellheads or surface mining with large natural barrens, the latter which make up a large proportion of the western landscape. To identify barrens caused by mining or other high intensity development and differentiate them from natural barrens we compiled a variety of individual datasets.

The location of mines has been represented in several datasets. To create a single layer, we compiled and integrated the following into a single coverage.

- USGS point shapefile of active mine and mineral processing plants in the US (USGS 2003).
- The Disappearing West project's human modification index category: mines (Theobald et al. 2016),
- LANDFIRE datasets category "Quarries-Strip Mines – Gravel Pits" (3295 in EVT_PHY, Landfire, U.S. Department of Agriculture and U.S. Department of the Interior 2016).

We also identified additional mining operations using USGS's significant topographic changes in the U.S. Dataset (USGS 2018), which captures areas of topographic changes from surface mining, urban development, and landfills.

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.

Landscape Condition:

Throughout the western landscape, these lands are slow to recover from disturbance from invasive, fire, and retired agriculture largely due to the lack of water. Steering committee member identified several permanent or semi-permanent factors that degraded the condition of the landscape and we incorporated those that could be mapped into the resistance grid.

Cheatgrass. Cheatgrass is invasive to the west. It has a short life cycle and high seed production. Cheatgrass dries out earlier than native grasslands, increasing fire potential. After fire, cheatgrass is likely to outcompete native plants and its effects are considered semi-permanent and largely irreversible. We compiled a cheatgrass dataset using Boyte and Wylie Near-Real-Time Cheatgrass Percent Cover in the Northern Great Basin (Boyte and Wylie 2018). This dataset estimates cheatgrass extent for four snapshots in 2017 and 2018. Estimates are based on enhanced Moderate Resolution Imaging Spectroradiometer (eMODIS) Normalized Difference Vegetation Index (NDVI) data at 250-meter resolution. This dataset was chosen over other cheatgrass datasets because of the resolution and spatial extent of the data. It provides a percent cover estimate for cheatgrass for each grid cell. Based on consultation, we gave a higher resistance value of 3 to any cell with greater than 15% cheatgrass in any time series.

Bromus rubens (red brome) is an invasive annual grass that grows in warmer deserts of the Southwest U.S. It can increase and carry fires into ecosystems that aren't fire adapted, causing lasting damage to desert flora. Within the Sonoran and Mojave Desert, dead and dry red brome is easily ignited, supporting fast-moving surface fires. Fire return intervals are also shortened, changing the vegetal composition through increase of non-native components and loss of native plant species. To measure areas effected by red brome, we used the USGS historic fire dataset (USGS 2019), which is a polygon dataset of fire locations from 2000 – 2018. We downloaded each dataset, converted to a raster and then summed the raster to get number of years of fire in the Sonoran and Mojave Desert Ecoregions. If an area had fire in one or more years of the data, it was likely to have invasive red brome and was given a resistance score of 3.

Former Agricultural Lands. We added former or retired agricultural lands to the resistance grid in the Arizona portion of the Sonoran Desert and Apache Highlands based on a published dataset (Guarinello et al. 2017). The recovery and restoration in desert areas is slow so these areas are unlikely to contain native biota and likely to hamper wildlife movement. Former agricultural lands are often adjacent to current agricultural lands and can be extensive (over 680,000 acres). These disturbances won't show up on most land cover data sets, thus deserts typically look more intact than they are. To account for this, we assigned former agricultural lands a resistance score of 3.

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 3.15). Streams and ponds that had less than 200 m of shoreline were all assigned a "1."

Roads:

The 2016 NLCD landcover data set (Yang et al. 2018) contains an embedded roads data set from the Bureau of Transportation Statistics that does not align with the newer and more accurate 2018 Tiger Road dataset (U.S. Census Bureau 2018). To correct this issue, we removed the older roads from the NLCD and replaced them with roads from the Tiger 2018 dataset. To do this, cells in the 2016 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 2018 Tiger roads were "burned in" on top of the 2016 NLCD replacing the older road data with the more recent data.

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).

The amount of resistance of a major road is effected by traffic volume. More cars traveling on a road increases the chances of collision, road noise, pollution, invasive species, and roadside fences. The US Department of Transportation Federal Highway Administration maintains a Highway Performance Monitoring System (HPMS, Federal Highway Administration 2019) that describes the condition of federal roads and includes traffic volume estimates for larger roads. We incorporated traffic volume into the resistant grid by increasing the width of the road line relative to their traffic volume. We classified the roads by their volume and increased the width by one cell for each volume class. Classification breaks followed the Industry Classifications (Federal Highway Administration 2019) and were examined using satellite imagery to confirm they were appropriate. Breaks were as follows:

Annual Average Daily Traffic (# of cars)	Width in Grid
500 – 2,500	1 cell (30 meters)
2,500 – 5,000: Two lane non divided highway with large shoulder	2 cells (60 meters)
5,000 – 10,000: Divided Highway, 2 lanes in each direction	3 cells (90 meters)
10,000+: Divided Highway, 2 directional lanes with service drive	4 cells (120 meters)

Residential roads and dirt roads are not consistently classified in the Tiger dataset, especially unpaved residential roads with low traffic volume. To separate roads with low traffic volume from higher volume road, we used "road name" after exploring the data and finding that named roads tended to be paved and occur in more residential settings than unnamed residential roads which were often unpaved and isolated. From the road name dataset, we removed roads with generic names (like Forest Service Road #202) and named road segments that were isolated or not connected to other roads. These roads still may not have much traffic on them, so we assigned them a low resistance score of 3.

Smaller dirt roads which crisscross the landscape but are infrequently used were assumed to pose little barrier for connectivity. They were not included in the resistance grid.

Energy Transportation – Pipelines and Powerlines:

To account for the influence of energy infrastructure, we added the locations of powerlines to the landcover datasets. To do this, we obtained power industry GIS data (Ventyx 2019, 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 (Duke Energy 2019):

- 30-m width for transmission lines <230 kilovolts,
- 180-m width for lines > 230 kilovolts.

All pipelines were given a 30-m width but after a discussion among our steering committee, we decided to omit them from the resistance grid as most are buried and do not pose much of a barrier to connectivity. This was reinforced by visual exploration using satellite image, where we could rarely find the mapped pipelines.

Powerlines and their right-of-way's in a non-forested landscape vary little from the surrounding landscape; we assigned them a resistance of 2. Powerlines and their right-of-way's in a forest landscape can act as more of a fragmenting feature and we assigned them a higher resistance score of a 3.

Agricultural Modifications

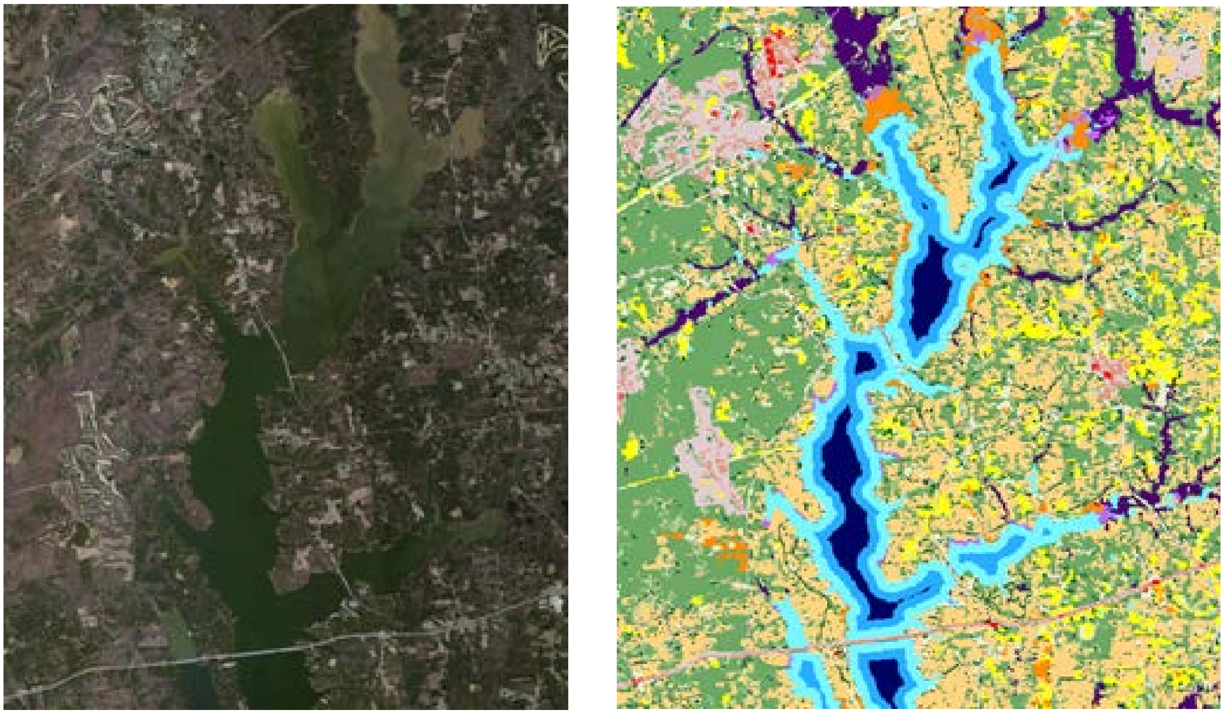
Over most of this region the Hay/Pasture landcover class in the NLCD is likely to be active agriculture with mowing and irrigation, which creates a slight barrier to movement We assigned this category a resistance of 3. However, in the south Texas ecoregion, Tamaulipan thorn scrub, our steering committee found many errors where the natural scrubby grasslands were consistently mapped as Hay/Pasture. In this ecoregion we gave Hay/Pasture a resistance score of a 1.

Building Footprints

The NLCD often misses or misclassified very low-density residential areas in rural, agricultural, and natural western landscapes. Fortunately, Microsoft has just released a building footprint dataset (Microsoft 2019) that accurately maps all the individual building footprints for the whole US. They used deep learning, computer vision and artificial intelligence to create the map. We downloaded each data by state, converted it from GEOJSON format to ESRI shapefile, merged all the state shapefiles to one regional building footprint shapefile.

With over 35 million building footprints in the region, the polygon dataset of building footprints was too big to work with in GIS. To be computationally possible to analyze such a large dataset, we converted the polygons to centroid and then ran a kernel density in 100 meters to capture the footprint of the building. We chose a kernel density because unlike just a straight buffer because it calculates a magnitude per unit area score, which gives areas with more building footprint centroids a higher score. Any area with a kernel density > 2 were given a resistance score of 9.

Figure 3.15: 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+ .



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 3.16 and 3.17).

Figure 3.16: 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.

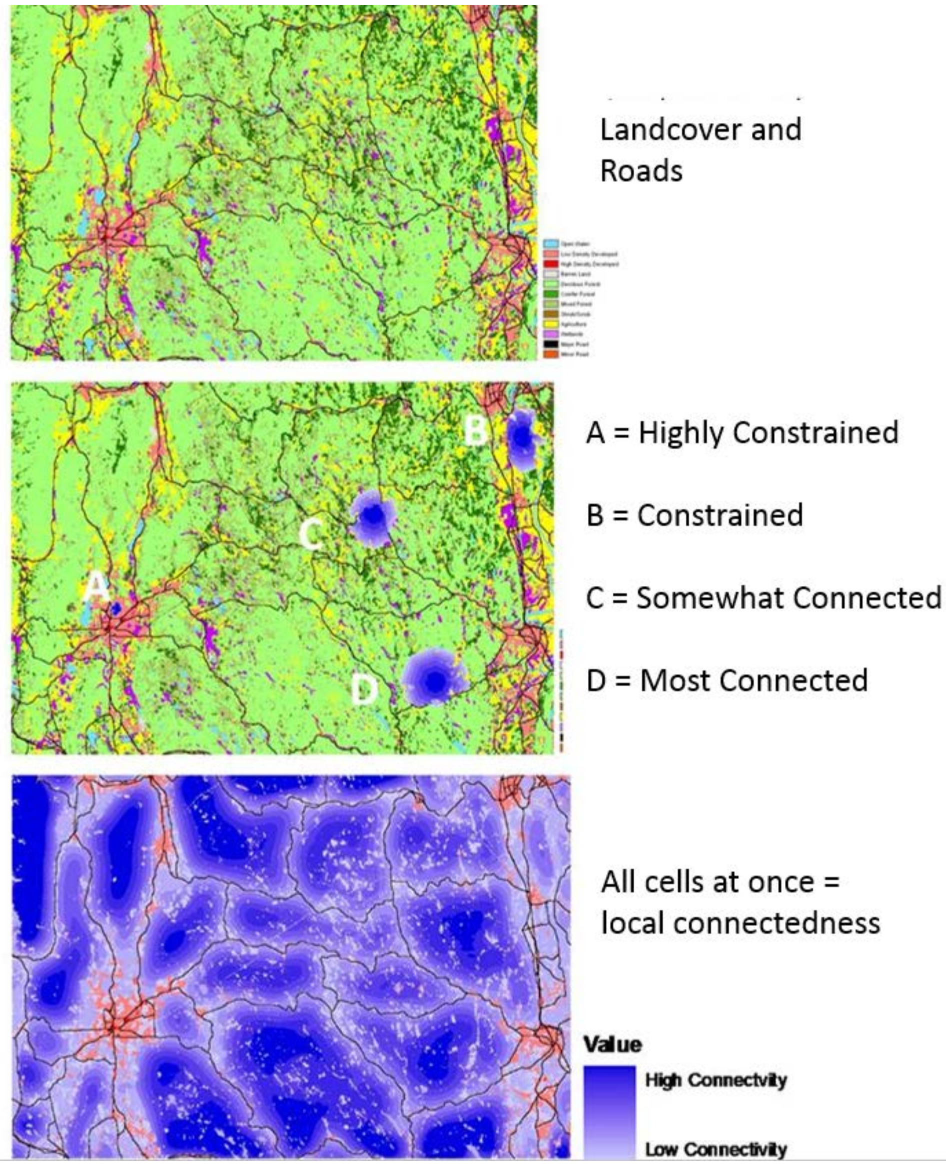
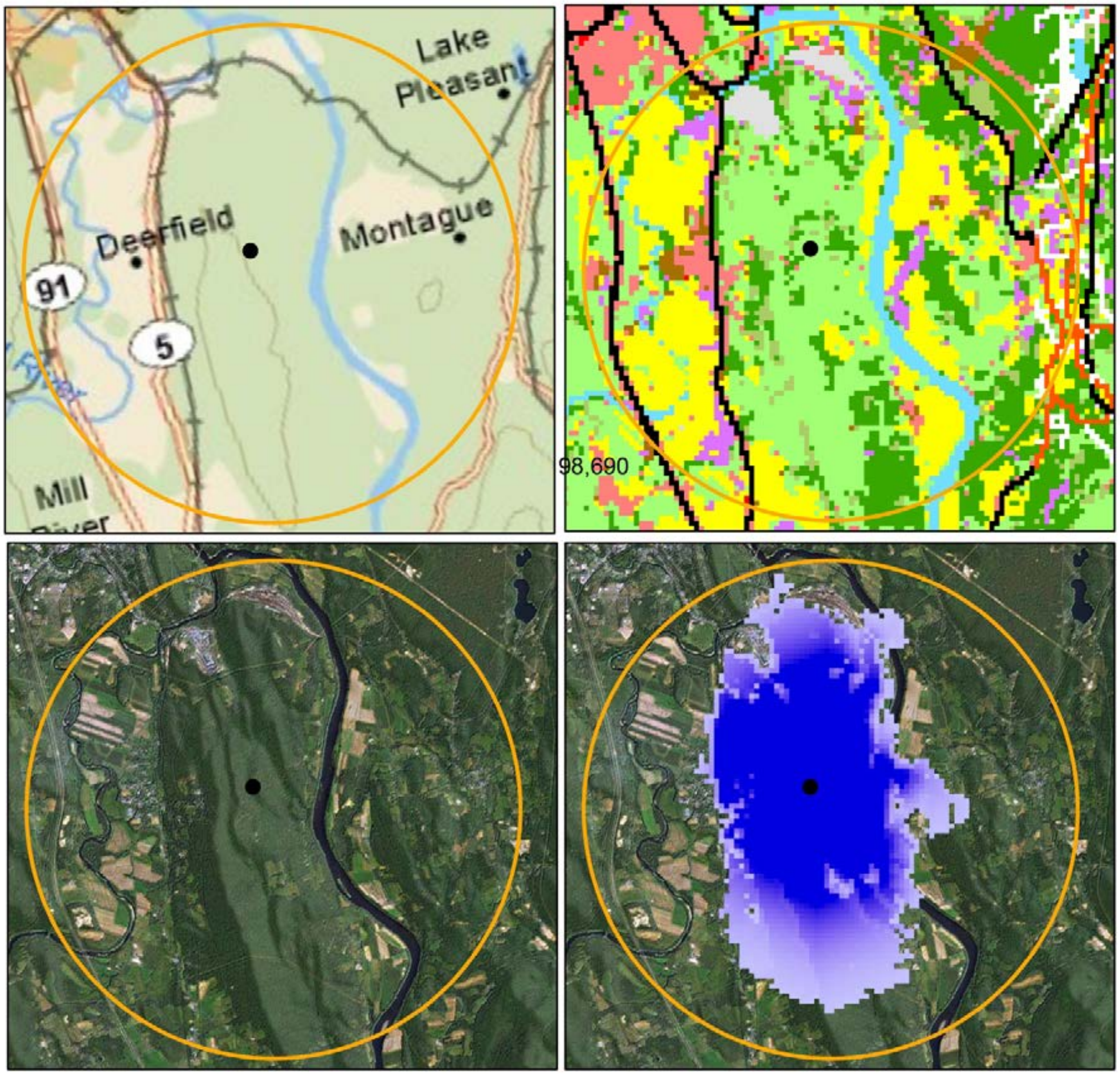


Figure 3.17: Detailed look at Kernel B in Figure 3.16. The top left image shows the topographic map. The top right image shows the land use grid details. The bottom left panel shows the aerial image with the 3-km circular resistant kernel distance outlined in orange. The bottom right box shows the kernel 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 0.80 and a standard deviation of 0.21 for the region. 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 3.15).

Numerical scores were transformed to Z-scores based on the mean and standard deviation of each ecoregion, creating a local connectedness map for each (Figure 3.19).

Figure 3.18: 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 = 0.01
Regional Z Score = -3 SD

High intensity oil and gas development

RK Value = 0.40
Regional Z Score = -1 SD

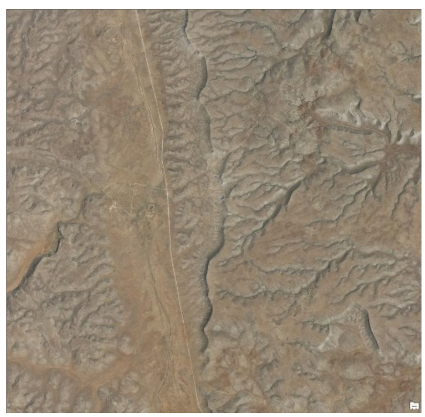
Natural landuse surrounded by paved roads and low-density development

RK Value = 0.61
Regional Z Score = -0.5 SD

Low Density rural development on dirt roads.

RK Value = 0.86
Regional Z Score = 0 SD

Several small roads and a transmission line



RK Value = 0.90
Regional Z Score = 1 SD

One road on the edge

RK Value = 0.91
Regional Z Score = 1.5 SD

No development

Figure 3.19: Local Connectedness. This map estimates the degree of connectedness of a cell with its surroundings within a 3-km radius with a custom ecoregional stratification.

Transforming Local Connectedness Scores

With over 87% of the region in natural landcover, the distribution of local connectedness scores is skewed towards natural. The same pattern holds true within each ecoregion, except in the Tamaulipan Thorn Scrub where the local connectedness distribution was close to normal. For the Tamaulipan Ecoregion, we used a standard normal transformation to convert the raw connectedness scores to Z-scores based on the mean and SD of the ecoregion. For all other ecoregions we developed an alternative transformation to account for the skewed distribution.

To describe how we transformed the left skewed data to approximate a Z-score we will use the Colorado Plateau ecoregion as an example. The transformation was necessary so the score could be combined with the landscape diversity score giving equal weight to both for the integrated resilience score and providing realistic differentiation within the local connectedness score. The Colorado Plateau is very intact, the local connectedness scores have the following distribution:
Mean = 83.6, Median = 90.3, Mode = 91.9, Max = 91.9, Min = 0.0025

Here over half the region scores above 90% and the maximum local connectedness score, 92, is also the mode (most common value). Fragmented areas with cities, roads, or energy development score low (0.003%-20%) but make up such a small portion of the ecoregion that statistically they are outliers.

In this right skewed pattern, most of the relevant information is concentrated at the two extremes. To account for this, we treated values to the left and right of the mean differently. At the low end we used ecologically meaningful thresholds to reflect and account for fragmentation. At the high end we used non-parametric statistics (quartiles) to break the high values into equally distributed categories.

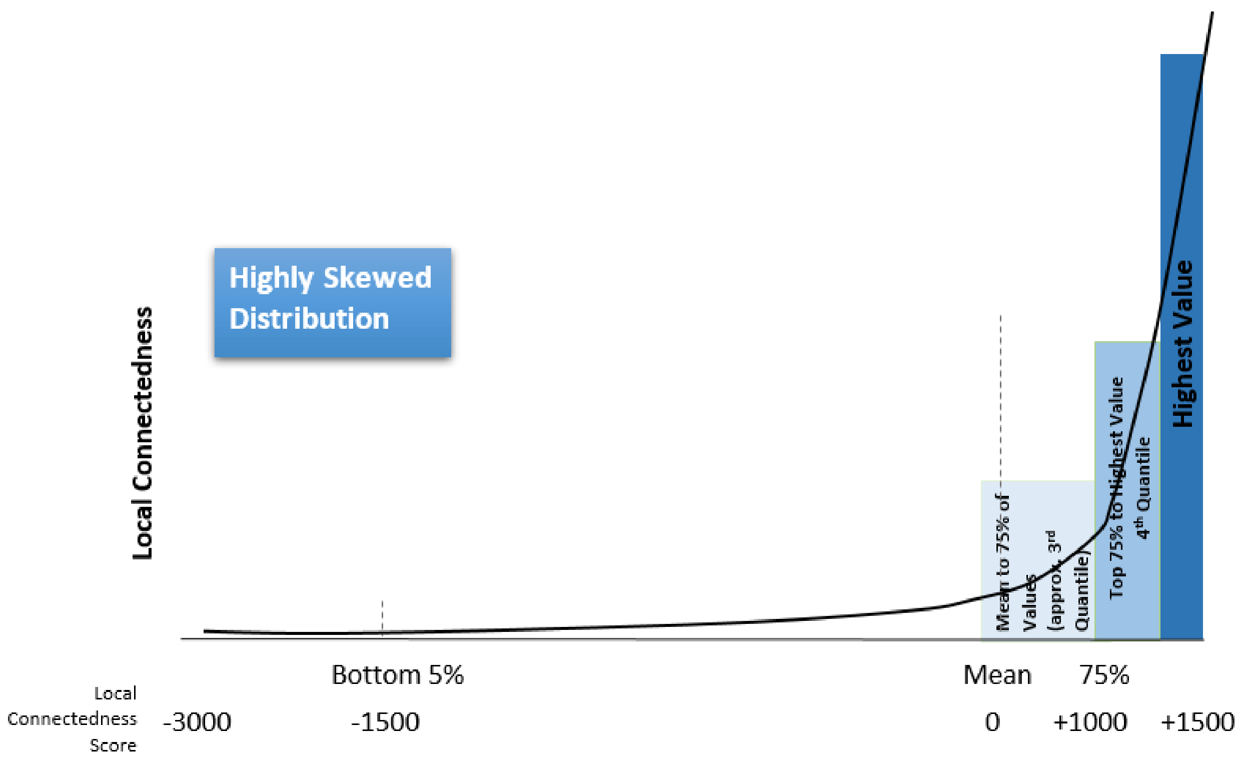
At the low end, where the land was fragmented by development, industrial agricultural, large solar farms, or high-density oil and gas, we assigned the actual resistant kernel scores (0%-5%) to the Z-scores -3.0 to -1.5 SD, and distributed the intervening sores in proportion to their actual values (for example 0, 2.5, 5 became -3.0, -2.25, -1.5 SD). For slightly less fragmented areas (5% to Mean) we similarly assigned 5% to Z-score -1.5 SD and the Mean to Z-score 0. We then distributed scores in between these to end in proportion to their actual values (Table 3.4). In total area, this portion of the land was always less than 25% and usually less than 20%.

For the high end, intact land with values above the mean we used quartiles and max/mode to identify thresholds and matched these to the Z-scores as follows: Mode/Max = 1.5 SD, Q3 = 1.0 SD, Mean = 0. As for the low-end scores, values in between were distributed in relation to their actual value (Figure 3.20). We intentionally limited the increase that an above-average site could get to 1.5 SD because areas above the mean were still very close to the mean.

Table 3.4: Comparison of Scores for a Normal Distribution and Left Skewed Distribution

Score	**Normal Distribution**	**Left Skewed** Thresholds	**Left Skewed** % of Area
Far Below Average	-3.0 SD	0%	21%
	-2.5 SD		
	-2.0 SD		
Below Average	-1.5 SD	5%	
	-1 SD		
Slightly Below Average	-0.5 SD		
Average	Mean (0)	Mean	
Slightly Above Average	+ 0.5 SD		29%
Above Average	+ 1.0 SD	Q3	25%
	+ 1.5 SD	Max/Mode	25%
Far Above Average	+ 2.0		
	+ 2.5		
	+ 3.0		

Figure 3.20: Local Connectedness Score Diagram. This diagram shows the skewed distribution of the local connectedness results and the classification into a local connectedness score.



Section 3: Combined Resilience Factors

Combining Landscape Diversity and Local Connectedness

In the Tamaulipan Thornscrub ecoregion, we combined the landscape diversity score with the local connectedness score by first converting the scores to a standard normal distribution (Z-scores) and taking the average of the summed values. This method assures equal weight to both variables which now have a mean of zero and a standard deviation of 1. The normalized score prevents factors with a larger mean or variance from having more influence.

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"

Resilience was calculated as follows:
Site Resilience = (Landscape Diversity + Local Connectedness)/2

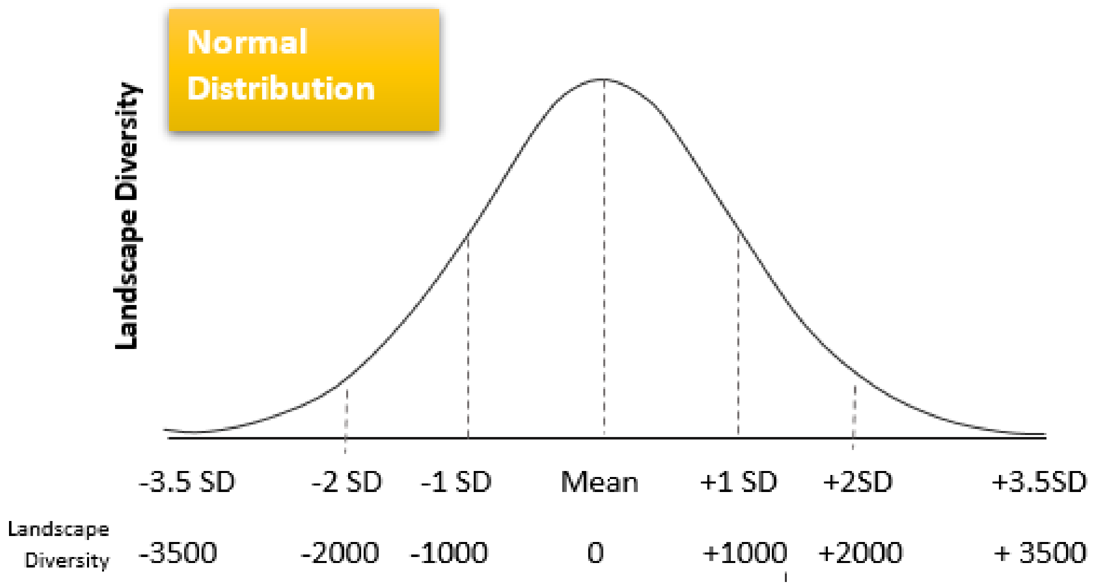
For all other ecoregions we first transformed the local connectedness in Z-score units using the method described above for left skewed distributions, Local connectedness for this region in most ecoregions is so skewed toward intact that 50% of each ecoregion have raw scores between 81 and 92. Rather than averaging the Local Connectedness and Landscape Diversity scores we used the following categories to bump up the Landscape Diversity score to create the Resilience Score (Figure 3.21):

- >1.5 SD Completely intact natural area: add 0.25 SD
- 0 to 1.5 SD. Lightly modified landscape: increase between 0 and 0.25 SD
- 0.0 SD. Ecoregional average: add 0, so Resilience = Landscape Diversity
- -1.5 to 0.0 SD. Human altered landscape: decrease between 0 and 1.5 SD
- -3.0 to -1.5 SD. High developed landscape: Resilience = Local Connectedness

In each of the categories the scores are distributed relative to their actual value. For example, in the lightly modified landscape a score of 1 gets a 0.2 increase while a score of 0.5 gets a 0.1 increase. In the lowest category we let the high degree of development (cities or high density oil and gas), local connectedness overrides any landscape diversity.

Site Resilience Scores are also in Z-units calculated as follows:
Site Resilience = (Landscape Diversity + Local Connectedness increase/decrease)

Figure 3.21: Combining Landscape Diversity and Local Connectedness. This diagram illustrates how the combined the normally distributed Landscape Diversity Score and the left skewed Local Connectedness Score



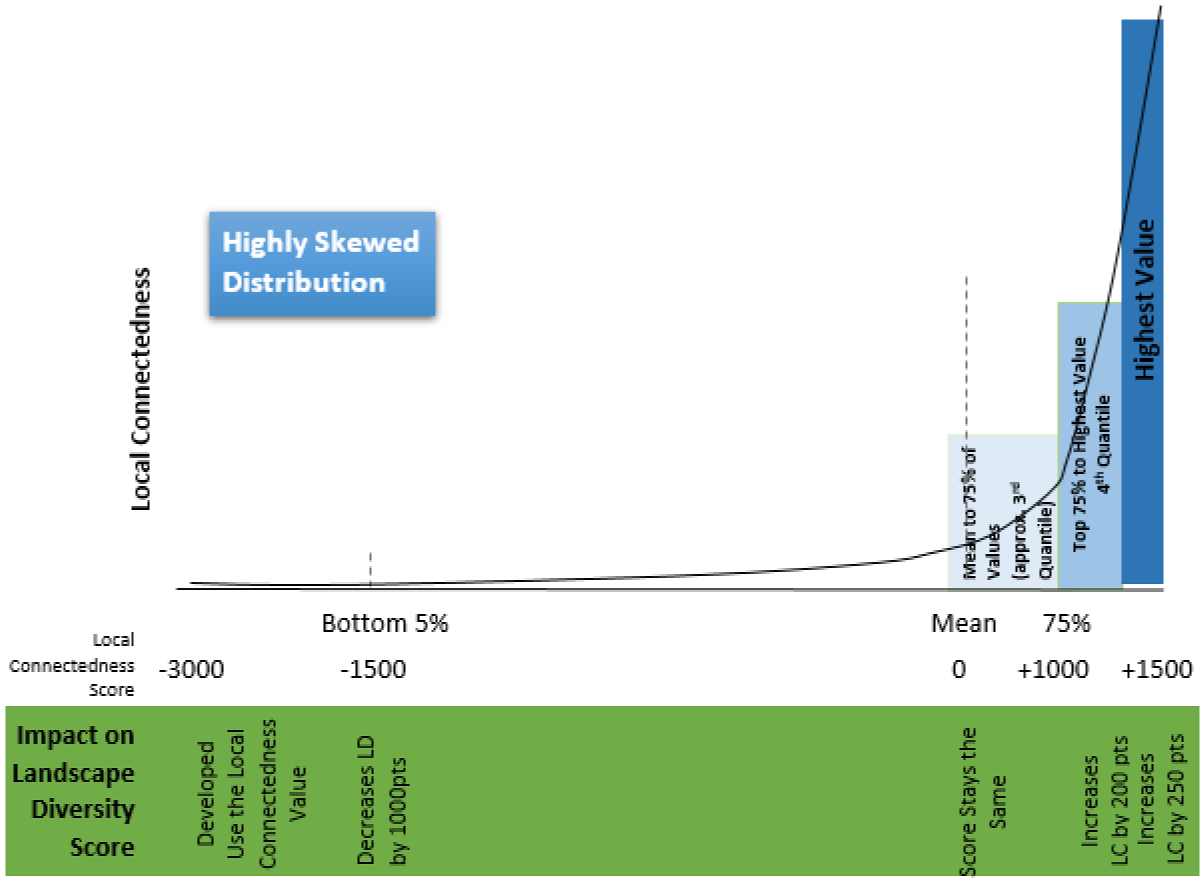
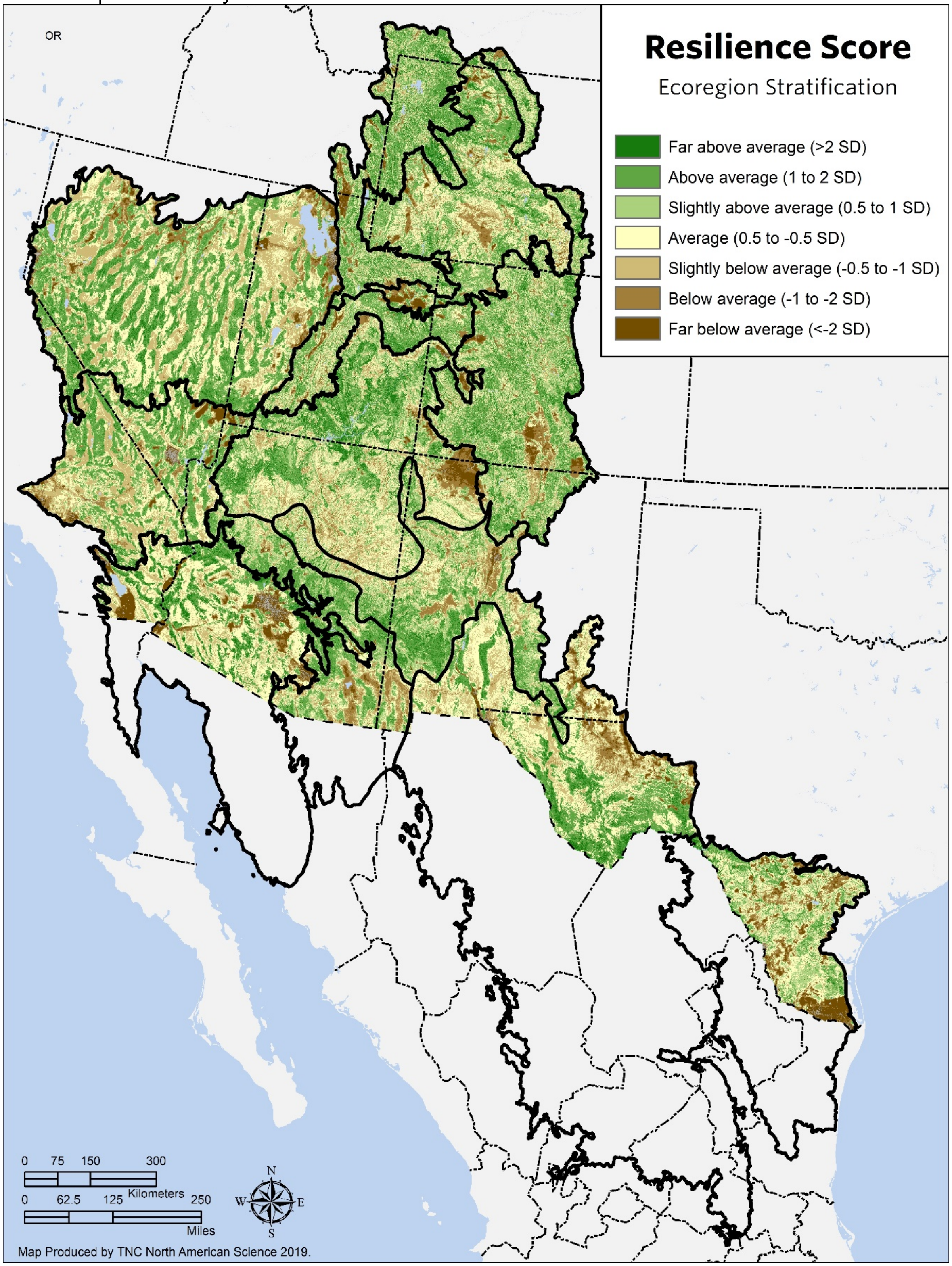

Highly Skewed Distribution
Local Connectedness
Highest Value
Top 75% to Highest Value 4th Quantile
Mean to 75% of Values (approx. 3rd Quantile)
Bottom 5%
Mean
75%
Local Connectedness Score
-3000
-1500
0
+1000
+1500
Impact on Landscape Diversity Score
Developed Use the Local Connectedness Value
Decreases LD by 1000pts
Score Stays the Same
Increases LC by 200 pts
Increases LC by 250 pts

Figure 3.20: Site Resilience Score by Ecoregion. This map shows the combination of Landscape Diversity and Local Connectedness.



Appendix 3.1

Open Water: Steps to create a single integrated layer

Open water was mapped using the National Hydrography Dataset (NHD) Medium resolution non-intermittent waterbodies and wide river polygon areas. We included all non-intermitted wide river polygons but reduced the non-intermittent NHD waterbodies with additional queries to remove "non-natural" waterbodies. This was done using the NHD waterbody base type codes to remove highly altered non-natural waterbodies (type aquaculture, disposal-tailings pond, disposal-unspecified, evaporator, treatment, treatment-cooling pond).

Even after removing the NHD altered waterbodies there were still quite a few farm ponds and storage tanks showing up as open water. To further improve the data, we intersected the NHD with the National Wetland Inventory data and the NHD high resolution data which had many of the same small ponds coded with modifiers indicating their non-natural status. We removed any waterbodies <100 acre coded with NWI wetland/waterbody class: excavated, farmed, dike/impounded, or spoil. We also remove small reservoirs <100 acres coded as reservoirs/non-natural waterbodies in NHD high resolution.

We kept large reservoirs >100 acres in the dataset as many larger waterbodies were dammed reservoirs but unlikely to be removed/a more permanent source of water. We also limited the NHD waterbodies to the area also confirmed as water in our NLCD2016 to make the shapes of the waterbodies align better with our most recent NLCD dataset. We did not limit the NHD areas (wide rivers) to NLCD2016 confirmed water as many of them were narrow rivers not always mapped by NLCD and we wanted a continuous, not broken up, representation of these rivers.

We then augmented the NHD wide river areas data with river linework from the NHD Medium Resolution flowlines for any perennial (or artificial path) NHD flowline in our medium tributary or larger river class (>518 sq.km upstream drainage area) because we noticed that sometimes these rivers were not mapped with a polygon NHD area in the arid west given how narrow they were even with large drainage areas. We needed to make sure the Rio Grande, Colorado, and a few other major rivers which were deemed perennial in the NHD line/arc dataset were transferred into the landform dataset as water. This particularly increased the mapped rivers in the mountain region and added the few occurring perennial medium tributary and mainstem rivers and the larger artificial path/canals connecting them in the desert regions.

Finally, we noticed that there were some large NLCD 2016 based waterbodies missing from our NHD derived water dataset. In some cases, these appear to have been due to new dams creating large lake features that were not in the NHD Medium resolution waterbodies or areas. To include those largest missing open water areas, we looked for NLCD2016 water which was not in our above water dataset. Many of the small waterbodies appeared to be manmade farm ponds we did not want to add as permanent natural water features. We used the NWI non-natural water overlay to focus again on the larger more permanent waterbodies. We choose to include any additional NLCD based waterbody >250 acres to augment the previous NHD based larger waterbodies. This added the larger waterbodies not included in the NHD base data, and removed more ephemeral/less permanent/manmade small farm feed ponds, tailing ponds, treatment cooling ponds etc. that were in the NLCD2016

The combined waterbody areas were then limited to >2-acre ones to focus on more substantial waterbodies. The resulting dataset resulted in a water dataset that focused on larger water larger natural and/or permanent waterbodies and removed the many smaller non-natural waterbodies from NHD or NLCD water as best as possible which we felt were ephemeral and non-natural resources.

Wetland were mapped using the NLCD 2016 “emergent wetland” or “forested wetland” categories as our base wetland dataset and took steps to further reduce its extent and eliminate non-natural wetland areas.

The NLCD 2016 wetland dataset was more recent than the NWI wetlands (circa 1980’s and 1990s primarily) but included many diked/excavated/and other non-natural wetlands given remote sensing reflectance cannot easily distinguish between natural and non-natural wetlands. These NLCD 2016 wetlands were thus reduced further by eliminating any area falling under a known older NWI polygon (wetland/waterbody) with Non-natural special modifiers including excavated, farmed, dike/impounded, or spoil as this indicated a type of non-natural management or origin of the wetland pixel. The NLCD 2016 wetlands were also limited by removing any NLCD2016 pixel falling in Cropscape >= 5 years crop/fallow land (USDA 2019).

Wetlands were then limited to appropriate landforms (Lower slope NE cool, Lower slope SW warm, Cove NE cool, Cove SW warm, Dry flat, Pluvial flat, fluvial flat Valley/toeslope). Water was then burned on top of them. The remaining cells were grouped so only wetland patches >2 acres remaining were added to the landform grid to focus addition of wet flat landforms only where there were substantial sized patches of the most natural wetlands.

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 12 ecoregions of the Rocky Mountain and Southwest Desert 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.

As with all the 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 Tamaulipan Thornscrub would likely score average or even low in the more topographically diverse and intact Southern Rocky Mountains. Results for the study area as a whole 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.

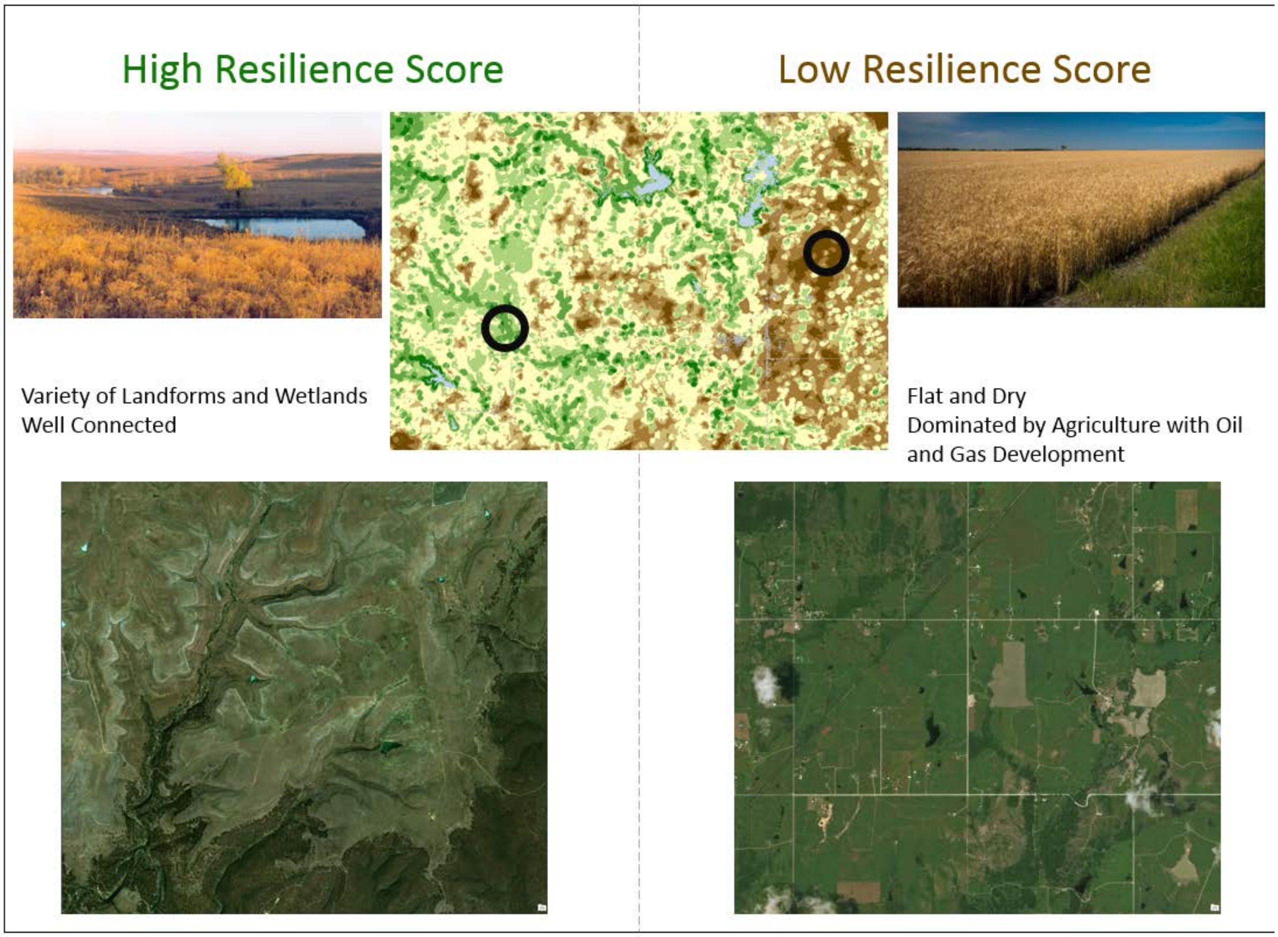
Coarse-scale climate models can provide useful estimates of the directional changes in temperature, and (with higher levels of uncertainty) project future changes in precipitation and related variables like evaporative demand. However, within the extent of a single spatial unit of a mapped climate projection (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 Adirondack Park NY (a region of relatively low relief) were estimated to have an average of 128 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 sites 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 species adapted to high levels of disturbances and anthropogenic degradation increase. 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 sand in the Great Basin Ecoregion, then a score of 1 SD means the site has greater landscape diversity and local connectedness than 84% of the other sites on sand in the Great Basin, and thus is mapped 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 Great Basin, 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 Great Basin Ecoregion. Because different ecoregions have different average scores, what scores average in one ecoregion might score high in another.

The final ecoregion site resilience map contains a modification to adjust for biases against sites that *were not* the highest in the ecoregion but *were* the highest for their geophysical setting in the ecoregion. Our goal was to identify the most resilient areas for all settings, even those that are in relatively poor condition. Some of these sites may need restoration fully sustain diversity.

The method for creating the maps followed a linear progression. 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.

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

This section presents the results for each ecoregion arranged in the following order

Mountains:

13. Utah-Wyoming Rocky Mountains
14. Utah High Plateaus
15. Southern Rocky Mountains
16. Arizona-New Mexico Mountains

Cold Deserts:

17. Wyoming Basin
18. Great Basin
19. Colorado Plateau

Warm Deserts:

20. Mojave Desert
21. Sonoran Desert
22. Apache Highlands
23. Chihuahuan Desert

Figure 4.2: Ecoregions

Tropical Lowland and Coastal

24. Tamaulipan Thorn Scrub

For each of the 12 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), and we provide a short description of each map below. Region-wide results are presented in Chapter 5.

For each ecoregion (Figure 4.3), 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

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 (life zone and geology)
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. In the Mountainous regions the large extent of high elevation life zones make it hard to see the various geology types so in these regions we created thee maps: Life Zone, Geology/Soils/ Geophysical setting.

2) Map of Landscape Diversity
The landscape diversity metric evaluates the number of species-relevant landforms within a 40-ha (100-acre) moving window, It incorporates elevation and wetland influence metrics that increases the score in areas with long slopes or 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 deep loess is 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).

Utah-Wyoming Rocky Mountains

This ecoregion description was adapted from: Noss et al. 2001. A Biological Conservation Assessment for the Utah-Wyoming Rocky Mountains Ecoregion.

The Utah-Wyoming Rocky Mountains Ecoregion encompasses most of what is known as the Middle Rockies. It includes the mountains just north of Yellowstone National Park in south-central Montana, the Bighorn Mountains in northeast Wyoming, the Uinta Mountains of northeast Utah and Northwest Colorado, Utah's Wasatch Range, and the mountains and valleys of the southeastern corner of Idaho.

Embedded in this vast area is the Greater Yellowstone Ecosystem, considered one of the last intact temperate ecosystems on Earth, and the farthest south in North America. Yellowstone is an extraordinary place containing the greatest concentration of geysers, hot springs, and other thermal features in the world. Yellowstone Park is the only large area in the coterminous U.S. that has never been farmed, ranched, or logged. It is home to all the native species that existed at the time of first Europeans exploration except for passenger pigeon: 337 species of mammals, birds, and fish, and more than 12,000 species of insects. It is home to one of the last remaining grizzly bear populations in the lower 48 states and the last continuously wild buffalo herd in the country. It has the greatest concentration of elk in the world.

Ecosystem-scale ecological processes as wildfire and predation by large predators still function over much of the landscape. Much of the ecosystem is protected from unbridled development with key areas like Yellowstone and Grand Teton National Park, the Uinta Mountains, High Uinta Wilderness, Dinosaur National Monument, and parts of Wyoming's Bighorn Mountain Range an isolated outlier of the Rockies. Human activities include logging, mining, oil and gas development, livestock production, industrial tourism, and a burgeoning population growth with attendant issues of sprawl and development.

Figure 4.3: Utah-Wyoming Rocky Mountains: Life Zones.

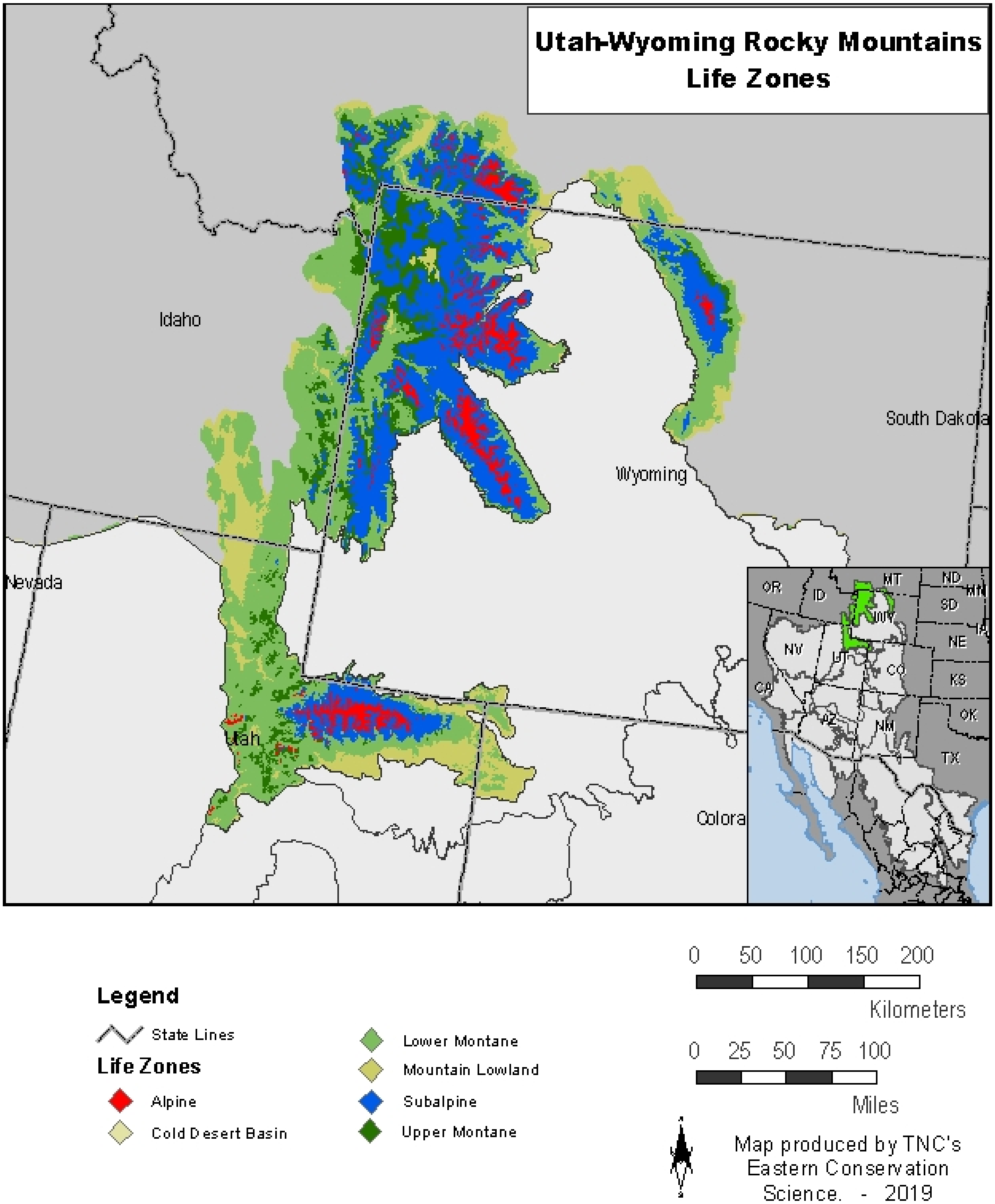


Figure 4.4: Utah-Wyoming Rocky Mountains: Geology/Soils.

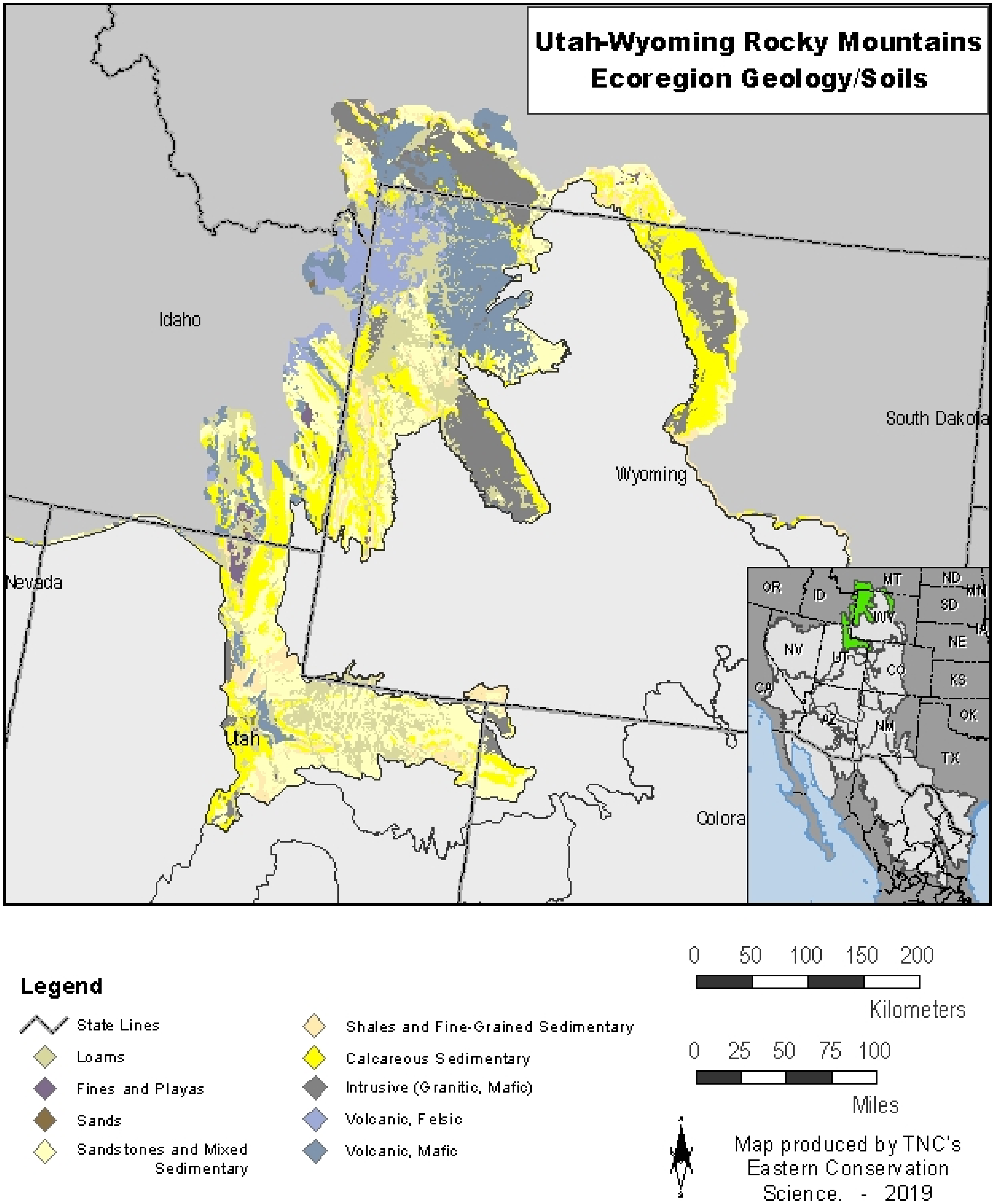


Figure 4.5: Utah-Wyoming Rocky Mountains: Geophysical Settings.

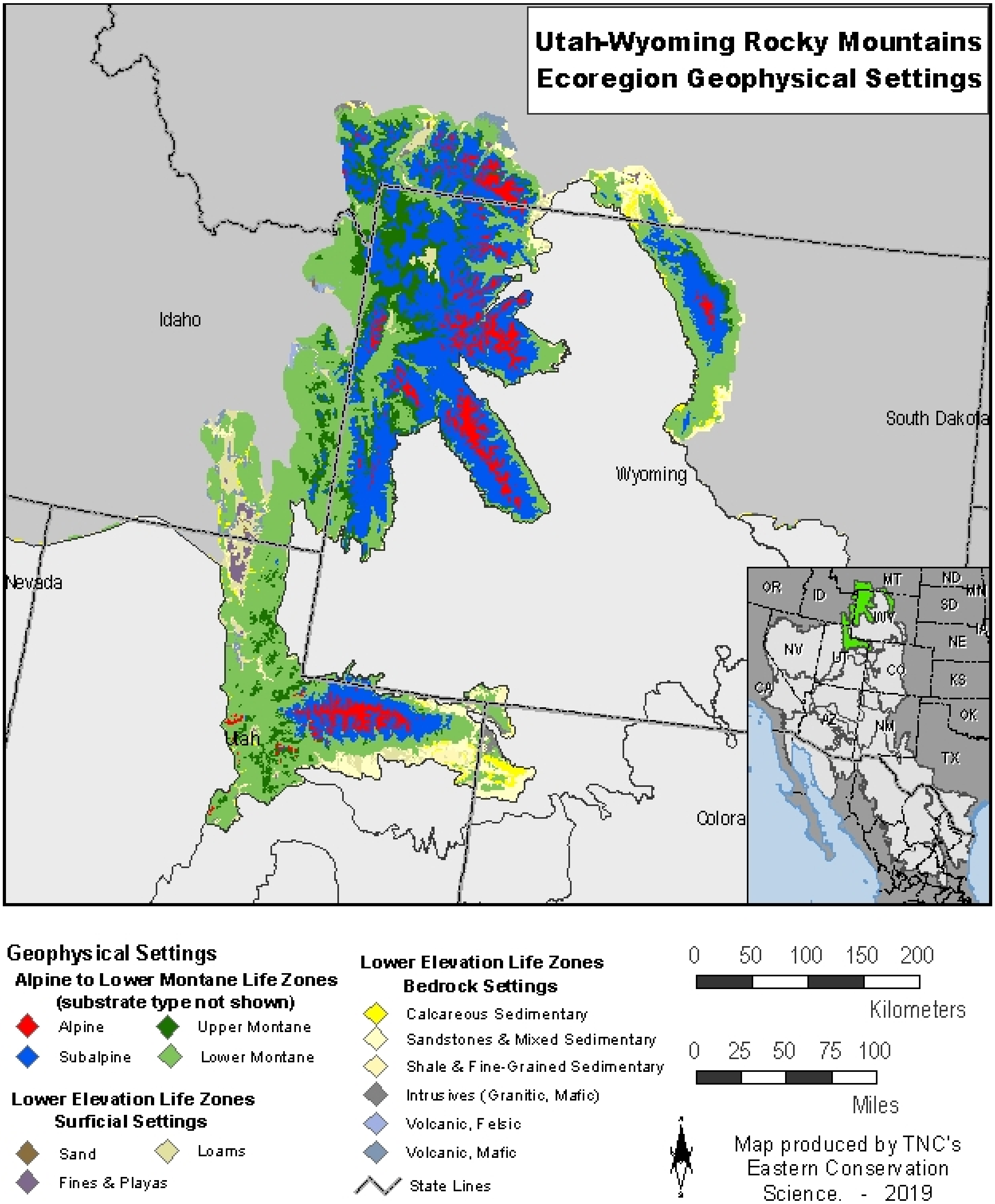


Figure 4.6: Utah-Wyoming Rocky Mountains: Landscape Diversity.

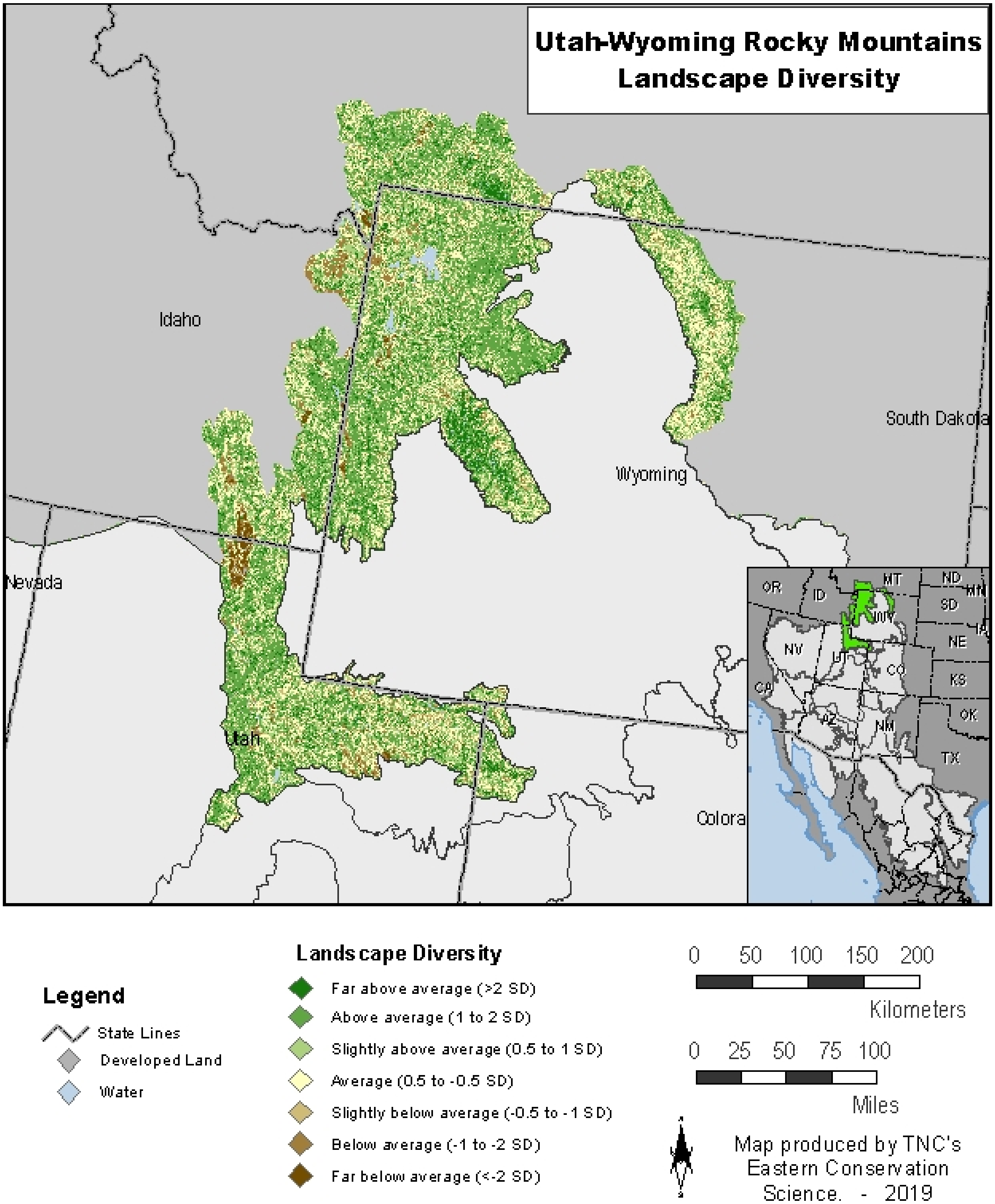


Figure 4.7: Utah-Wyoming Rocky Mountains: Local Connectedness.

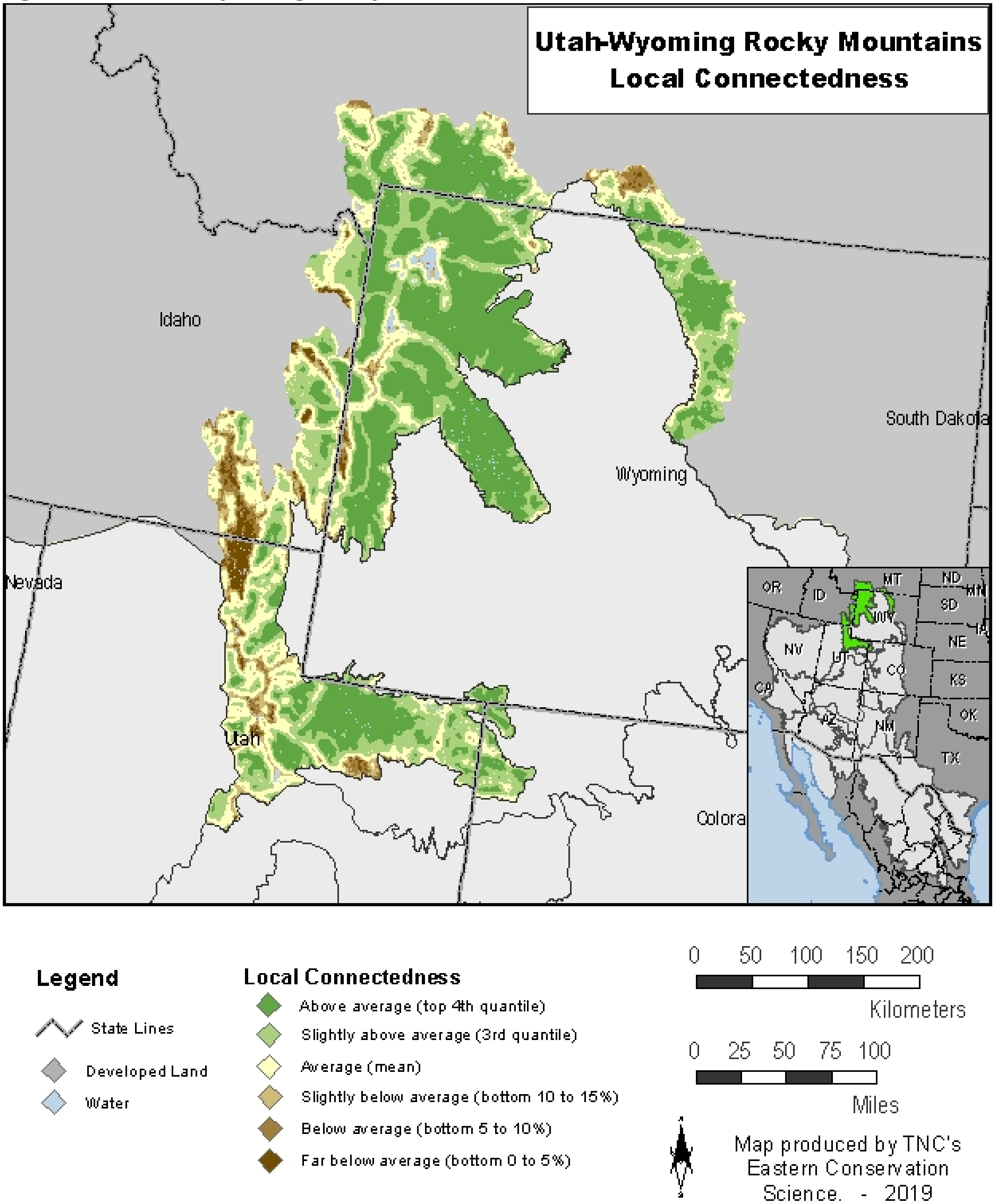


Figure 4.8: Utah-Wyoming Rocky Mountains: Site Resilience.

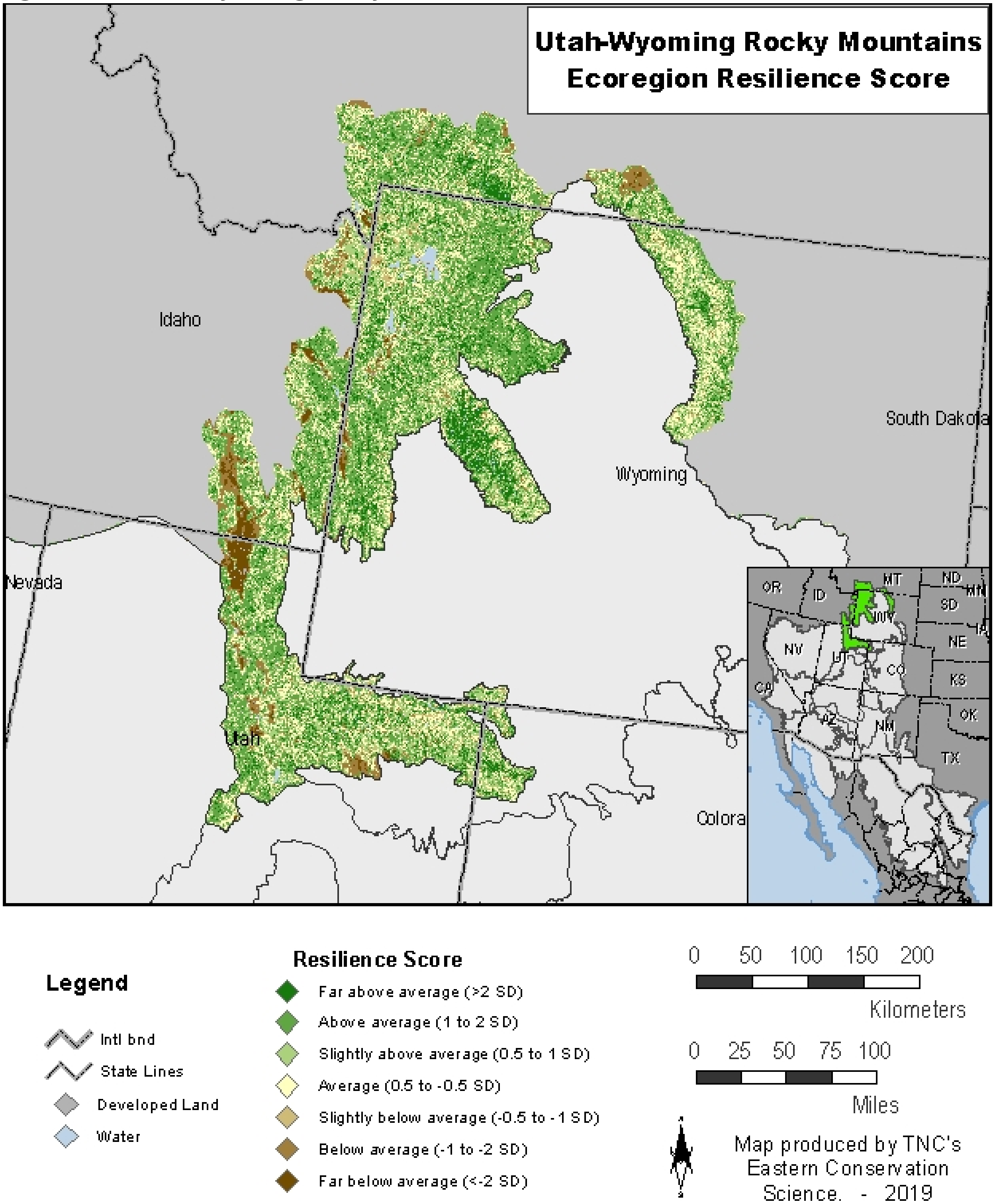


Figure 4.9: Resilient Areas for Each Geophysical Setting Within the Utah-Wyoming Rocky Mountains Ecoregion.

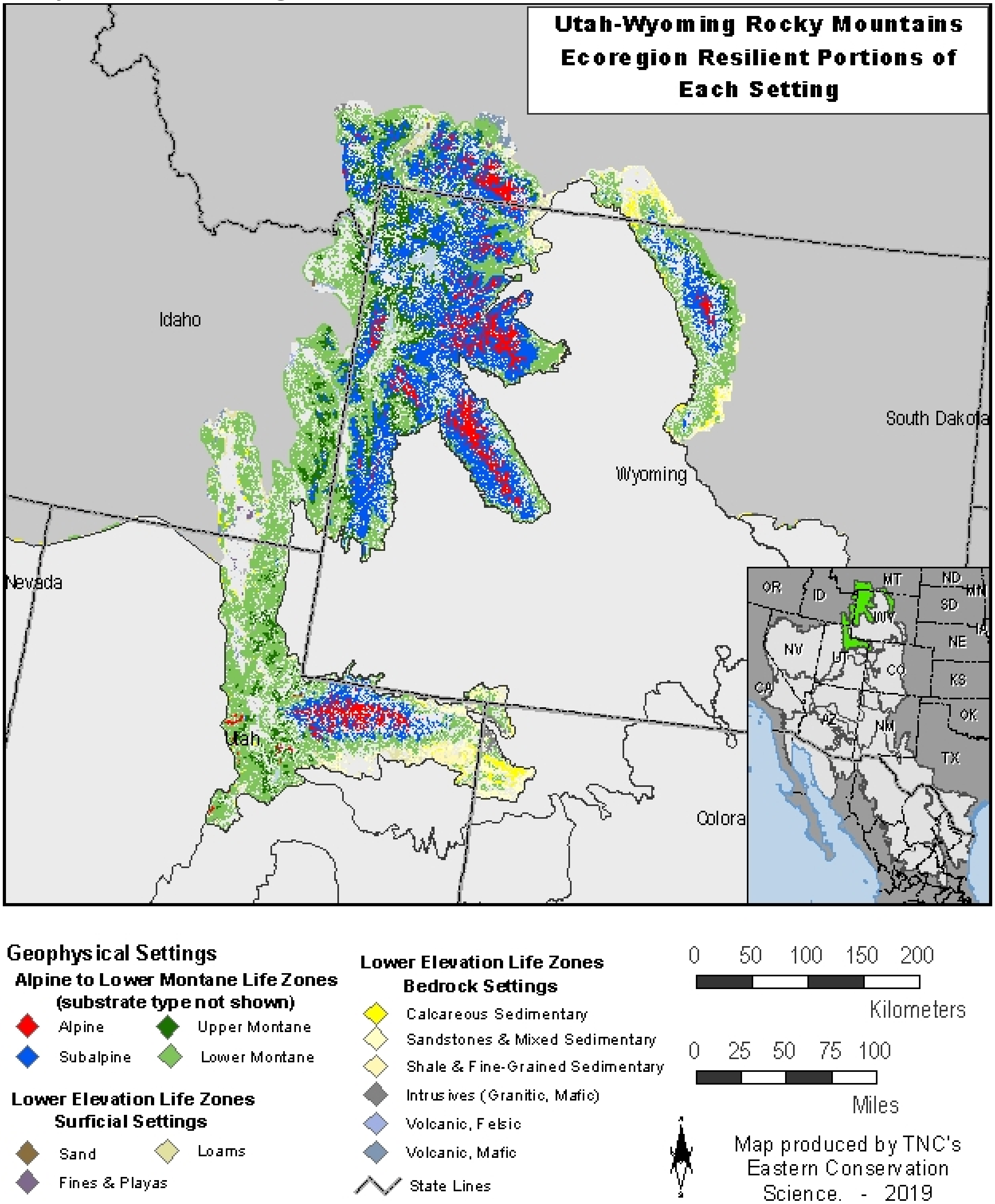
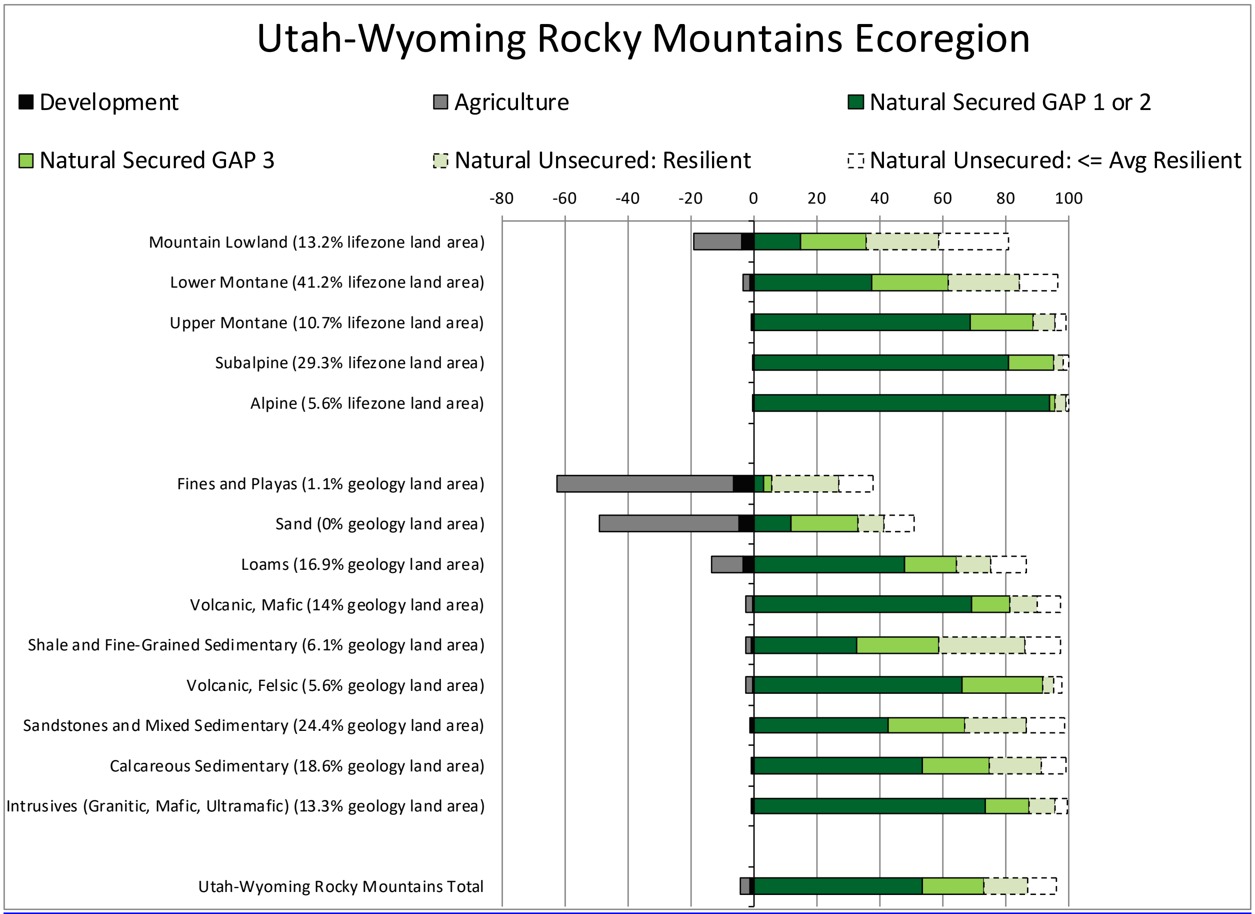


Figure 4.10: Conversion and Securement of the Utah-Wyoming Rocky Mountains Ecoregion by Geophysical Setting. This ecoregion covers 27 million acres and is 68% resilient. The ecoregion is 4% converted and 73% secured. Within this ecoregion, 14% of the land area (3.9 million acres) is resilient unsecured natural land.



This ecoregion description was adapted from: Woods et al. 2001, Ecoregions of Utah

The Utah High Plateau is a high ecoregion of plateaus and benchlands centered in Utah and covering portions of Western Colorado and Arizona. The North-South mountain chain includes the southern Wasatch Mountains and High Plateaus region, the former underlain by sedimentary and metamorphic rock and the latter capped by flat-lying igneous rock. This portion of the ecoregion ranges is largely above 8,000 feet in elevation. Subalpine fir, Engelmann spruce, Douglas-fir, and aspen communities of plants and animals are widespread with ponderosa pine at lowest elevations.

The East-West arm running into Colorado includes the semiarid benchland, canyons and escarpment regions. With elevations ranging from 5,000 to 7,500 feet, this region is characterized by broad grass, shrub, and woodland-covered benches and mesas. Bedrock exposures are common. The escarpments region is characterized by extensive, deeply-dissected, cliff-bench complexes that ascend dramatically. These include the scarp slopes of the Tavaputs Plateau, the Book Cliffs, and the Grand Staircase. Natural vegetation ranges from Douglas-fir forest on steep, high, north-facing slopes to desert and semidesert grassland or shrubland on lower, drier sites. Deep eolian soils support warm season grasses, winterfat, Mormon tea, four-wing saltbush, and sagebrush.

Grazing, irrigated cropland, irrigated pastureland, and rangeland are common, while turkey farms, feedlots, and dairy operations occur locally.

Figure 4.11: Utah High Plateaus: Life Zones.

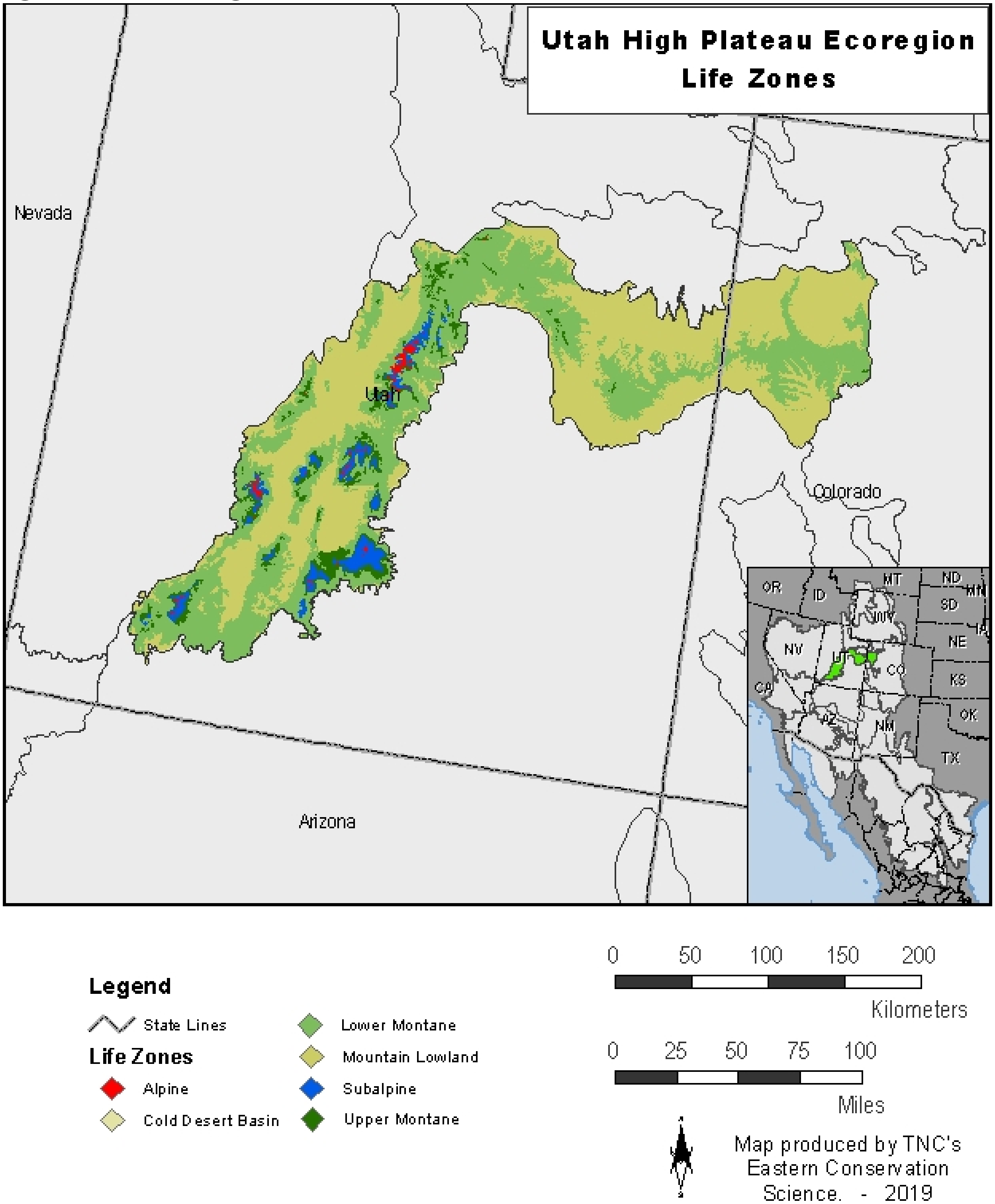


Figure 4.12: Utah High Plateaus: Geology/Soils.

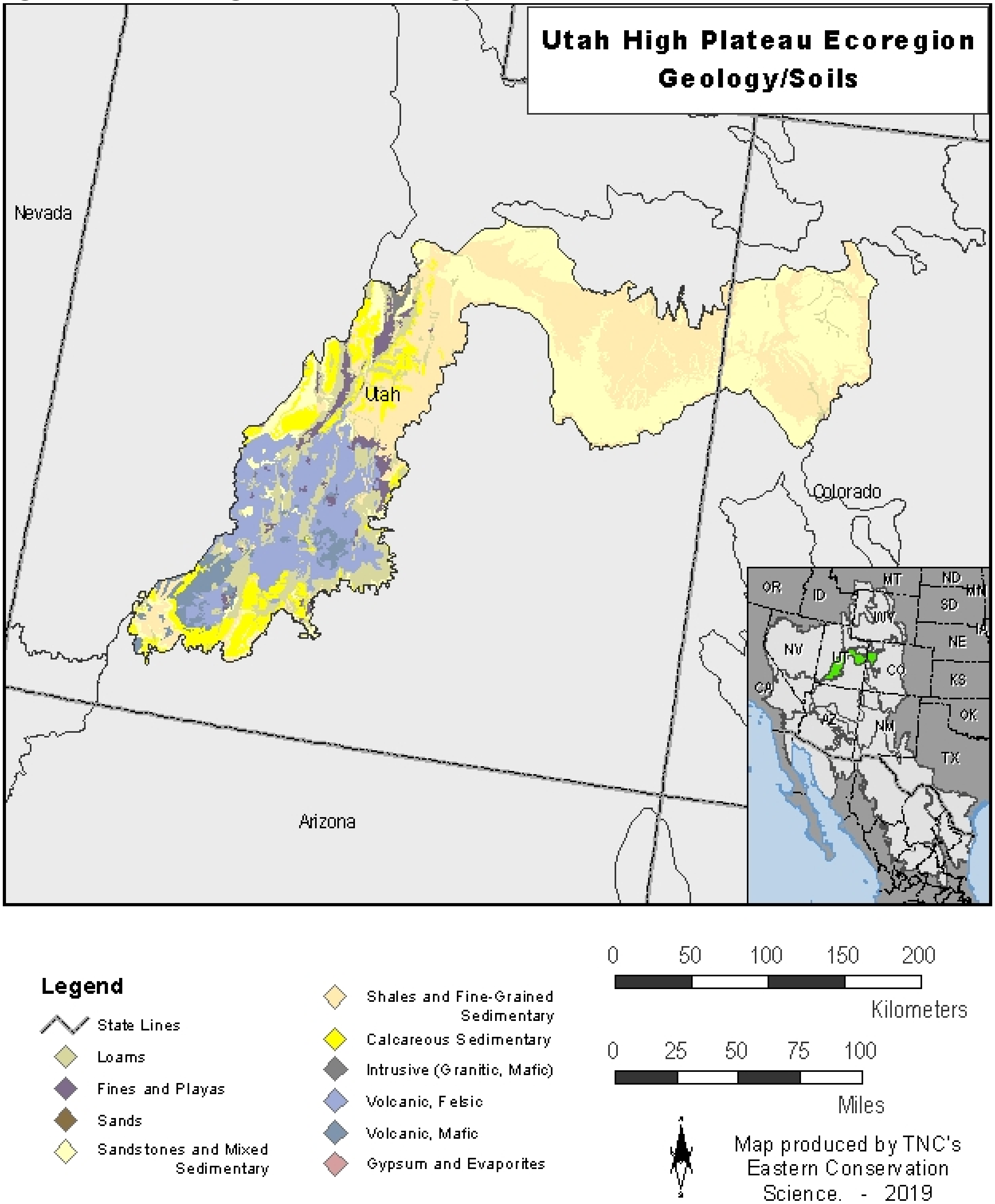


Figure 4.13: Utah High Plateaus: Geophysical Settings.

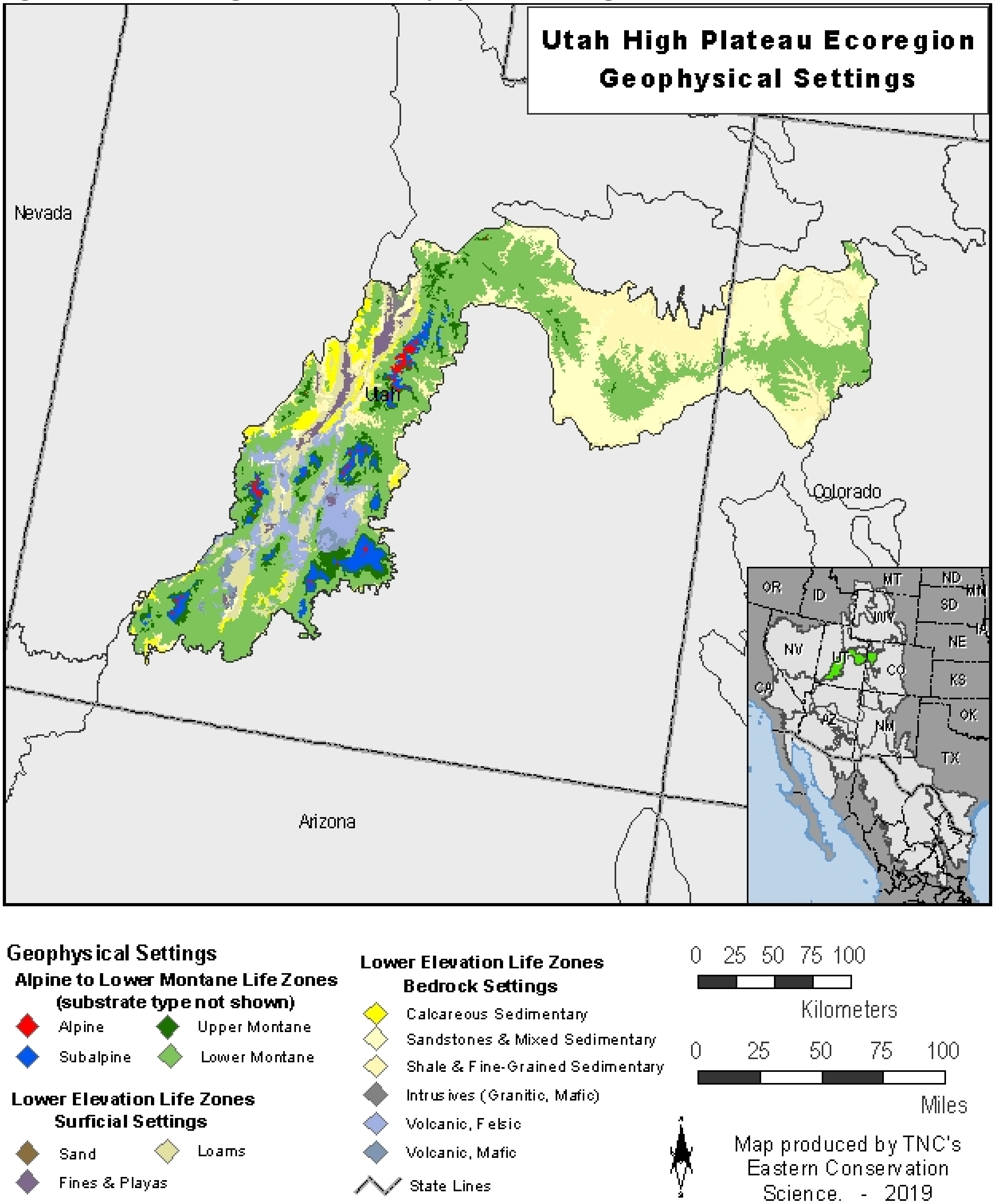


Figure 4.14: Utah High Plateaus: Landscape Diversity.

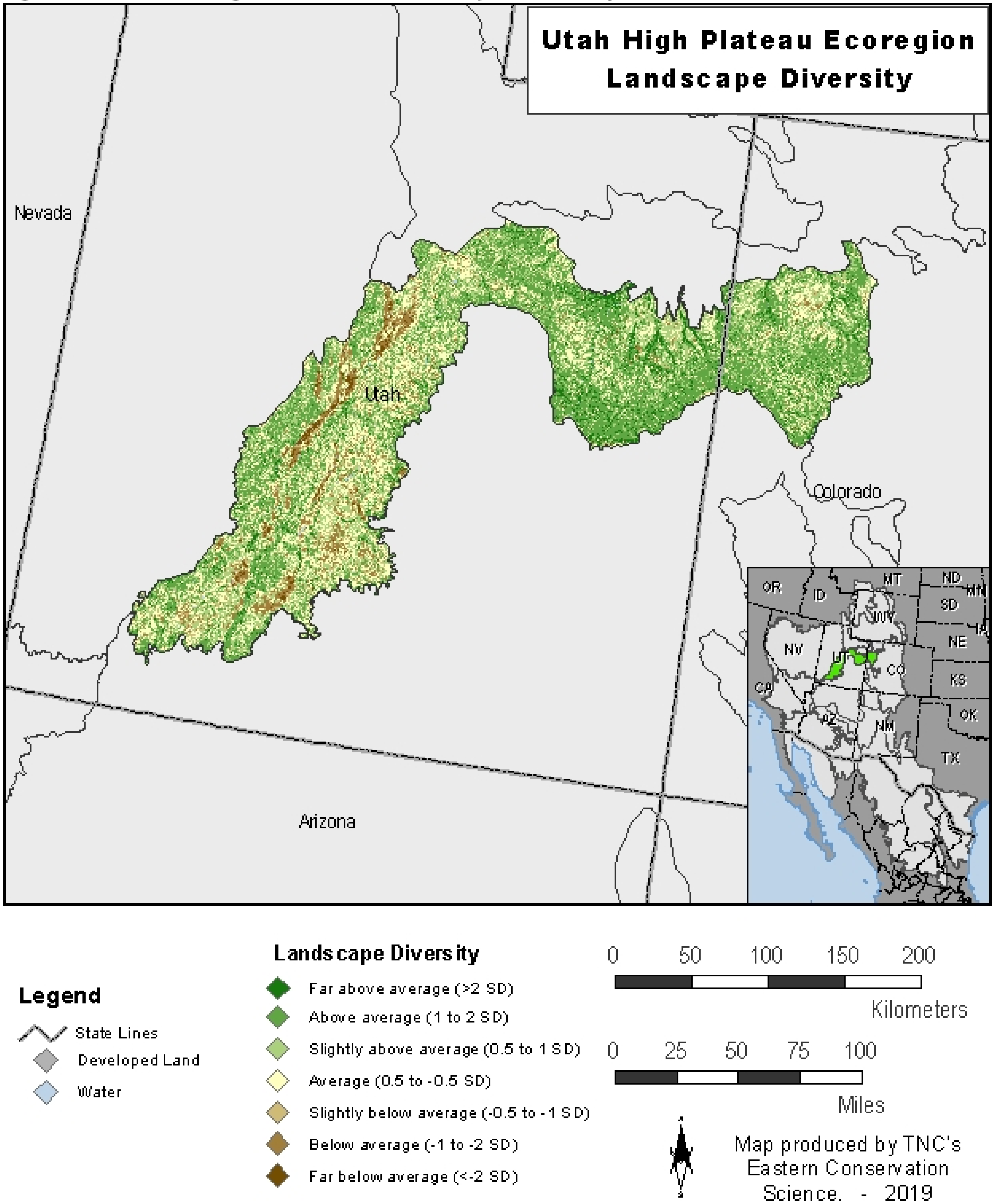


Figure 4.15: Utah High Plateaus: Local Connectedness.

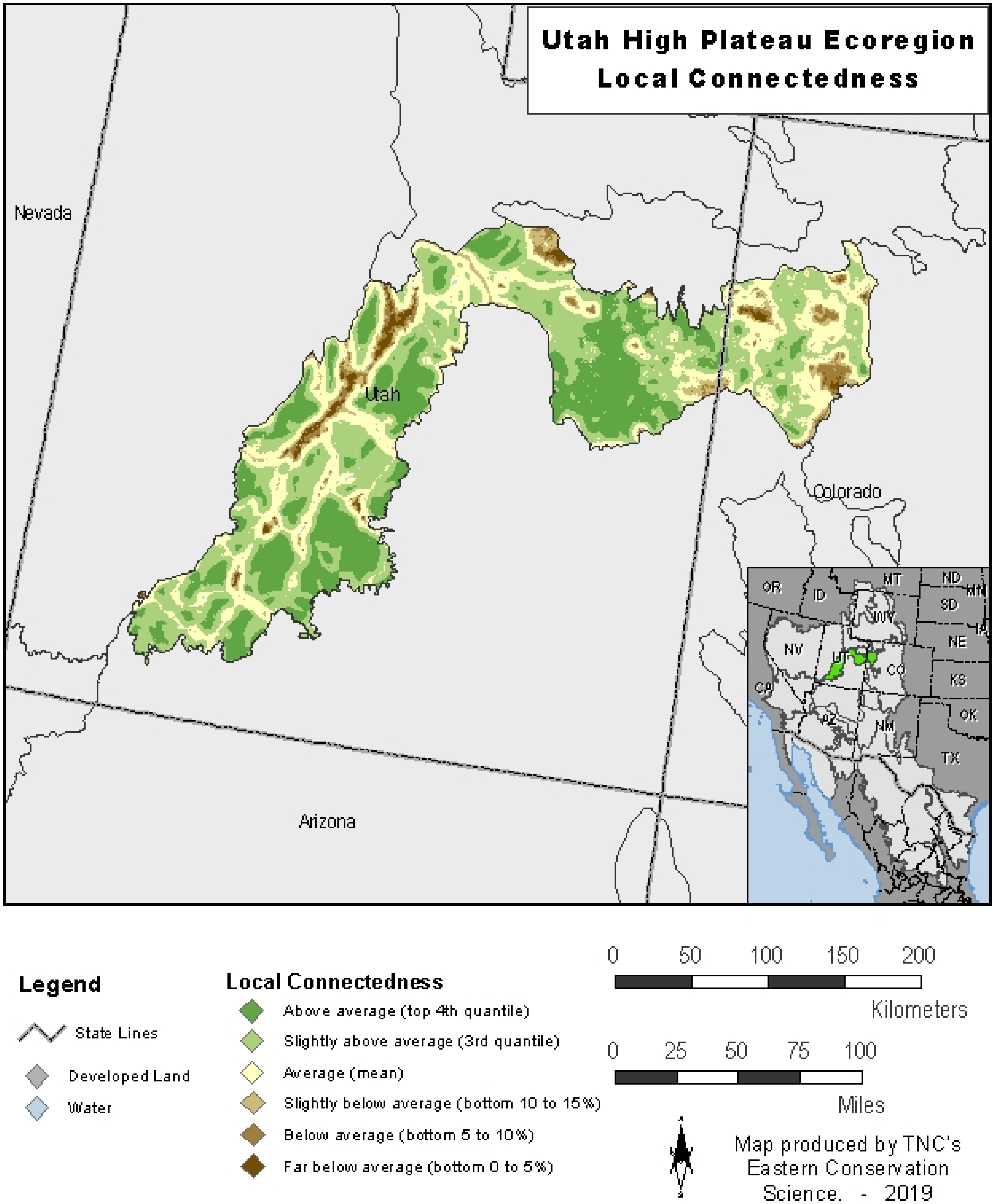


Figure 4.16: Utah High Plateaus: Site Resilience.

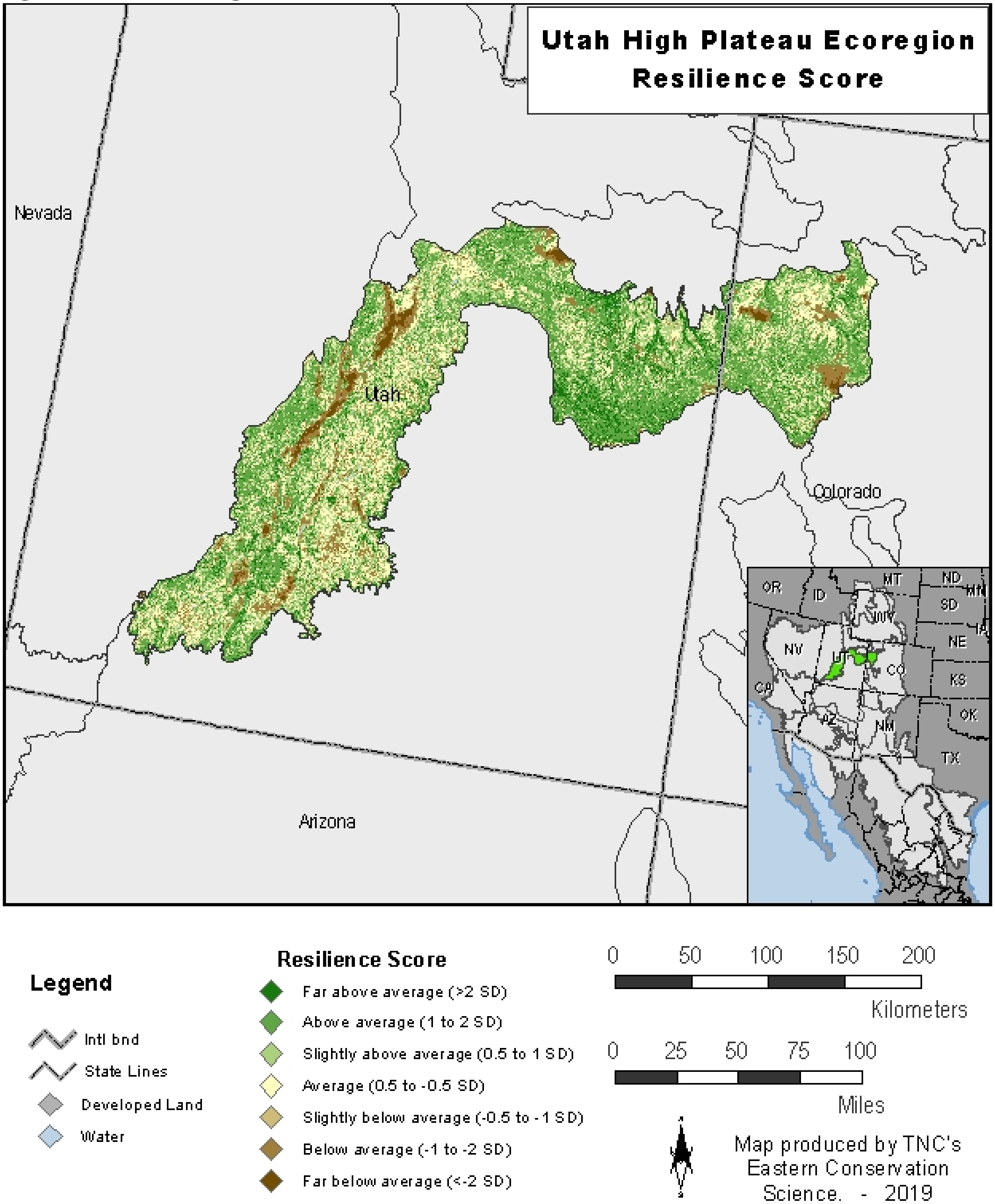


Figure 4.17: Resilient Areas for Each Geophysical Setting Within the Utah High Plateaus Ecoregion.

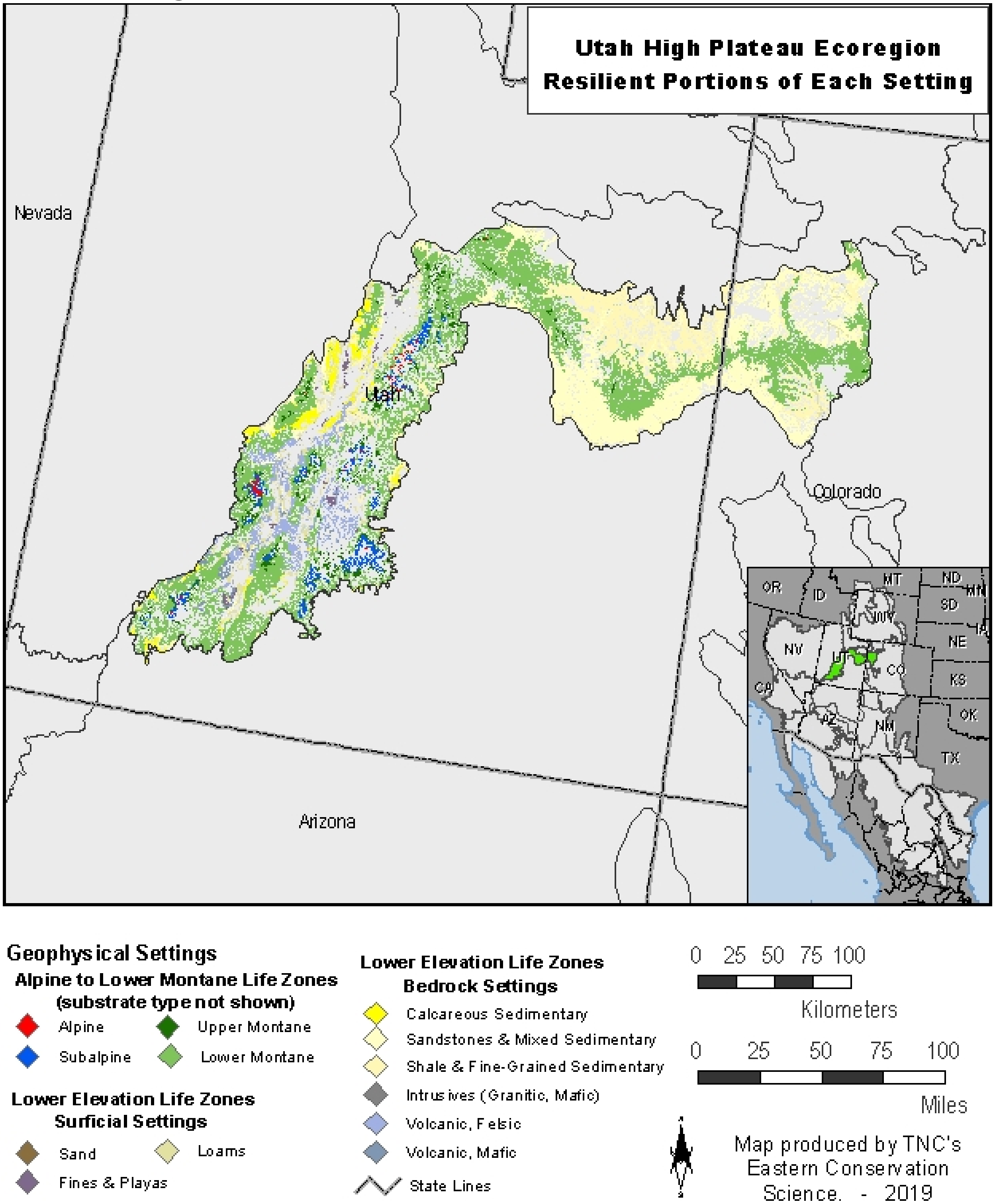
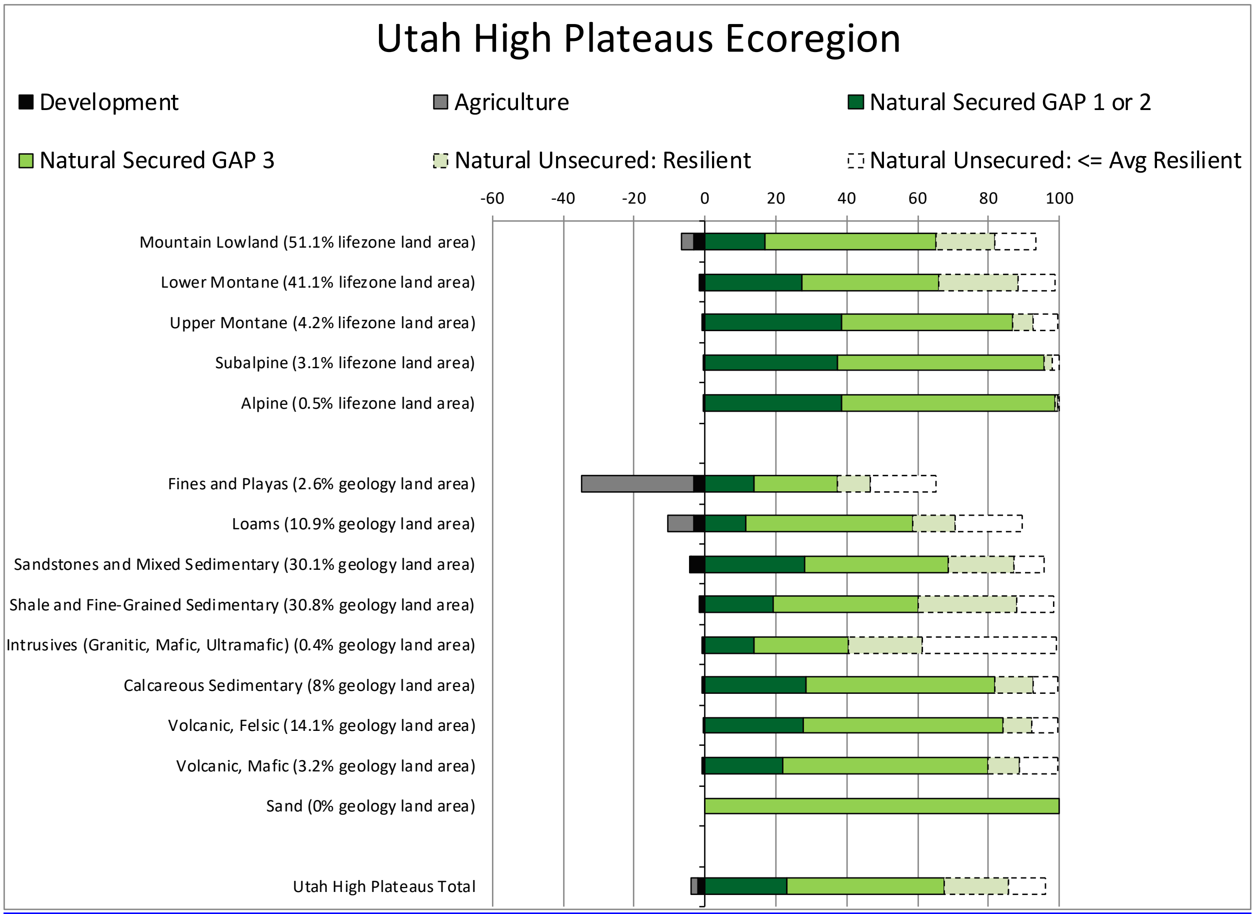


Figure 4.18: Conversion and Securement of the Utah High Plateau Ecoregion by Geophysical Setting. This ecoregion covers 11.3 million acres and is 65% resilient. It is 4% converted and 68% secured. Within this ecoregion, 18% of the land (2 million acres) is resilient unsecured natural land.



This ecoregion description was adapted from: Neely et al. 2001. Southern Rocky Mountains: An Ecoregional Assessment and Conservation Blueprint, TNC

The Southern Rocky Mountains (SRM) ecoregion extends over nearly 40 million acres and includes portions of southern Wyoming, central and western Colorado, and northern New Mexico. Elevation ranges from approximately 3,700 ft to over 14,400 ft. The ecoregion is characterized by two major mountain belts and intervening intermontane valleys and parks encompassing four broad ecological zones: alpine, subalpine, upper montane, and lower montane/foothill. The primary ecological processes maintaining the natural systems and the biodiversity are fire, hydrological regime, herbivory, insect outbreaks, snow avalanches, and wind.

The dramatic elevation gain within the ecoregion makes distinguishing broad ecological zones simple, and the dominant vegetation reflects these zones. The four dominant ecological zones— Alpine, Subalpine, Upper Montane, and Lower Montane-Foothill—have long been used to characterize the Rocky. A combination of elevation, latitude, direction of prevailing winds, and slope exposure, which all influence precipitation and natural disturbance processes, control the zones. Generally, the vegetation zones are at higher elevations in the southern part of the province than in the northern, and they extend downward on east-facing and north-facing slopes and in narrow ravines and valleys subject to cold air drainage

At least 184 species and subspecies are known to be endemic to the ecoregion (not known from anywhere else in the world). The richest groups are plants (118 endemics) and invertebrates (51 endemics), followed by mammals (12 endemics), birds (2 endemics), and amphibians (1 endemic). Although the ecoregion contains largely intact or functional landscapes, a number of species have been extirpated from the ecoregion, including seven mammal species: grizzly bear, gray wolf, wild populations of bison, black-footed ferret, lynx, wolverine, and river otter.

Figure 4.19: **Southern Rocky Mountains**: Life Zones.

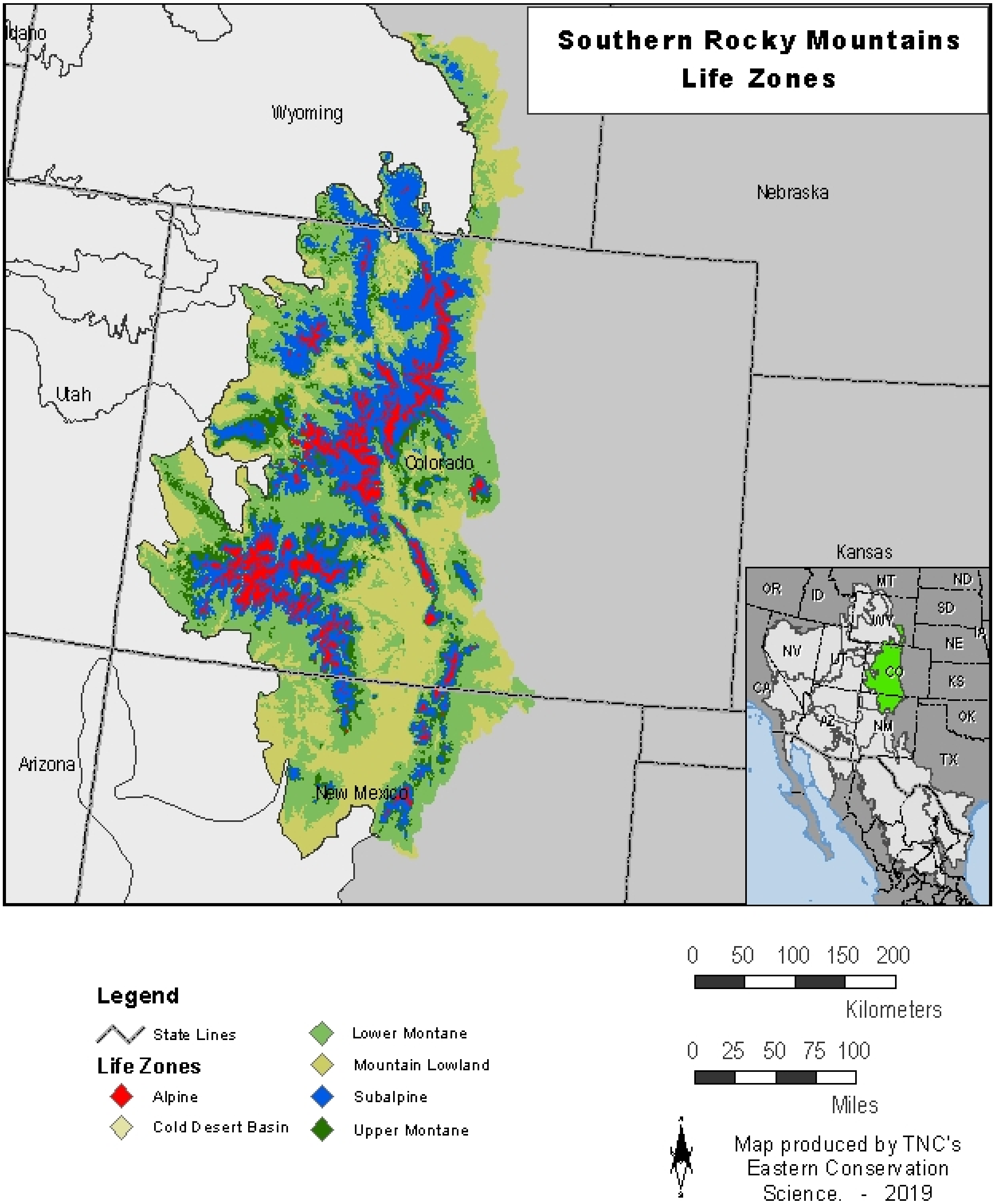


Figure 4.20: Southern Rocky Mountains: Geology/Soils.

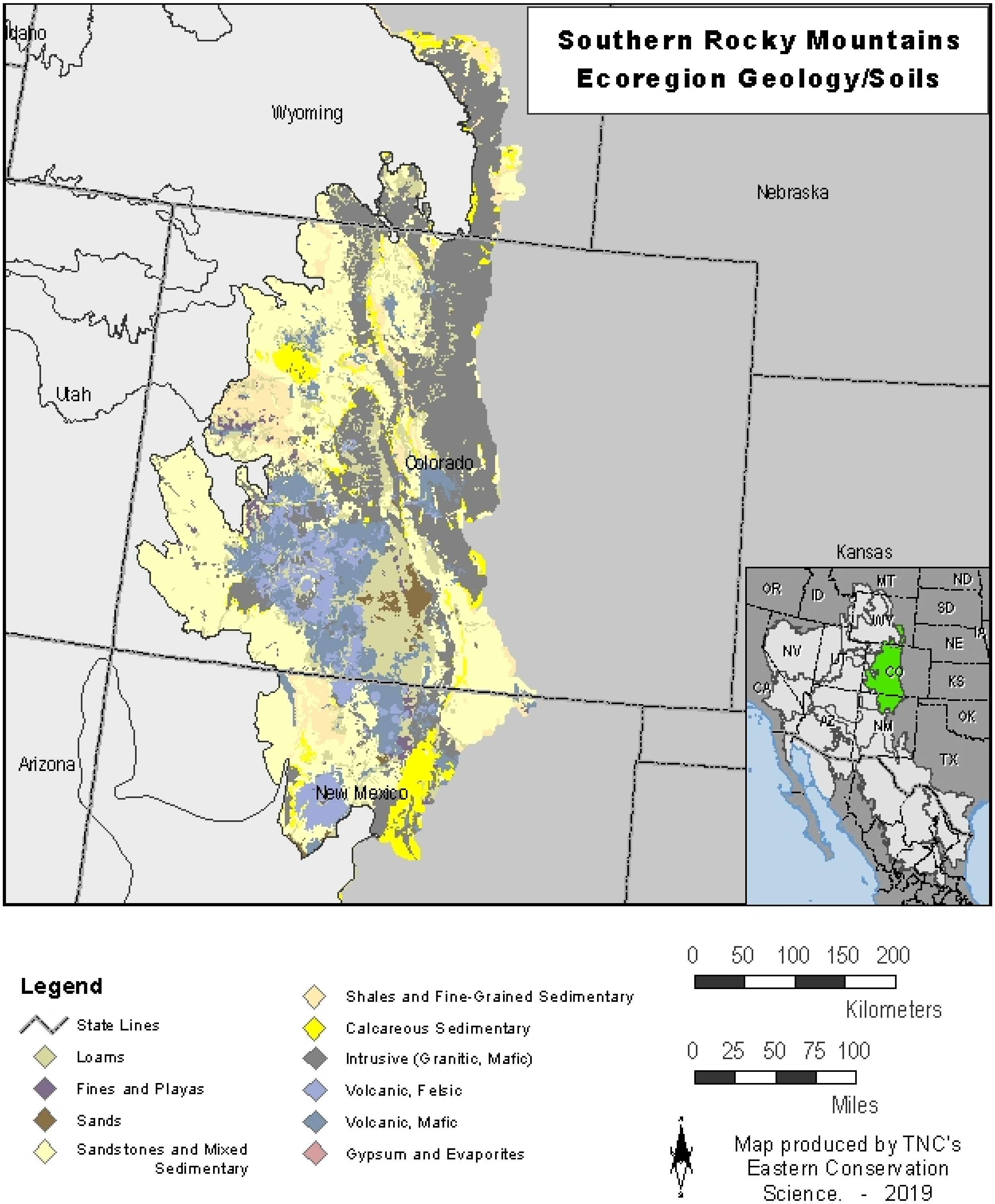


Figure 4.21: Southern Rocky Mountains: Geophysical Settings.

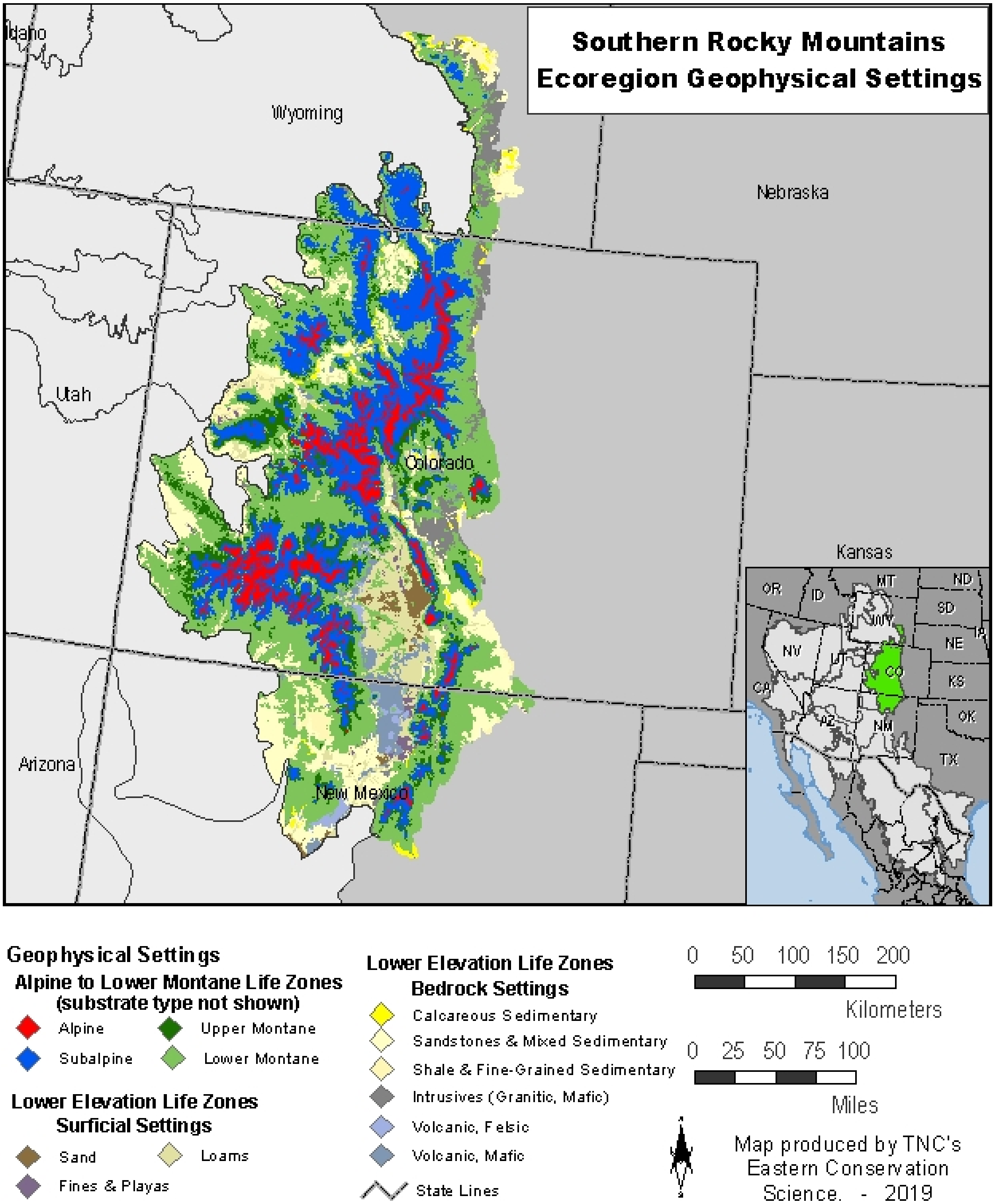


Figure 4.22: Southern Rocky Mountains: Landscape Diversity.

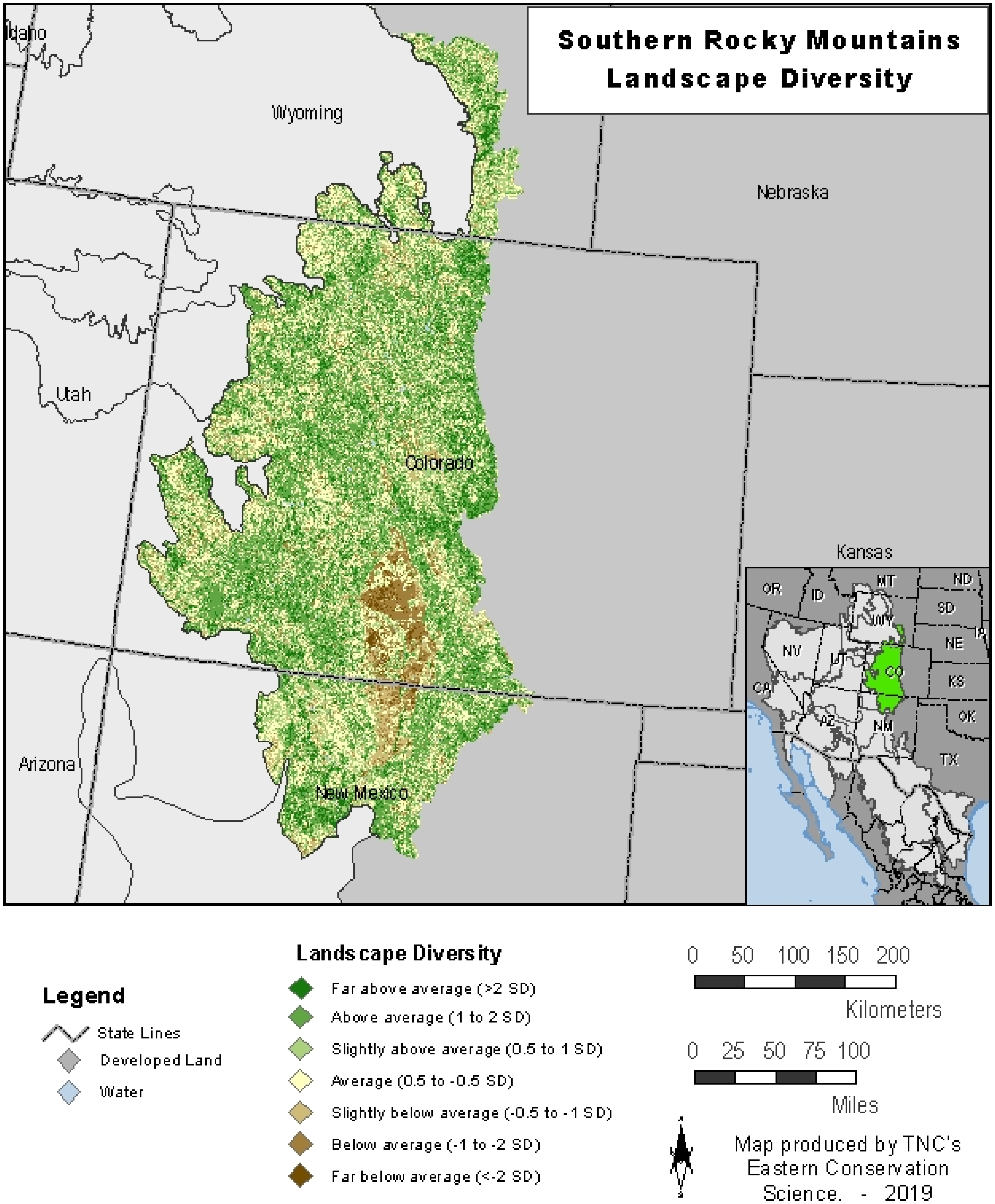


Figure 4.23: Southern Rocky Mountains: Local Connectedness.

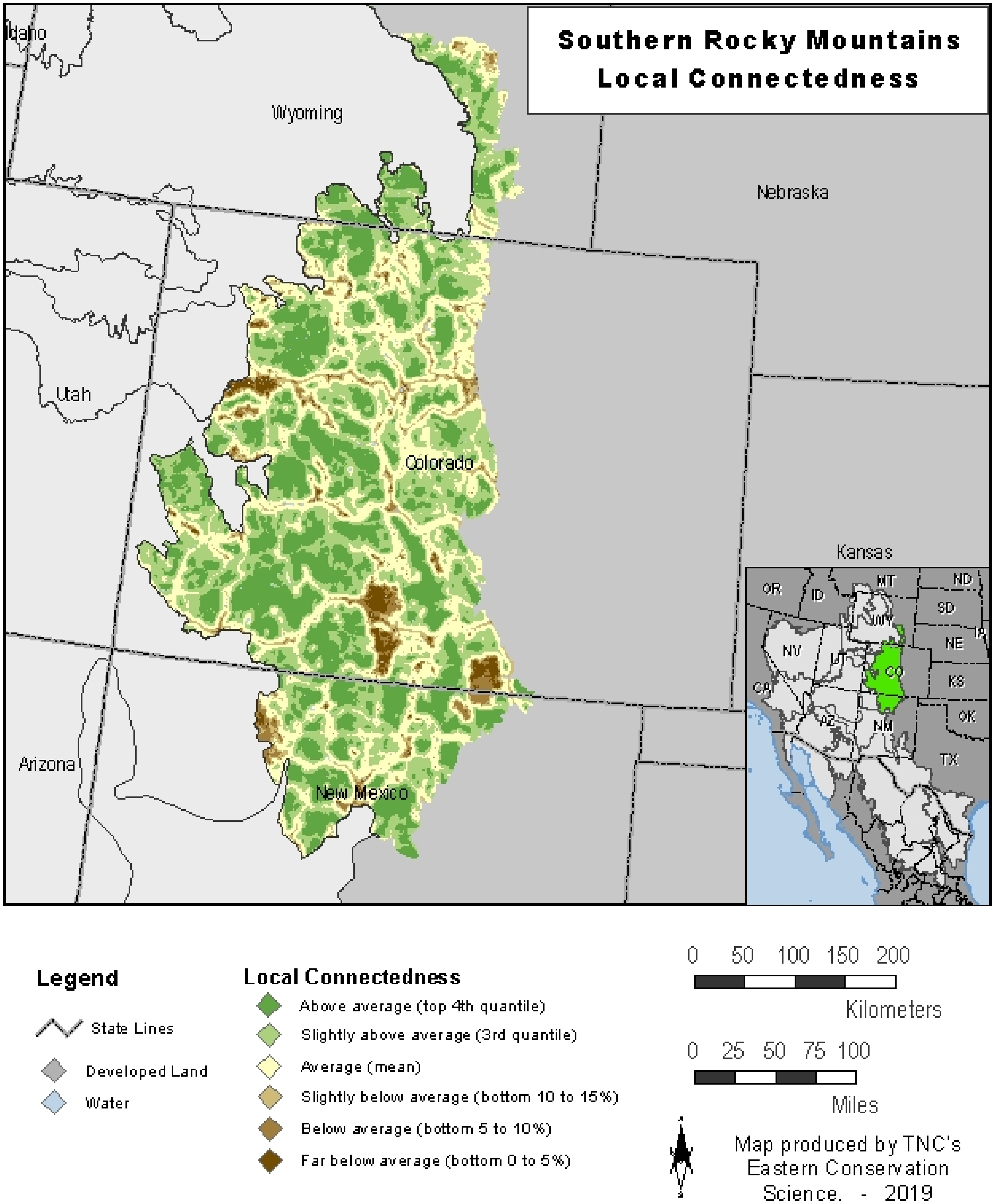


Figure 4.24: Southern Rocky Mountains: Site Resilience.

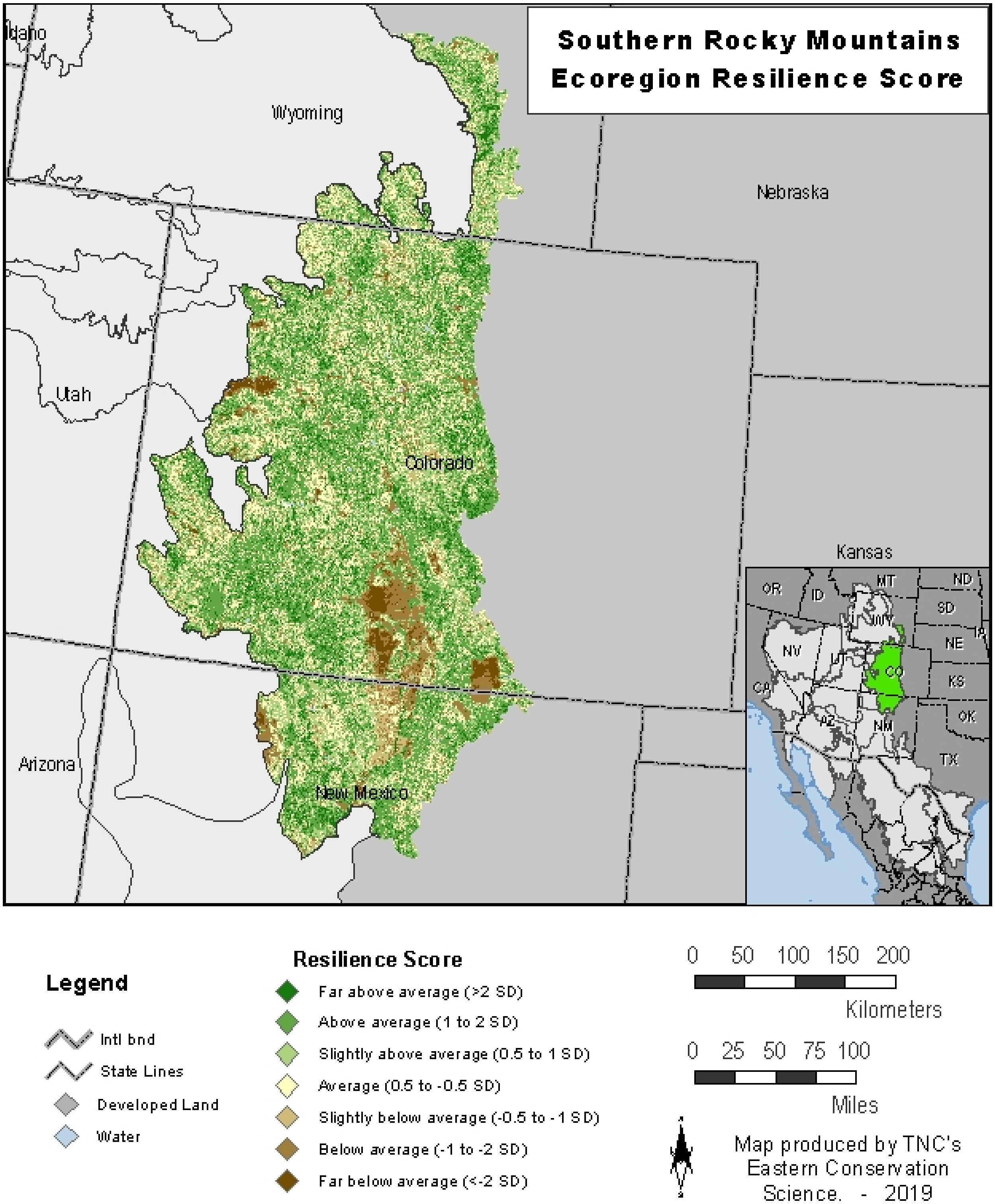


Figure 4.25: Resilient Areas for Each Geophysical Setting Within the Southern Rocky Mountains Ecoregion.

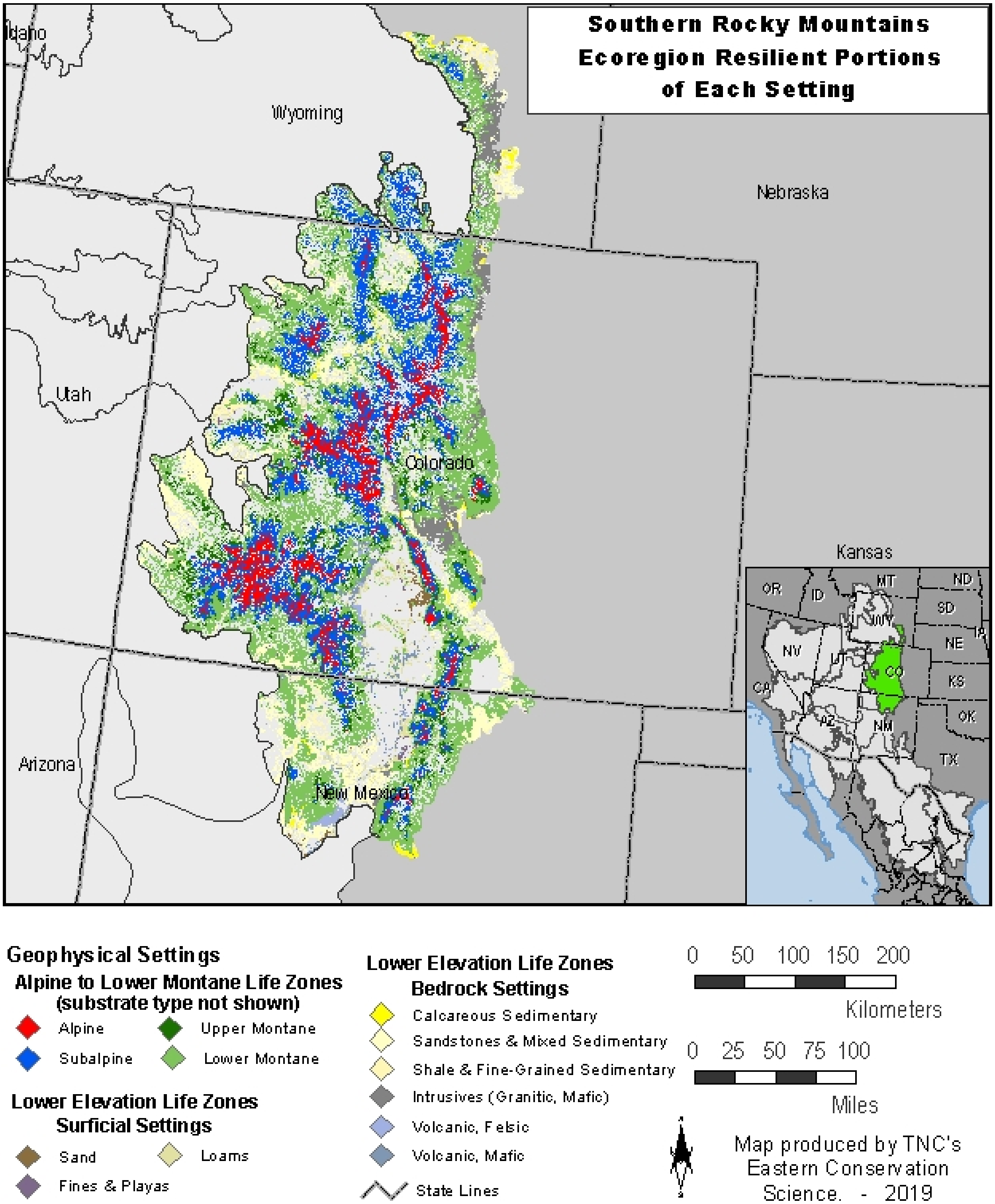
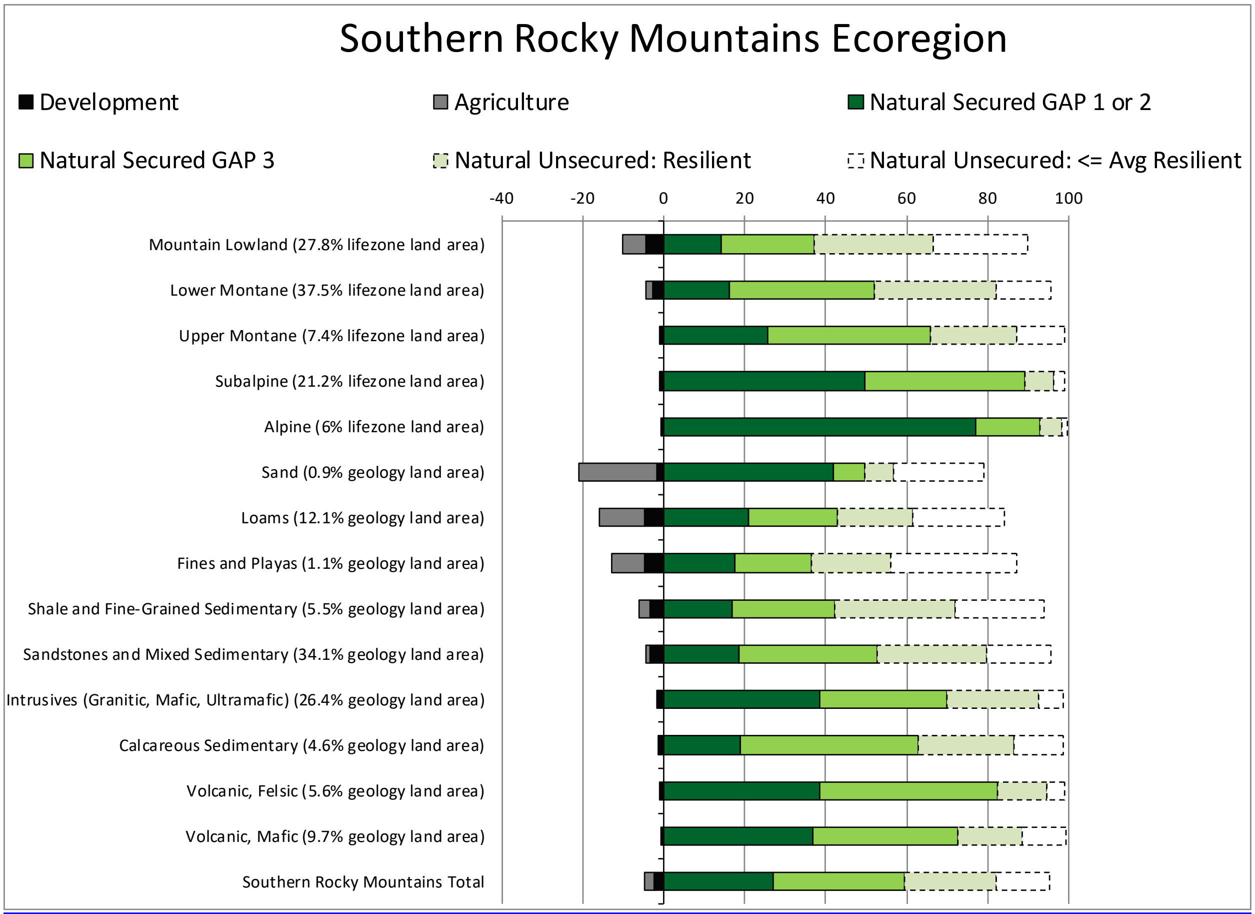


Figure 4.26: Conversion and Securement of the Southern Rocky Mountains Ecoregion by Geophysical Setting. This ecoregion covers 40 million acres and is 66% resilient. The ecoregion is 5% converted and 60% secured. Within this ecoregion, 23% of the land area (9.3 million acres) is resilient unsecured natural land.



Arizona-New Mexico Mountains

Photo credit: TNC

This ecoregion description was adapted from: Ecoregional Conservation Analysis of the Arizona - New Mexico Mountains, The Nature Conservancy 1999.

The Ecoregion encompasses the highlands of eastern Arizona and western and central New Mexico. Much of the land in the ecoregion is under federal ownership, especially by the U.S. Forest Service. Also included with the boundaries are portions of the nations of the White Mountain Apaches, Mescalero Apaches, Navajos, and Zunis.

The ecoregion is based upon the oldest mountains in the southwest, containing Precambrian igneous rocks as old as 1.5 billion years. These older volcanic rocks are overlain with more recent sediments and volcanics. The result is an extremely diverse physiographic region with elevations ranging from about 5,000 to more than 10,000 feet above sea level. A prominent feature is the Mogollon Rim, which stretches almost 200 miles and defines the southern edge of the ecoregion.

The Arizona / New Mexico Mountains is an area of plateaus and mountains rising above the surrounding desert plains. It is best known as an area of big trees, especially ponderosa pine. Natural communities are typically ponderosa pine and white fir forest types above 5,500 feet and piñon pine savannas at lower elevations, although the ecoregion also includes grasslands, shrublands, and riparian forests. The mountains contain the headwaters for a number of important streams and rivers including the Little Colorado, the Gila, the Mimbres, and the Verde. These riparian areas are the life-blood of the southwest, but all are badly compromised through decades of abuse.

The ecoregion is one of the ecological treasure troves of the U.S., containing more species of birds and mammals than any other ecoregion in the Southwest.
rare plants and animals, more than 30 of them listed as endangered or threatened by the federal or state governments.

Figure 4.27: Arizona-New Mexico Mountains: Life Zones.

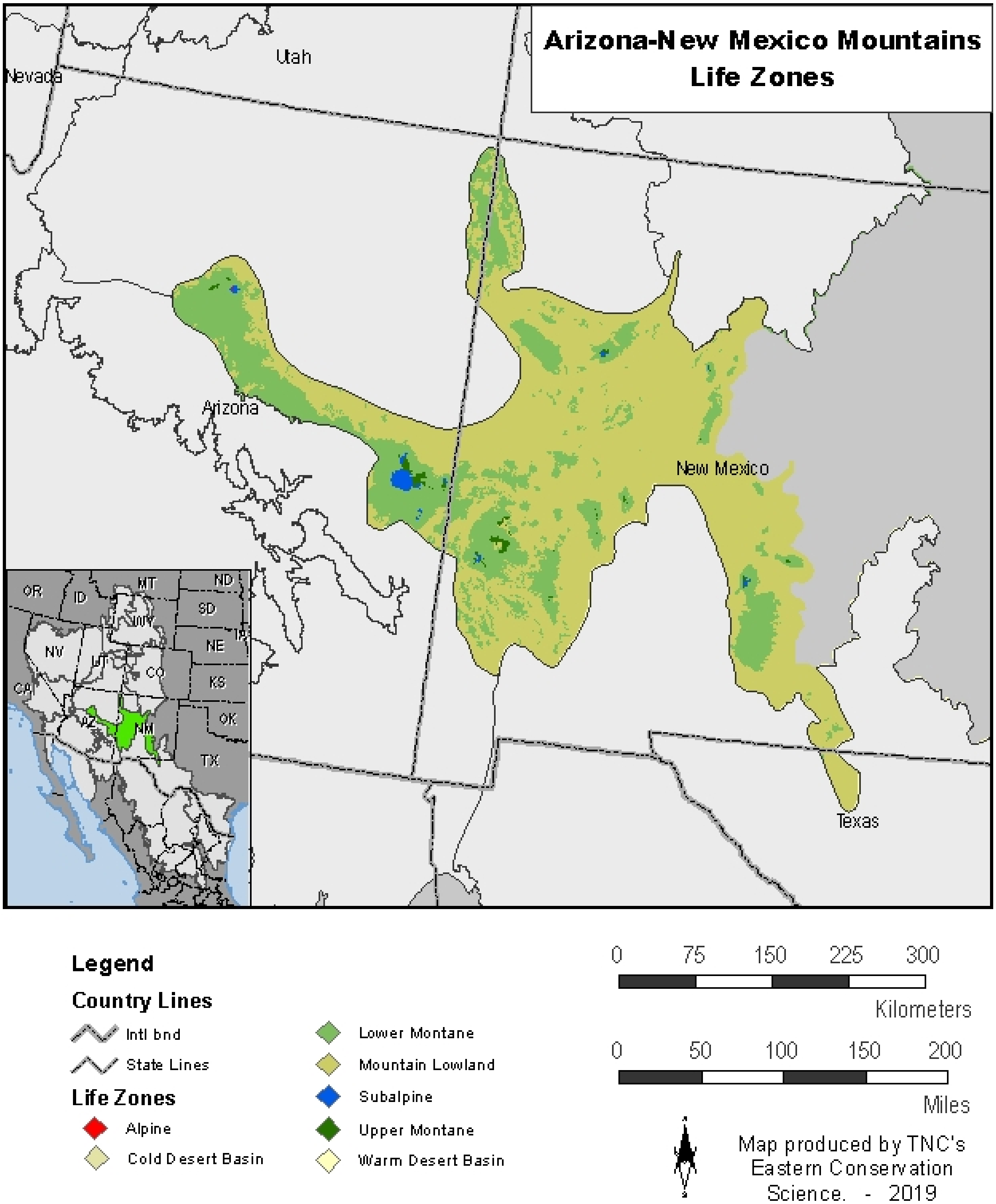


Figure 4.28: Arizona-New Mexico Mountains: Geology/Soils.

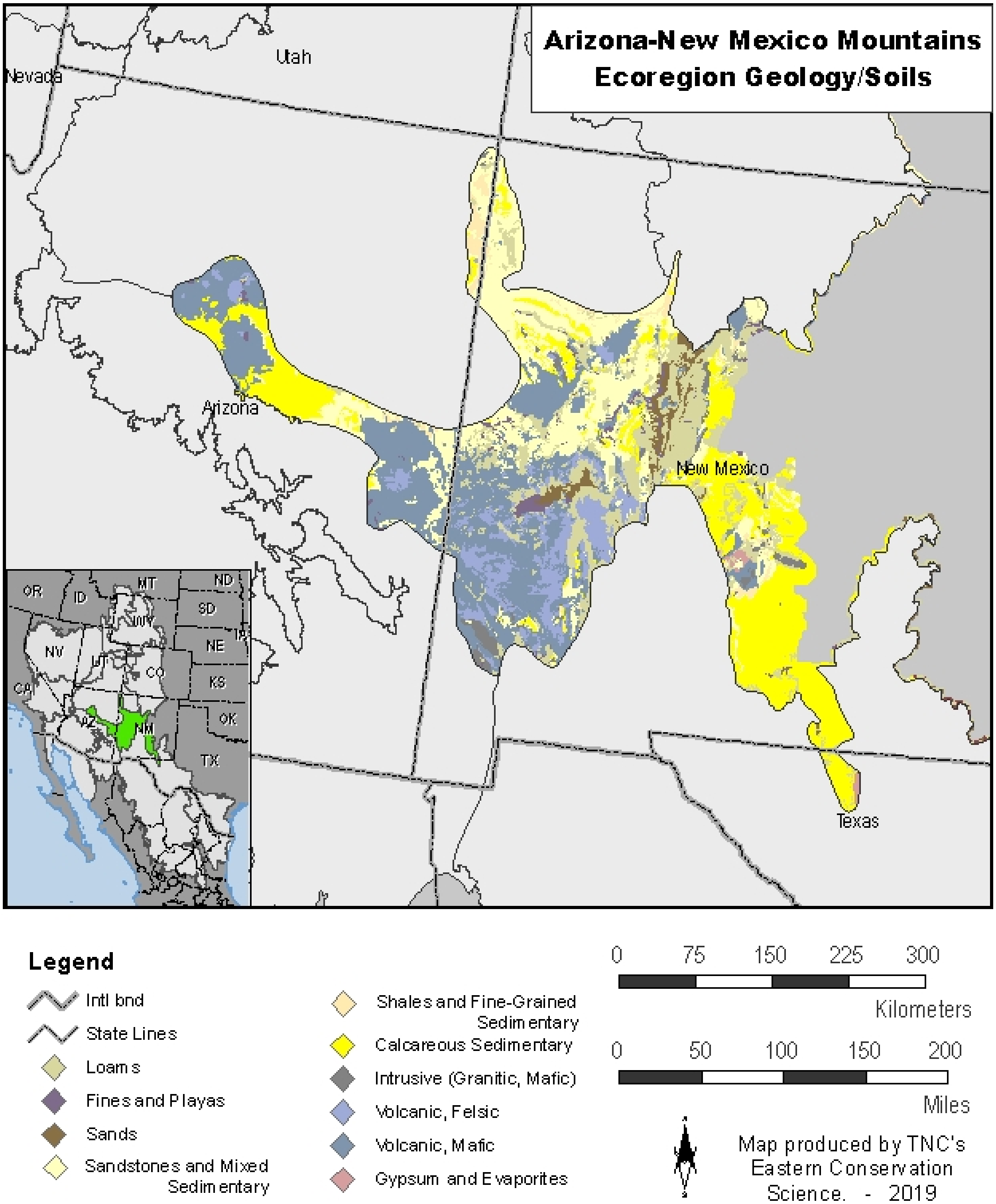


Figure 4.29: Arizona-New Mexico Mountains: Geophysical Settings.

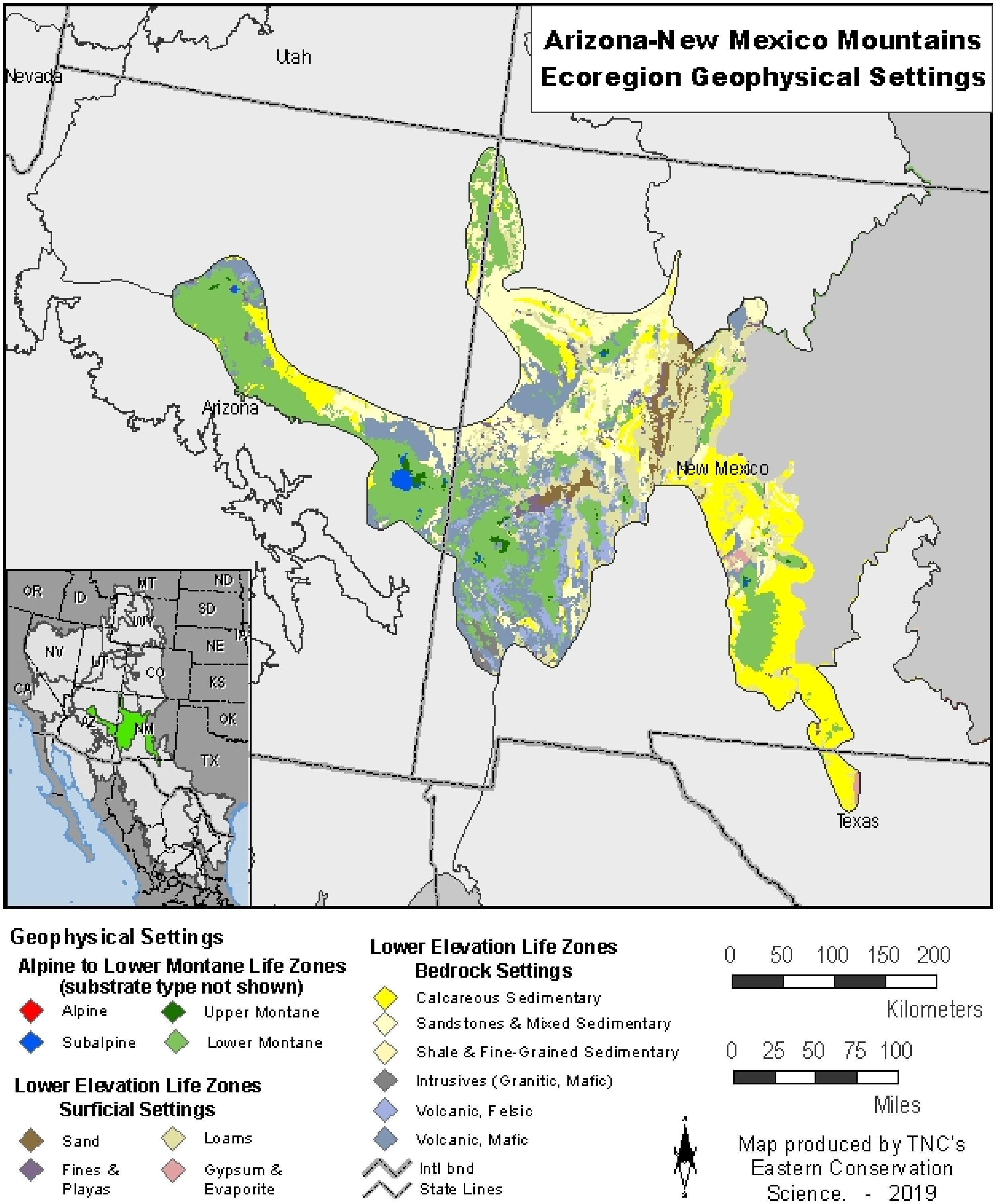


Figure 4.30: Arizona-New Mexico Mountains: Landscape Diversity.

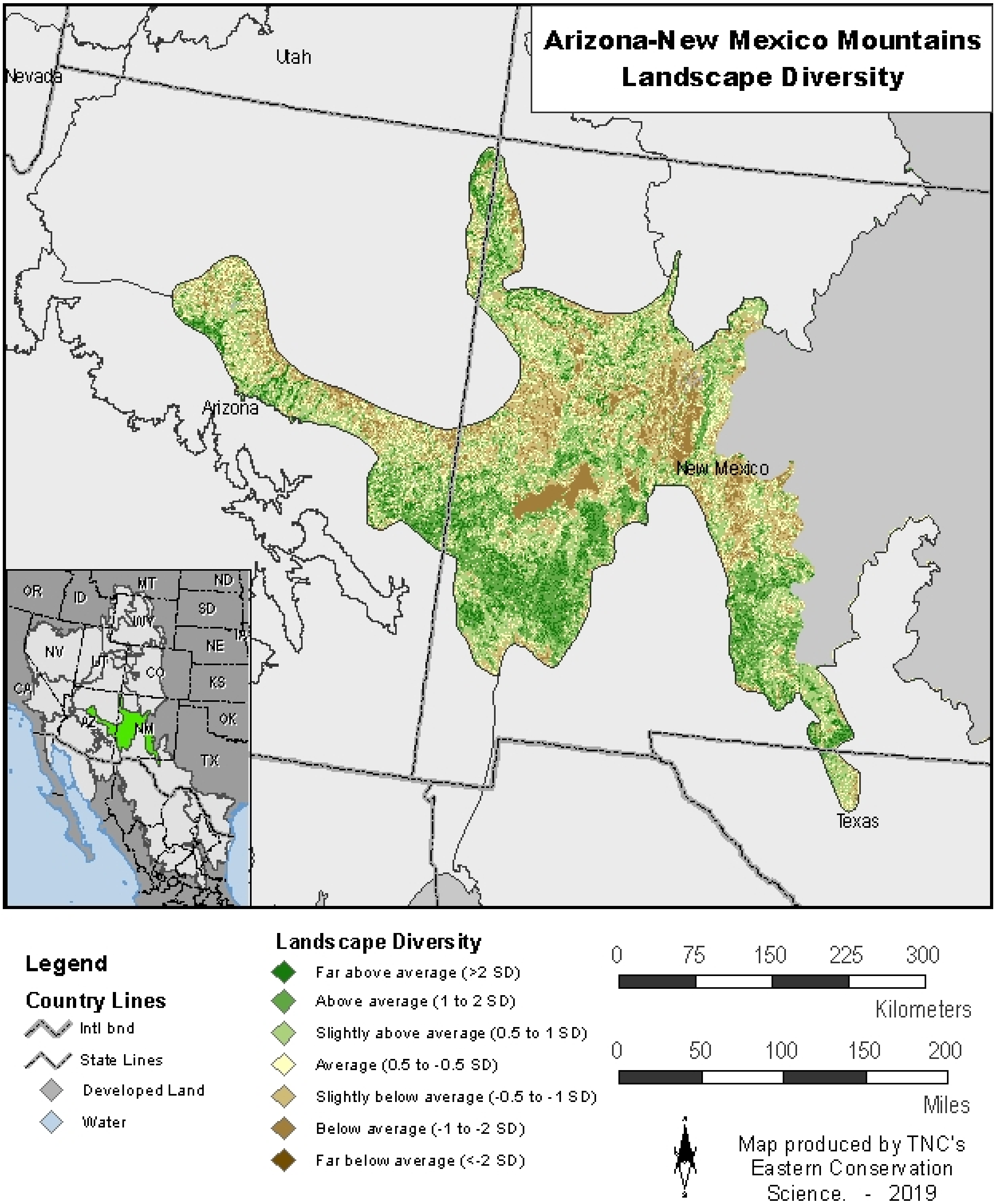


Figure 4.31: Arizona-New Mexico Mountains: Local Connectedness

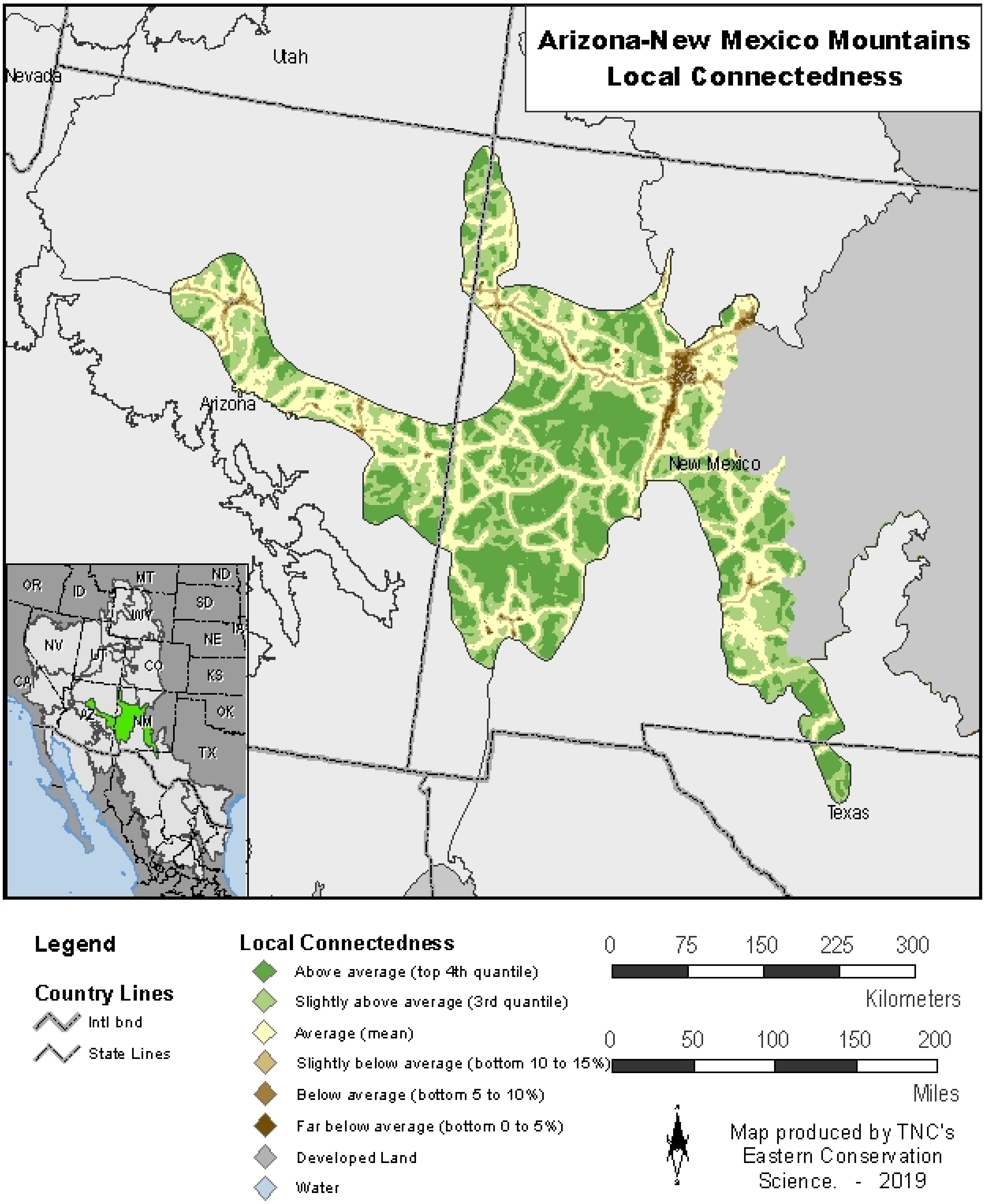


Figure 4.32: Arizona-New Mexico Mountains: Site Resilience.

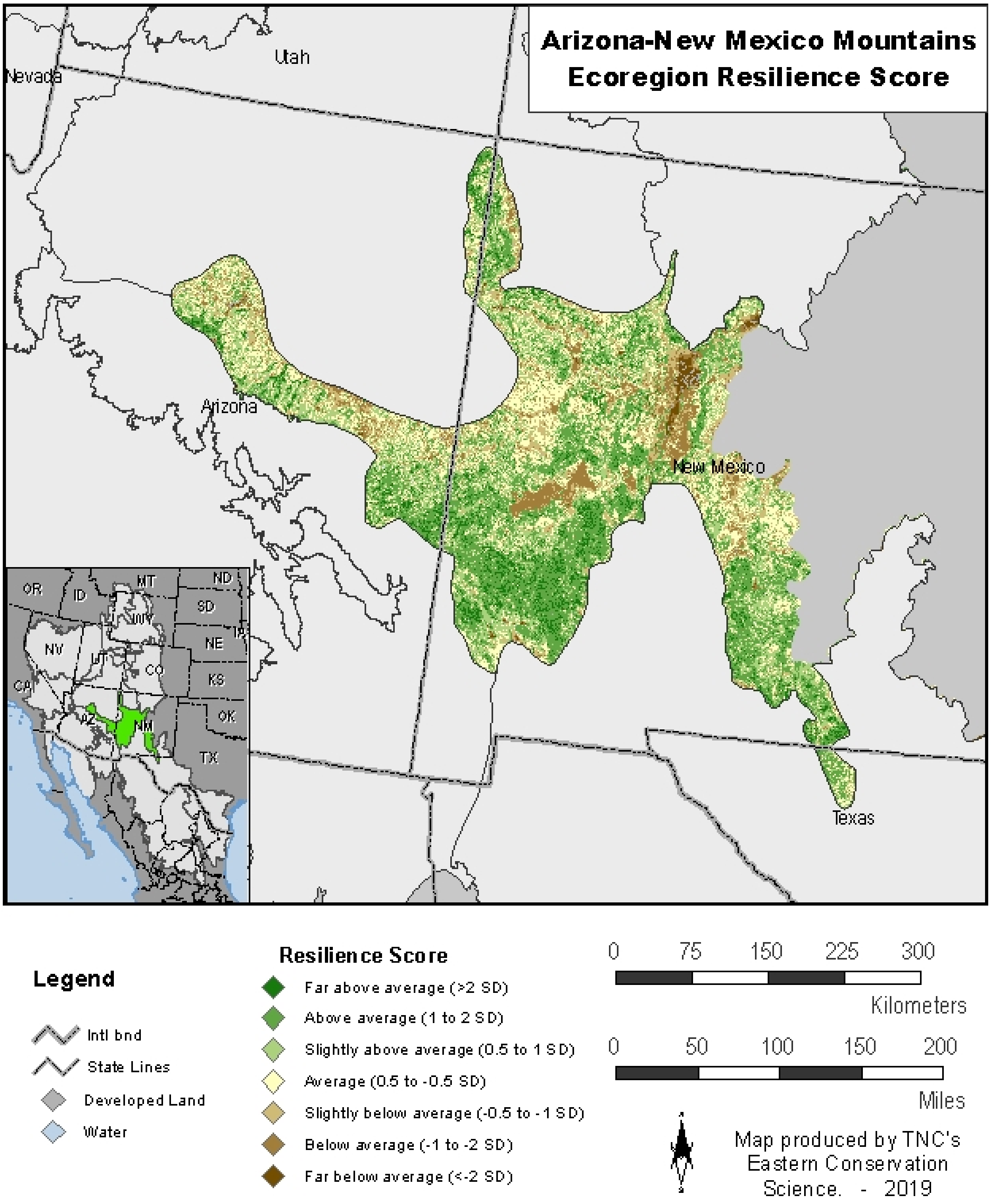


Figure 4.33: Resilient Areas for Each Geophysical Setting Within the Arizona-New Mexico Mountains Ecoregion.

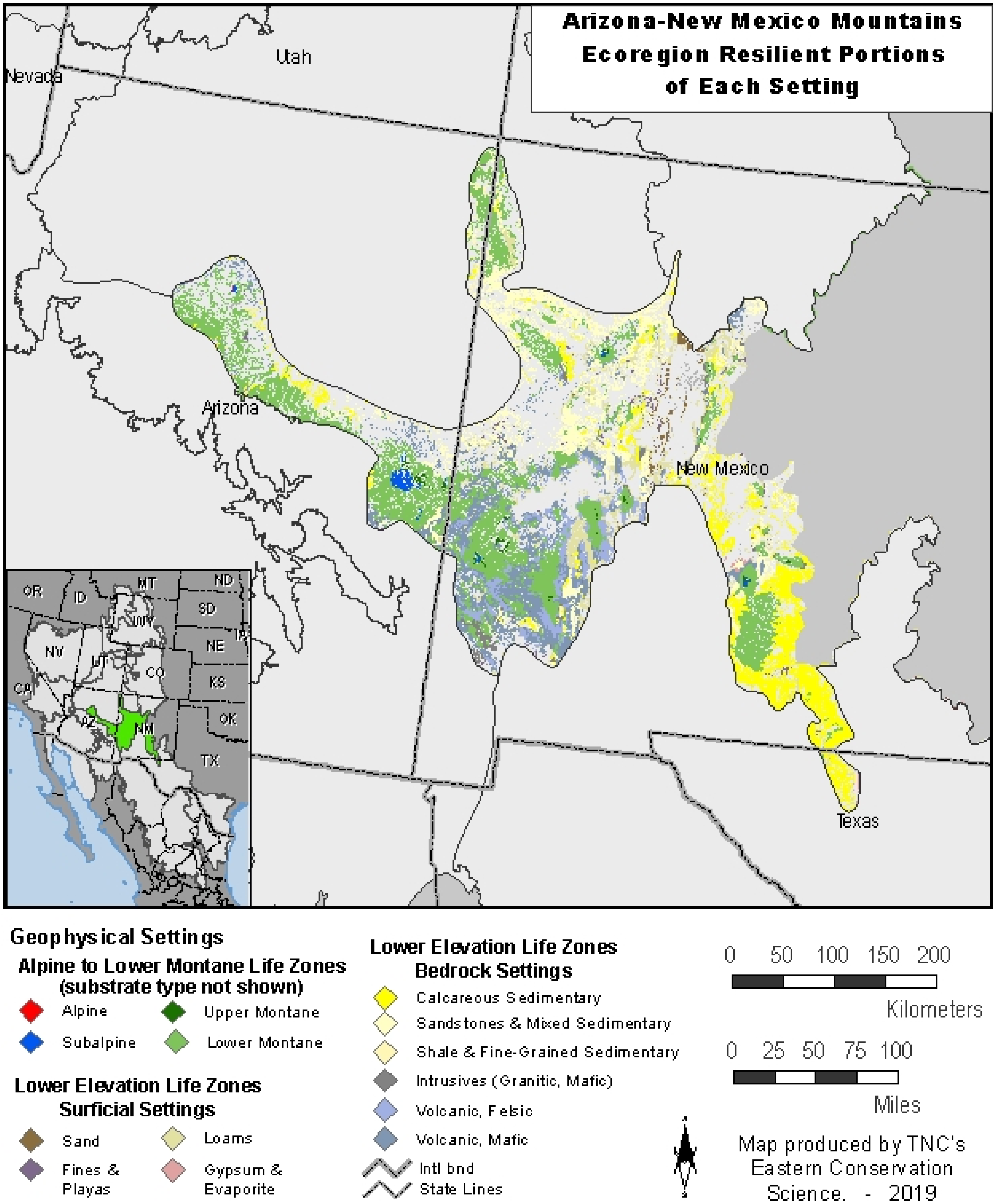
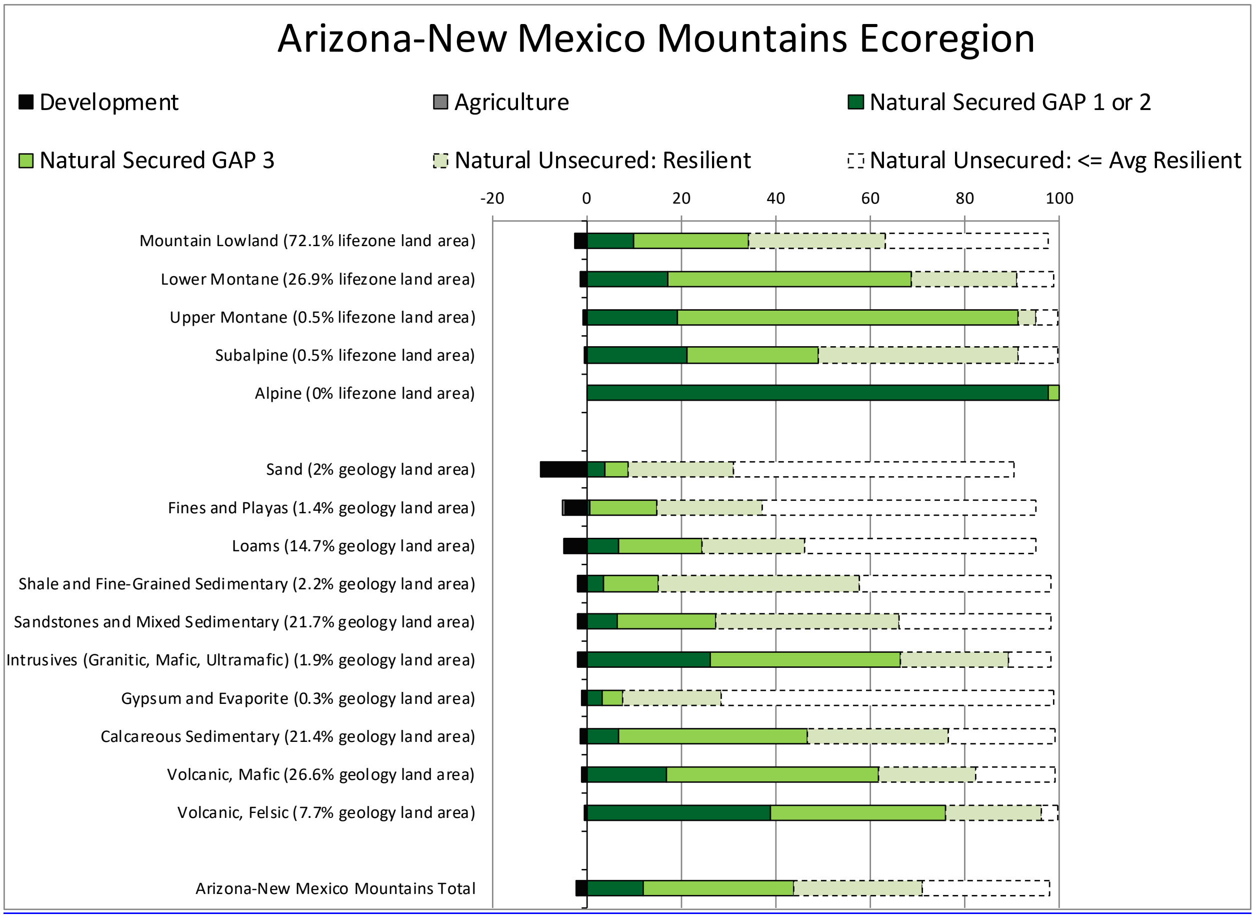


Figure 4.34: Conversion and Securement of the Arizona-New Mexico Mountain Ecoregion by Geophysical Setting. This ecoregion covers 28.7 million acres and is 59% resilient. The ecoregion is 2% converted and 44% secured. Within this ecoregion, 27% of the land area (7.9 million acres) is resilient unsecured natural land.



This ecoregion description was adapted from: The Wyoming Basins Ecoregional Plan, The Nature Conservancy 2001.

The Wyoming Basins ecoregion comprises 51,605 square miles of basin, plain, desert, and "island" mountains in Wyoming, Montana, Idaho, Colorado, and Utah. The area is a veritable "ocean" of sagebrush interspersed with unusual rock formations, sand dunes, and saltbush communities. Mountains rising from the basins are timbered with limber pine, Douglas fir, and stands of aspen.

In this dry country, water imposes strong limits. The riparian zones support important populations of neotropical migrant birds and are the habitat of several rare or endangered fish species. Long, linear ridges of sand dunes, some running 100 miles or more, cross parts of the region. Plant life on the dunes may be quite specific to these harsh locations and may include blowout grass, Indian ricegrass, sandhill muhly, and other species. Fully two thirds of the rare plants endemic to Wyoming are found here. The ecoregion is home to numerous grassland birds (such as Brewer's sparrow, grasshopper sparrow, and mountain plover), identified as the nation's most endangered. The region is home to prairie dogs, whose range has now been reduced to less than 2% of that they formerly occupied. Other unusual species include: greater sage-grouse, black-footed ferret, ferruginous hawks, swift fox, and burrowing owls.

Figure 4.35: Wyoming Basins: Geophysical Settings.

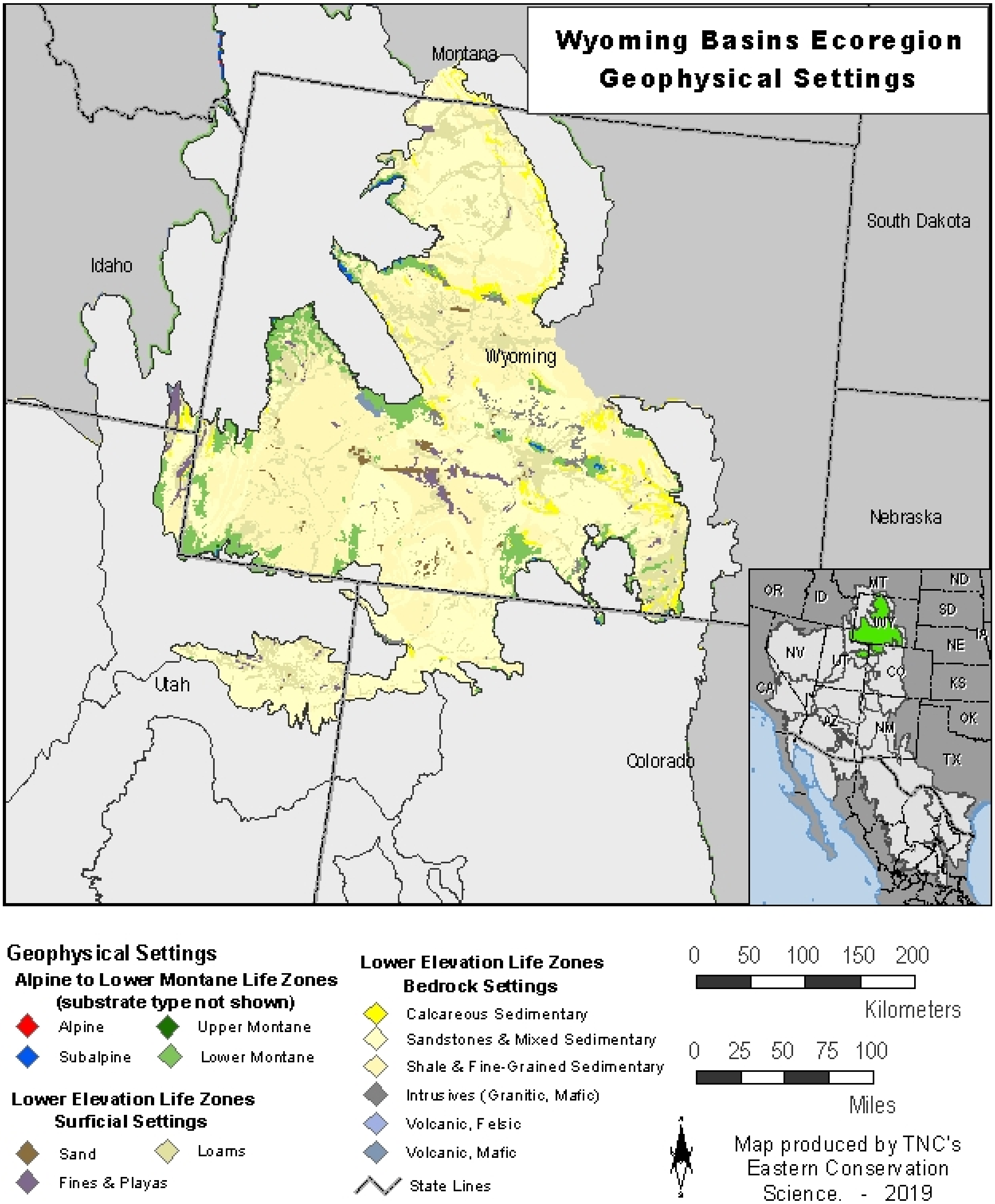


Figure 4.36: Wyoming Basins: Landscape Diversity.

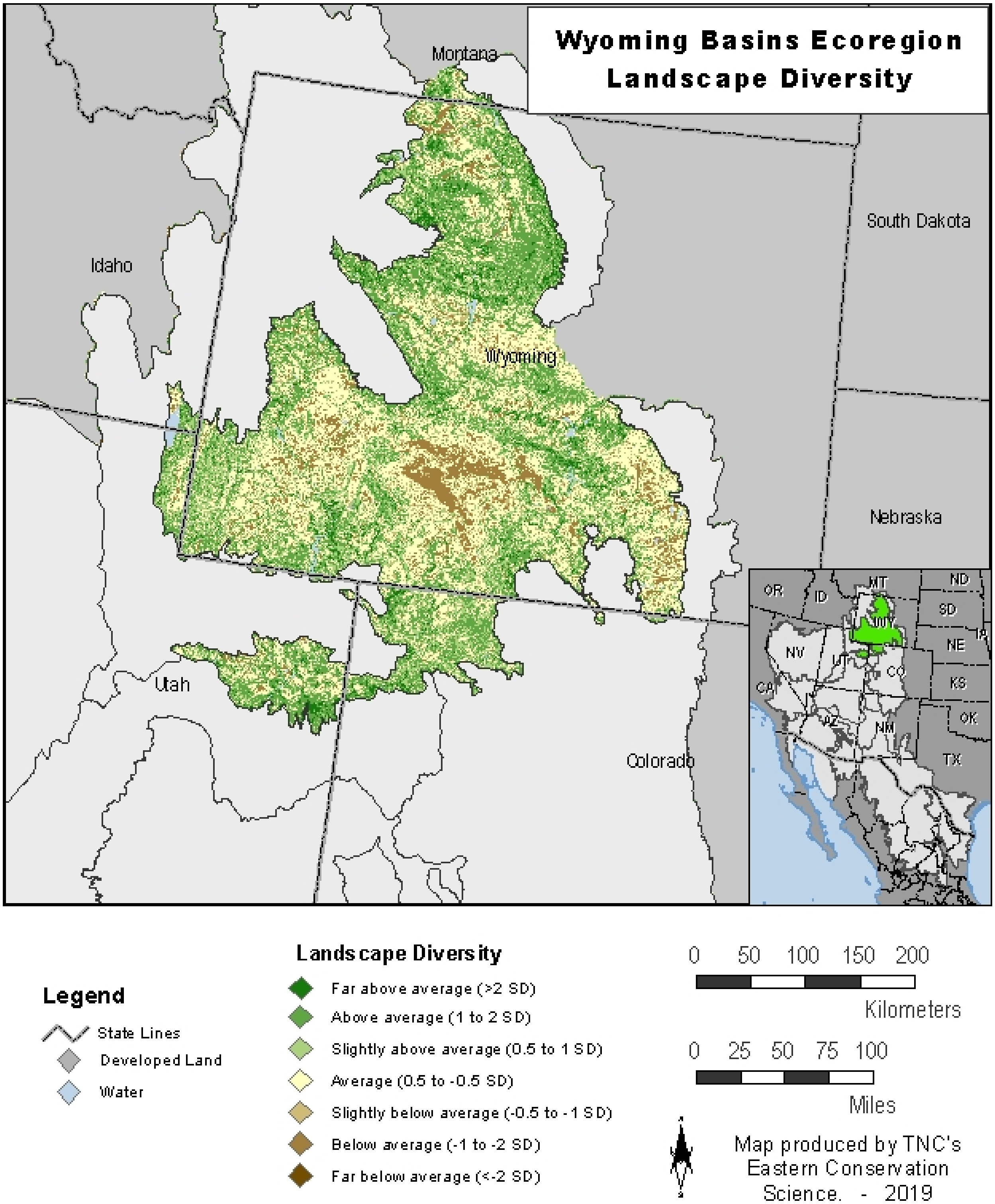


Figure 4.37: Wyoming Basins: Local Connectedness.

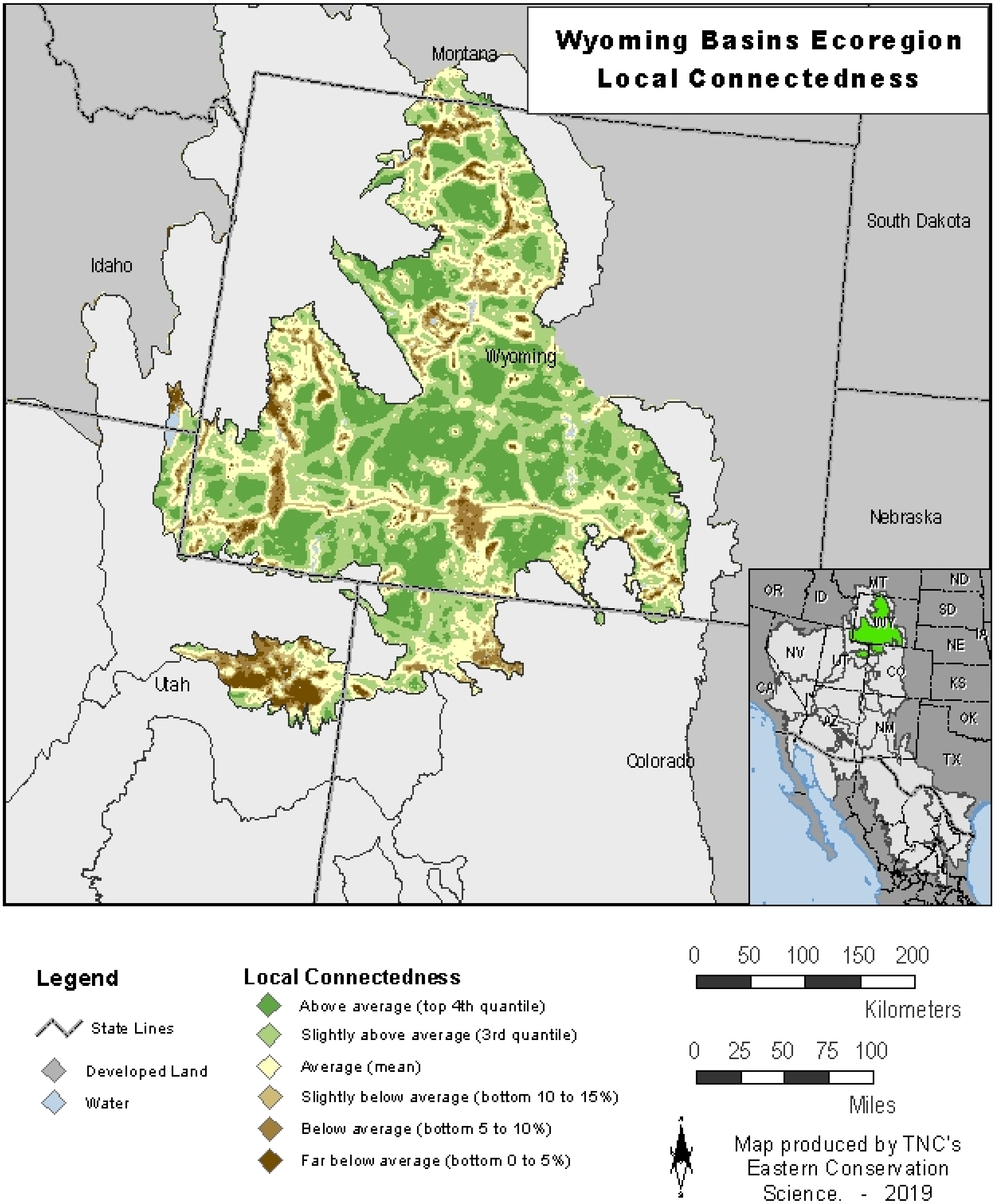


Figure 4.38: Wyoming Basins: Site Resilience.

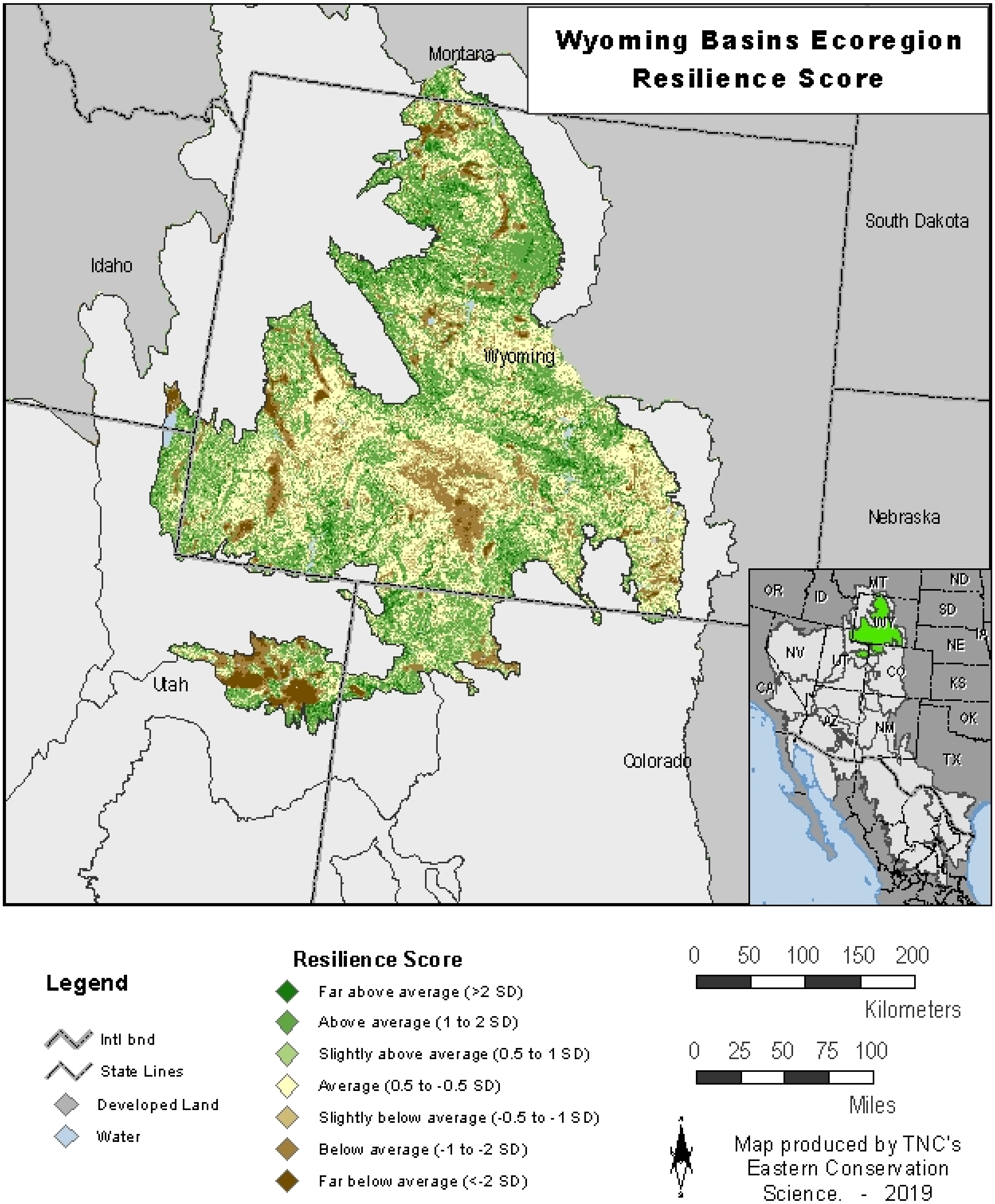


Figure 4.39: Resilient Areas for Each Geophysical Setting Within the Wyoming Basins Ecoregion

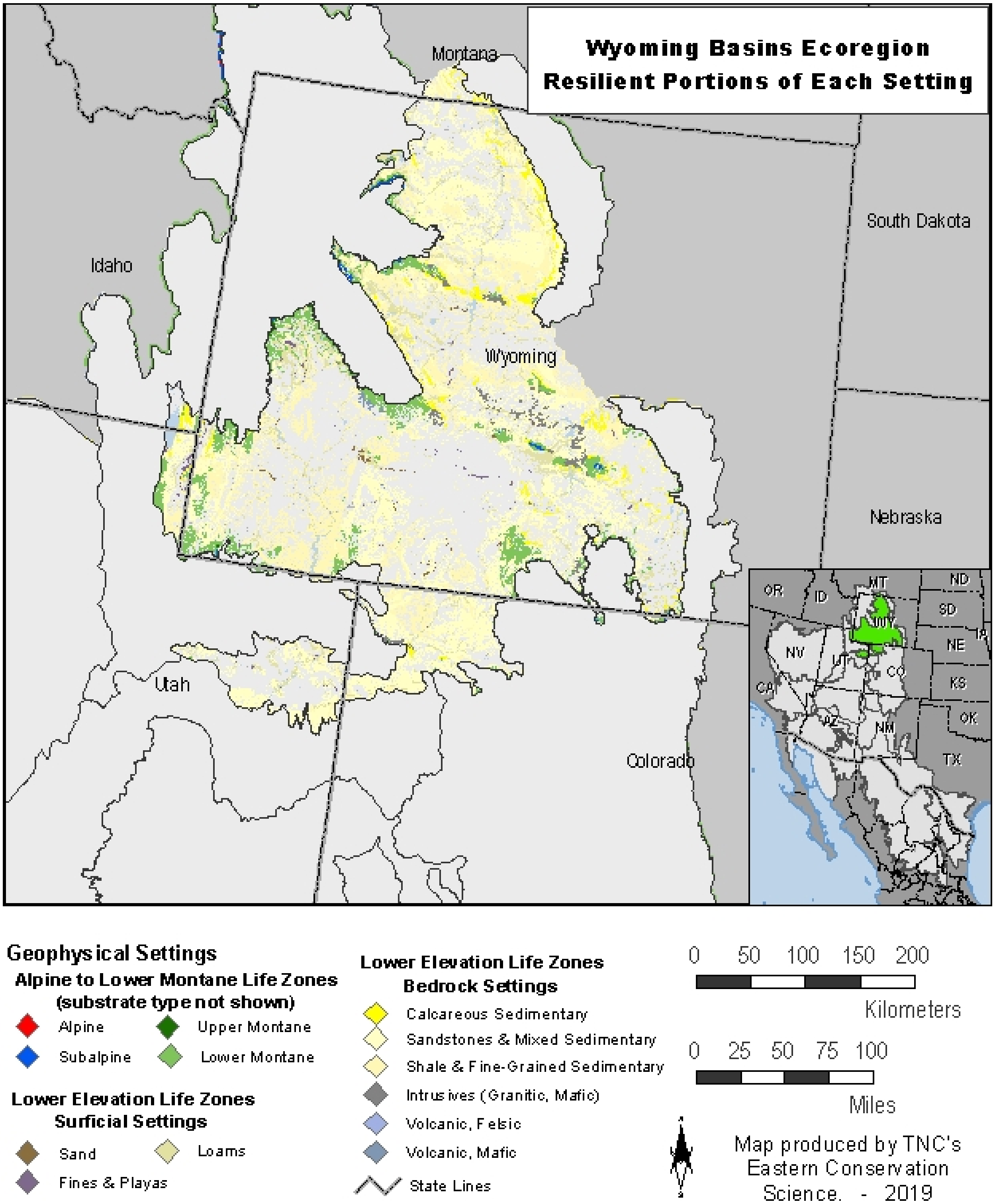
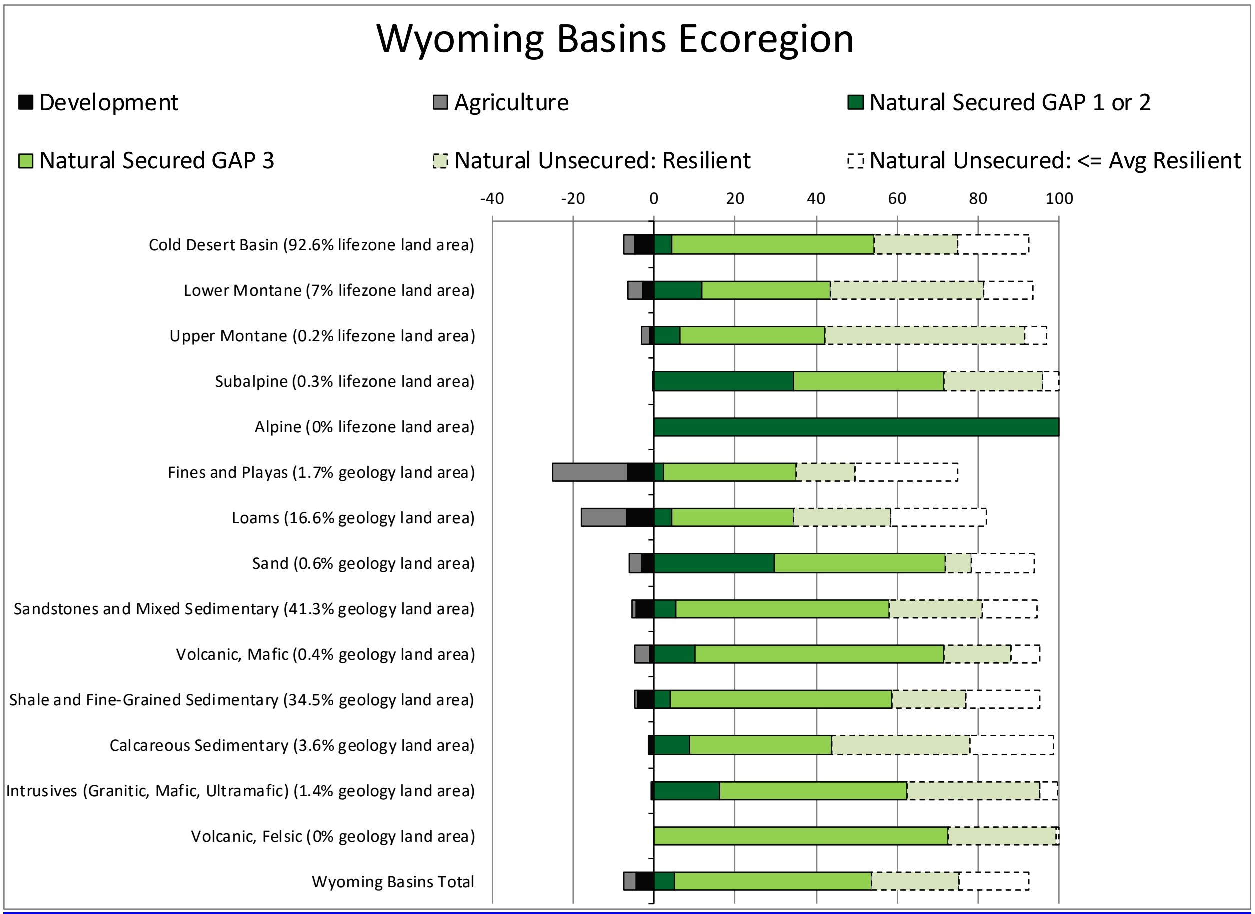


Figure 4.40: Conversion and Securement of the Wyoming Basins Ecoregion by Geophysical Setting. This ecoregion covers 32.7 million acres and is 52% resilient. This ecoregion is 8% converted and 54% secured. Within this ecoregion, 22% of the land area (7.1 million acres) is resilient unsecured natural land.



This ecoregion description was adapted from GREAT BASIN: An Ecoregion-based Conservation Blueprint (The Nature Conservancy 2001).

The Great Basin encompasses more than 72 million acres of semidesert vegetation from the east slope of the Sierra Nevada across much of Nevada to the Wasatch Mountains of the western Rocky Mountains in central Utah. It would be simplifying matters too much to merely imagine the region as the gigantic bowl its name conjures up. Between the outer mountain boundaries lie more than 300 mountain ranges interspersed among long, broad valleys, a landscape that has once been likened to an army of caterpillars crawling northward out of Mexico.

The ecoregion is characterized by salt desert scrub and sagebrush shrublands in the valleys and the lower slopes, and by pinyon-juniper woodlands, mountain sagebrush, open conifer forests, and alpine areas in the mountain ranges. Upon closer inspection, these larger ecological systems reveal important aquatic, riparian, wetland, badland, and dune habitats nestled within. Isolated mountain tops, isolated aquatic habitats in valley bottoms, and unusual badlands and sand dunes highlight the Great Basin's unique biological diversity: more than 280 plants and animals are considered endemic (occurring nowhere else) to this cold desert ecoregion.

In addition to 29 terrestrial ecological systems, 36 imperiled terrestrial communities, and 32 aquatic ecological systems, the list of all imperiled species, all federally listed threatened and endangered species and a representative subset of species of special concern amounts to over 600 plants and animals.

Figure 4.41: Great Basin: Geophysical Settings.

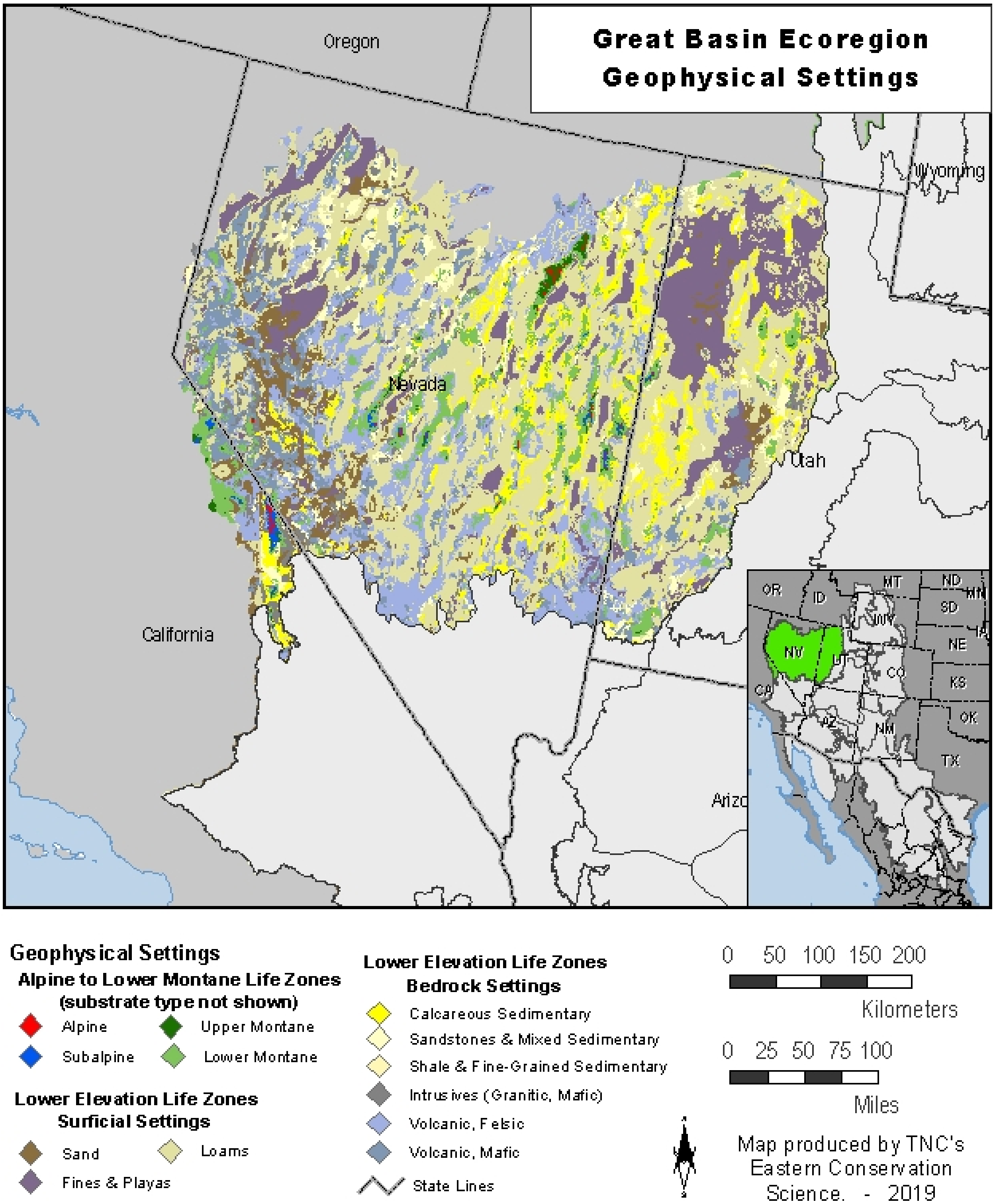


Figure 4.42: Great Basin: Landscape Diversity.

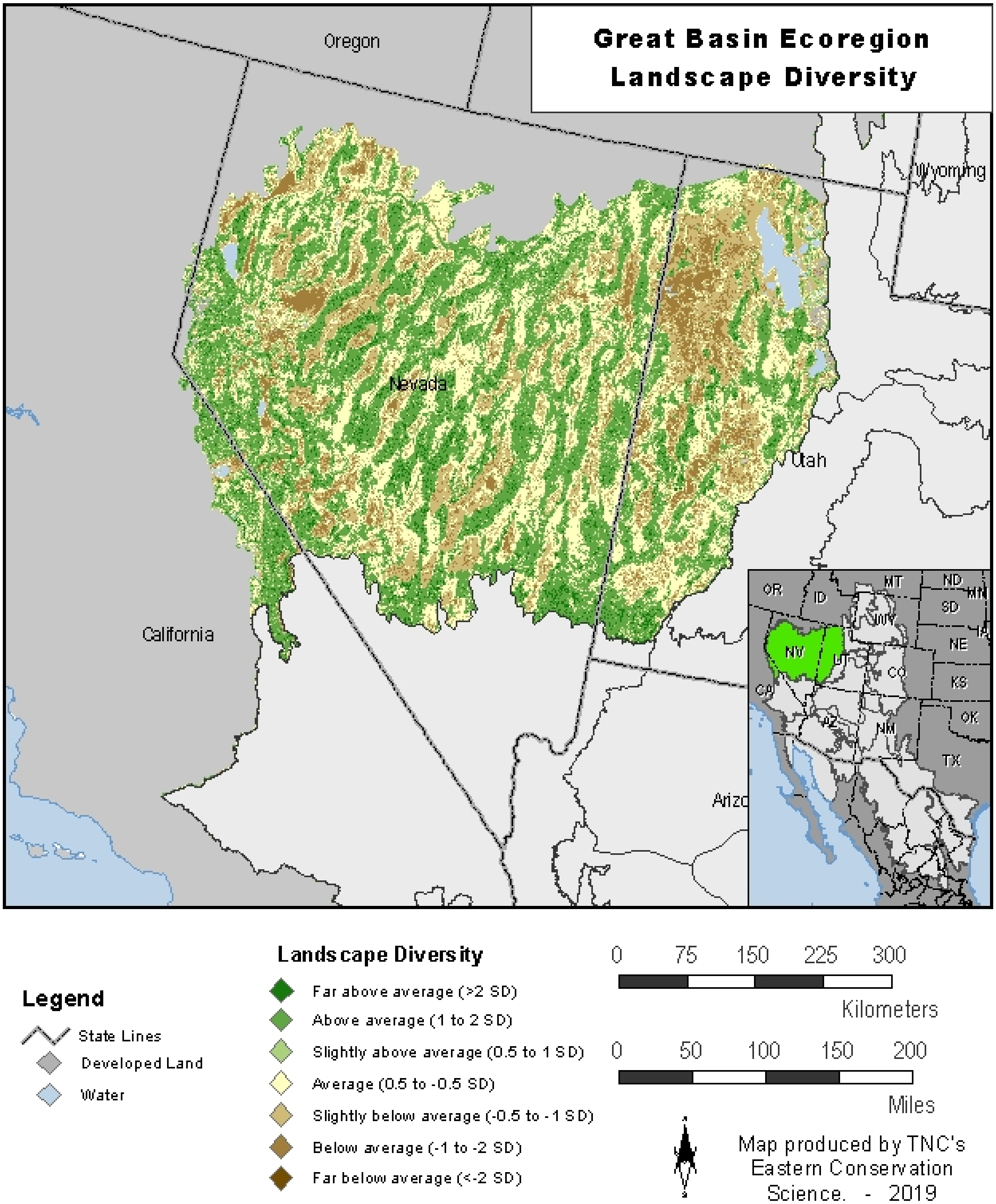


Figure 4.43: Great Basin: Local Connectedness

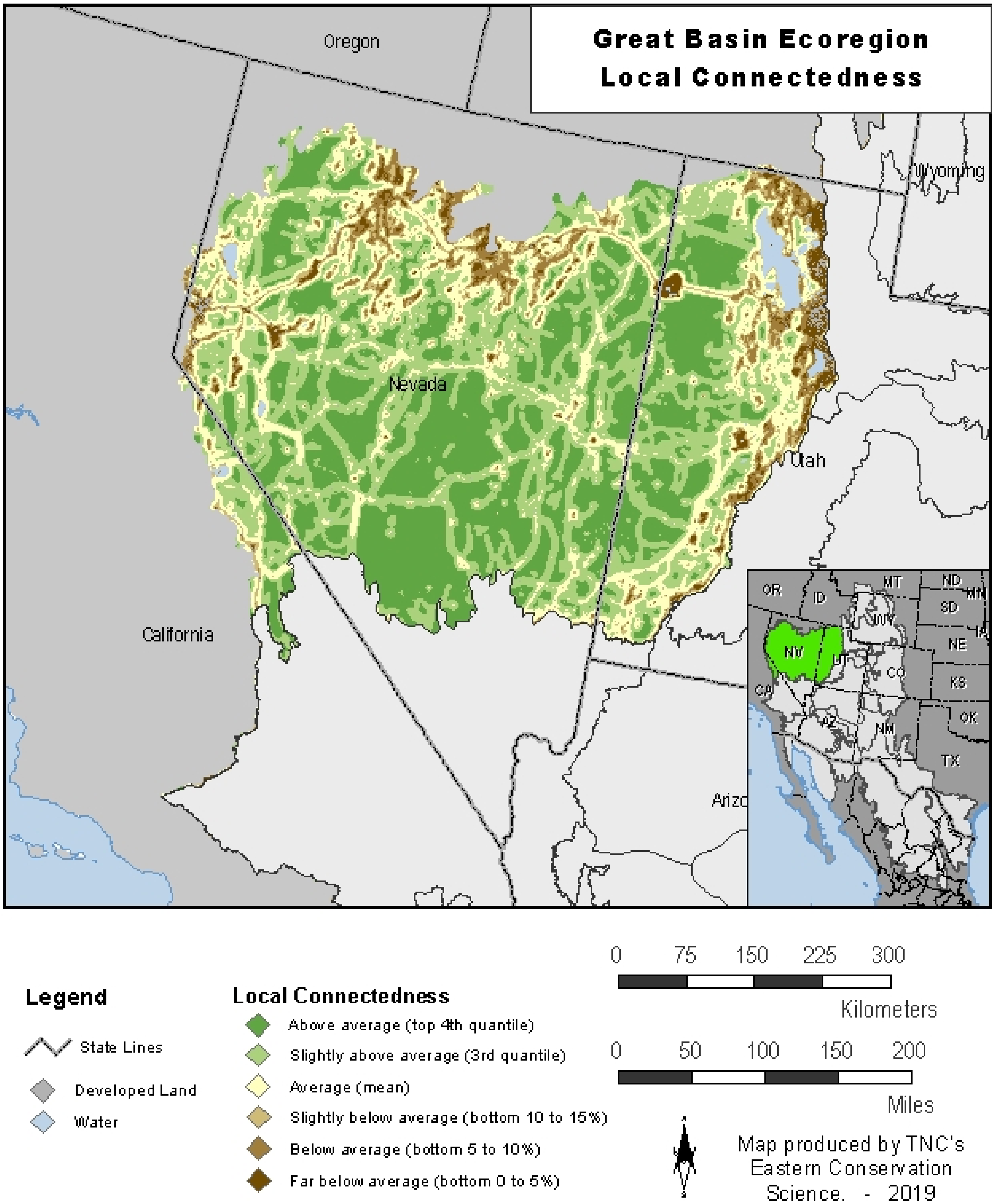


Figure 4.44: Great Basin: Site Resilience.

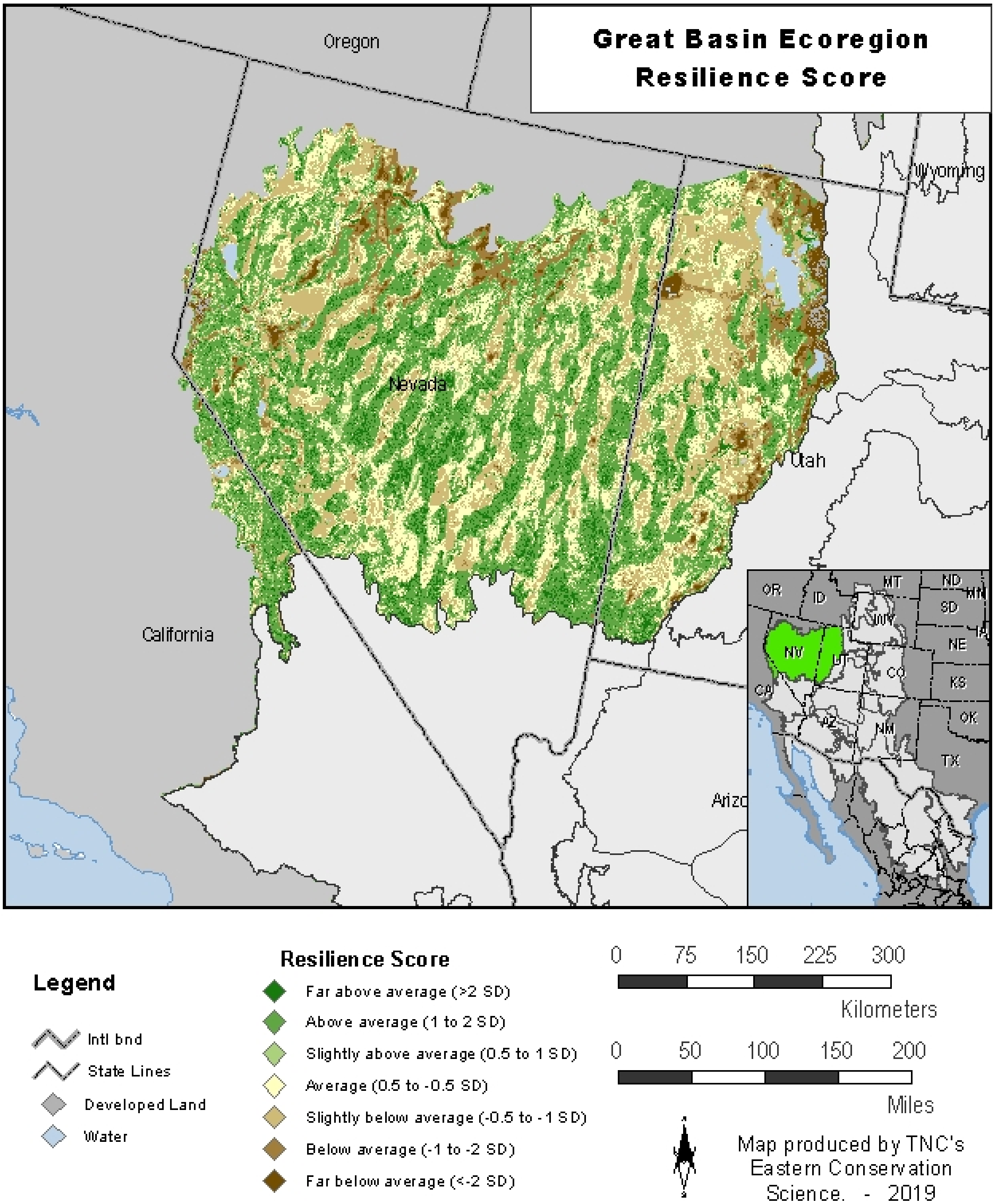


Figure 4.45: Resilient Areas for Each Geophysical Setting Within the Great Basin Ecoregion.

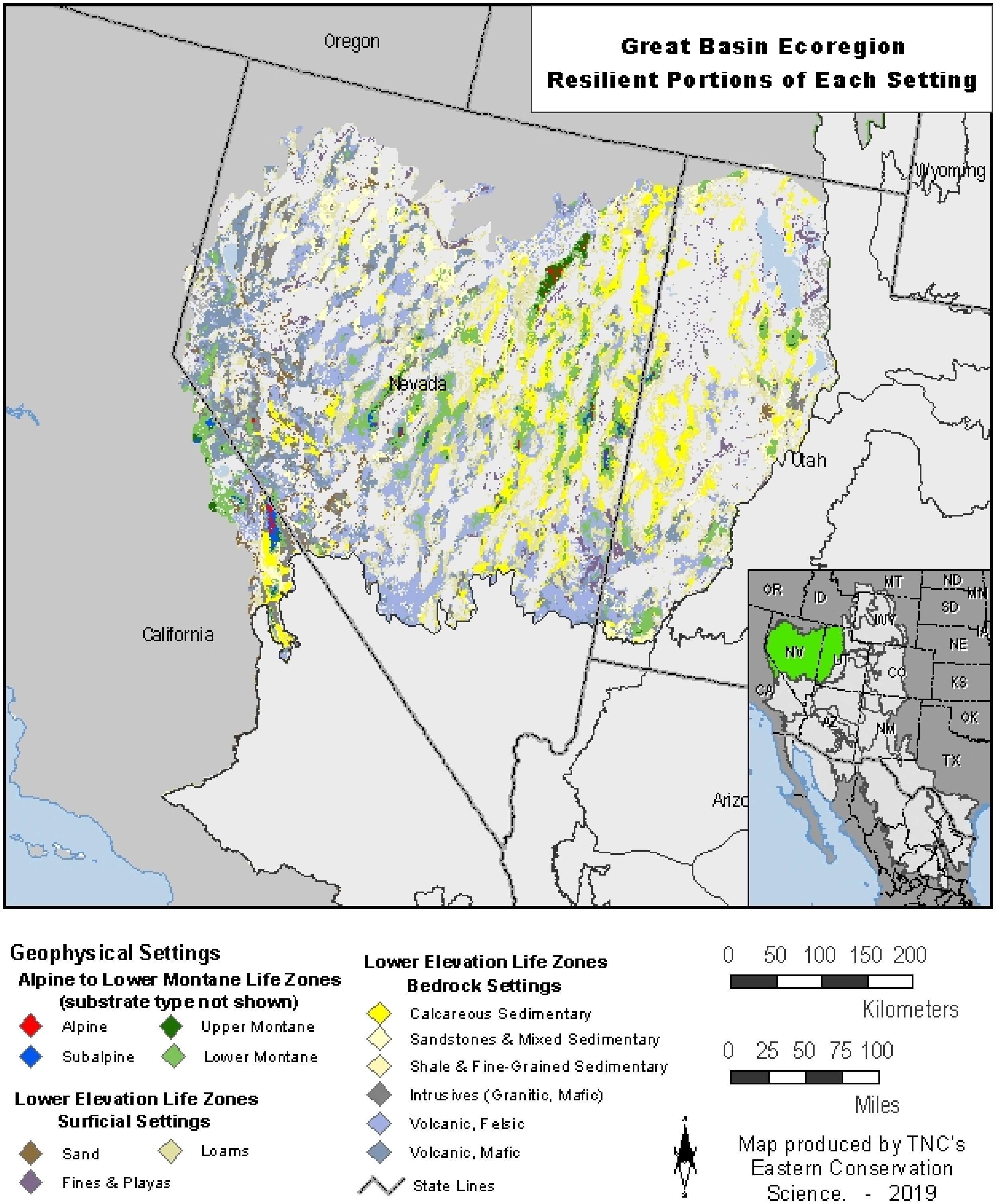


Figure 4.46: Conversion and Securement of the Great Basin Ecoregion by Geophysical Setting. This ecoregion covers 72.4 million acres and is 53% resilient. The ecoregion is 4% converted and 73% secured. Within this ecoregion, 10% of the land area (7.2 million acres) is resilient unsecured natural cover land.

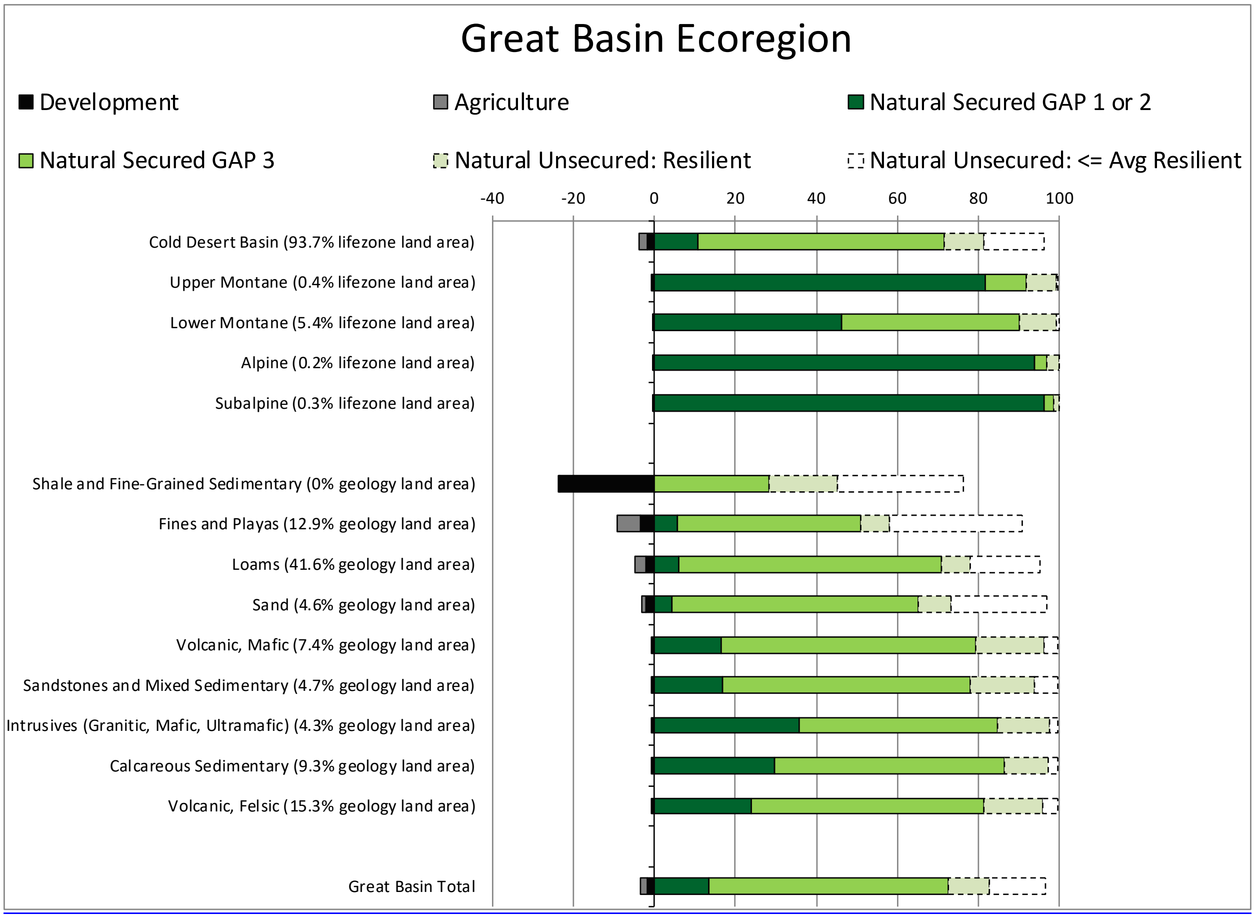


Photo credit: Mark Anderson

This ecoregion description was adapted from: Tuhy et al. 2002, A Conservation Assessment of the Colorado Plateau Ecoregion. The Nature Conservancy.

The Colorado Plateau ecoregion covers about 49 million acres (20 million ha) in portions of southeastern Utah, northern Arizona, western Colorado, and northwestern New Mexico. This region is a semi-arid land that includes some of the most spectacular scenery in the world. An extraordinary thickness of sedimentary rocks has been carved by erosion into myriad sheer-walled canyons, buttes, mesas, badlands and plains.

The elevational range extends to around 11,500 feet and results in a great diversity of ecological zones, distinguished and reflected in the dominant vegetation. The Alpine and Subalpine zone includes the highest mountain peaks with snow fields, moist to wet alpine meadows, cold alpine streams. The Upper Montane zone includes aspen forest, white fir/mixed-conifer forests, montane grassland, mountain sagebrush shrublands. The Lower Montane-Plateau zone encompasses the transition from montane ecosystems to the predominant plateaus of the ecoregion and include ponderosa pine woodlands, pinyon-juniper woodlands, and sagebrush shrublands.

The Canyon-Desert zone support extensive areas of blackbrush-mixed desert scrub and saltbush-shadscale shrublands, and canyons of five major rivers. The largest, the Grand Canyon Section covers 39% of the ecoregion where deep sheer-walled canyons, lines of cliffs, elevated plains, low plateaus, mesas, buttes, and badlands dominate.

At least 159 species are considered globally imperiled, including 27 ranked Endangered or Threatened by USFWS (such as Southwestern willow flycatcher and California Condor). Nearly 142 more are considered vulnerable or of special concern

Figure 4.47: Colorado Plateau: Geophysical Settings.

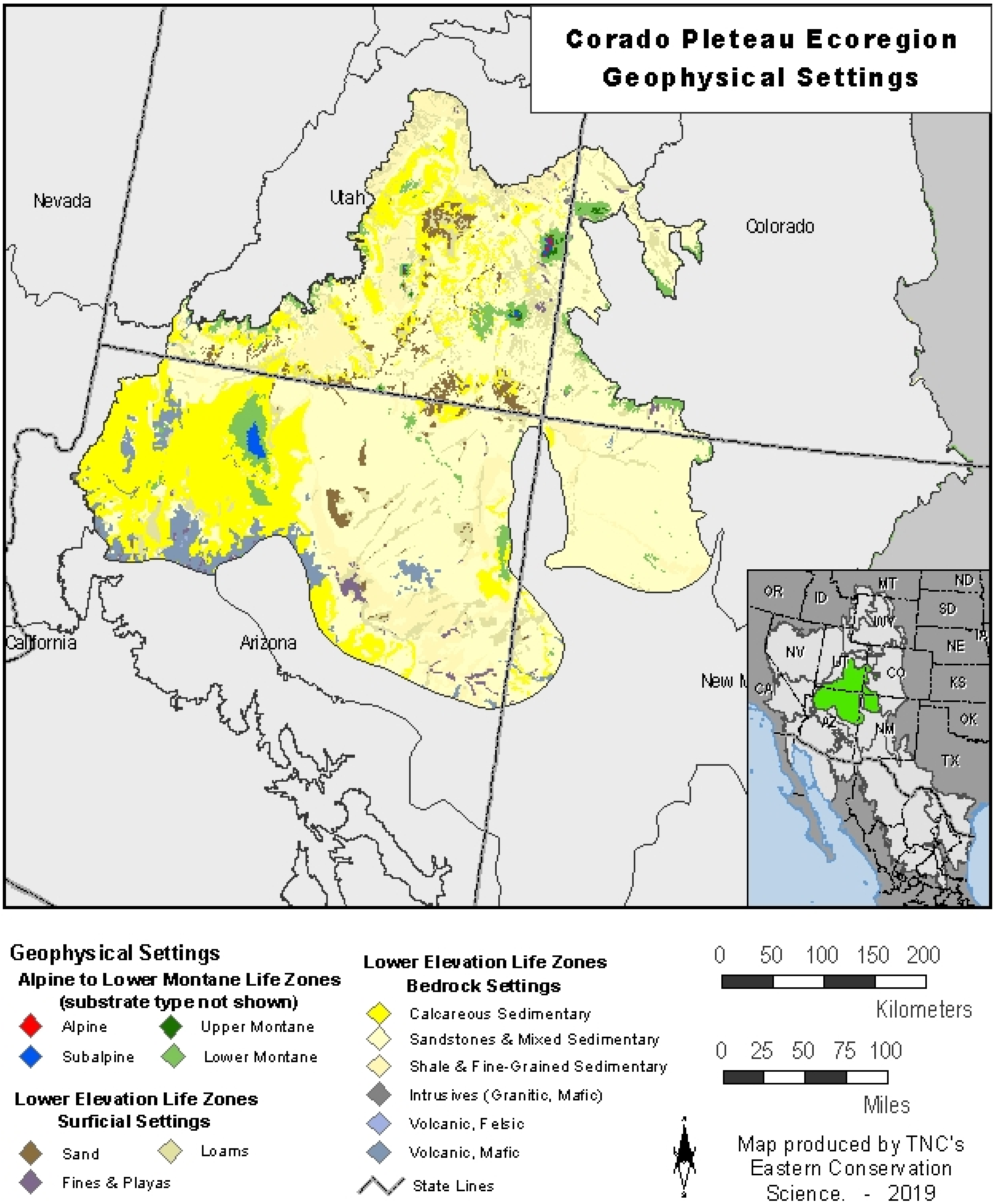


Figure 4.48: Colorado Plateau: Landscape Diversity.

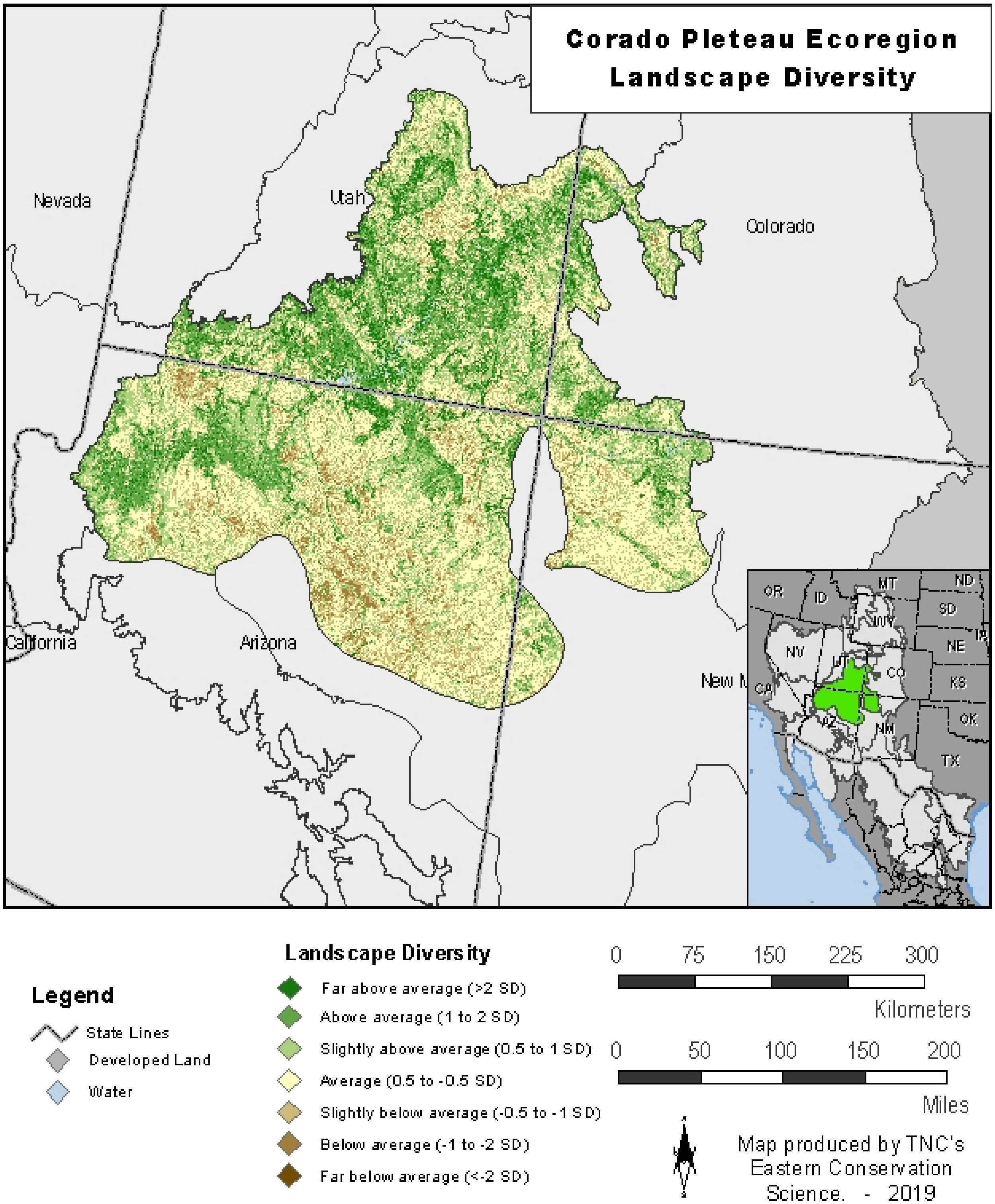


Figure 4.49: Colorado Plateau: Local Connectedness.

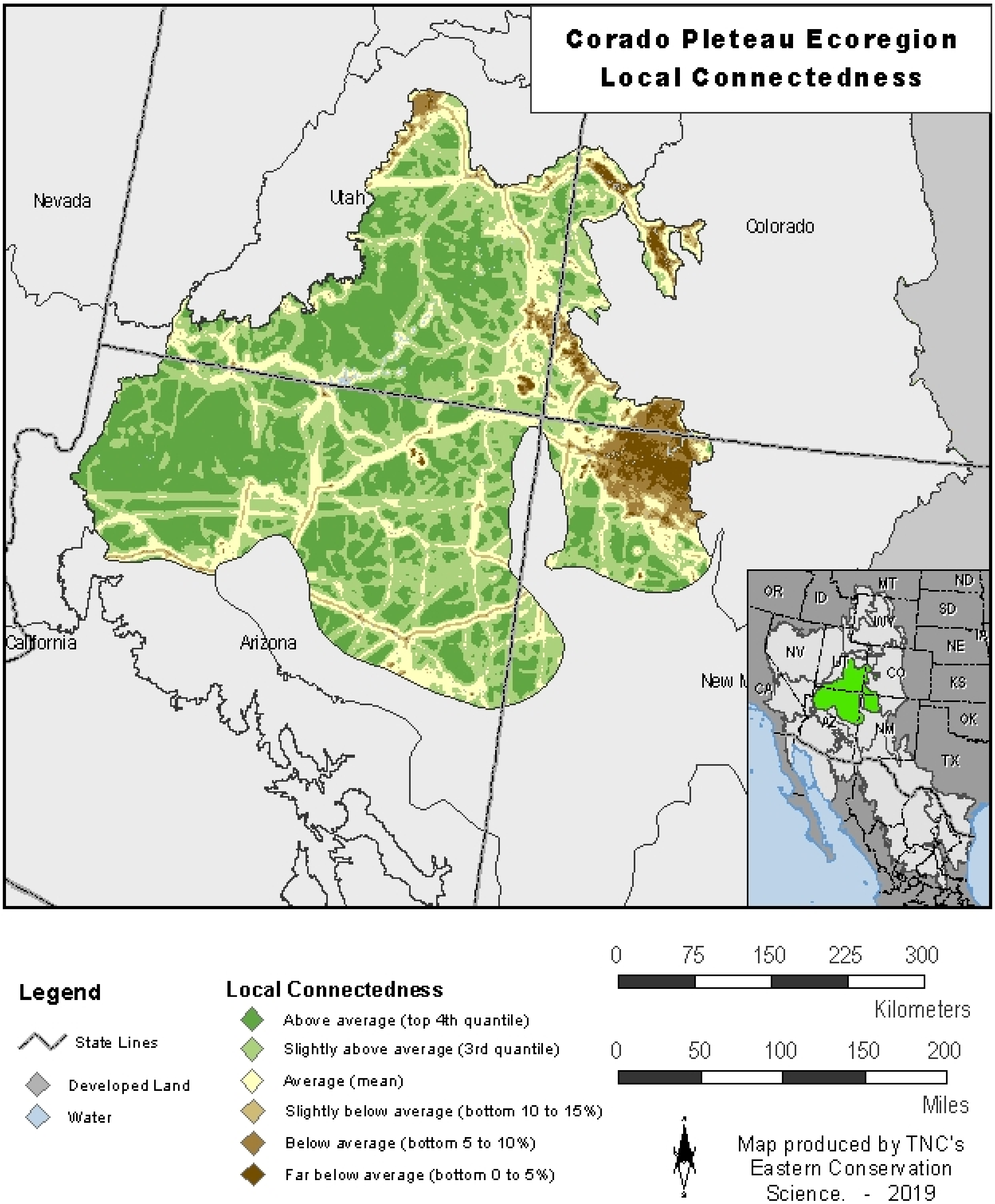


Figure 4.50: Colorado Plateau: Site Resilience.

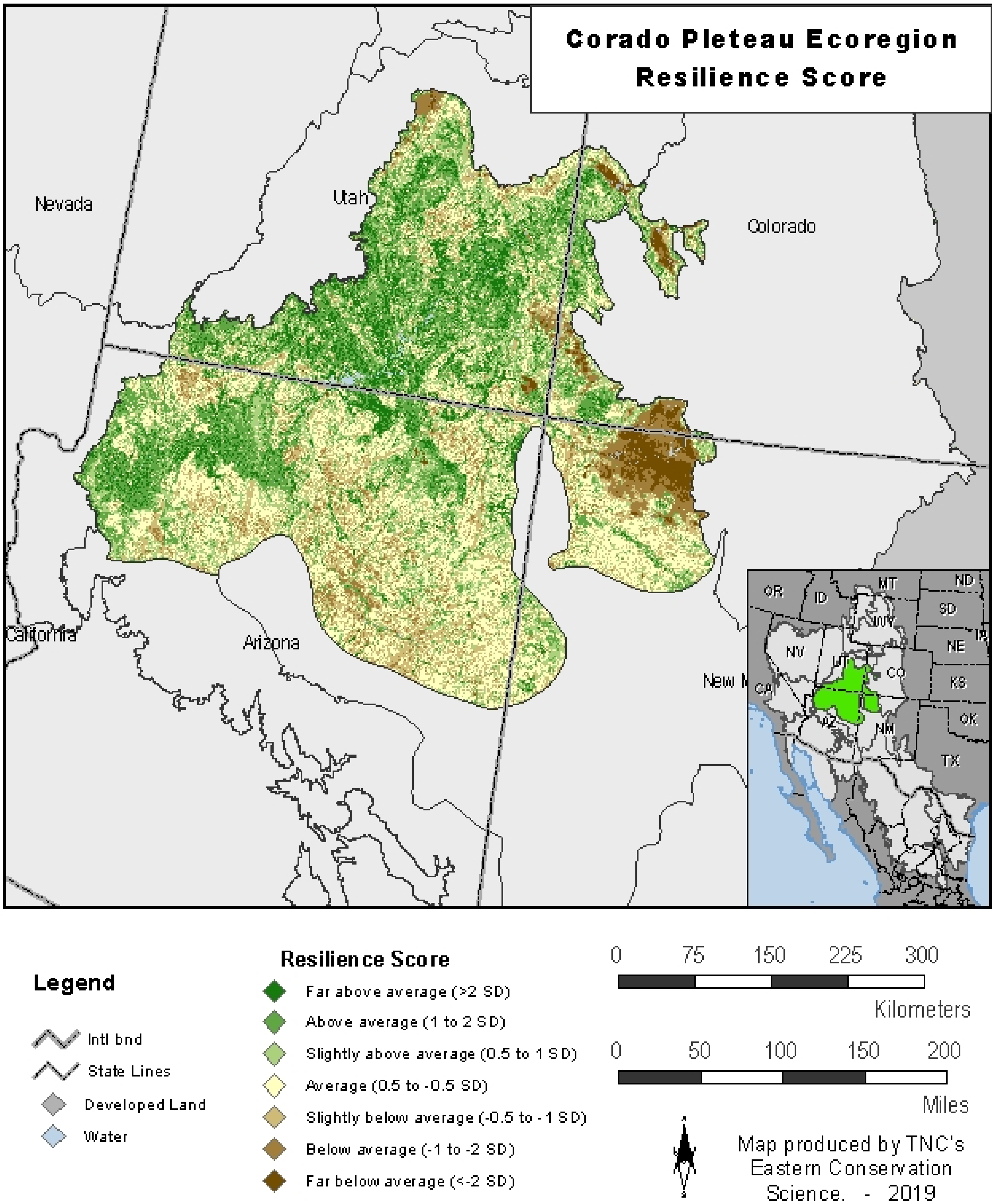


Figure 4.51: Resilient Areas for Each Geophysical Setting Within the Colorado Plateau Ecoregion

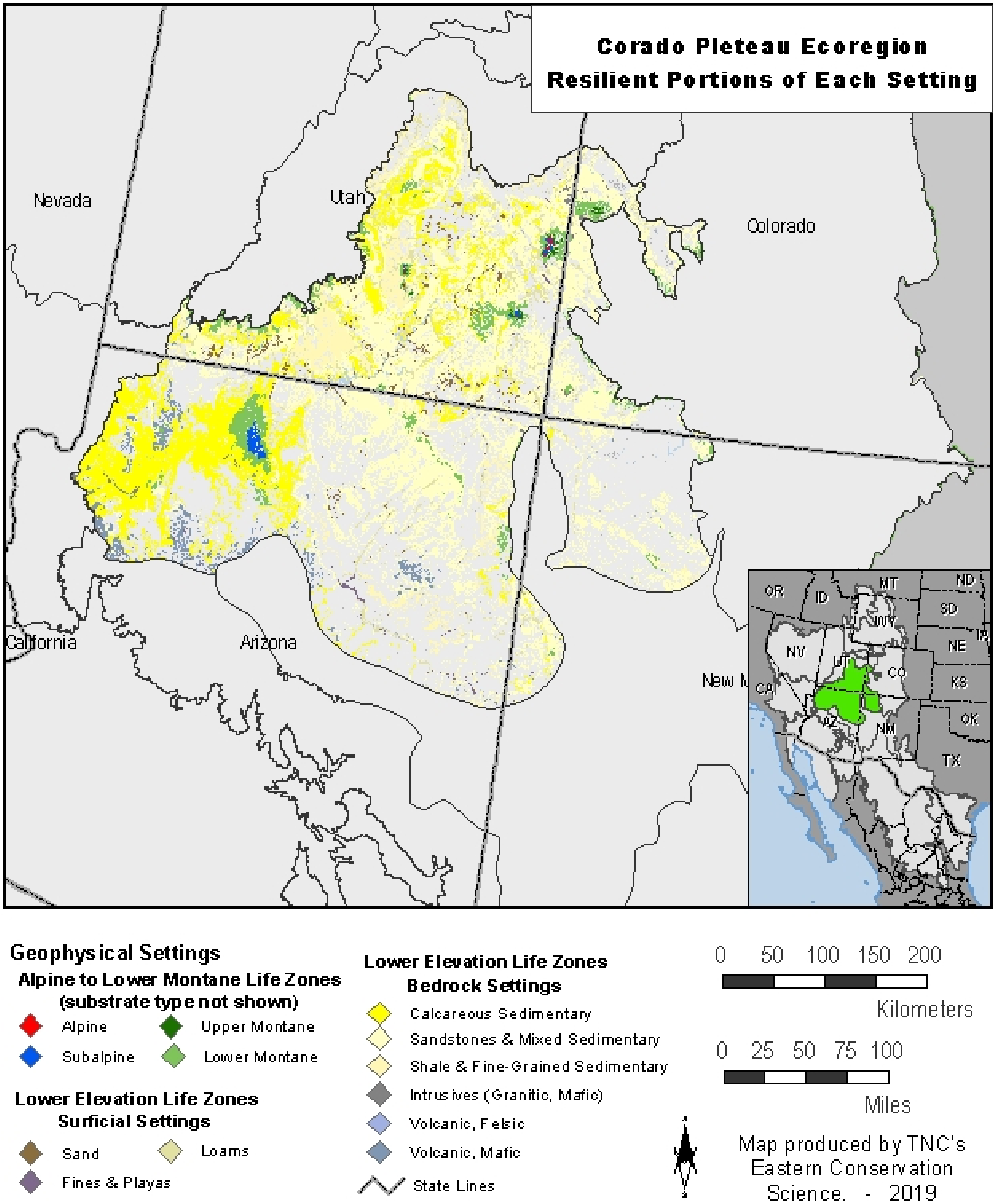
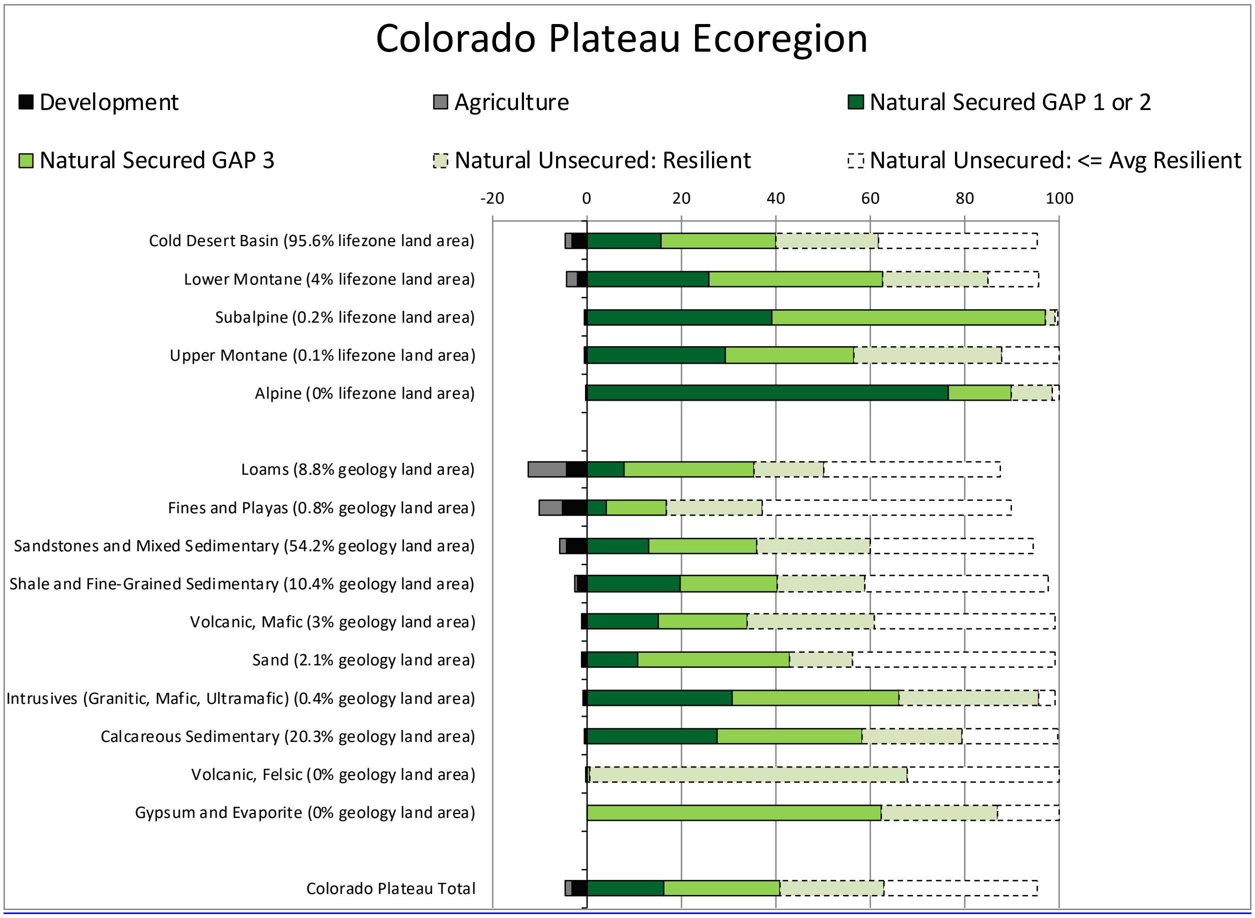


Figure 4.52: Conversion and Securement of the Coloardo Plateau Ecoregion by Geophysical Setting. This ecoregion covers 48.5 million acres and is 51% resilient. The ecoregion is 5% converted and 41% secured. Within this ecoregion, 22 % of the land area (10.6 million acres) is resilient unsecured natural land.



his ecoregion description was adapted from: Randall, et al. 2010. Mojave Desert Ecoregional Assessment. Unpublished Report. The Nature Conservancy, San Francisco, California. 106 pages

The Mojave Desert Ecoregion encompasses 32 million acres in California, Nevada, Arizona and Utah. One of North America's last great wilderness areas, the region is mostly undisturbed and harbors an extraordinary variety of plants, animals, and other organisms capable of surviving some of the harshest conditions on Earth. The arid climate and naturally slow pace of soil development, plant growth, and ecological succession render the region extremely fragile and slow to recover from disturbance.

The Mojave Desert harbors rich and distinctive biological diversity. The California portion alone is inhabited by at least 439 species and subspecies of vertebrates including 14 endemic to the Mojave and 28 that are federally listed as threatened or endangered. The flora boasts a large variety of shrubs and some 250 species of annual herbaceous plants, at least 80 of which are endemic, and many reveal themselves only during spring blooms. With its great topographic diversity and varied geology and soils, the Mojave also supports a wide variety of plant communities and ecological systems, from rare subalpine mesic meadows and isolated mesquite bosques, to widespread creosote bush-white bursage desert scrub, patches of desert pavement, and isolated sand dunes.

Surprisingly, the ecoregion supports large numbers of aquatic animals and plants, many endemic to a single isolated system of springs. This is spectacularly illustrated at Ash Meadows in southern Nevada which features 24 animals and plants found nowhere else in the world.

Figure 4.53: Mojave Desert: Geophysical Settings.

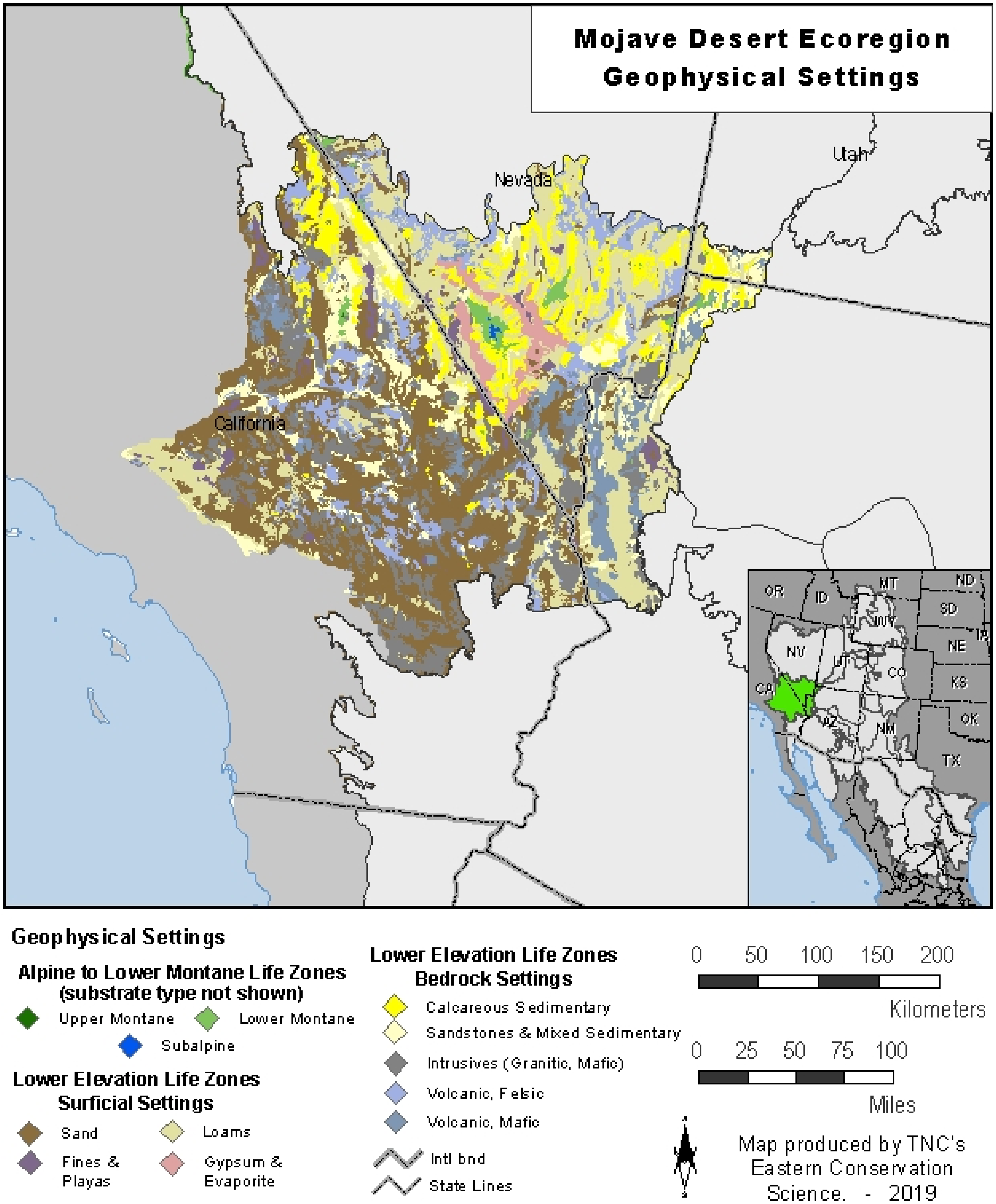


Figure 4.54: Mojave Desert: Landscape Diversity.

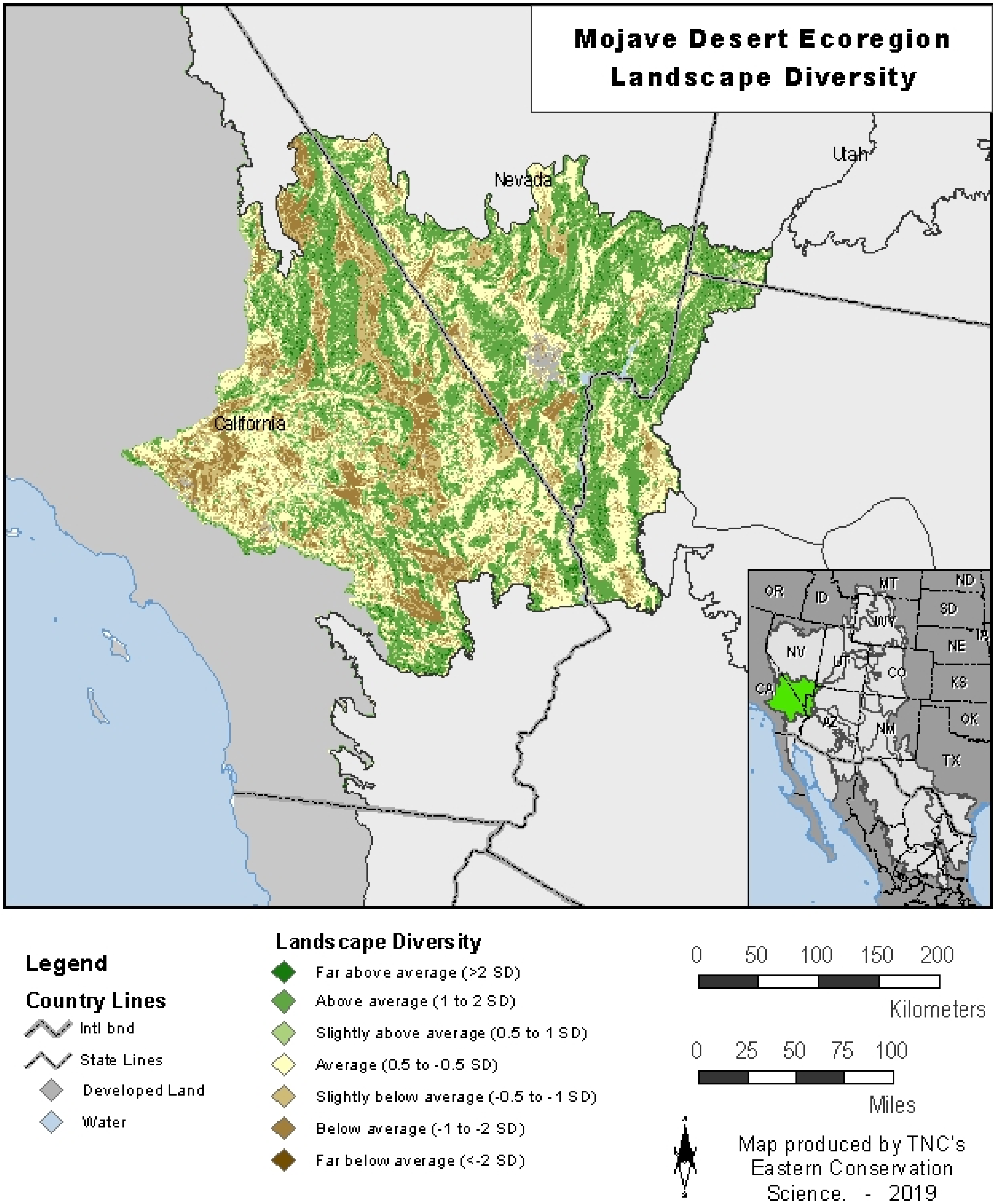


Figure 4.55: Mojave Desert: Local Connectedness.

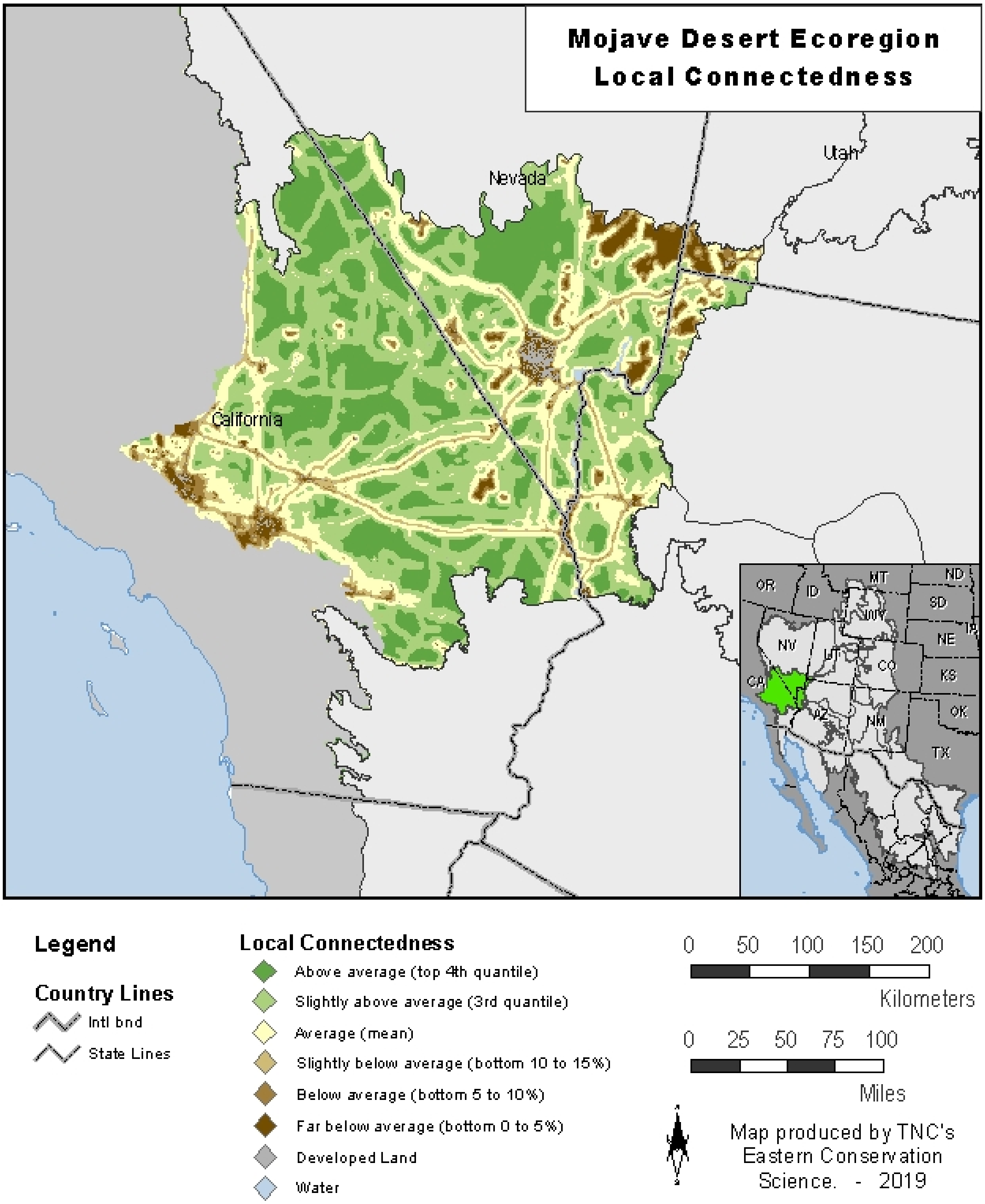


Figure 4.56: Mojave Desert: Site Resilience.

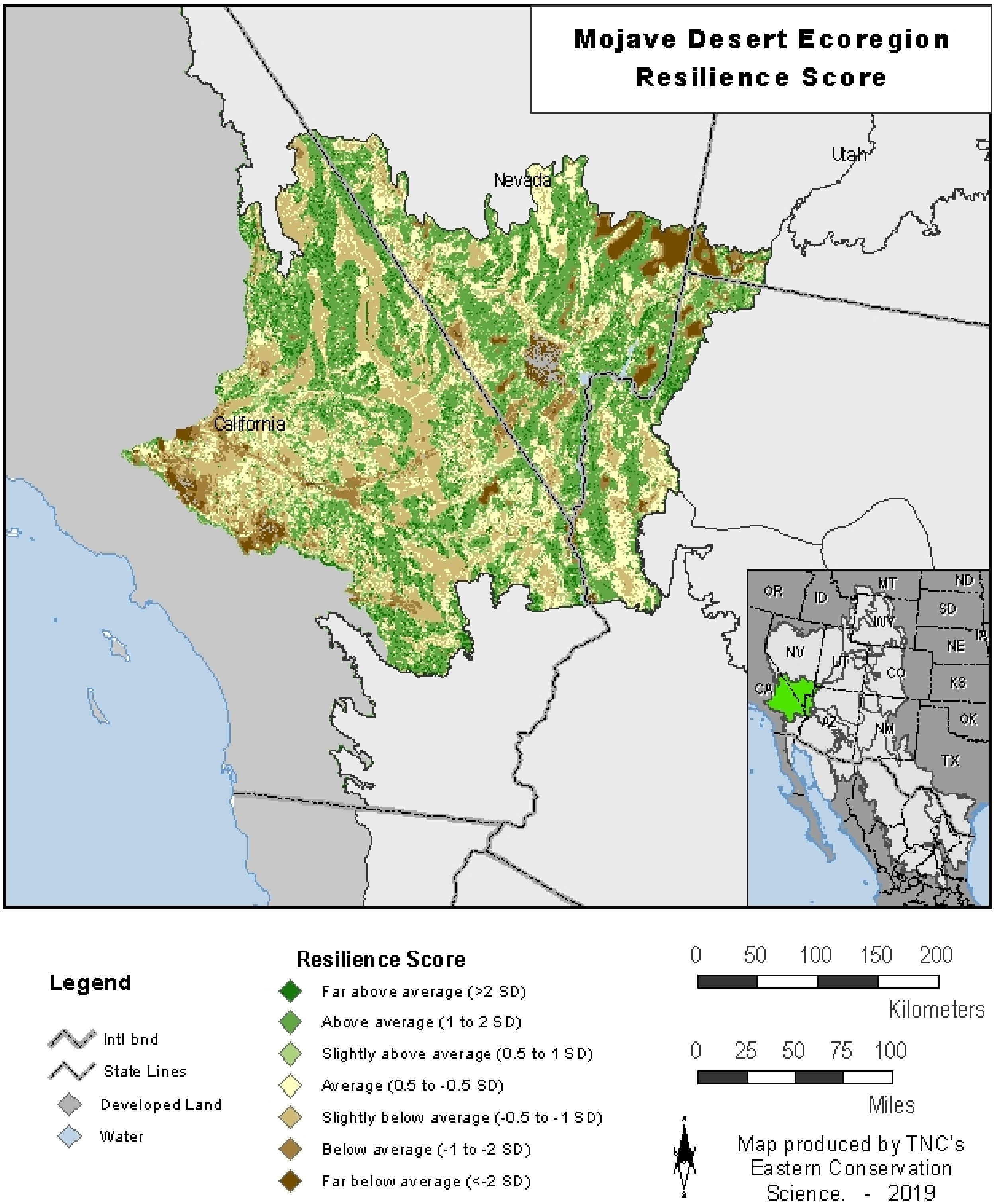


Figure 4.57: Resilient Areas for Each Geophysical Setting Within the Mojave Desert Ecoregion.

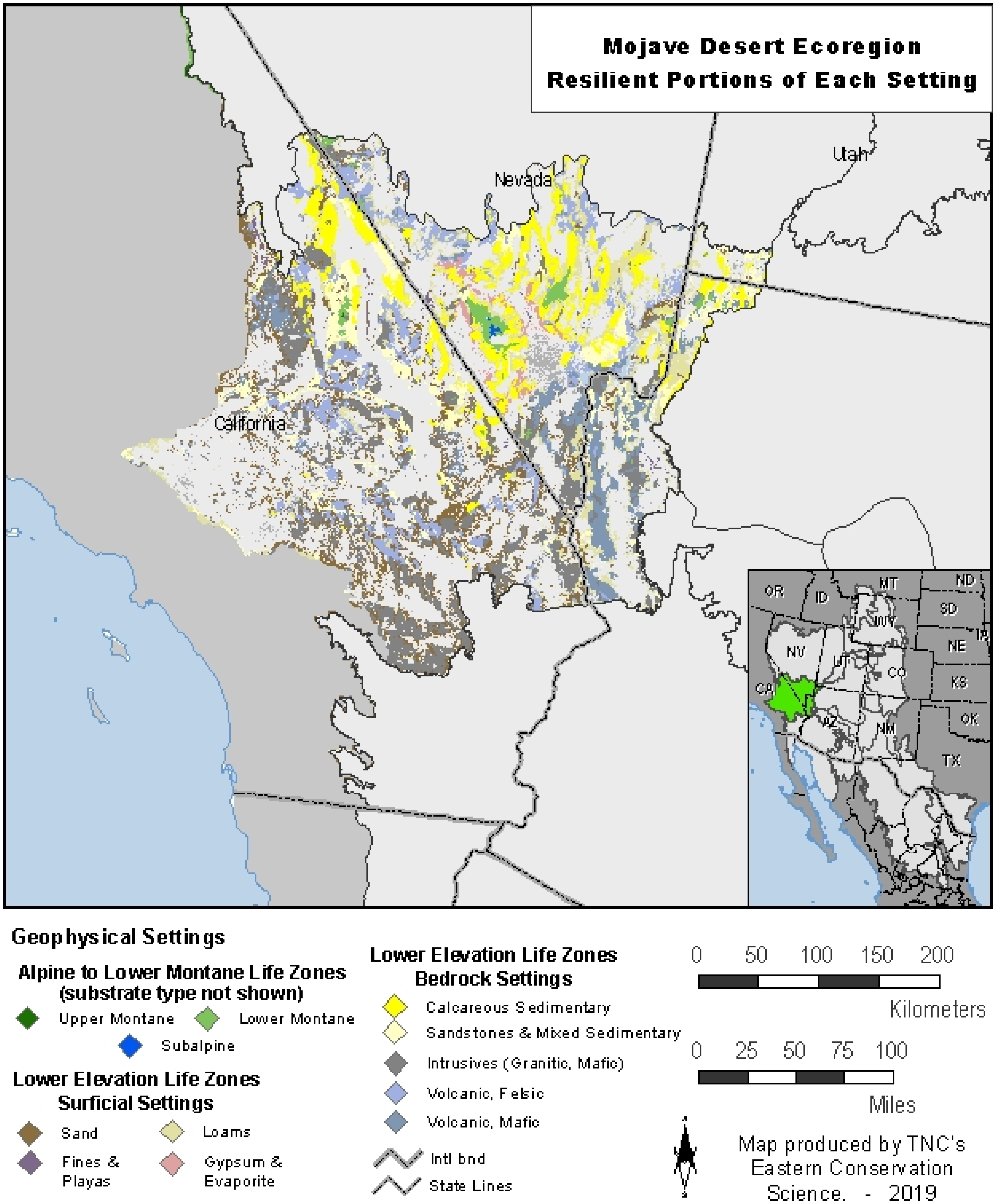


Figure 4.58: Conversion and Securement of the Mojave Desert Ecoregion by Geophysical Setting. This ecoregion covers 32.3 million acres and is 51% resilient. The ecoregion is 3% converted and 72% secured. Within this ecoregion, 11% of the land area (3.4 million acres) is resilient unsecured natural land.

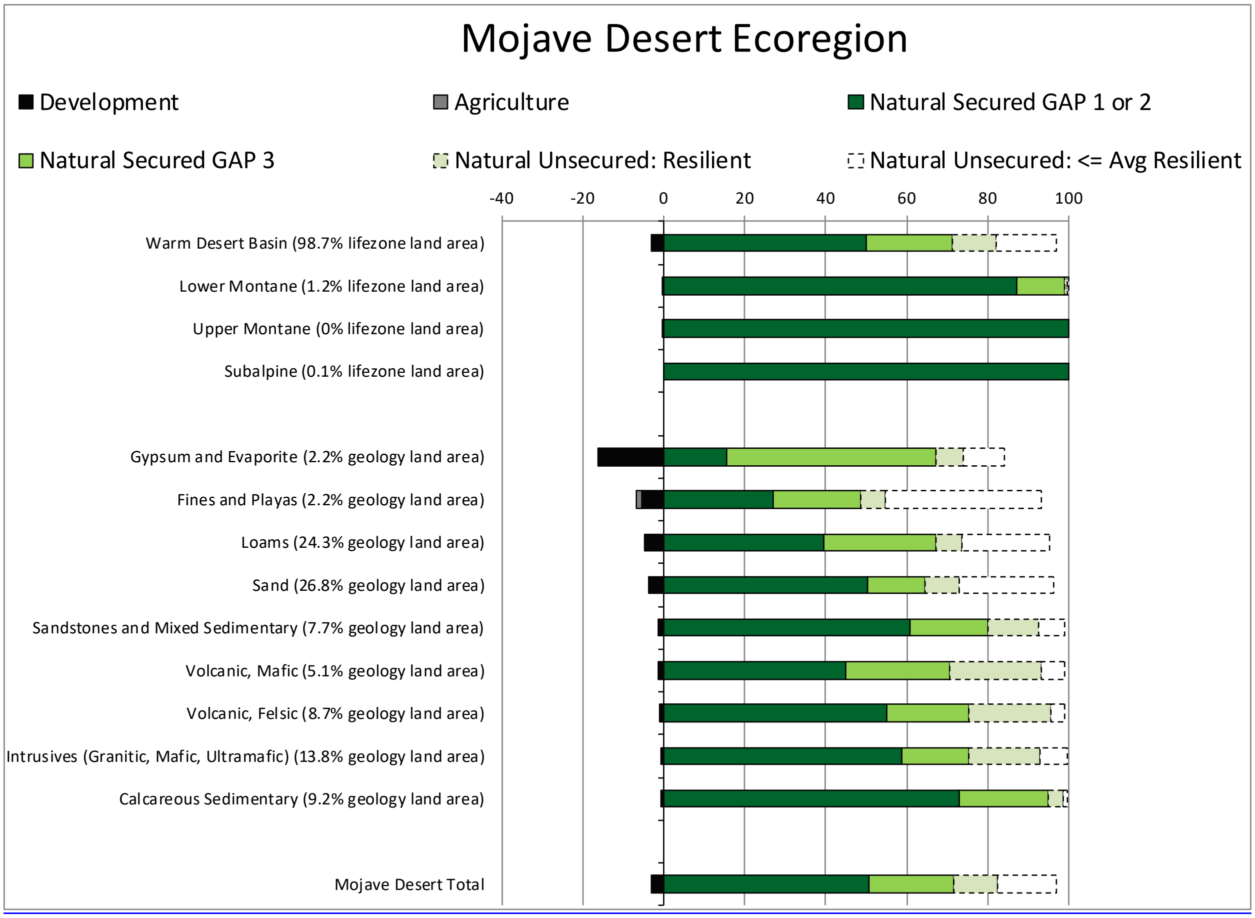


Photo credit: TNC

This ecoregion description was adapted from: Marshall et al. 2000. An Ecological Analysis of Conservation Priorities in the Sonoran Desert Ecoregion. TNC. 146 pp

The Sonoran Desert Ecoregion encompasses 55 million acres in southern Arizona, southeastern California, northern Baja, California, and northwestern Sonora. A relatively new desert, the vegetation communities were likely established within the past 4,500-9,000 years. Rich in biological diversity, the ecoregion harbors a high proportion of endemic plants, reptiles, and fish. Over 2500 pollinators are known including the highest known diversity of bee species in the world. More than 500 bird species migrate through, breed, or permanently reside in the Ecoregion. The Ecoregion is equally diverse in its human population with more than a dozen Native American Tribes represented, as well as many recent migrants to the region.

The Sonoran Desert is the most tropical of the three North American warm deserts. Most of the region it lies below 2,600 feet, and geographic boundaries are sharply defined where steep elevational gradients result in abrupt changes in micro-climate and vegetation. Underlying bedrock is mostly granite and gneiss, with extensive areas of volcanic origin and smaller areas of both calcareous and acidic bedrock. Mountain ranges are rocky and low, mostly below 4,000 ft. The Mexican portion of the ecoregion harbors the most extensive desert dune system in North America: the Gran Desierto.

The ecoregion is threatened by habitat loss, overuse of natural surface waters, improper livestock management, and other uses. It has been identified as one of the top 200 Ecoregions worldwide that deserve special conservation attention.

Figure 4.59: Sonoran Desert: Geophysical Settings.

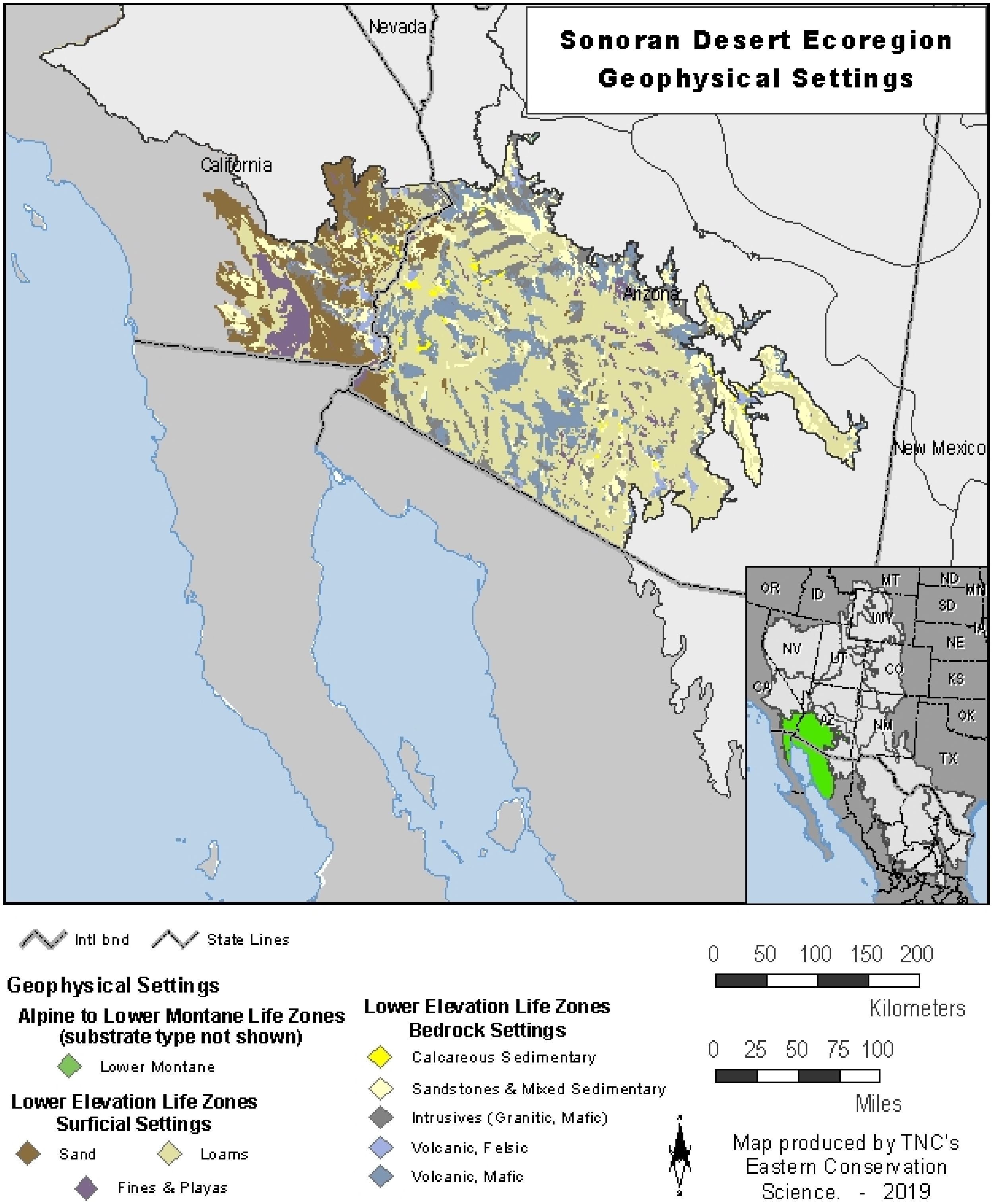


Figure 4.60: Sonoran Desert: Landscape Diversity.

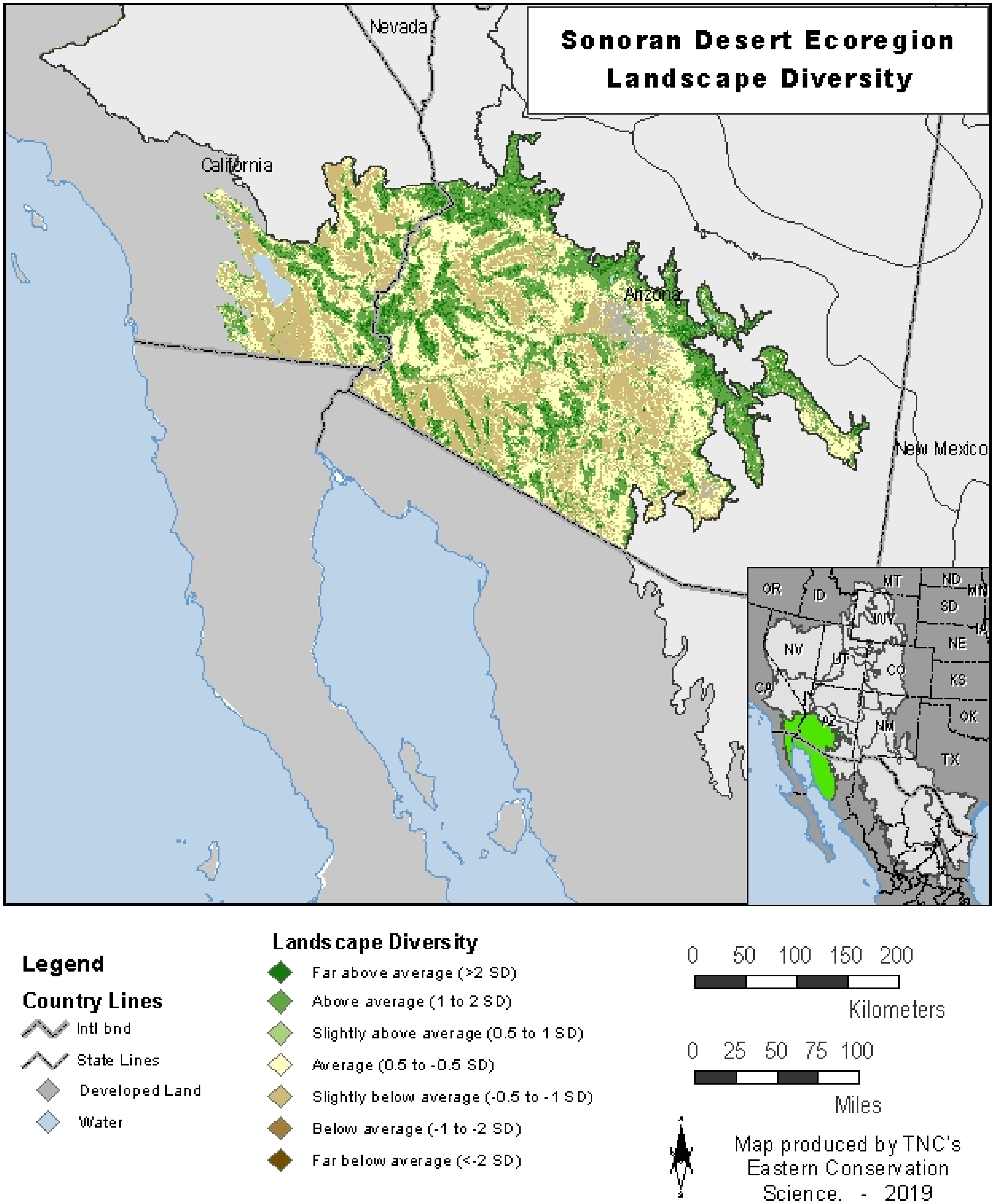


Figure 4.61: Sonoran Desert: Local Connectedness

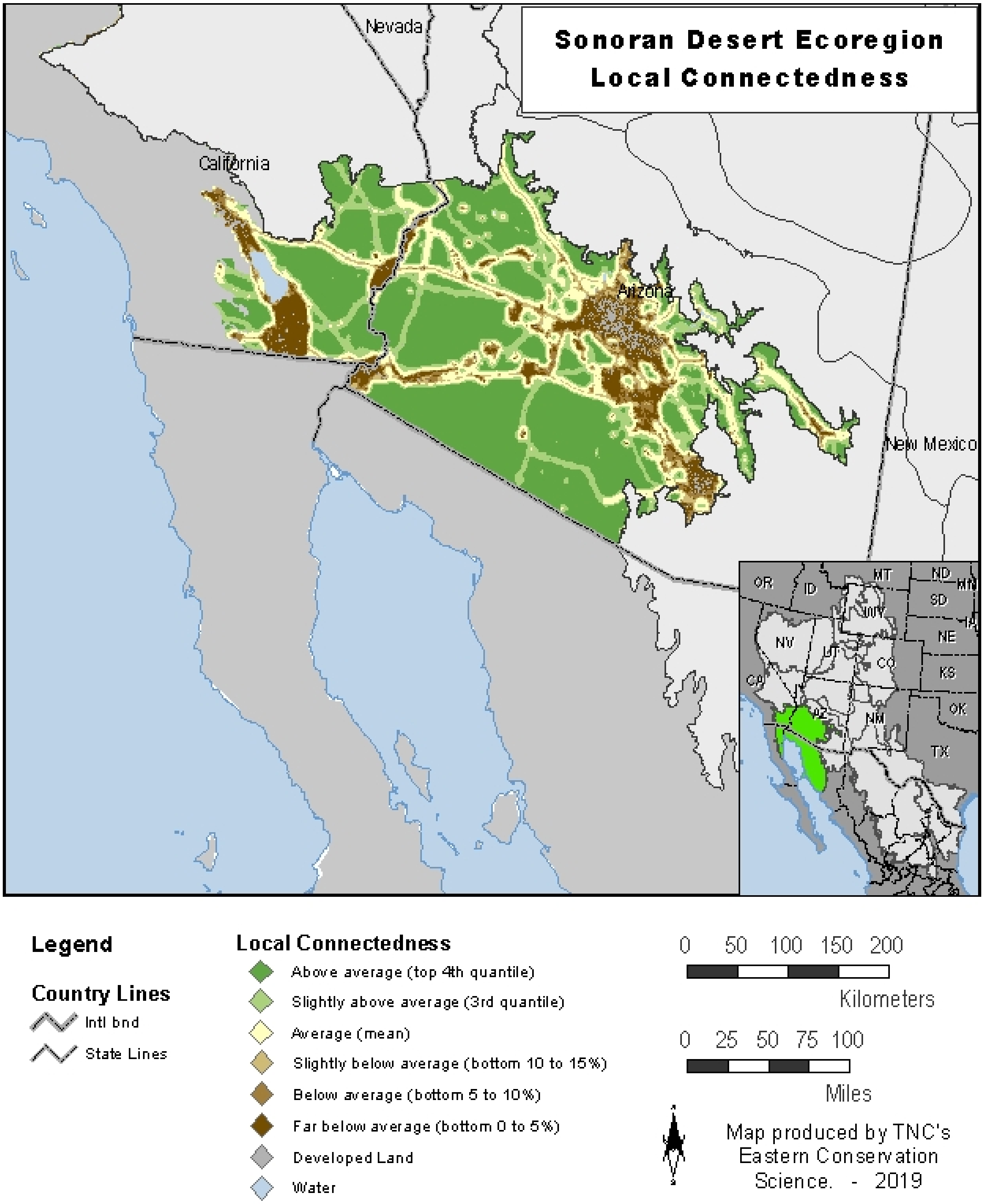


Figure 4.62: Sonoran Desert: Site Resilience.

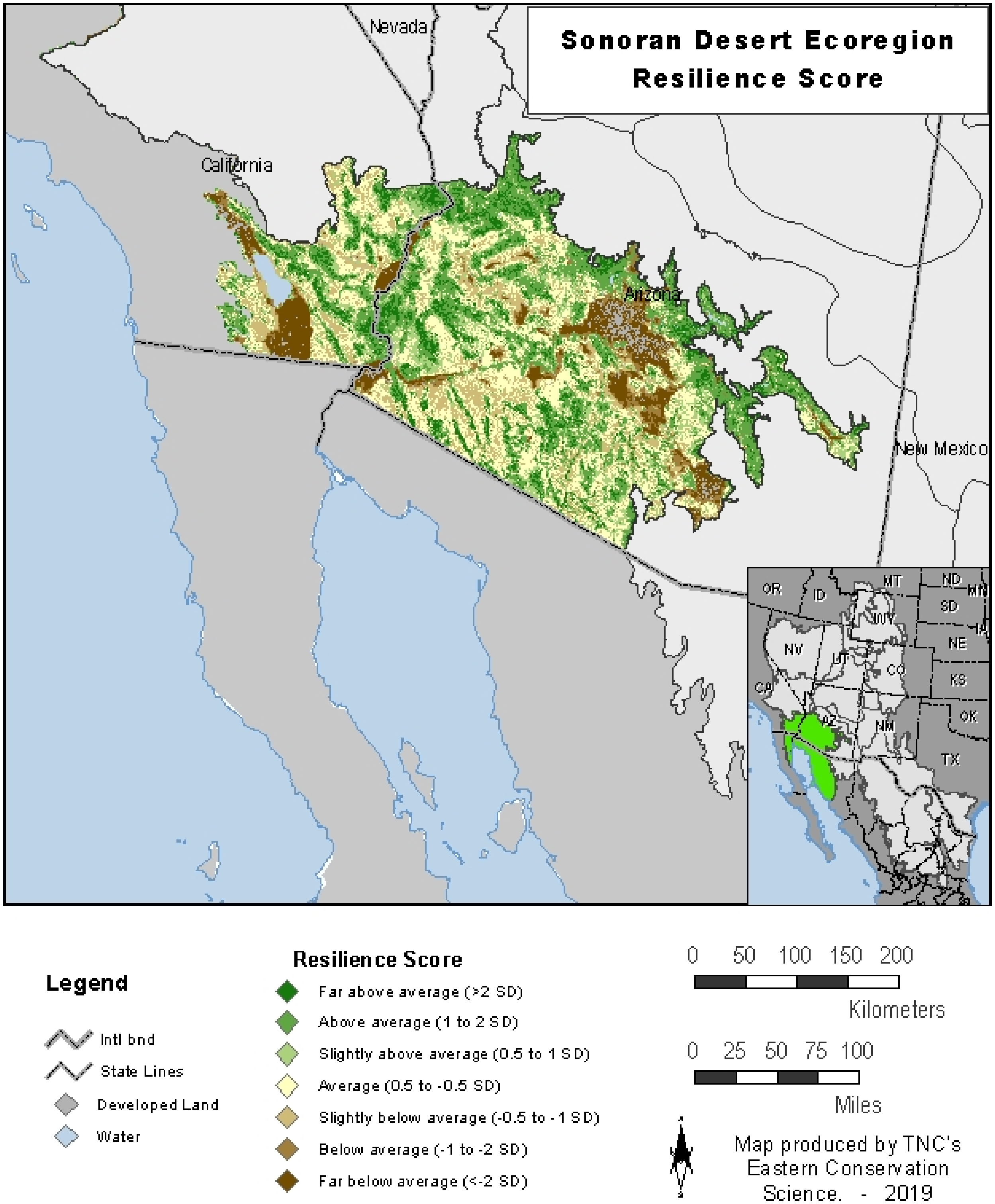


Figure 4.63: Resilient Areas for Each Geophysical Setting Within the Sonoran Desert Ecoregion

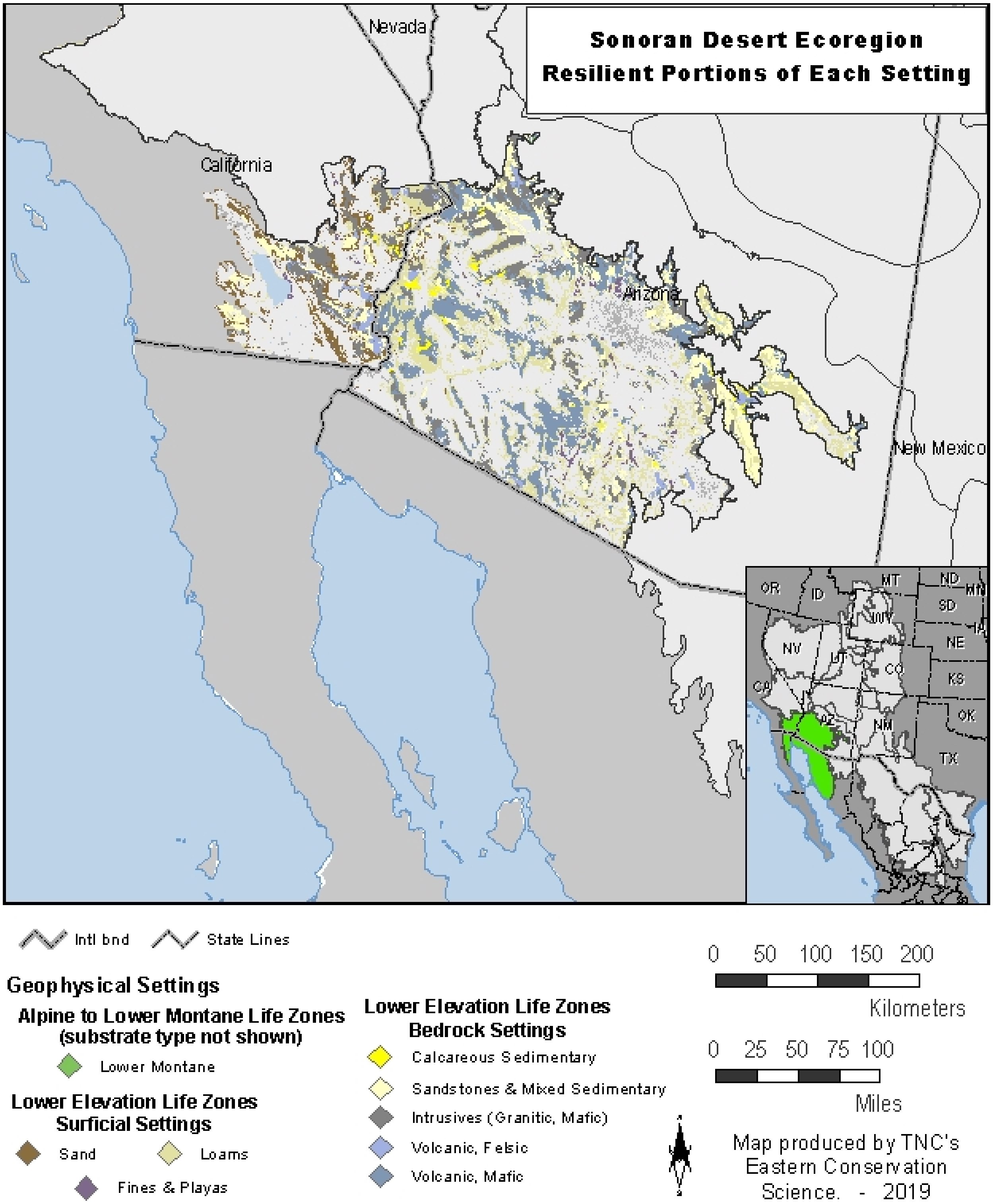
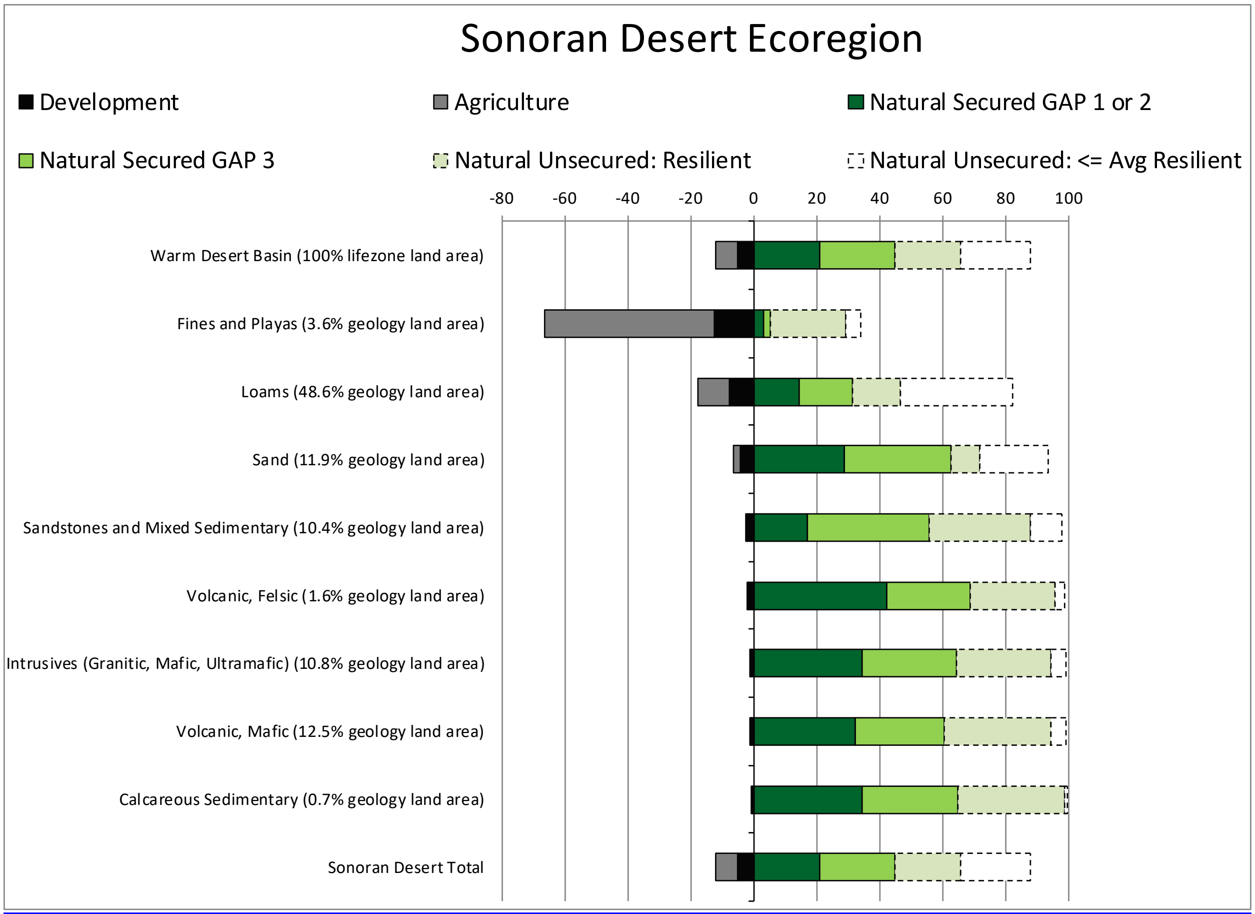


Figure 4.64: Conversion and Securement of the Sonoran Desert Ecoregion by Geophysical Setting. This ecoregion covers 28.7 million acres and is 49% resilient. The ecoregion is 122% converted and 45% secured. Within this ecoregion, 21% of the land area (6 million acres) is resilient unsecured natural land.



This ecoregion description was adapted from: Marshall et al. 2004. An Ecological Analysis of Conservation Priorities in the Apache Highlands Ecoregion. TNC. 146 pp

The Apache Highlands ecoregion spans 30 million acres and portions of four states in two countries: Arizona and New Mexico in the U.S. and Sonora and Chihuahua in Mexico. It is bounded on the edge of the Colorado Plateau (the Mongolon Rim), to the west by the Sonoran and Mojave deserts, to the south by the Sierra Madre Occidental, and to the east by the Chihuahuan Desert. The region is best known for its Madrean forest "sky islands." Over 40 mountain ranges cloaked in pine-oak woodland and mixed conifer forests rise abruptly from surrounding basins of grassland and desert scrub to form forested islands. The ecological result of this geologic phenomena is an unusually rich fauna and flora whose evolutionary patterns continue to be influenced by different environmental conditions. Here, jaguar, and thick-billed parrots meet bighorn sheep and northern goshawks.

More than 4,000 vascular plants species occur in this region as do 110 mammal species, 468 bird species, and more than 240 butterfly species. The desert seas and grassland basins between the sky islands also harbor rare species like the black-tailed prairie dog and wide-ranging mammals like pronghorn. The juxtaposition in major biotic communities as one moves across landscape gradients has played a critical role in the evolution of the biodiversity and will continue to play a role in shaping the biodiversity of tomorrow. In contrast to the sky islands the regions grasslands occur primarily on private land and 37% were found to have undergone a permanent cover-type conversion to shrublands due to changes in grazing and fire.

In Arizona, this ecoregion contains 32% of the state's perennial stream sytems and the status of these freshwater resources in the single most important issue to the sustainability of biotic diversity and human communities

Figure 4.65: Apache Highlands: Geophysical Settings.

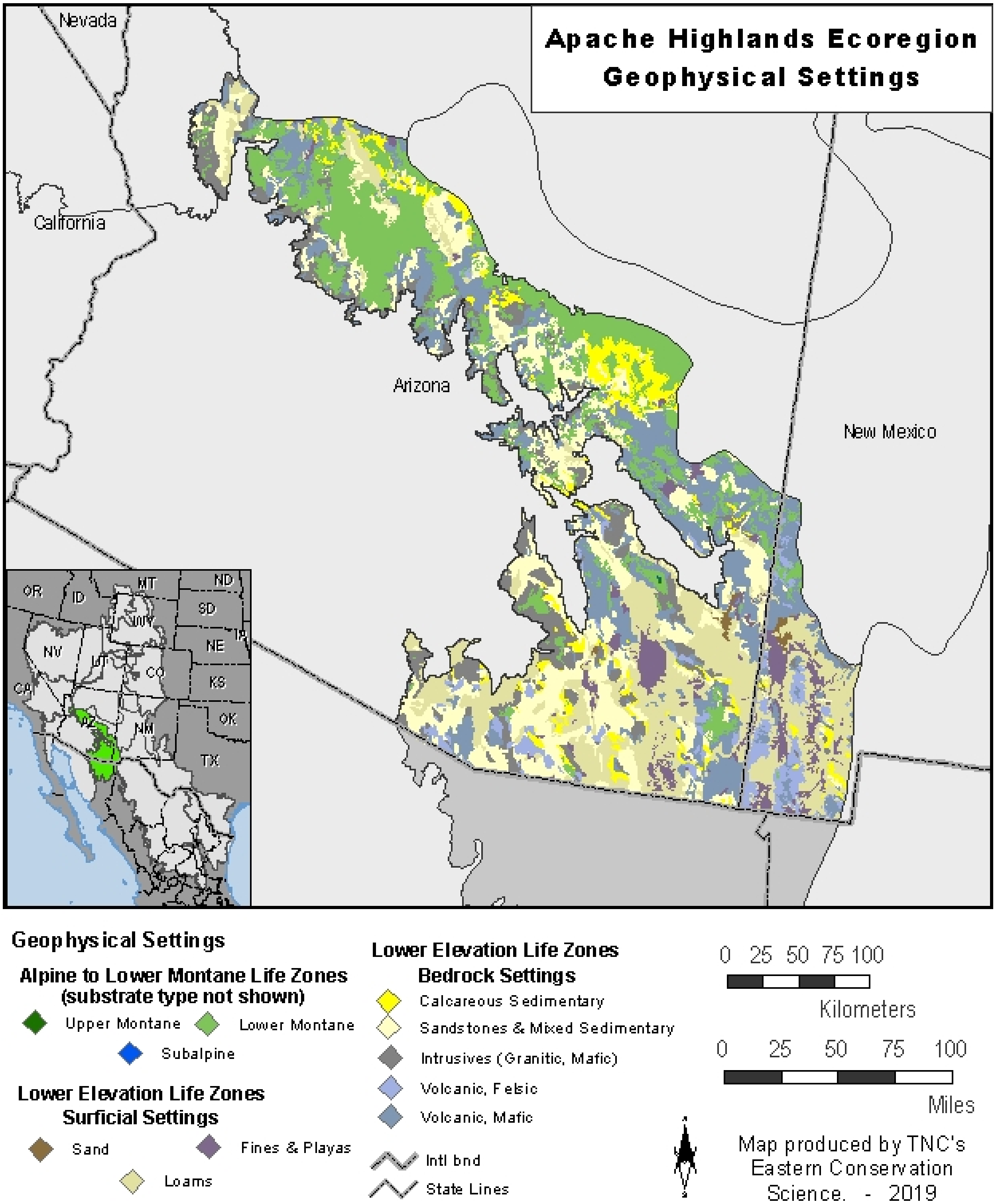


Figure 4.66: Apache Highlands: Landscape Diversity.

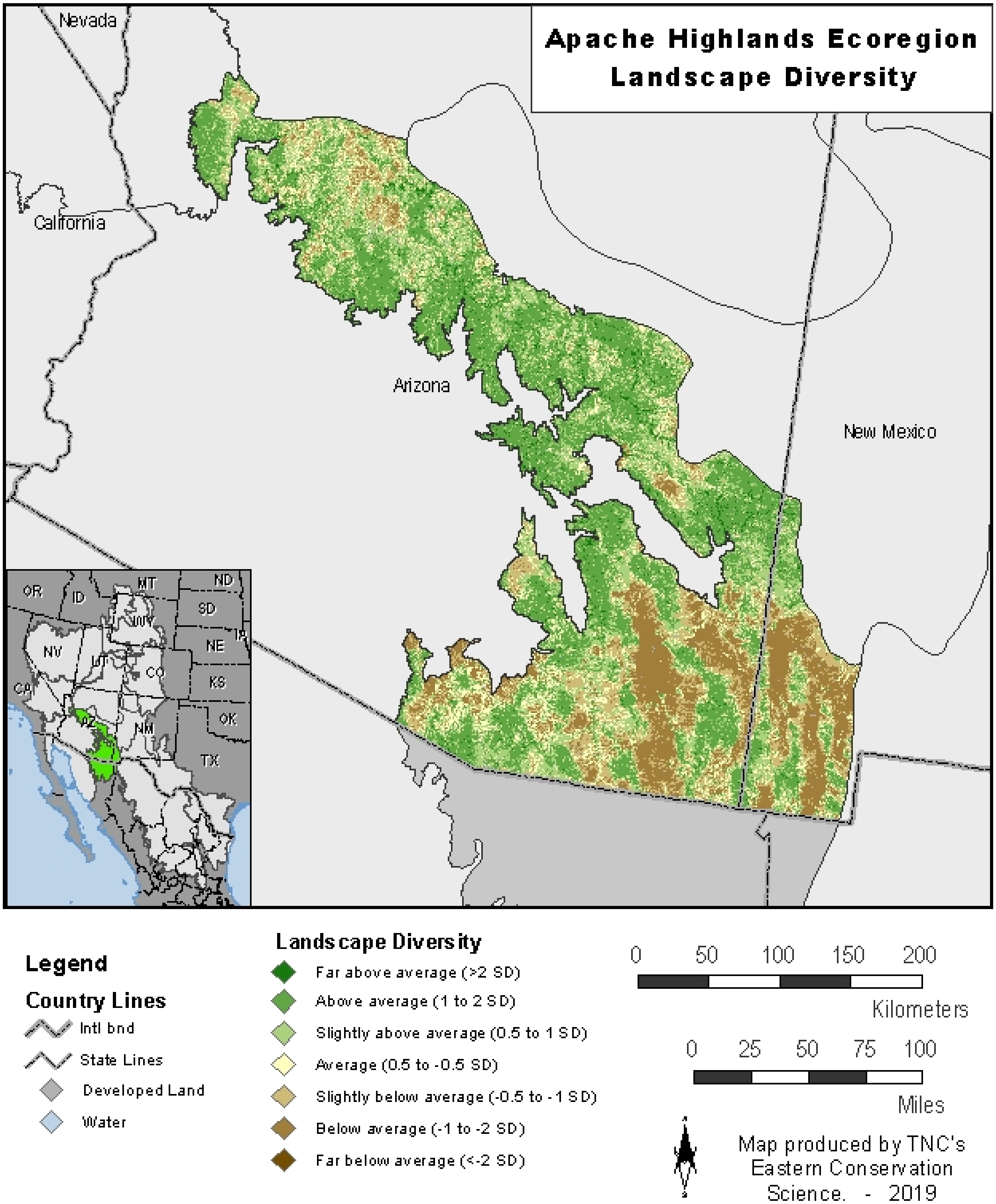


Figure 4.67: Apache Highlands: Local Connectedness

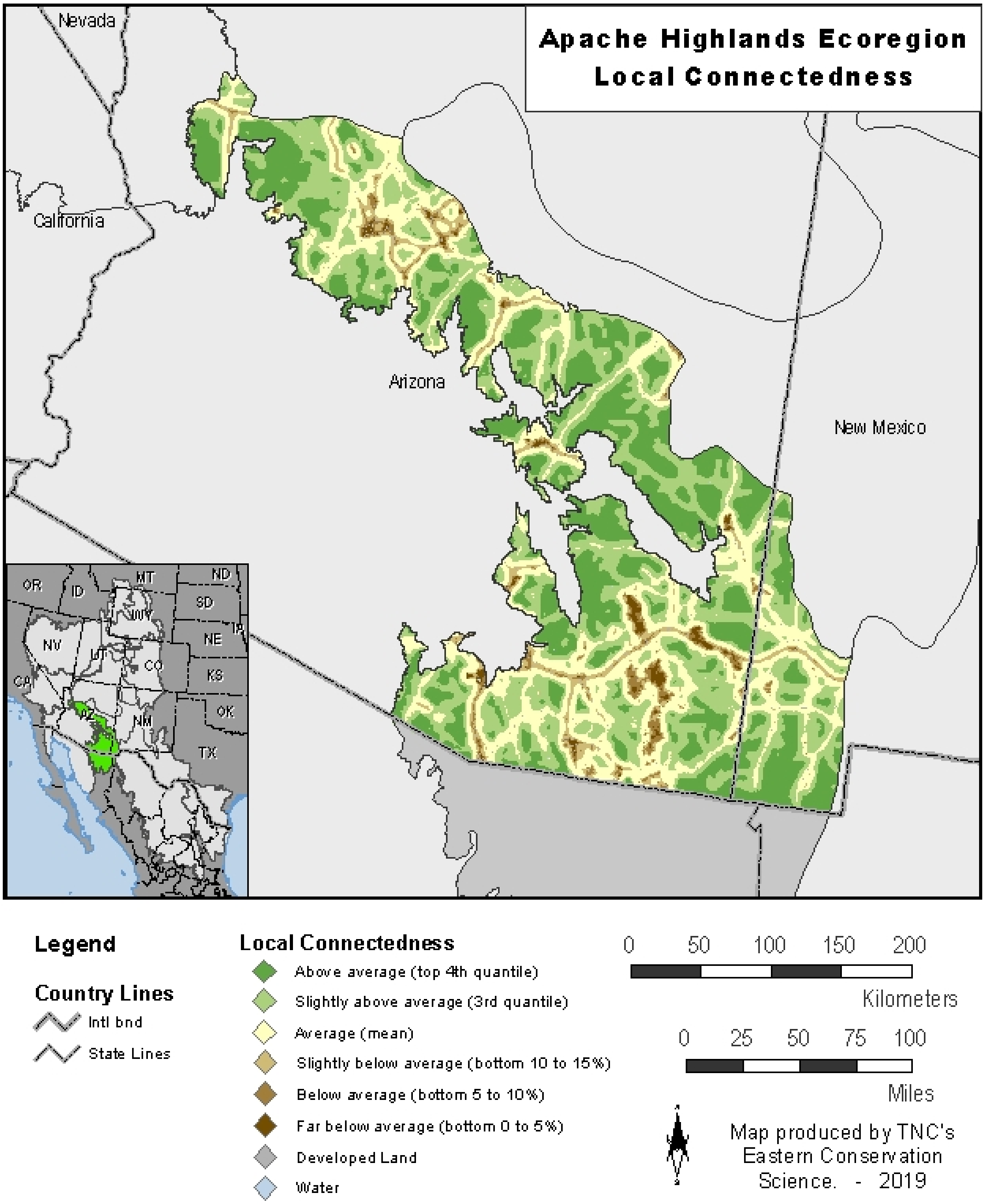


Figure 4.68: Apache Highlands: Site Resilience.

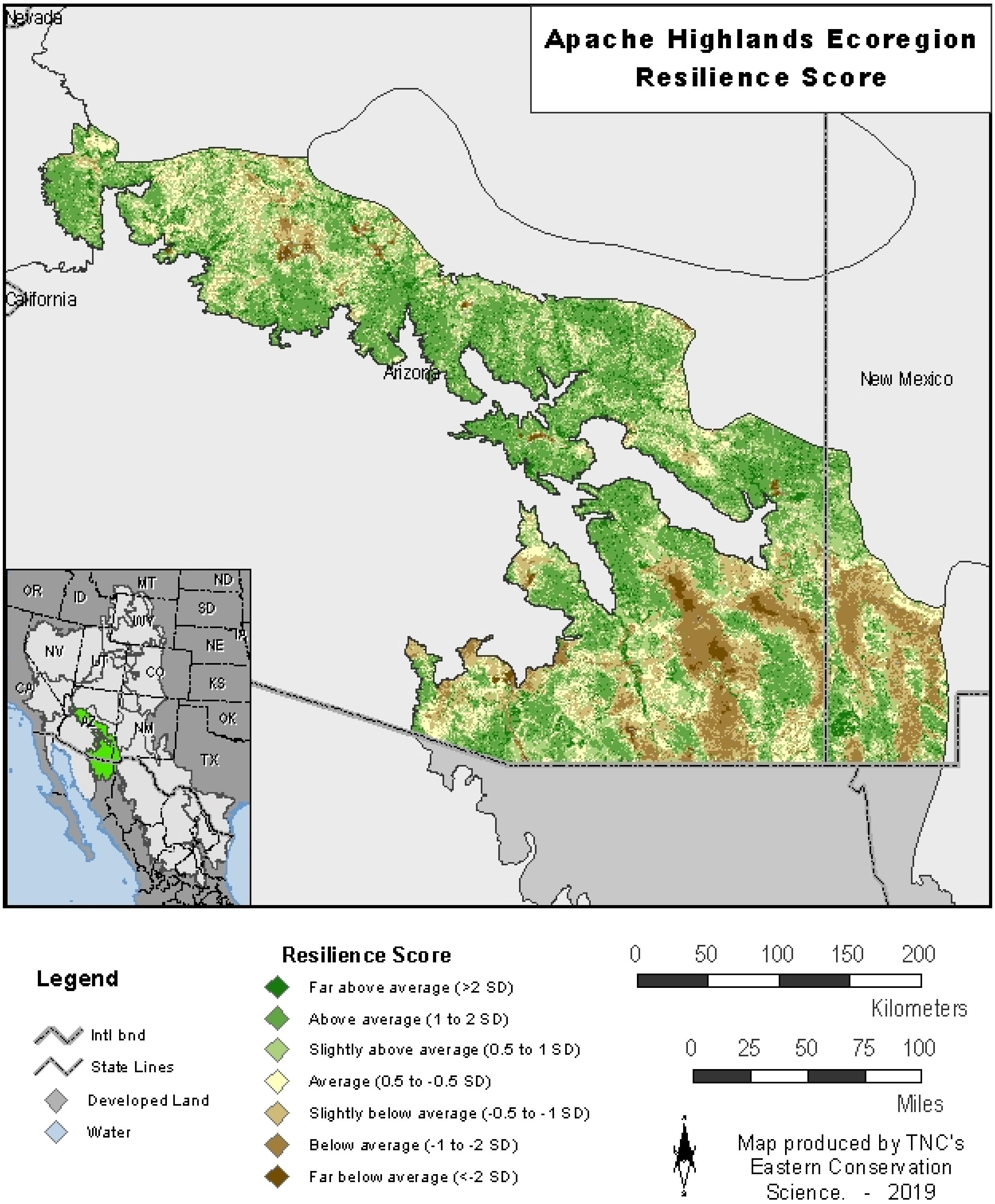


Figure 4.69: Resilient Areas for Each Geophysical Setting Within the Apache Highlands Ecoregion

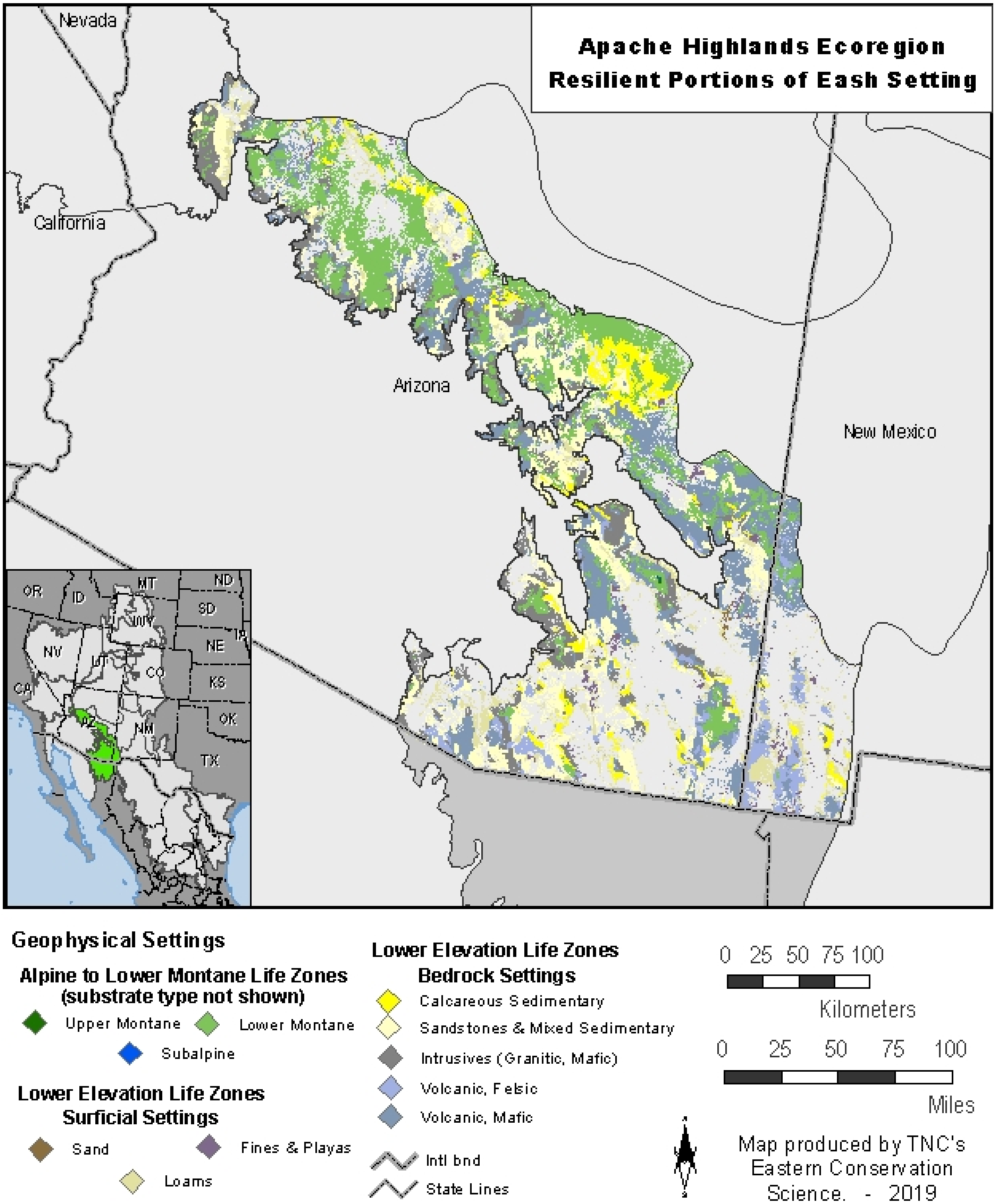
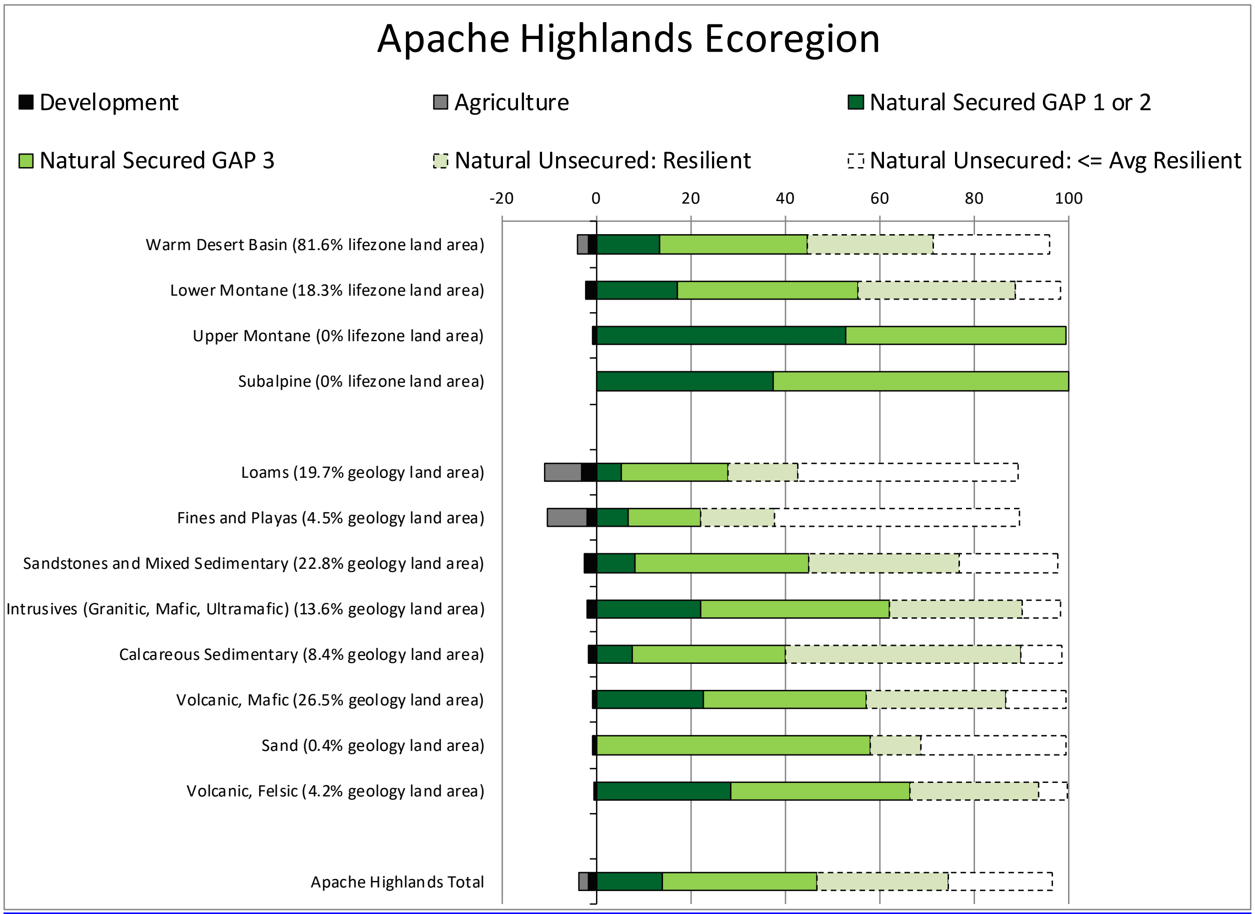


Figure 4.70: Conversion and Securement of the Apache Highlands Ecoregion by Geophysical Setting. This ecoregion covers 20.6 million acres and is 65% resilient. The ecoregion is 4% converted and 47% secured. Within this ecoregion, 28% of the land area (5.8 million acres) is resilient unsecured natural land.



Chihuahuan Desert

Photo credit: TNC

This ecoregion description was adapted from: Ecoregional Conservation Assessment of the Chihuahuan Desert, Second Edition, Revised July 2004. The Nature Conservancy.

The Chihuahuan Desert Ecoregion encompasses some 173 million acres occupying much of six Mexican states and significant areas of Texas and New Mexico. The area is characterized by the basins and ranges of the Mexican Plateau, surrounded by the foothills of the Sierra Madre Oriental on the east and the Sierra Madre Occidental on the west. While wetter than some North American desert areas, the Chihuahuan Desert experiences hot summers and cool, dry winters. The vegetation is typically grassland and desert scrub, with areas of chaparral and woodland in the mountains and narrow ribbons of riparian forest and scrub along stream channels and springs. With the notable exception of the Rio Grande and its tributaries, most river systems are within closed basins and many streams and springs are isolated.

There are at least 1,000 endemic plant taxa in the Chihuahuan Desert, an astonishing richness of biodiversity. The high desert area is a center for endemism of yuccas and cacti. The Sierra Madre Oriental is one of the oldest and richest centers of plant evolution on the continent. The dominant plant species throughout the desert is creosote bush but there are large areas of grama grasslands which serve as wintering grounds for Great Plains birds including declining species such as mountain plover, ferruginous hawk and Baird's sparrow. The region also supports more than 120 species of mammals, 300 species of birds, 110 species of fish, and more than 170 species of amphibians and reptiles with at least 18 species of the latter being are endemic.

The Chihuahuan Desert is a rather recent phenomenon – as recently as 9,000 years ago this area was more mesic and dominated by coniferous woodland. Like other areas of the Southwest it has been subject to a long history of grazing by domestic livestock.

Figure 4.71: Chihuahuan Desert: Geophysical Settings.

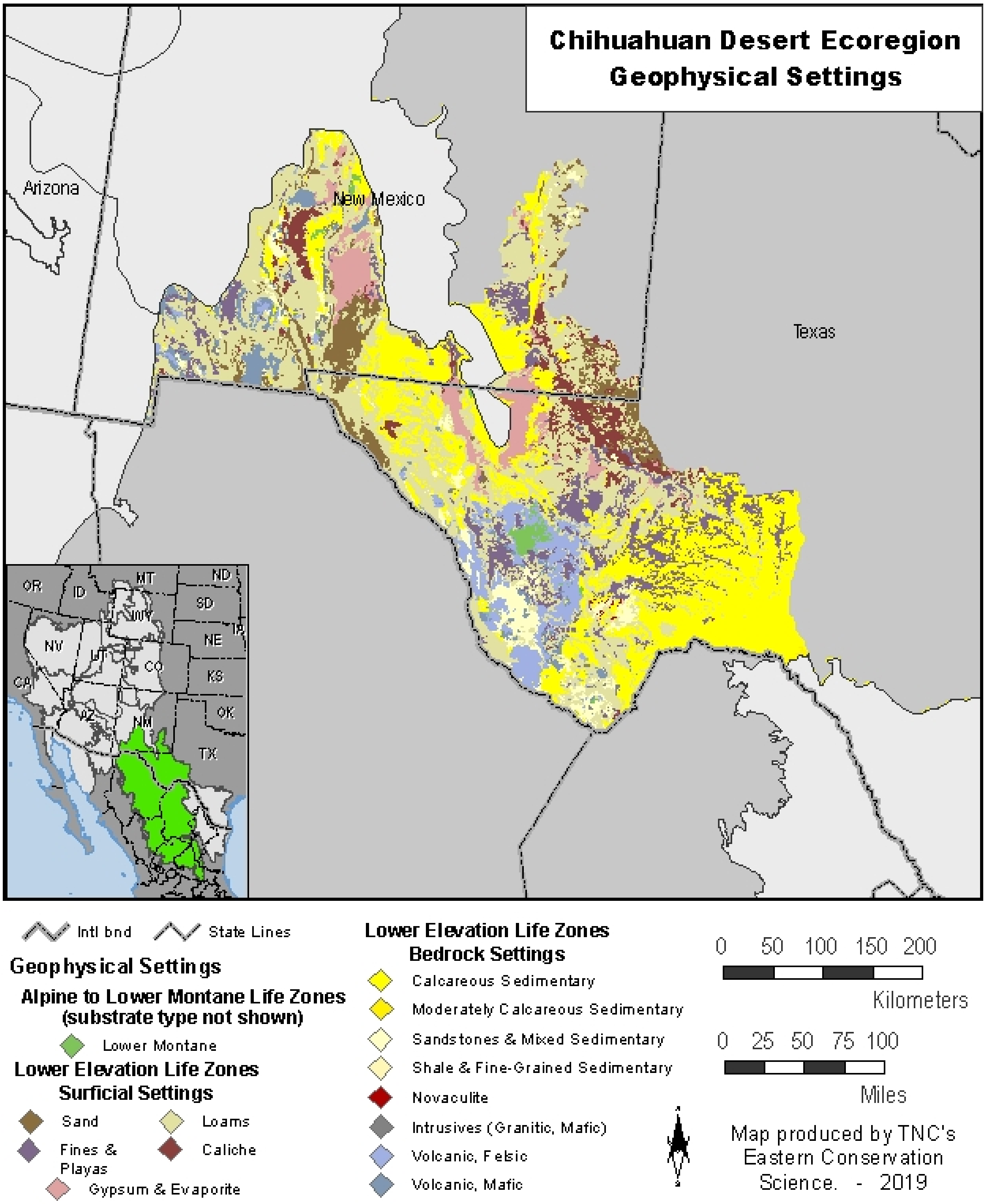


Figure 4.72: Chihuahuan Desert: Landscape Diversity.

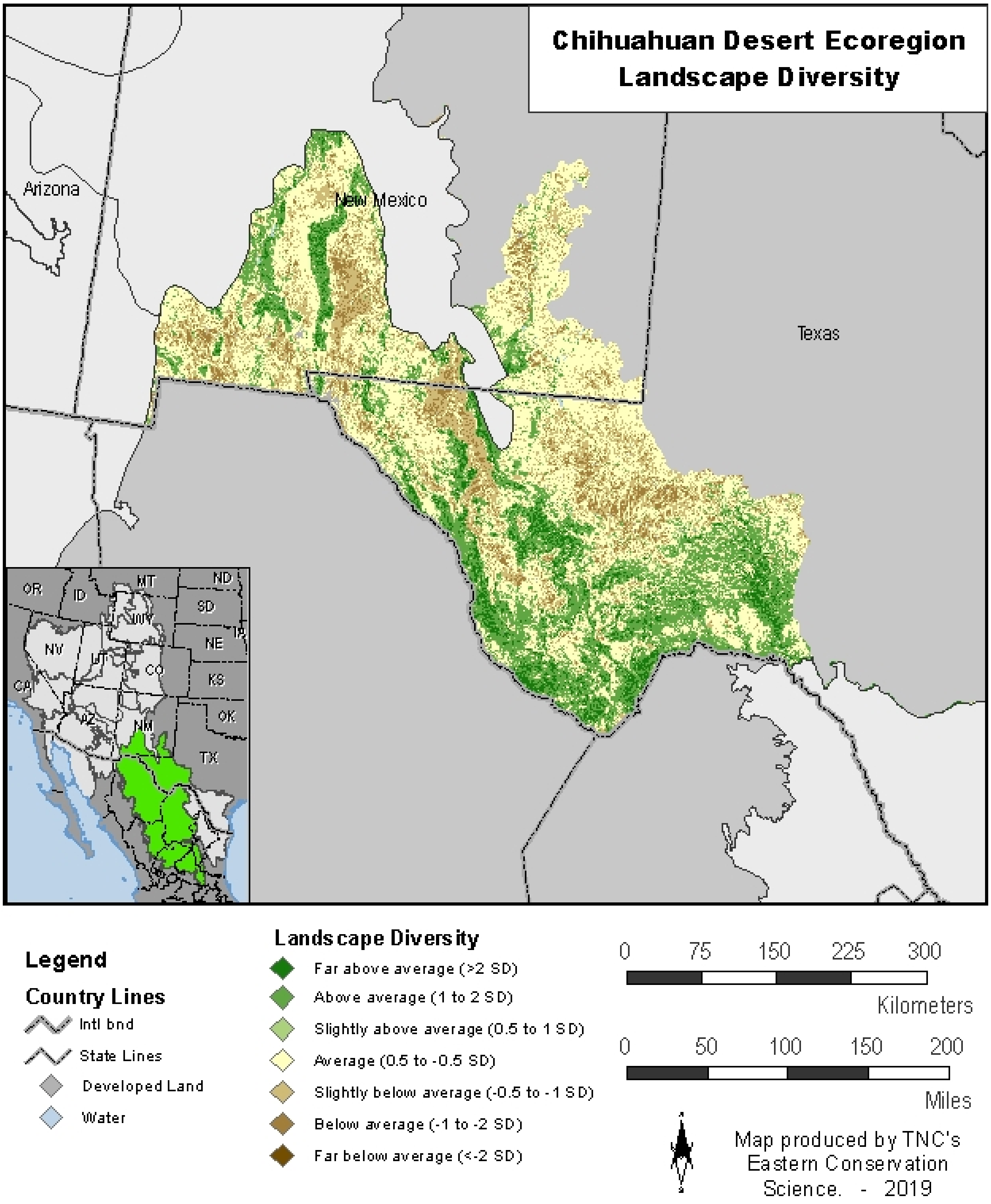


Figure 4.73: Chihuahuan Desert: Local Connectedness

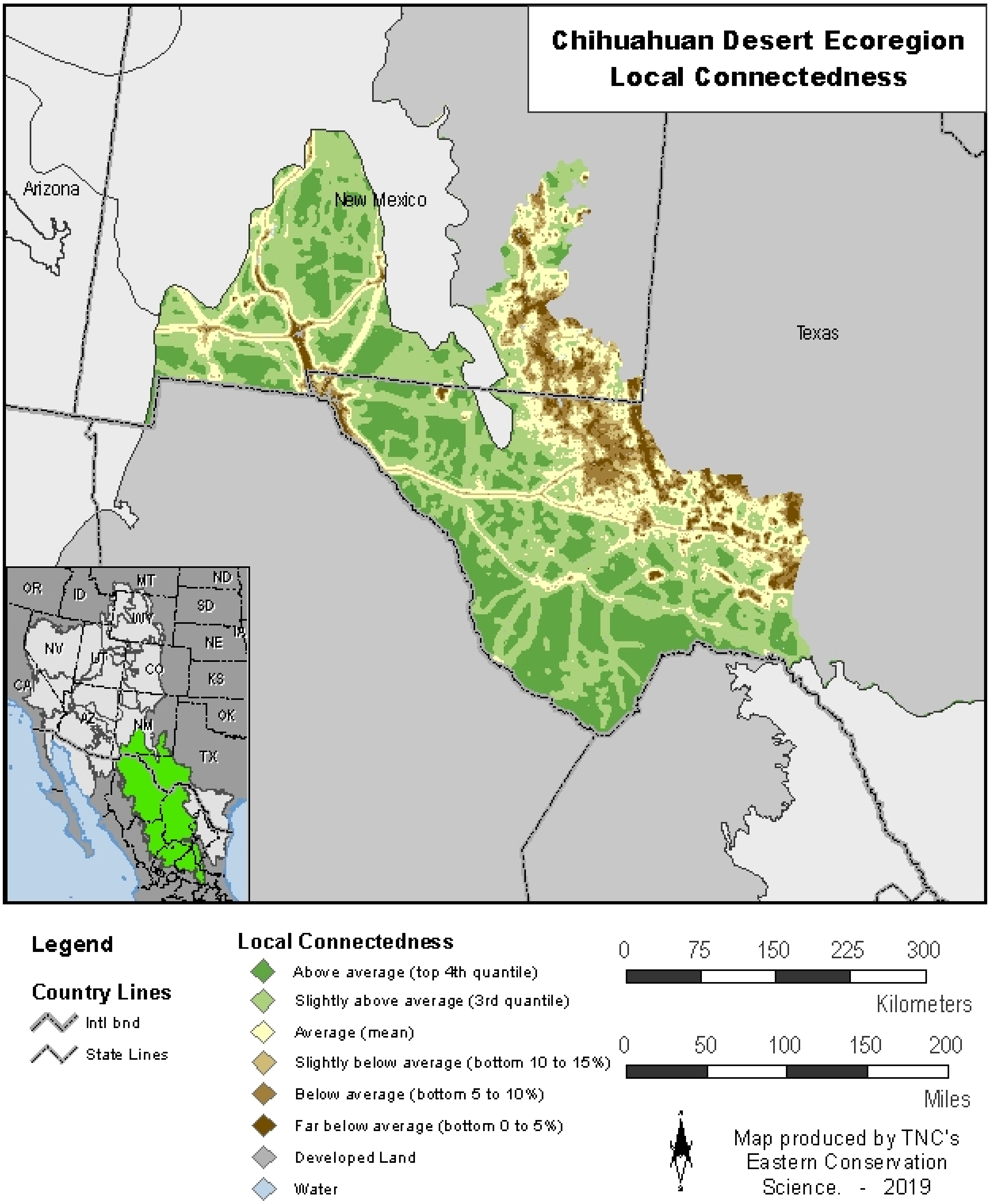


Figure 4.74: Chihuahuan Desert: Site Resilience.

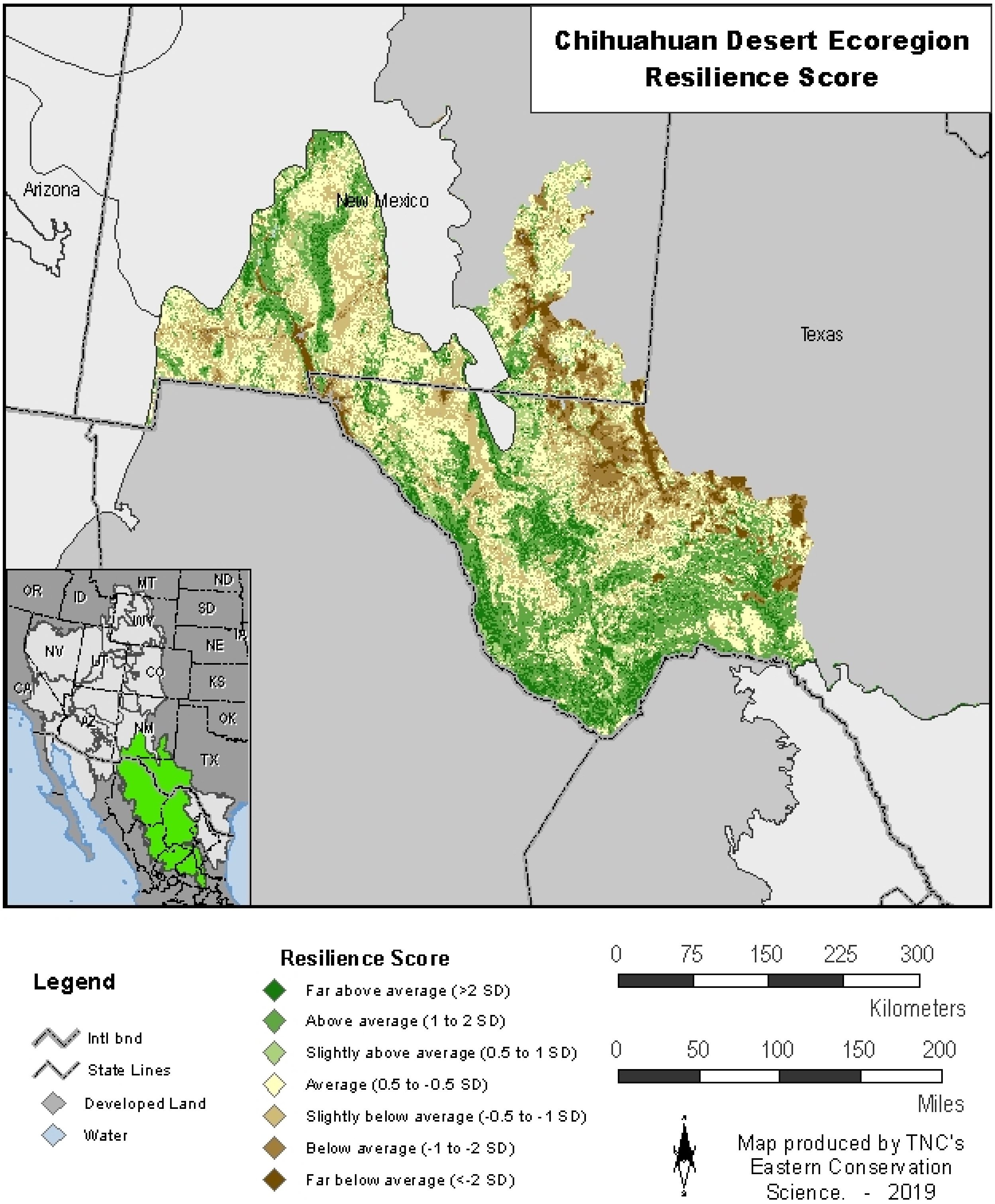


Figure 4.75: Resilient Areas for Each Geophysical Setting Within the Chihuahuan Desert Ecoregion.

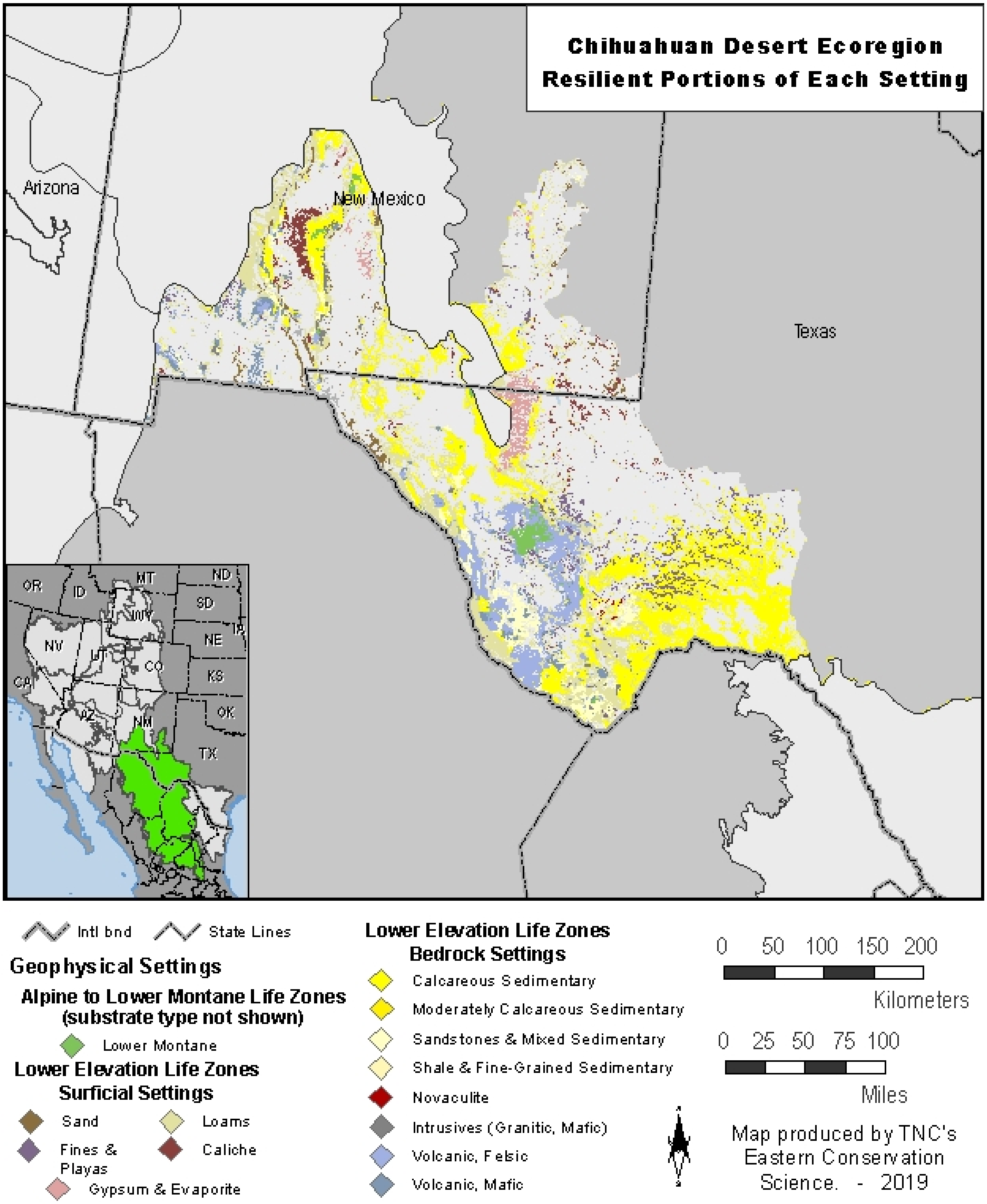
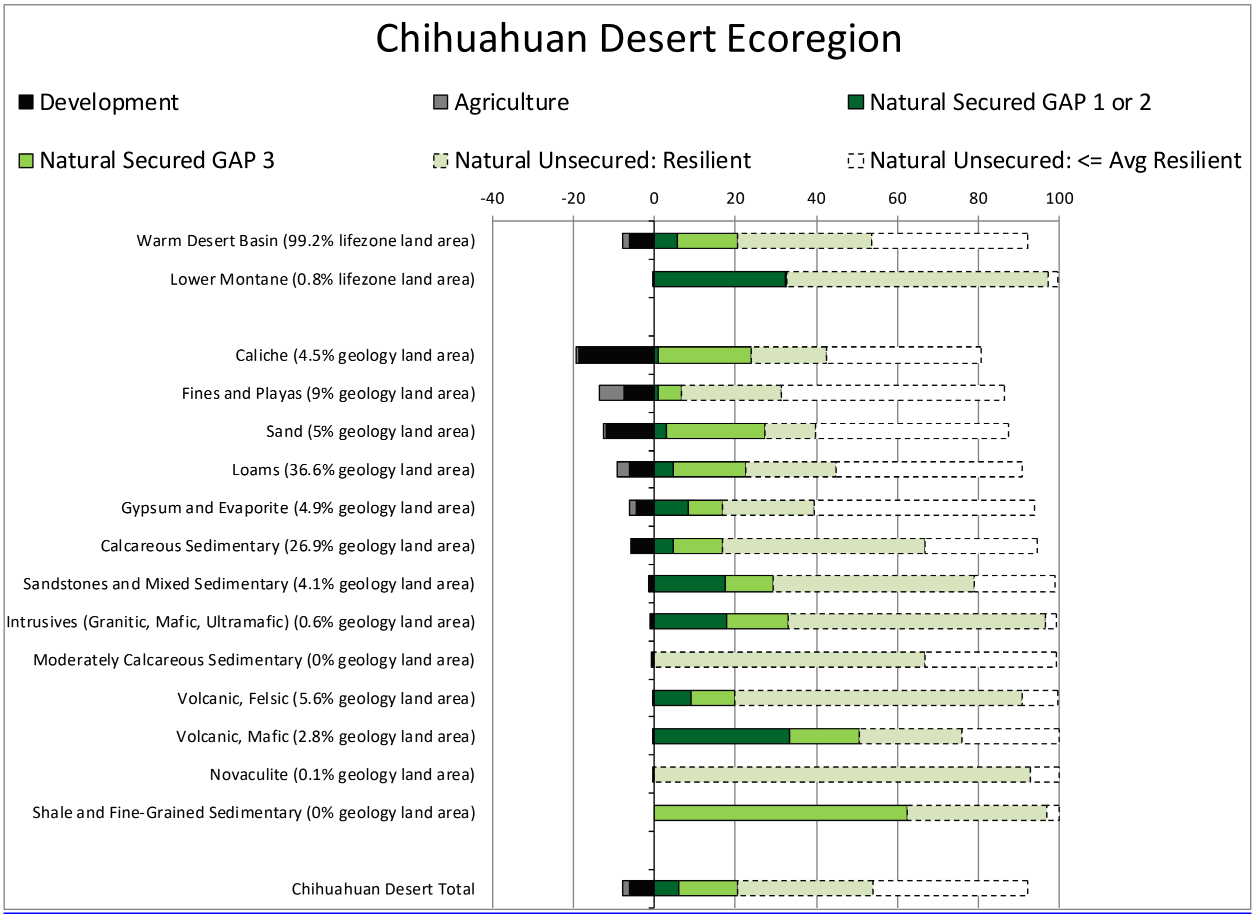


Figure 4.76: Conversion and Securement of the Chihuahan Desert Ecoregion by Geophysical Setting. This ecoregion covers 38.6 million acres and is 44% resilient. The ecoregion is 8% converted and 21% secured. Within this ecoregion, 34% of the land area (13 million acres) is resilient unsecured natural land.



This ecoregion description was adapted from A Conservation Blueprint for the Tamaulipan Thornscrub Ecoregion (TNC 2010) and World Wildlife Fund Terrestrial Ecoregions of the World https://www.worldwildlife.org/ecoregions/na1312.

The Tamaulipan Thornscrub ecoregion begins in the eastern part of the Coahuila State, in Mexico at the base of the Sierra Madre Oriental, and then proceeds eastward to encompass the northern half of the state of Tamaulipas, and into the U.S. through the south western side of Texas. Elevation increases northwesterly from sea level near the Gulf Coast to a base of about 1,000 ft (300 m) near the northern boundary of the ecoregion, from which a few hills or mountains protrude. The Rio Grande flows through this ecoregion and once formed a broad and meandering waterway that produced numerous resacas or oxbows within its floodplain, and an extensive marshy environment at its mouth.

The native vegetation type covering much of this ecoregion is mesquite-grassland. The Tamaulipan thornscrub, a subtropical, semi-arid vegetation type, occurs on either side of the Rio Grande. Spiny shrubs and trees dominate, but grasses, forbs, and succulents are also prominent. The slightly higher, drier, and rockier sites originally had vegetation of chaparral and cacti, whereas the flat, deep soils supported mesquite as well as taller brush and a few drought-resistant trees. The South Texas Sand Plain portion of this ecoregion is characterized by honey mesquite and escarpment live oak along with many shrub and grass species that range father east and north. The communities of this ecoregion support animal species such as ocelot, jaguarundi, reddish egret, Texas indigo snake, and over 400 species of birds (USFWS 1993).

Clearing and conversion of shrubland for agriculture has had the greatest impact on altering the patterns and processes of the landscape of this ecoregion.

Figure 4.77: Tamalulipan Thornscrub: Geophysical Settings.

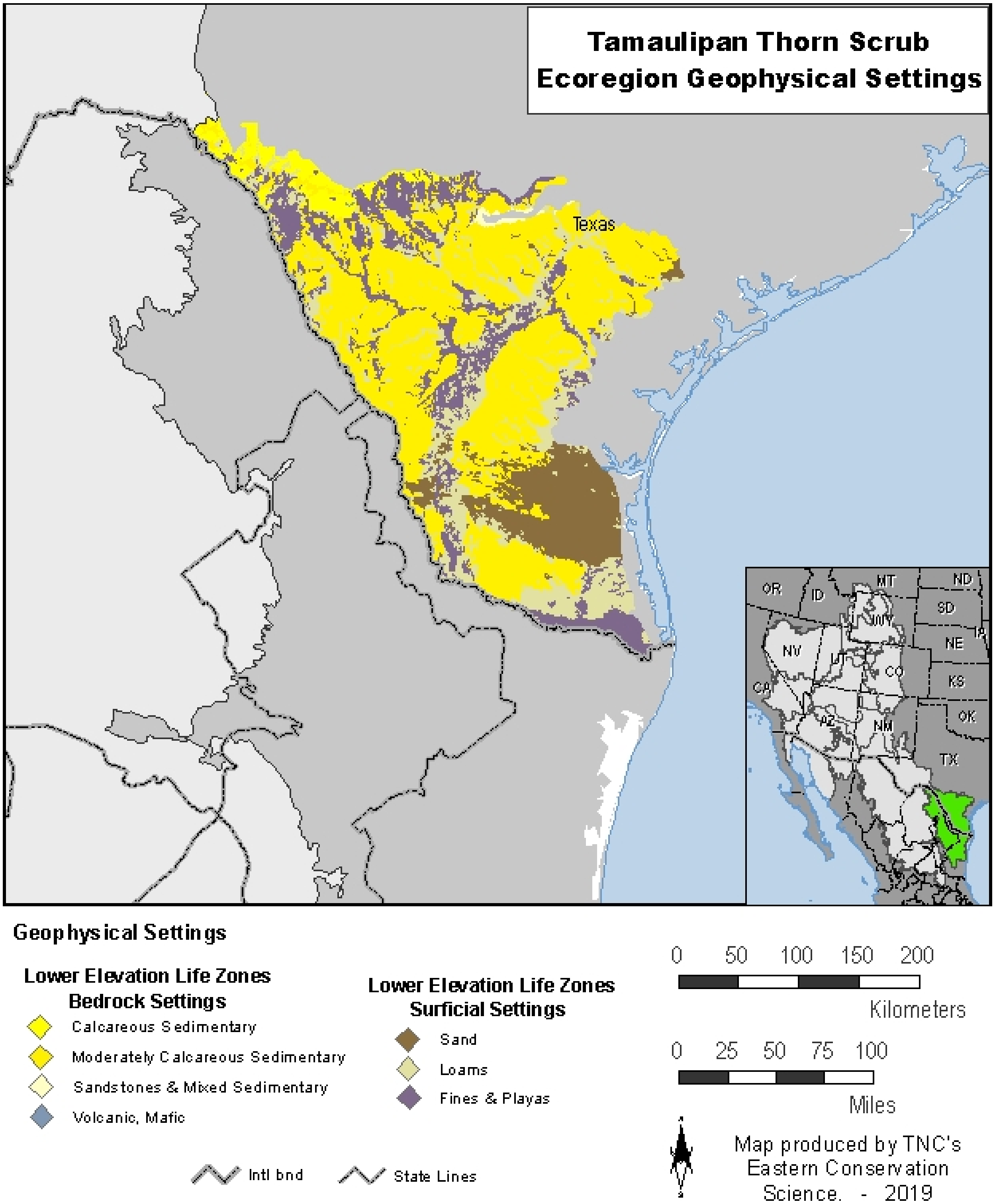


Figure 4.78: Tamaulipan Thornscrub: Landscape Diversity.

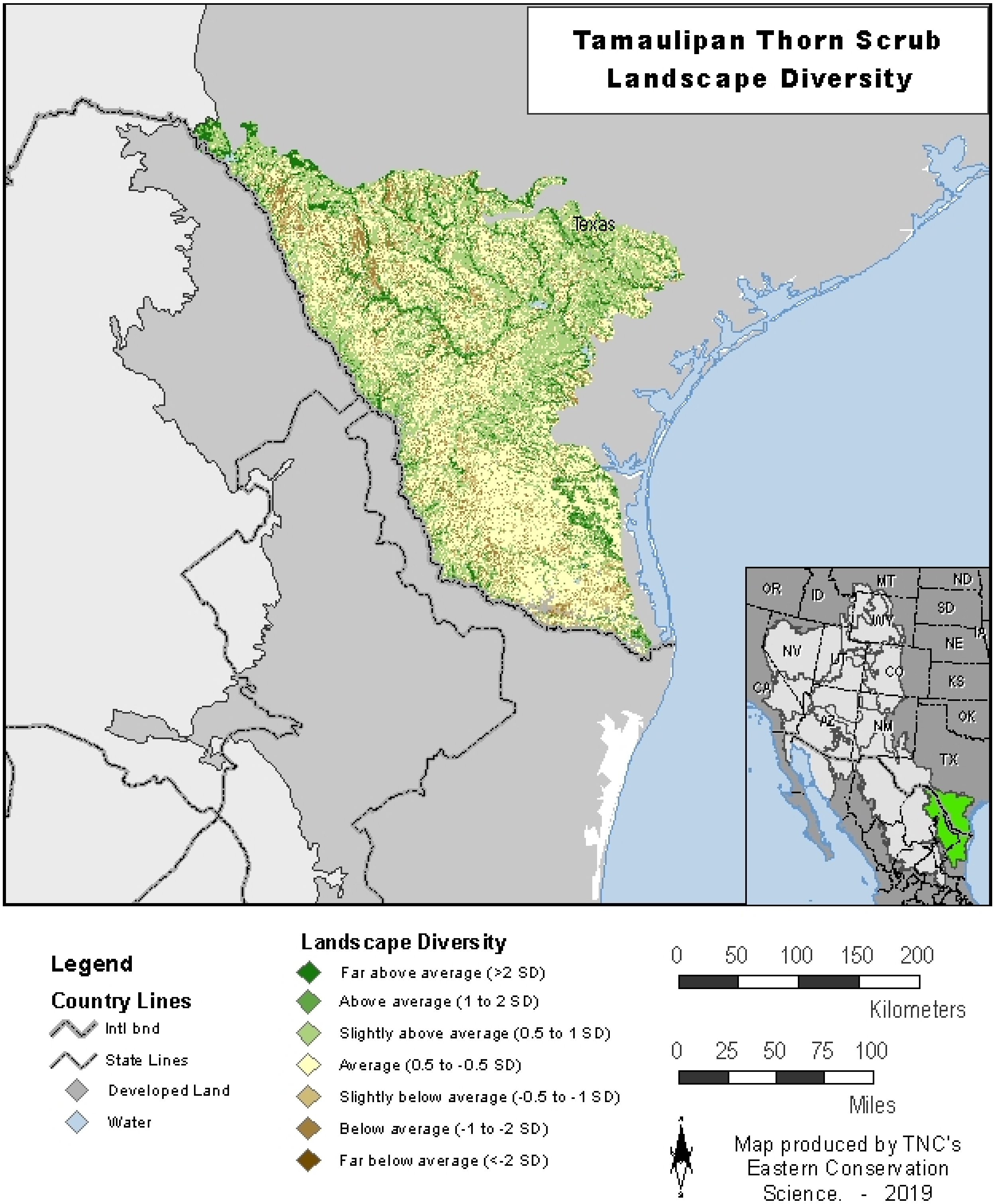


Figure 4.79: Tamaulipan Thornscrub: Local Connectedness.

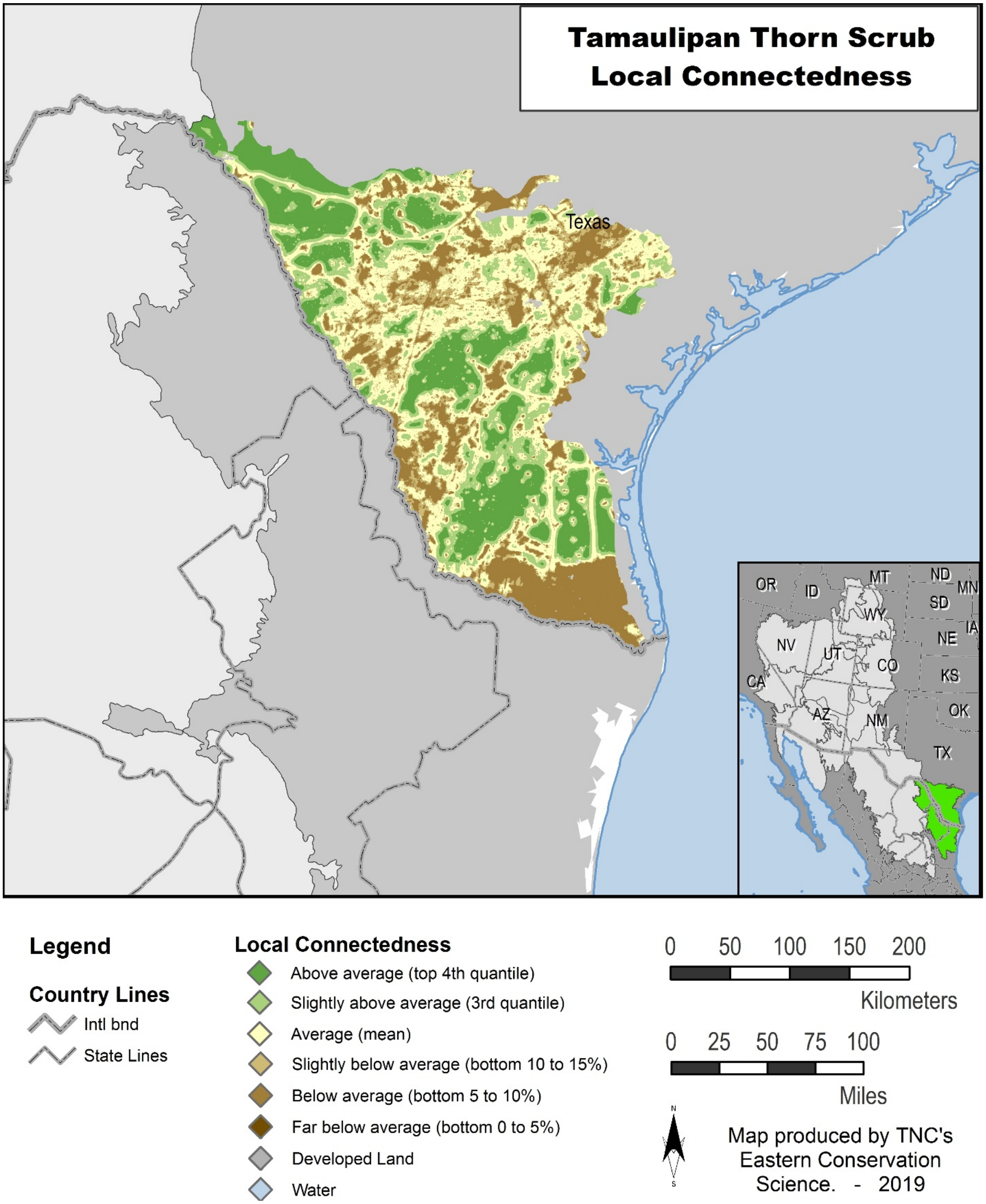


Figure 4.80: Tamaulipan Thornscrub: Site Resilience.

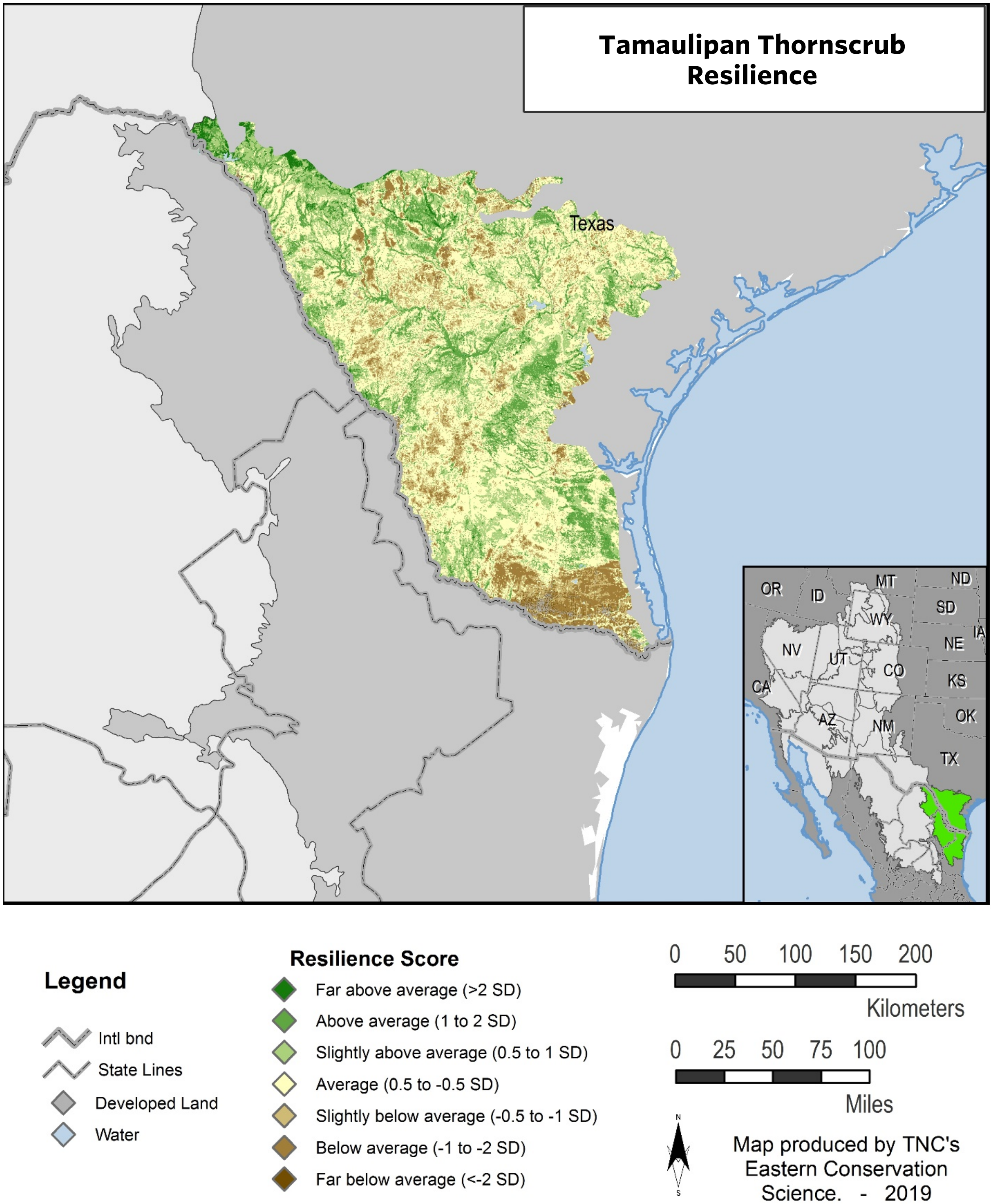


Figure 4.81: Resilient Areas for Each Geophysical Setting Within the Tamaulipan Thornscub Ecoregion.

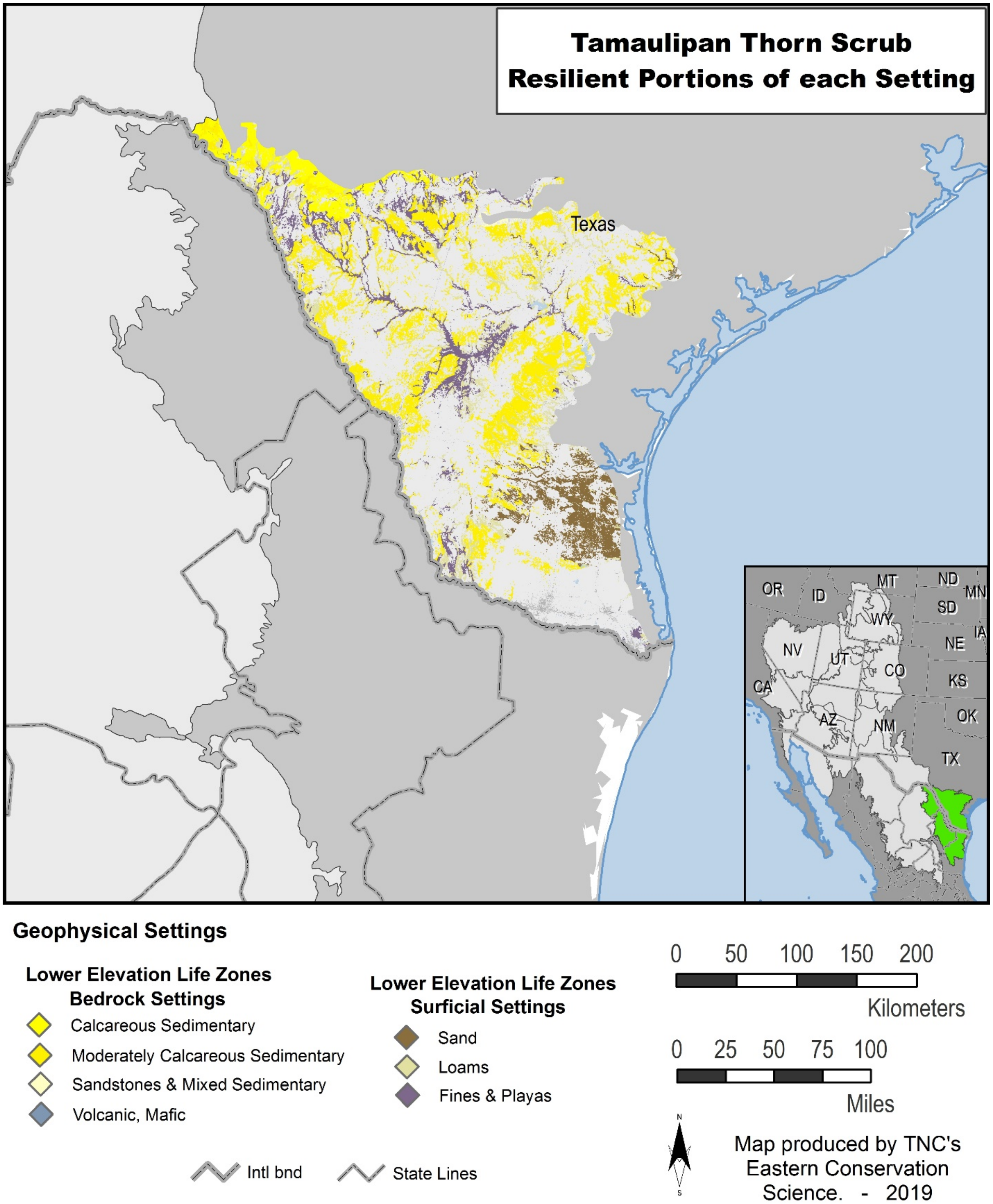
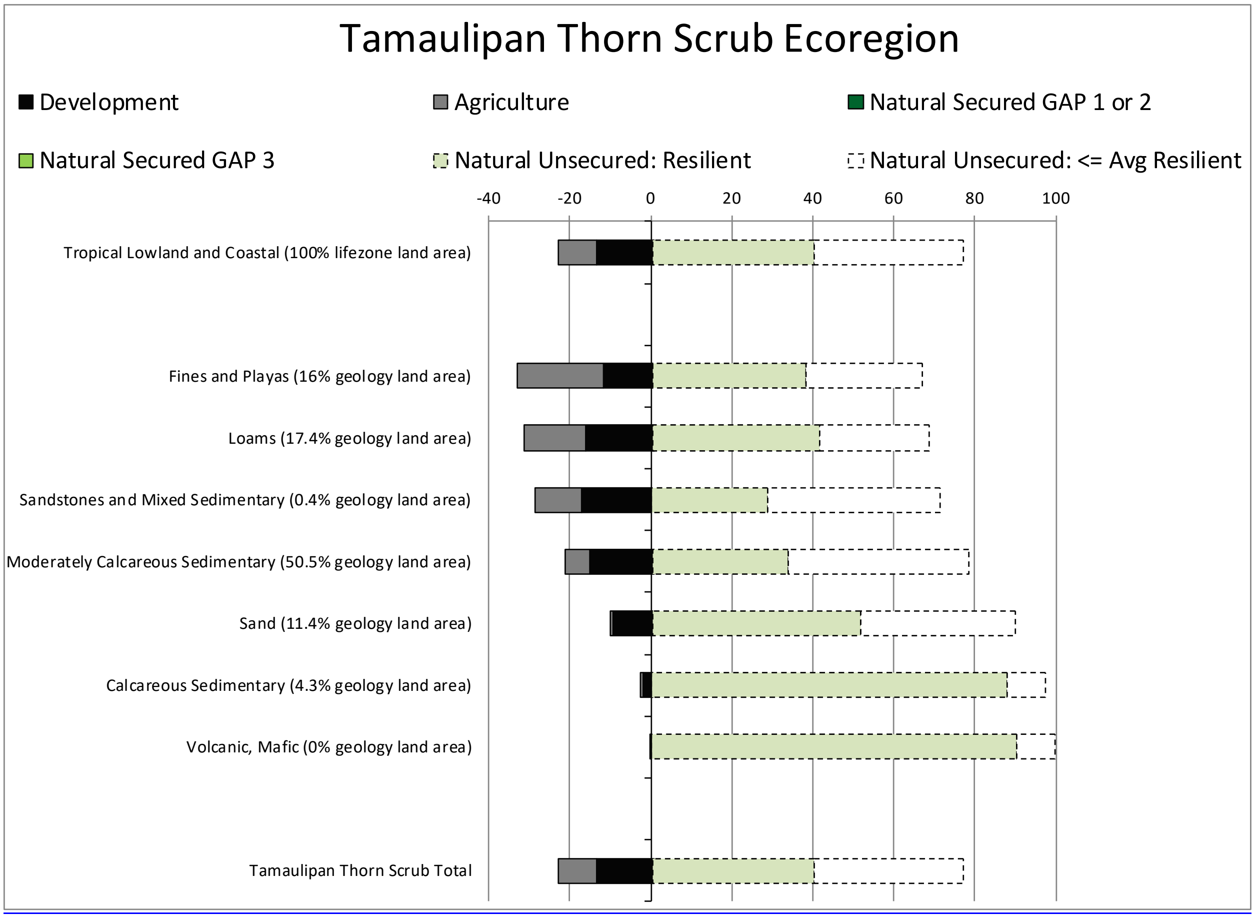


Figure 4.82: Conversion and Securement of the Tamaulipan Thorn Scrub Ecoregion by Geophysical Setting. This ecoregion covers 19.6 million acres and 37% resilient The ecoregion is 23% converted and 0.4% secured. Within this ecoregion, 37% of the land (7.3 million acres) is resilient unsecured natural land.



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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 study area 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 (ecoregion and geophysical setting); second, we examine the extent to which each geophysical setting is currently conserved within the Rocky Mountain and Southwest Desert 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 in the Rocky Mountain and Southwest Desert region, mountains and deserts. This brief section is intended to help frame application of these datasets, especially prior to the development of the large-scale connectivity (flow zones) and confirmed diversity information that will be used to develop a "resilient network".

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 (Figures 5.1 and 5.2). The final resilience map (Fig 5.2, Table 5.1) places 54% or just over 218 million acres in the above average resilience category. Of this land, 150 million acres or 37% of the region is greater than 1 SD above average. 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 Tamaulipan Thornscrub, is not equivalent in an absolute sense to a resilience score of 2 SD in the more intact Utah High Plateau, 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 high granitic mountains of the Rockies, 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 Sonoran Desert, or the calcareous substrate of that underlie the Tamaulipan Thornscrub. 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 Category	Acres	Percent
Far above average (> 2 SD)	28,412,817	7%
Above average (1 to 2 SD)	121,553,169	30%
Slightly above average (0.5 SD to 1 SD)	68,042,262	17%
Average (0.5 SD to -0.5 SD)	93,440,962	23%
Slightly below average (-0.5 SD to -1 SD)	48,733,954	12%
Below average (-1 SD to -2 SD)	26,130,547	7%
Far below average (<-2 SD	9,837,810	2%
Developed	2,167,342	1%
Water	2,611,420	1%
Grand Total	400,930,282	100%

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

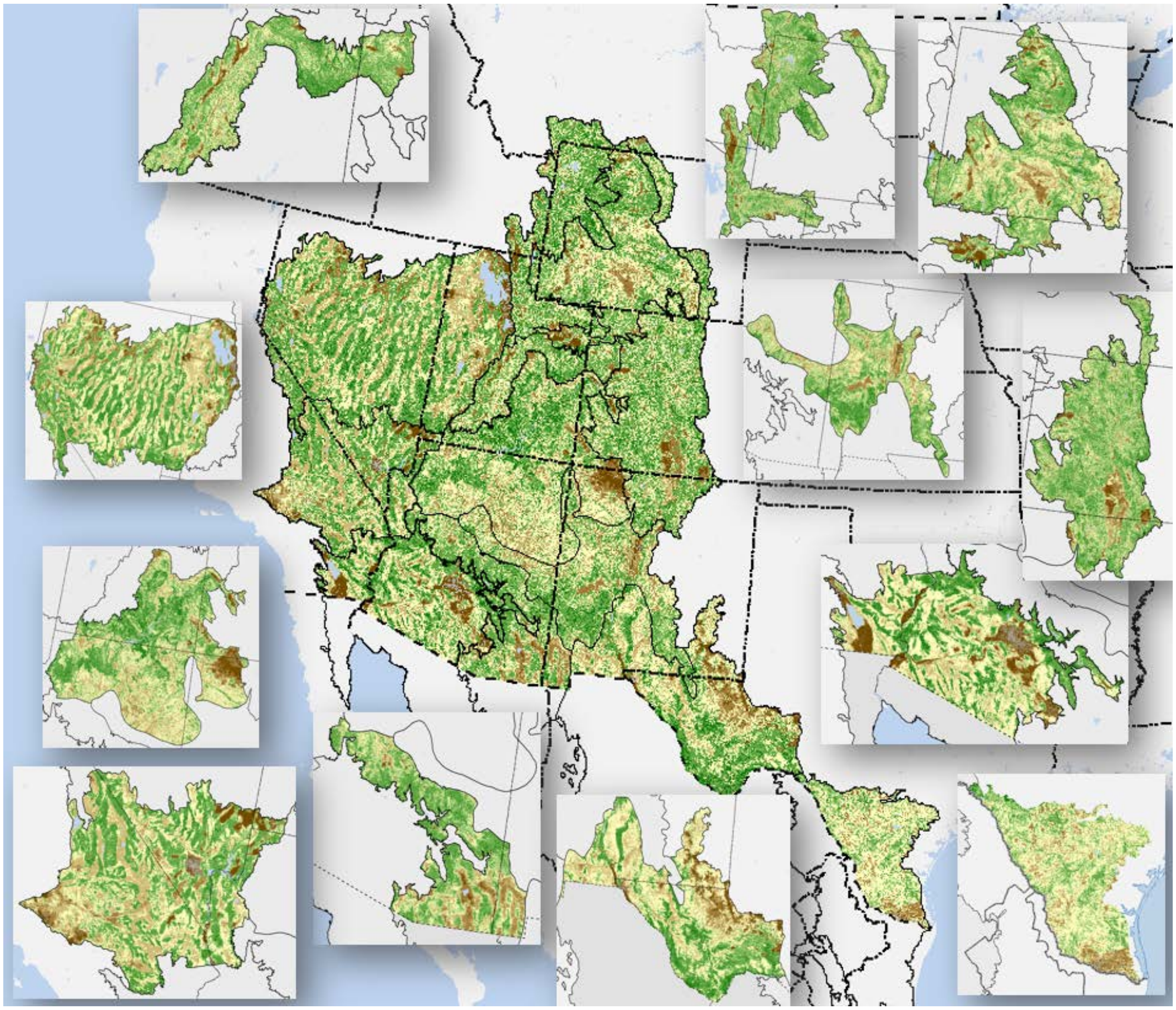
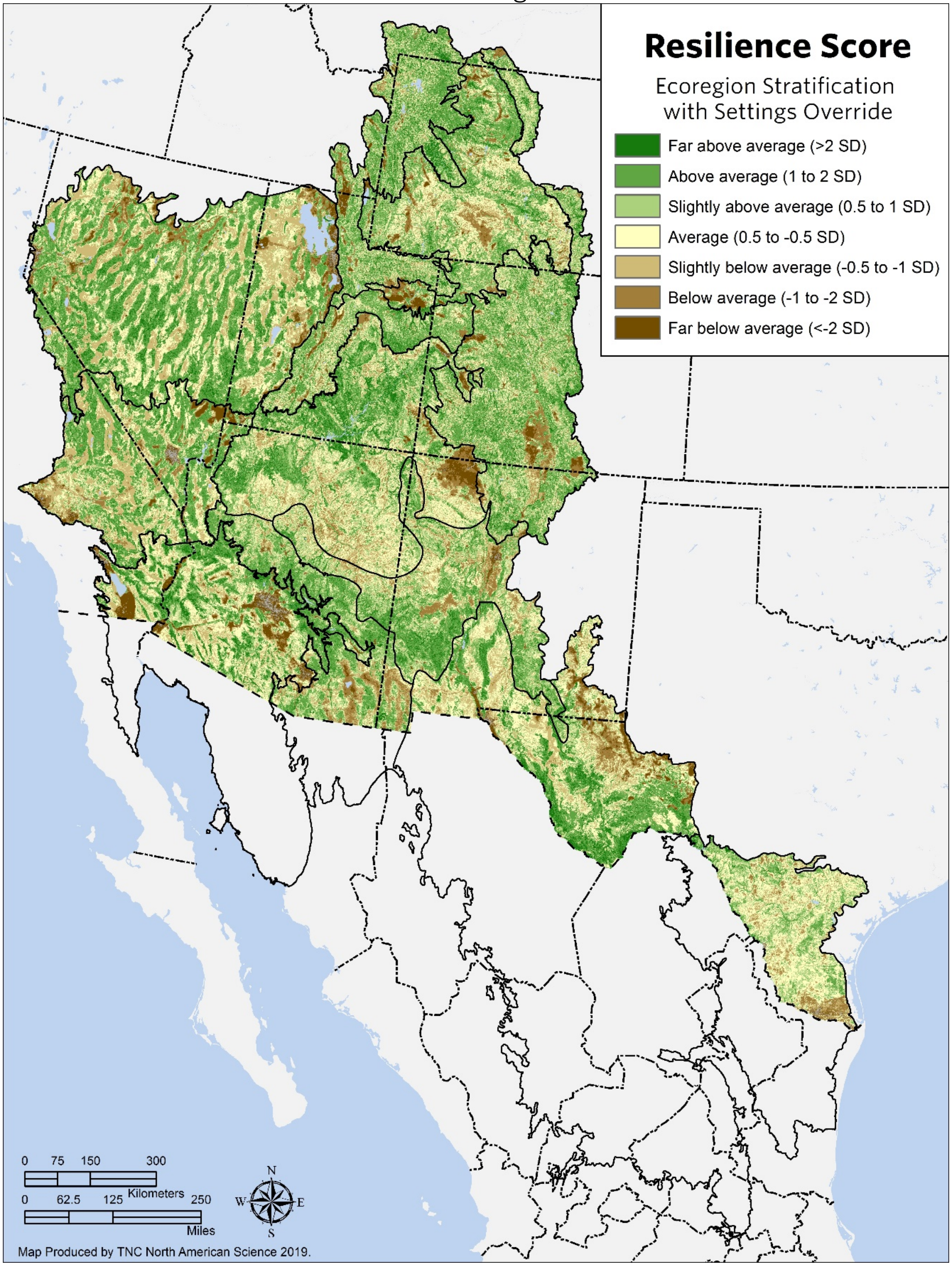


Figure 5.2: Final Regional Site Resilience Map. Areas in green score above average and are estimated to be more resilient to climate change relative to comparable geophysical settings in the same ecoregion. Areas in brown are below average and are considered more vulnerable to climate change.



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 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 Ecoregion only (Figure 5.3). This map shows the resilience scores for each ecoregion, displaying the score without the influence of the geophysical settings (life zones or geology). In most ecoregions, the highest-scoring areas are high elevation or bedrock settings, as they typically have more topographic variation and are less fragmented than low elevation and deep soil settings.

Site resilience relative to Geophysical Setting (Figure 5.4). This map shows the resilience scores for each geophysical setting within each ecoregion. This is the map that we use to correct bias in the Ecoregion map by adding in the most resilient areas for each geophysical setting (defined as >0.5 SD relative to the setting). The ecoregion cell score was overridden by the geophysical setting score if the latter is both greater and above 0.5 SDs. This adds-in areas that are the best options for resilience for every type of setting, even if some of them score lower than the ecoregion average

Resilience at Multiple Scales (Figure 5.5). This map shows the highest scoring sites across all three combinations— ecoregion, setting, and both. Cells that score high for both identify sites that are resilient from both perspectives.

Figure 5.3: Site Resilience Relative to Ecoregion only.

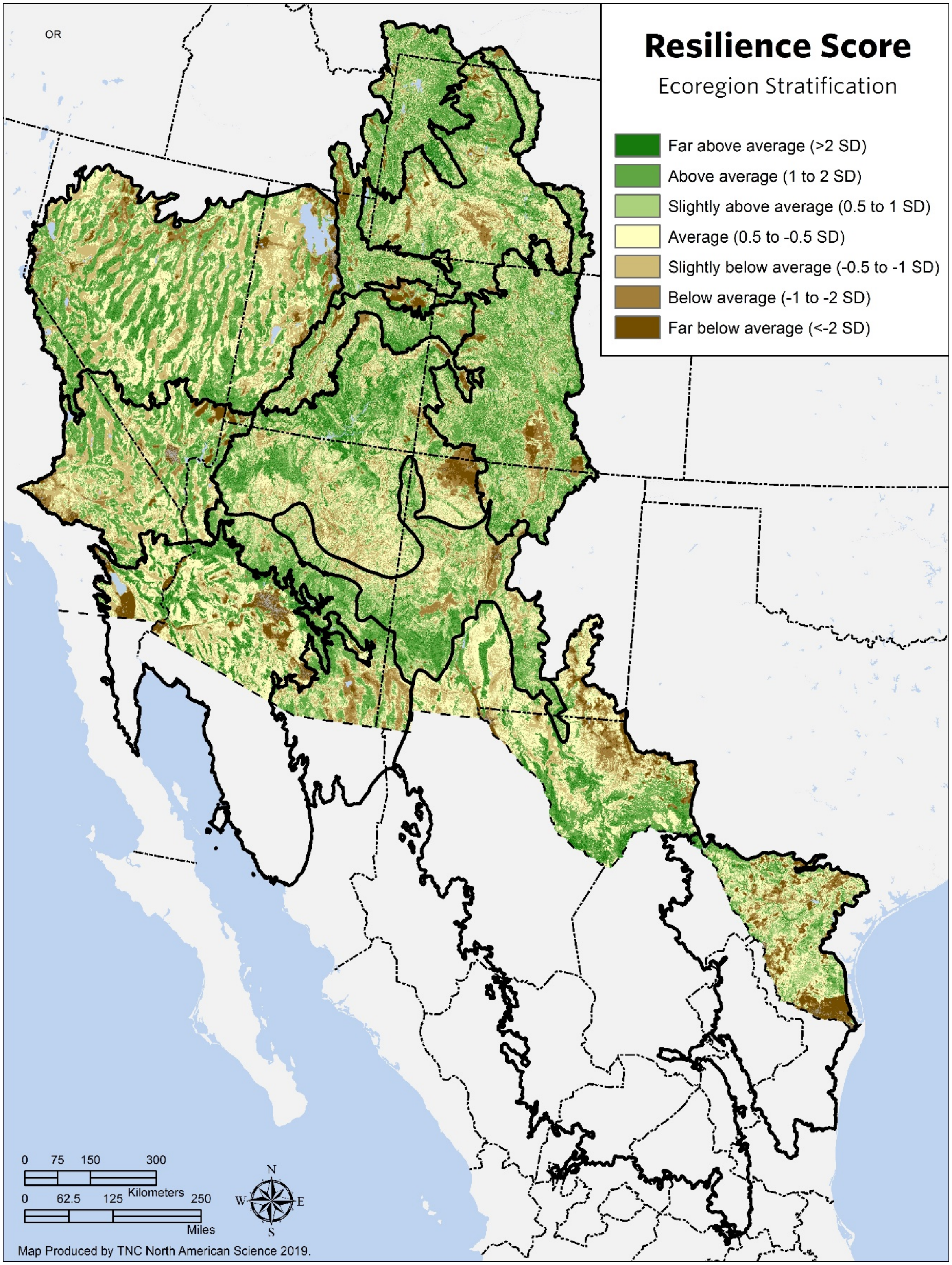


Figure 5.4: Site Resilience Relative to Setting within Ecoregion.

Figure 5.5: Site Resilience at Multiple Scales. This map shows the above average (>0.5 SD) scoring sites across all two scales—ecoregion and setting—in all combinations.

Methods for Creating the Final 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 each geophysical setting. This map was created using two grids, one stratified by ecoregion (map 5.4) and one stratified by setting (map 5.5).

First, we created a grid of the resilience values stratified be ecoregion (see chapter 3). Before combining the landscape diversity and local connectedness scores they were transformed to Z-scores (landscape diversity) or approximate Z-scores adjusted for skew (local connectedness) so they would have equal influence on the result. Because so much of the region had very high local connectedness (i.e., distribution was left-skewed with mean of 82%), local connectedness had the largest effect on the resilience score in places where the landscape was fragmented. Where the local connectedness was average, the ecoregional resilience score was equal to the landscape diversity score. Where local connectedness was above average it bumped the score up by a maximum of 0.25 SDs. Essentially, in the widespread and unfragmented portion of the ecoregions the resilience patterns between two sites reflected their landscape diversity values.

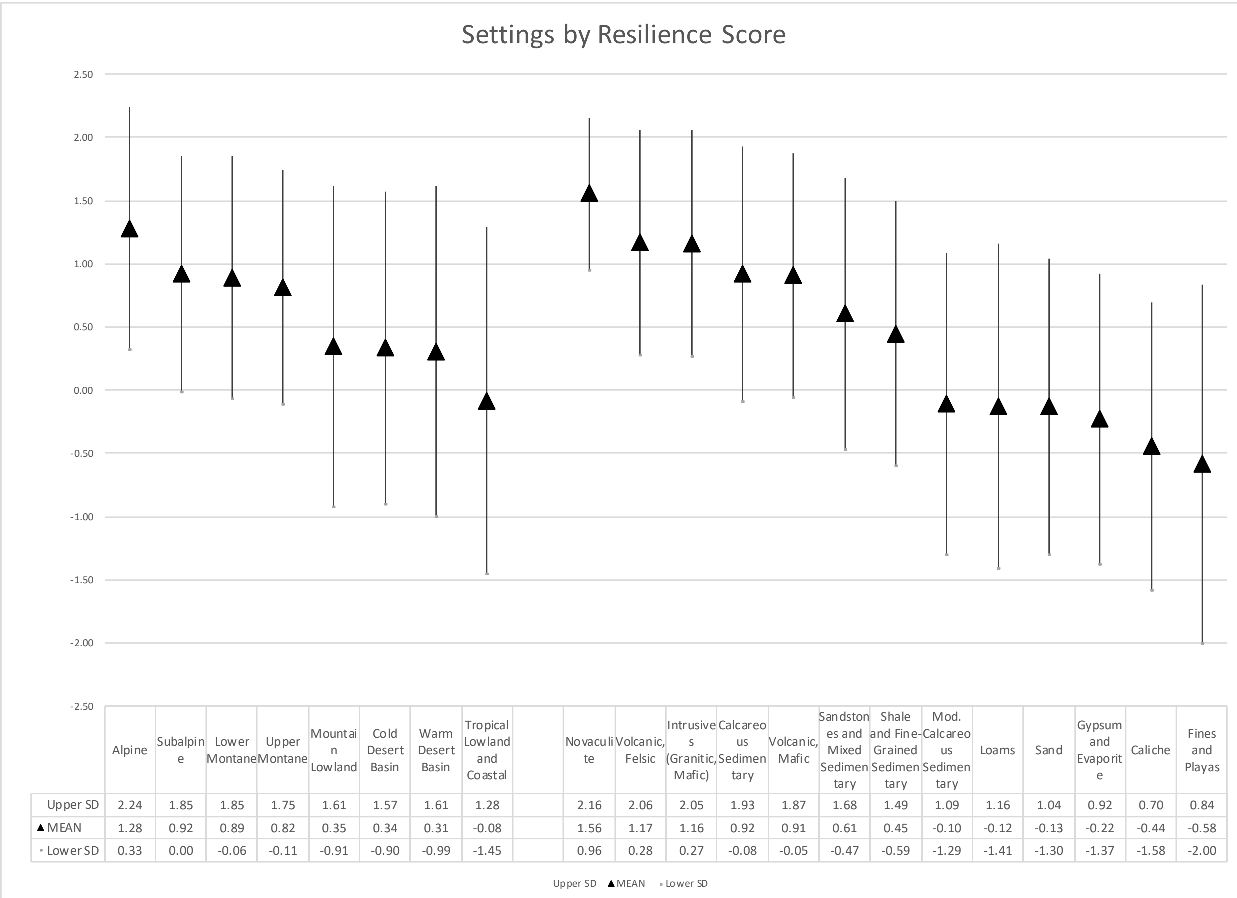
Second, we repeated the process, this time stratifying the ecoregion resilience score by geophysical setting within ecoregion and calculating the mean score for each setting within each ecoregion. Since the distribution of vales at this scale were close to normal we used standard Z-scores. If the geophysical setting score was greater than the ecoregion score AND the geophysical score was greater than or equal to 0.5 SD, the cell got the geophysical setting score. Otherwise, the cell got the score from the ecoregion map. See figure 5.5 for a map of where the scores came from in the final resilience map (figure 5.2).

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 at lower elevations with productive soils, and not surprisingly, most conservation areas are located on poor soils with higher elevations and steep slopes (Anderson et al. 2014b).

This pattern is reflected in the overall means of the resilience scores (i.e., z-scores calculated for the entire study region, Figure 5.10). For example, the four highest elevation life zones have much higher resilience means than the lower elevation zones. Within substrate, the novaculite, volcanic bedrock and intrusive granites have the highest mean resilience while the more fertile soils of lower elevation flatter areas including loams, sand, gypsum, and fine sediment have the lowest mean resilience. (Figure 5.10).

Figure 5.6: Resilience Scores by Life Zone and Geology. The average resilience score for each life zone and geology in standard normal units (z-scores). For example, the average score for the alpine setting is +1.28 SD higher than the regional mean.



	Alpine	Subalpine	Lower Montane	Upper Montane	Mountain Lowland	Cold Desert Basin	Warm Desert Basin	Tropical Lowland and Coastal		Novaculite	Volcanic, Felsic	Intrusives (Granitic, Mafic)	Calcareous Sedimentary	Volcanic, Mafic	Sandstones and Mixed Sedimentary	Shale and Fine-Grained Sedimentary	Mod. Calcareous Sedimentary	Loams	Sand	Gypsum and Evaporite	Caliche	Fines and Playas
Upper SD	2.24	1.85	1.85	1.75	1.61	1.57	1.61	1.28		2.16	2.06	2.05	1.93	1.87	1.68	1.49	1.09	1.16	1.04	0.92	0.70	0.84
▲MEAN	1.28	0.92	0.89	0.82	0.35	0.34	0.31	-0.08		1.56	1.17	1.16	0.92	0.91	0.61	0.45	-0.10	-0.12	-0.13	-0.22	-0.44	-0.58
▪ Lower SD	0.33	0.00	-0.06	-0.11	-0.91	-0.90	-0.99	-1.45		0.96	0.28	0.27	-0.08	-0.05	-0.47	-0.59	-1.29	-1.41	-1.30	-1.37	-1.58	-2.00

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.

We applied a smoothing to resolve sharp differences in resilience scores between the bedrock settings and the surficial settings. Sharp edge effects occur when adjacent settings had wide differences between their mean scores. To smooth the difference in GIS, we first shrank the surficial settings by 360 meters (the search radius for landscape diversity). Then, we calculated the means and standard deviations of the scores based on this smaller extent, reducing the effect of the transition lines. The "setting fade" uses a distance-weighted average of the cell values near all setting boundaries, so that the scores of cells near the boundary reflect the relative scales of BOTH settings in proportion to the distance of the cell from the boundary. For instance, a cell directly on the boundary receives 50% of its score from each setting, but a cell closer to the center of one setting receives a higher proportion of its relativized score.

Resilience and Conservation Lands

Overall, 52% of the land in this region is permanently secured against conversion, and 6% is converted to development or agriculture (Figure 1.1, 1.2). Land securement is highest in the Utah-Wyoming Rocky Mountains, Great Basin, and Mojave Desert ecoregions each with 72-73% of their land areas secured. Land securement is lowest in the Tamaulipan Thorn Scrub region with only 0.4%, followed next by Chihuahuan Desert with 21% secured.

Of the above-average resilient land, 61% is secured from conversion and 42% is unsecured. The level of securement of above-average resilient land is highest in the Great Basin ecoregion at 81% and again least in the Tamaulipan Thorn Scrub and Chihuahuan Desert. Please see Table 5.2 for more details.

Table 5.2: Securement and Resilience of Land. Summary by ecoregion of the acres and percent of vulnerable and resilient land secured or unsecured from conversion.

		Resilient Acres (Above Average)					Vulnerable Acres (Avg or Below)							
Ecoregion	% Resilient	Secured (GAP 1-3)	%	Not Secured	%	Total	Secured (GAP 1-3)	%	Not Secured	%	Total	Total Land	Total Water	Total Acres
Apache Highlands	65%	7,558,520	37%	5,810,510	28%	13,369,030	2,130,457	10%	5,140,764	25%	7,271,221	20,640,251	4,277	20,644,528
Arizona-New Mexico Mountains	59%	8,982,545	31%	7,885,826	27%	16,868,370	3,654,009	13%	8,251,859	29%	11,905,868	28,774,238	14,802	28,789,040
Chihuahuan Desert	44%	3,988,546	10%	13,046,837	34%	17,035,383	4,205,055	11%	17,294,543	45%	21,499,598	38,534,980	43,346	38,578,326
Colorado Plateau	51%	14,288,738	29%	10,679,996	22%	24,968,733	6,166,580	13%	17,254,504	36%	23,421,084	48,389,817	166,371	48,556,189
Great Basin	53%	31,412,959	43%	7,214,770	10%	38,627,729	20,725,992	29%	12,003,096	17%	32,729,088	71,356,817	1,054,287	72,411,104
Mojave Desert	51%	13,026,222	40%	3,473,305	11%	16,499,526	10,133,636	31%	5,510,347	17%	15,643,983	32,143,509	136,455	32,279,964
Sonoran Desert	49%	8,042,402	28%	6,006,095	21%	14,048,497	4,772,587	17%	9,552,599	33%	14,325,185	28,373,683	295,303	28,668,985
Southern Rocky Mountains	66%	16,954,240	42%	9,374,100	23%	26,328,339	6,823,861	17%	6,641,931	17%	13,465,792	39,794,132	135,398	39,929,530
Tamaulipan Thorn Scrub	37%	47,078	0%	7,277,139	37%	7,324,217	67,402	0%	12,111,105	62%	12,178,507	19,502,724	142,703	19,645,427
Utah High Plateaus	65%	5,320,946	47%	2,086,539	18%	7,407,486	2,440,268	22%	1,471,078	13%	3,911,346	11,318,831	24,112	11,342,944
Utah-Wyoming Rocky Mountains	68%	14,434,968	53%	3,900,185	14%	18,335,154	5,203,028	19%	3,225,026	12%	8,428,055	26,763,209	293,866	27,057,074
Wyoming Basins	52%	9,792,599	30%	7,403,184	22%	17,195,783	8,543,665	26%	6,987,222	21%	15,530,887	32,726,670	300,500	33,027,171
Grand Total	54%	133,849,762	33%	84,158,486	21%	218,008,248	74,866,540	19%	105,444,074	26%	180,310,614	398,318,862	2,611,420	400,930,282

Geophysical Setting Securement

Patterns in land securement and conversion are useful for understanding which geophysical settings are well-protected and which ones 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 5.3).

Figure 5.7: Above Average Resilience Land by Securedment.

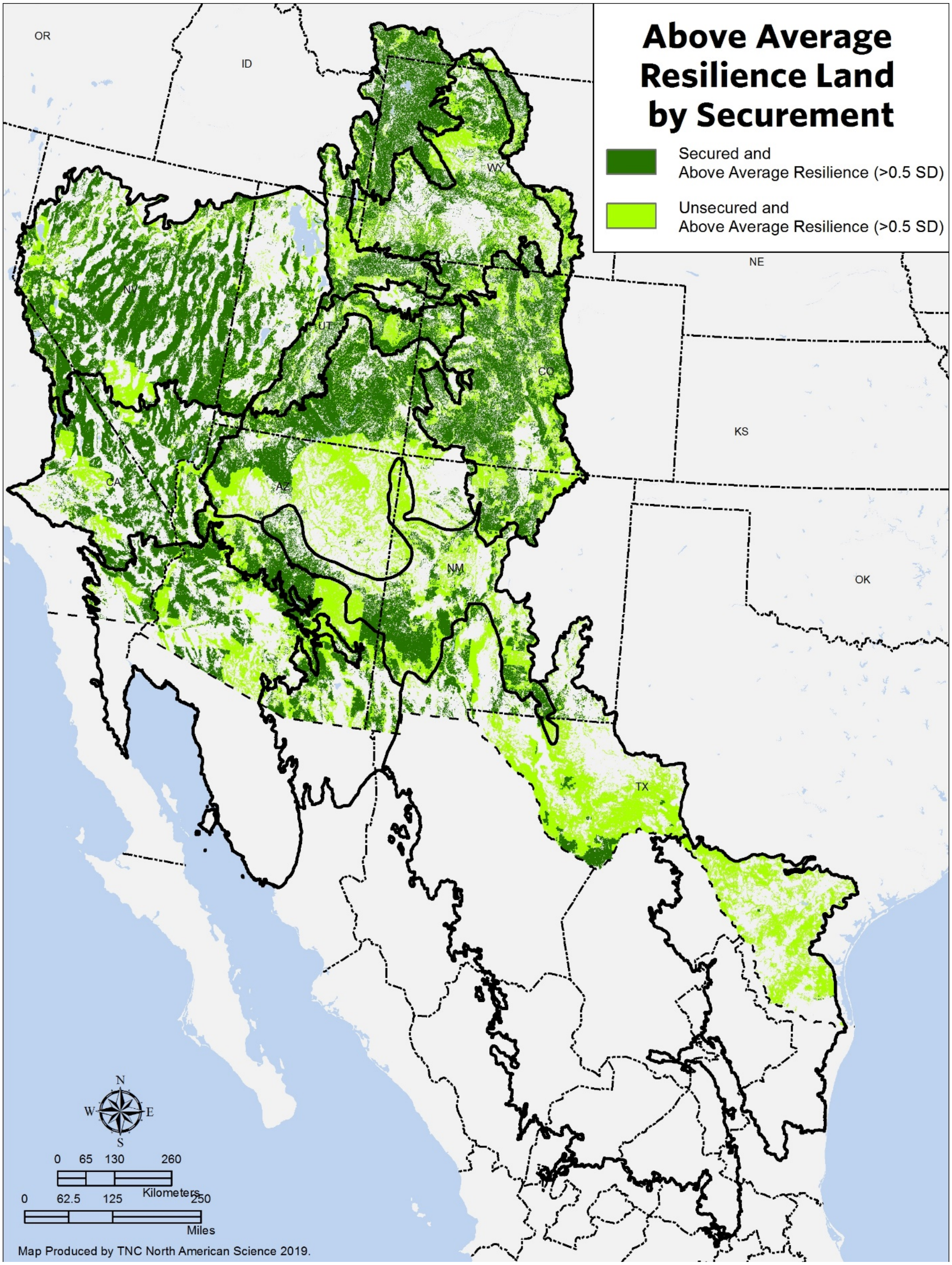
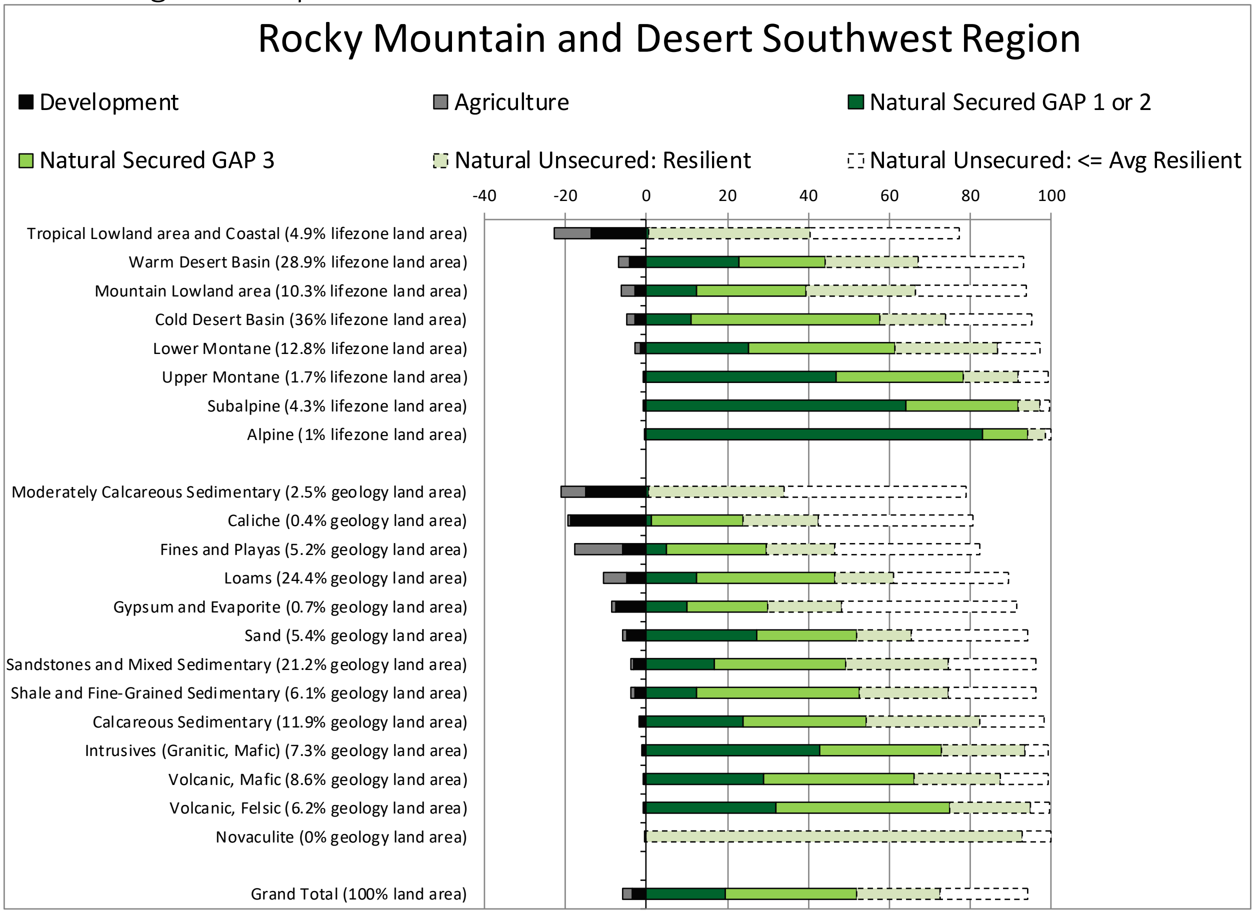


Table 5.3: Geophysical Settings: Conversion and Securement. Summary for each geophysical setting of the total number of acres, percent converted to either development or agriculture and percent "secured" in protected status. The table is sorted by descending % Acres Converted. (Note: water is excluded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

Geophysical Settings	Total Acres of Land	% of Acres Converted	% of Acres Secured	Ratio Converted to Secured Acres
Life Zones				
Tropical Lowland and Coastal	19,502,659	22.8	0.4	52.0
Warm Desert Basin	115,197,531	7.1	44.0	0.2
Mountain Lowland	41,119,337	6.4	39.5	0.2
Cold Desert Basin	143,388,893	4.8	57.7	0.1
Lower Montane	50,918,776	2.9	61.4	0.0
Upper Montane	6,883,571	0.9	78.3	0.0
Subalpine	17,215,633	0.5	91.8	0.0
Alpine	4,089,463	0.2	94.1	0.0
Substrate Types				
Moderately Calcareous Sedimentary	9,856,118	21.3	0.4	52.9
Caliche	1,726,182	19.4	24.0	0.8
Fines and Playas	20,812,129	17.7	29.5	0.6
Loams	97,306,437	10.6	46.3	0.2
Gypsum and Evaporite	2,684,213	8.5	29.9	0.3
Sand	21,634,937	5.8	51.7	0.1
Sandstones and Mixed Sedimentary	84,603,820	4.0	49.2	0.1
Shale and Fine-Grained Sedimentary	24,257,906	3.8	52.5	0.1
Calcareous Sedimentary	47,560,289	1.7	54.3	0.0
Intrusives (Granitic, Mafic)	28,890,066	0.9	72.7	0.0
Volcanic, Mafic	34,214,845	0.9	66.1	0.0
Volcanic, Felsic	24,745,337	0.6	74.9	0.0
Novaculite	23,586	0.1	0.0	0.0

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 (Figure 5.8). The Tropical Lowlands and Warm Deserts had the greatest risk among the life zones. Among the geology and soils, moderately calcareous bedrock, caliche and fine sediment had the greatest risk. 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.

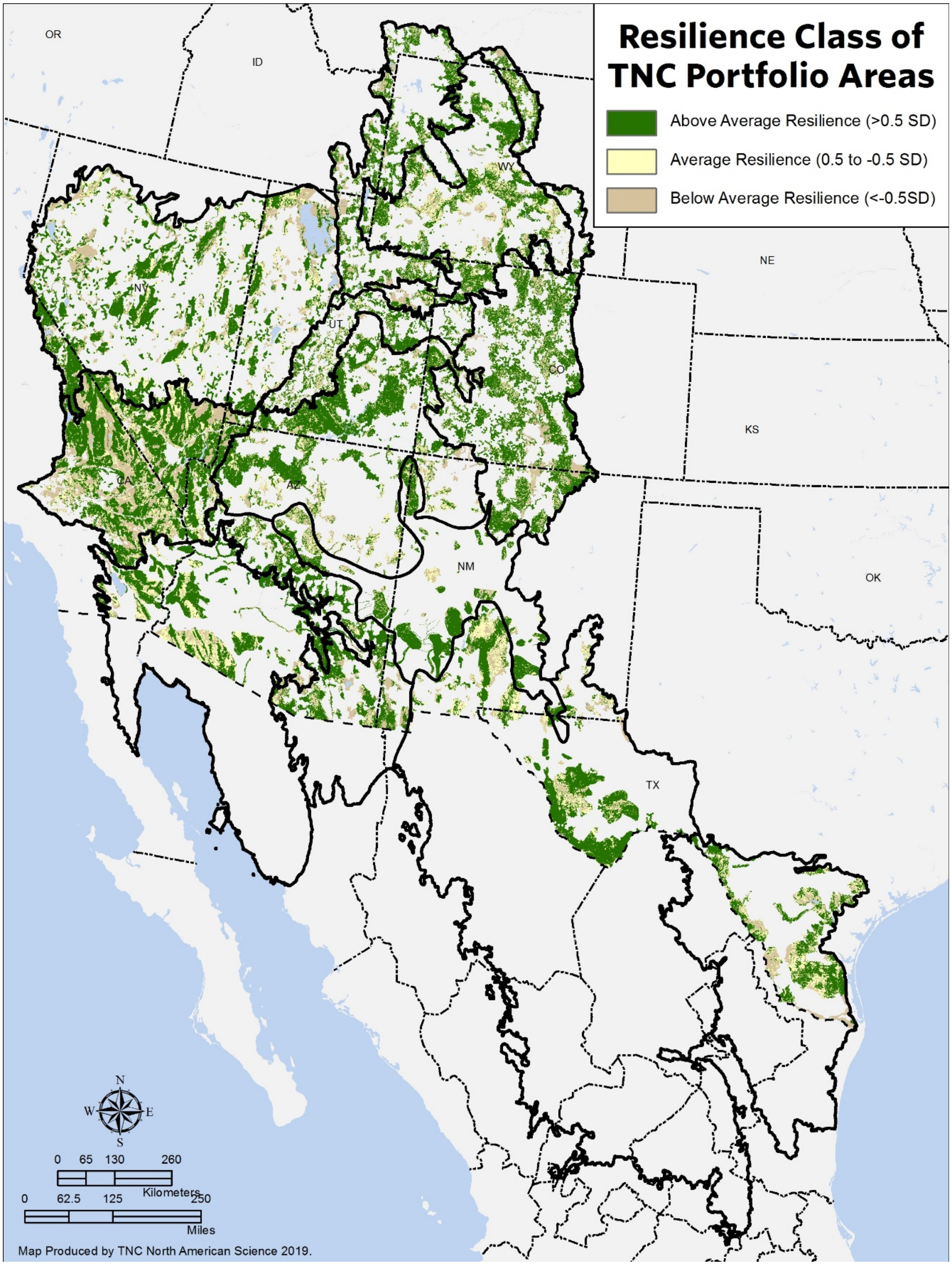
Figure 5.8: Conservation Risk Index of each Geophysical Setting. The proportion of conversion to securement for each setting, further divided by the type of conversion and the resilience score of the remaining unsecured natural land. The chart is sorted in descending order of percent converted.



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 (enhanced version of TNC Rollup 2016, see chapter 8) and the regional resilience map to highlight place that score high both for resilience and current biodiversity (Figure 5.14). Results indicate that 82% of the TNC portfolio occurs on land that scores average or above for resilience, including 61% that scores above average and 21% that scores average (-0.5 to +0.5 SD). 18% of the portfolio occurs on vulnerable land that scores below average for resilience (<-0.5 SD).

Figure 5.9. Resilient Areas and Existing TNC Conservation Portfolio. (Data Source: TNC Ecoregional Rollup, 2016)



Resilience Thresholds and the Western US

The methods we used to estimate site resilience were developed in the Eastern US and further refined in the Central and Coastal regions. When we applied them to the Rocky Mountain and Southwest Desert region it was necessary to adjust the methods to account for the remarkable intactness and other properties of the western landscape. Foremost among this was the Local Connectedness score. The low level of development and fragmentation in the West compared to other regions was striking, with the average raw score (81 out of 100) being higher than even the highest scores in other regions.

How we accounted for the skewed distriburion is described in Chapter 3 but suffice to say a large proportion of the landscape was rightly scored as above-average for local connectedness. Similarly, in this relatively dry but topographically complex region we gave more weight to the moisture collecting portions of the landscape and to long elevation slopes that offer temperature gradients. Additionally, some of the ecoregions were very homogenous, bounding specific mountain ranges and not including the low elevation regions. As a result: a larger proportion of the landscape scored above-average for resilience (>0.5 SD) than in the Eastern and Central ecoregions. Some, like the Wyoming-New Mexico mountains containing Yosemite and the Grant Tetons, averaged almost 70%. Despite this, the results look realistic and comparable to the results for the rest of the country (Figure 5.10).

For reasons discussed earlier in this work, we think these results are objective and appropriate, however, to account for this, users may want to impose a higher bar for resilience than our standard cutoff of >0.5 SD (slightly-above-average). If one applies a higher standard to identify resilient areas that are at least 1 standard deviation above the mean (>1 SD) the map looks rather different (Figure 5.11). We encourage users to incorporate this understanding into their planning and perhaps use a sliding scale to identify the most critical areas for conservation actions.

Figure 5.10. Results Compared to Other Regions. In this map the results are mapped with the results of other US Geographies. Note California and Pacific Northwest are in draft form.

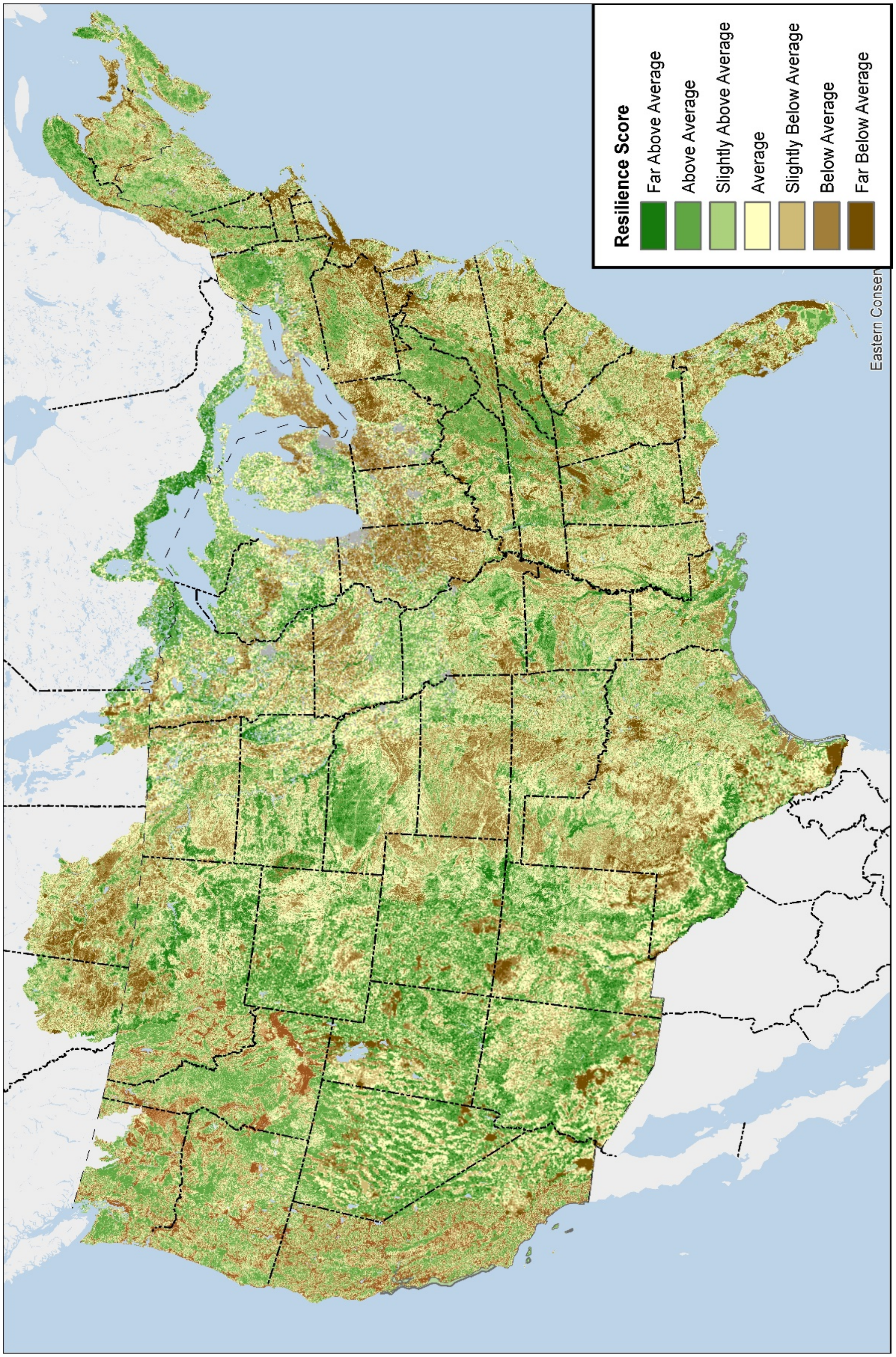
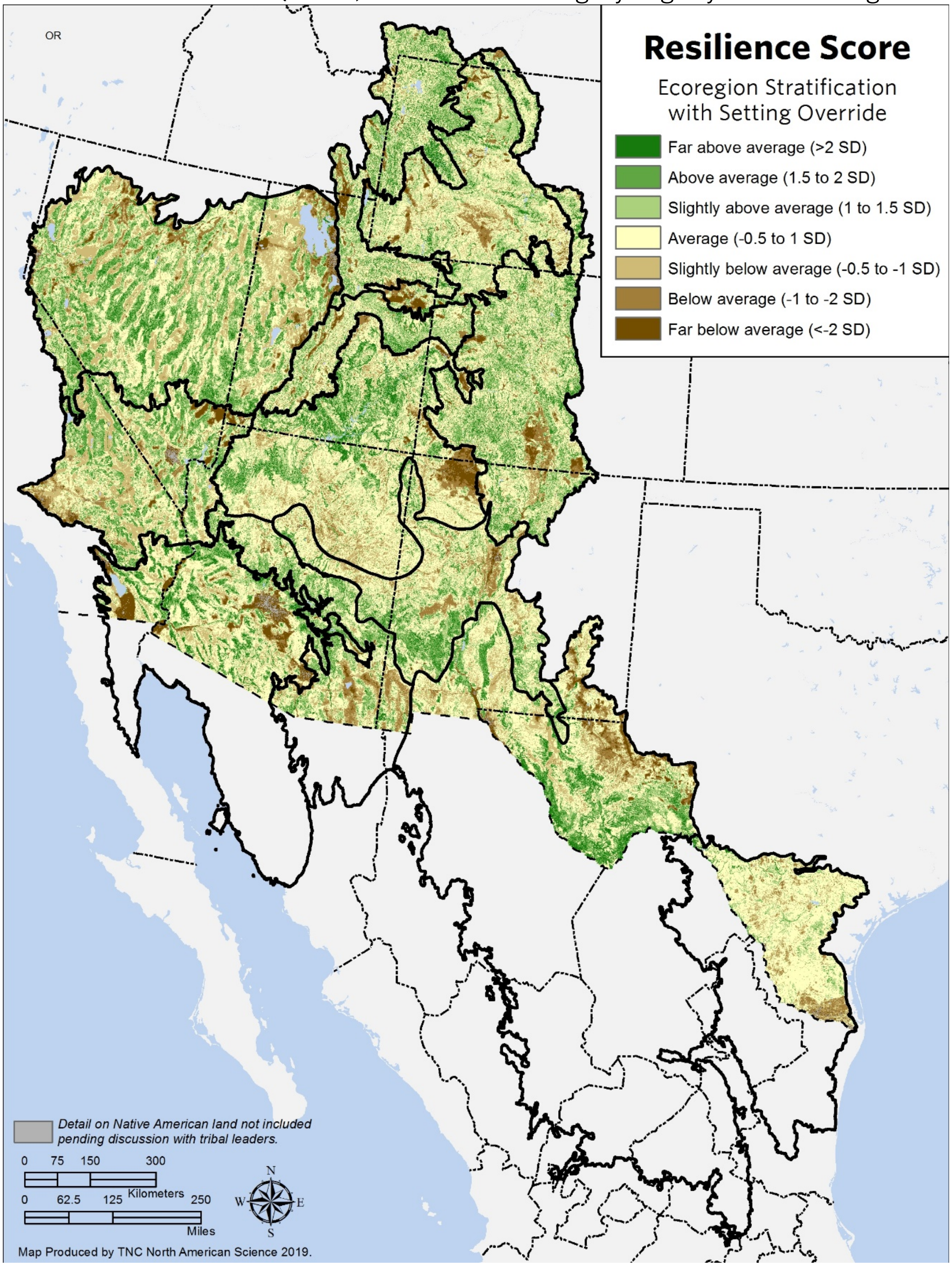


Figure 5.11. Applying a Higher Resilience Threshold. In this map we use a threshold of 1 standard deviation (>1 SD) to define the category Slightly above average.



Discussion

This project assessed the Rocky Mountain and Southwest Desert region of the US to identify the areas with the highest estimated resilience relative to each of 12 ecoregions and 73 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 four 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 U.S. 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 our best 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, populations 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:

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.

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.

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.

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.

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 the Organism is 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.

<u>Microclimates and Rates of Change:</u> 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 time scales 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.

Our three basic landscape elements were as follows:

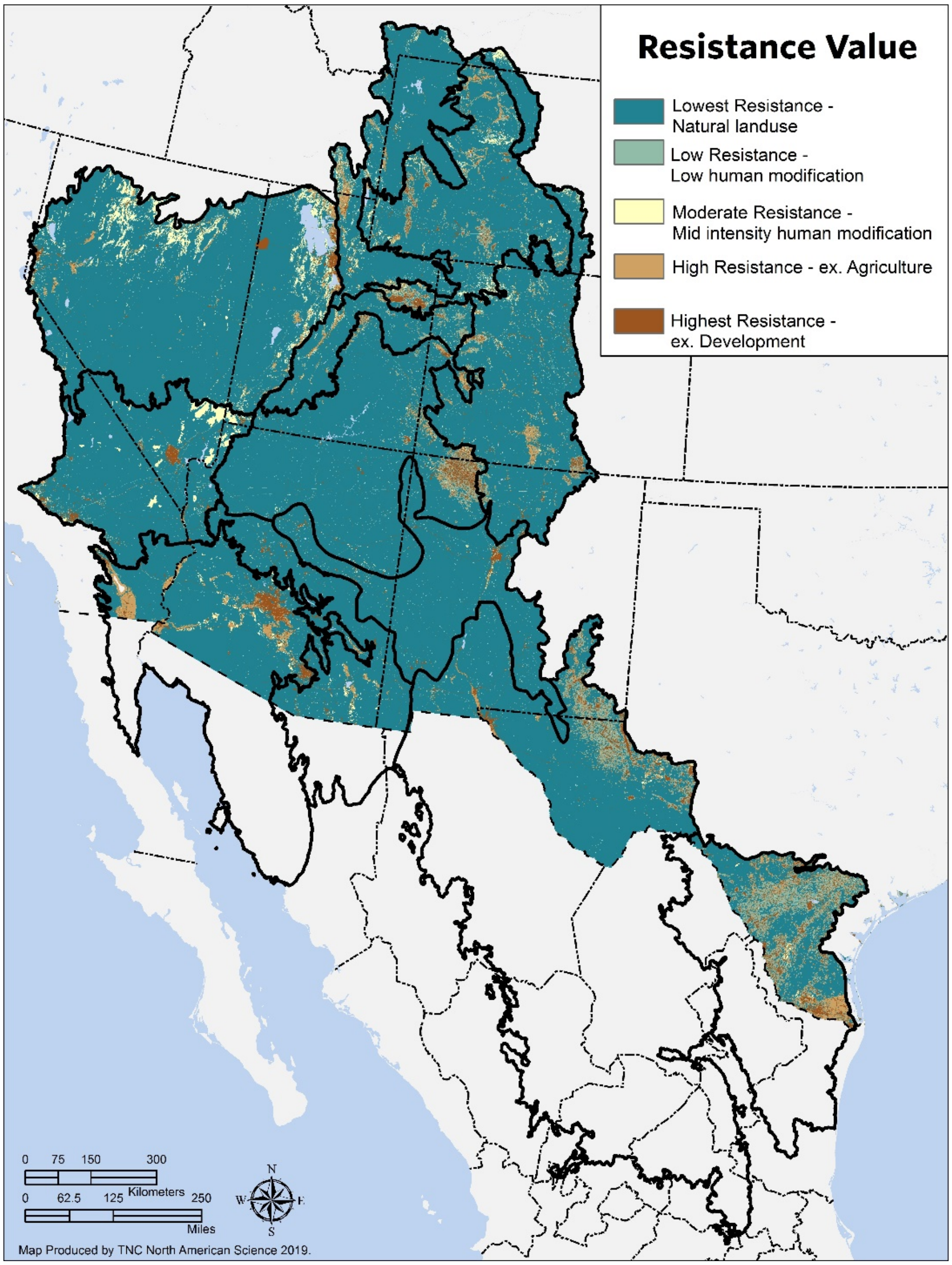
Natural lands: landscape elements where natural processes are unconstrained and unmodified by human intervention such as forest, wetlands, or natural grasslands. Human influences are common, but are mostly indirect, unintentional, and not the dominant process.

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.

We used the same anthropogenic resistance grid that was created for local connectedness analysis with the exception of roads (See Chapter 3). Unpaved minor roads create little resistance for regional movement, so we removed them from the reistance grid, but kept the major roads and development which create barriers for regional connectedness (Figure 7.1).

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.



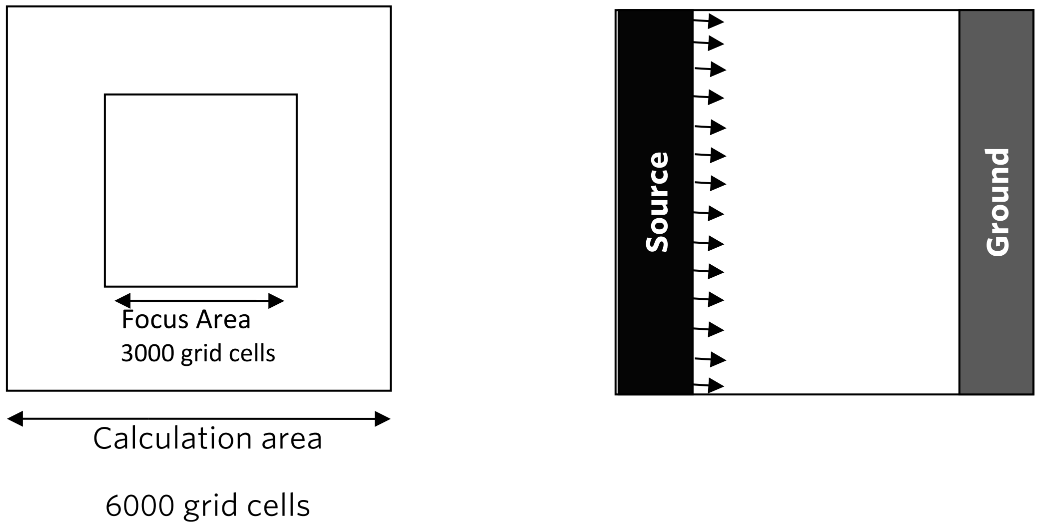
Mapping Regional Flow

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 (focus area in Figure 7.2) 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 216 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).

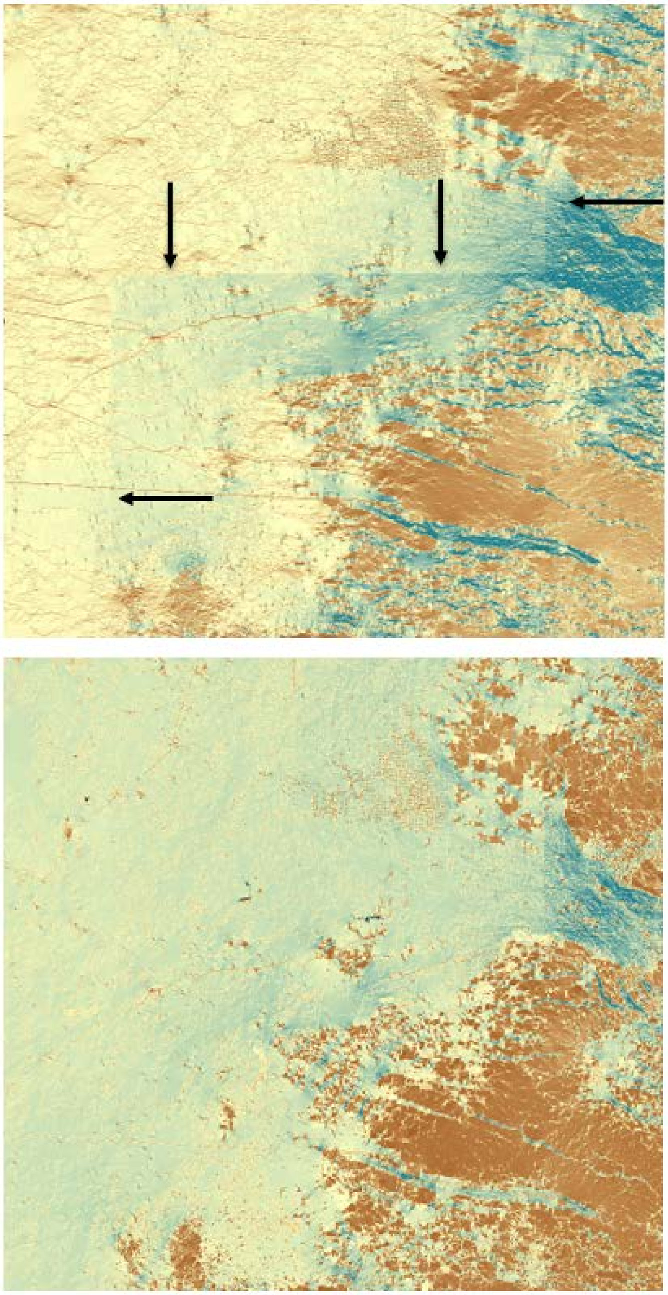
Figure 7.2: Diagram of tiles used in the Circuitscape analysis.
The image on the left shows the focus area in comparison to the calculation area. The image on the right shows how current is injected from every cell on the source (on the left) and can flow to any cell in the ground (right).



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 (Figure 7.4 & 3.5). To symbolize the results in this very natural landscape, we used a similar method as we described for local connectedness (Chapter 3). When the score was above-average the classification were based on quantiles for the Rocky Mountain and Desert Southwest. When the score was below-average the values for the lowest two quantile breaks were based off the quantiles for a larger western area that included the Great Plains. This created a more accurate representation of the distribution of developed land.

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:

- <u>Diffuse flow</u>: 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.
- <u>Concentrated flow</u>: 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.
- <u>Constrained flow</u>: 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.
- <u>Blocked/Low flow</u>: 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.

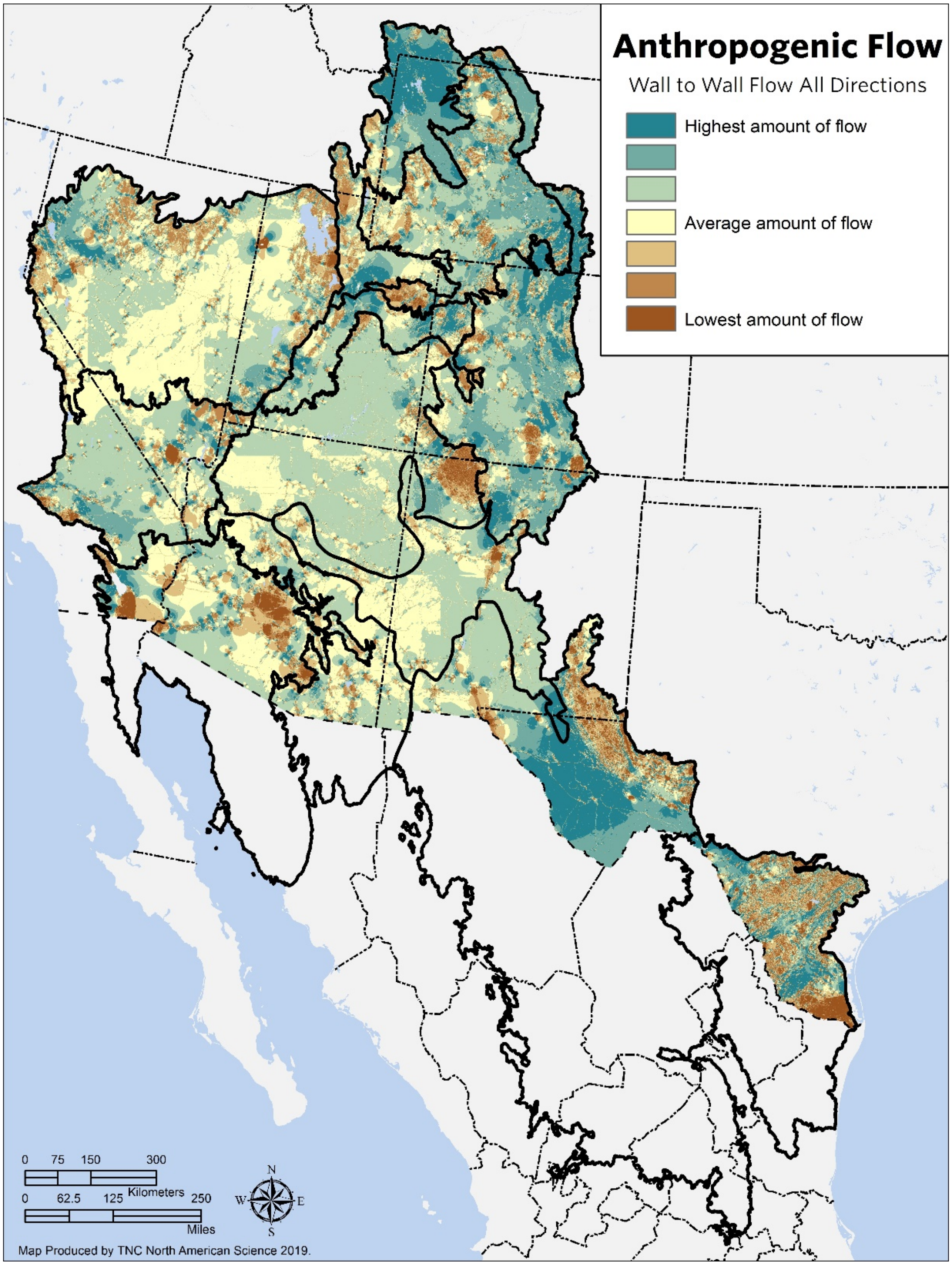


Figure 7.5: Western Context around the wall-to-wall Circuitscape Results. The data and legend is the same as for Figure 7.5, but this shows the results for West.

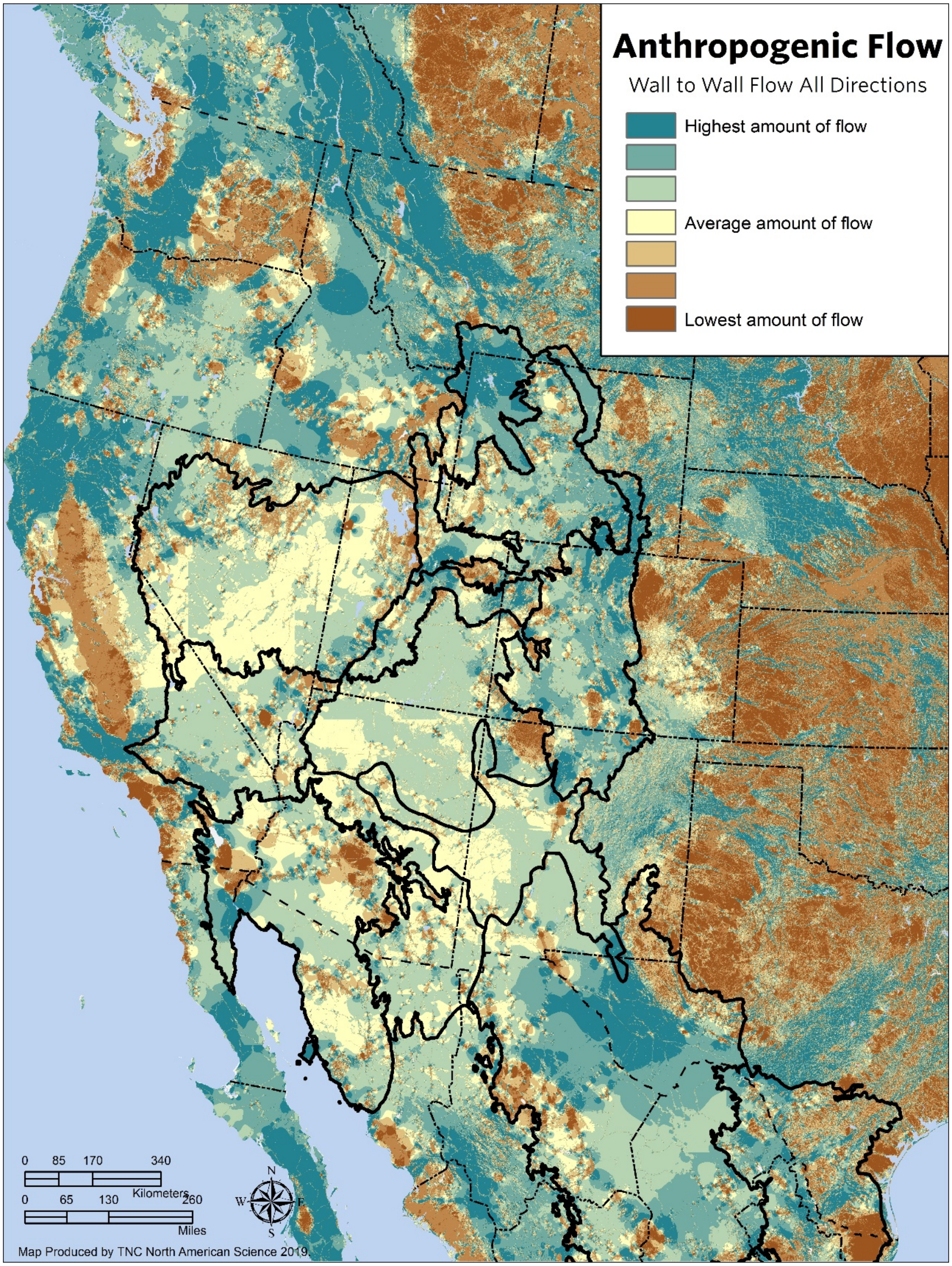
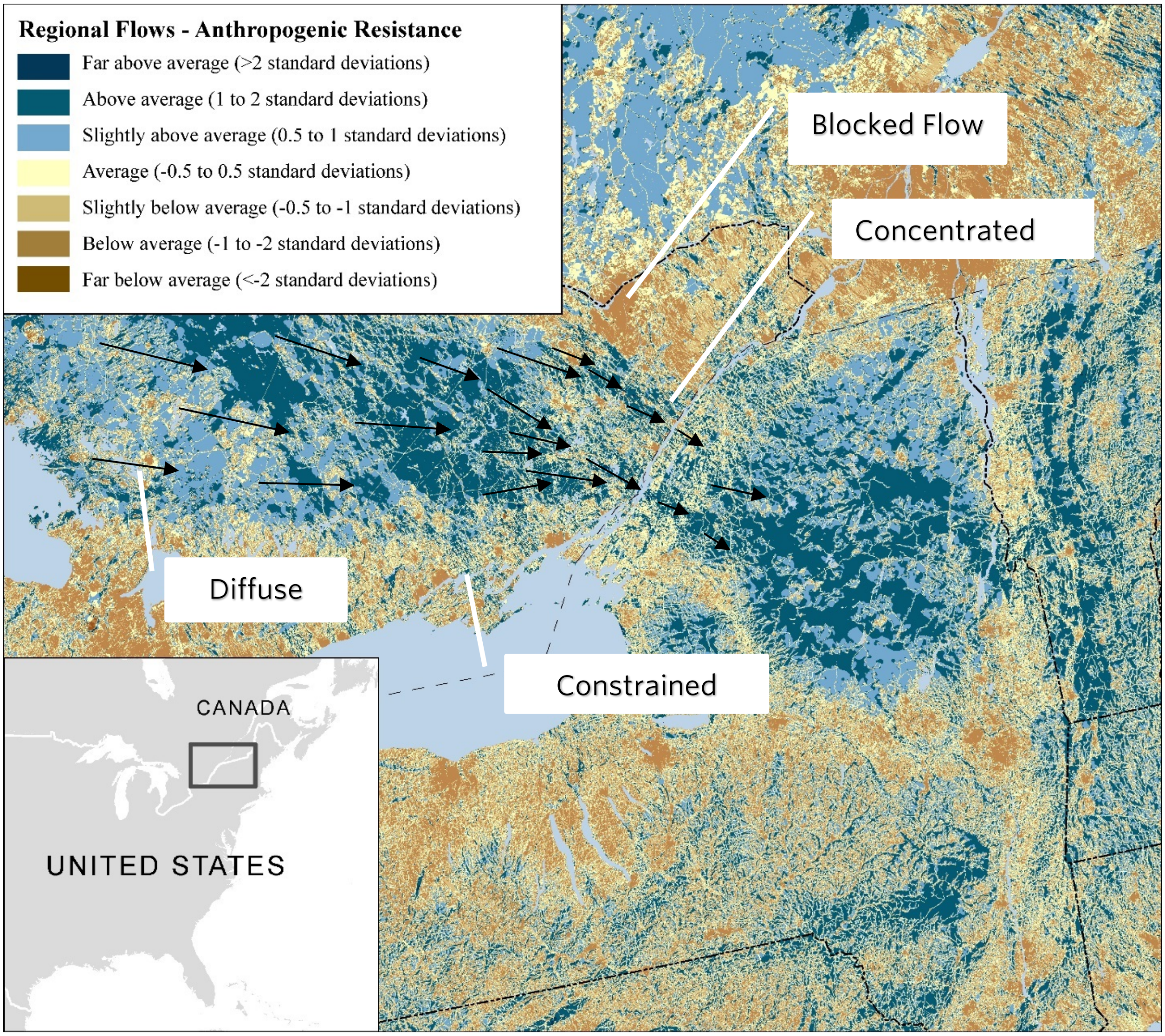


Figure 7.6: Flow types. This figure shows how the four flow types reflect the dynamics of a moving population over time. Location: St Lawrence Valley between the Algonquins and the Adirondaks.



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). This region is not very fragmented, so the majority of the flow is diffuse, with small amounts of concentrated flow in the Sonoran Desert and the Tamaulipan Thornscrub ecoregions.

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.

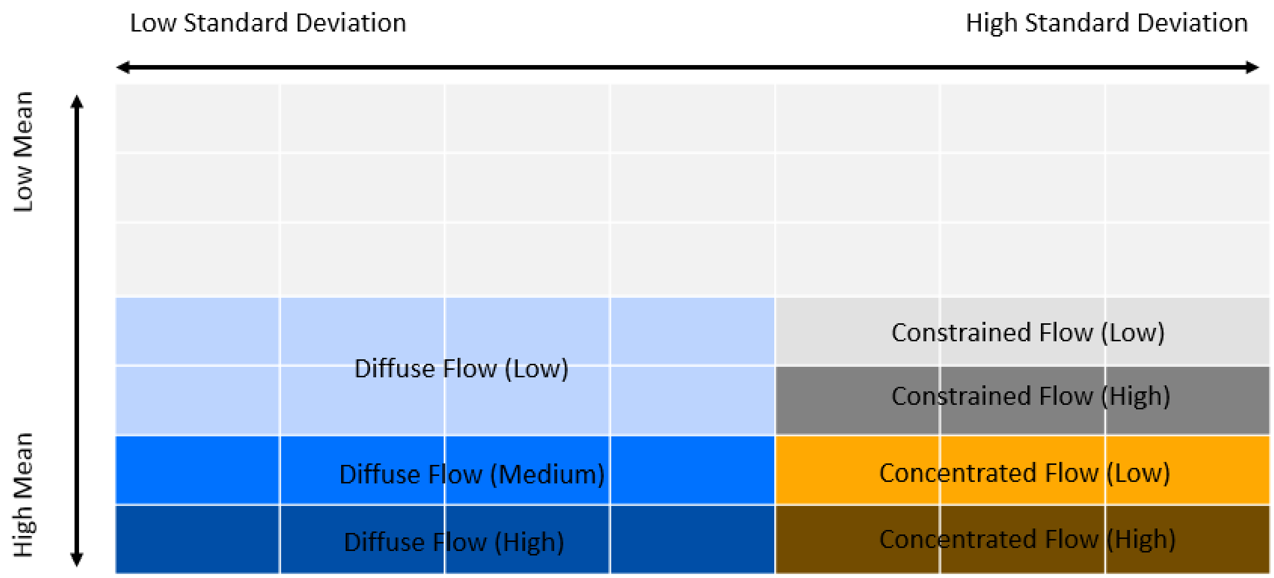
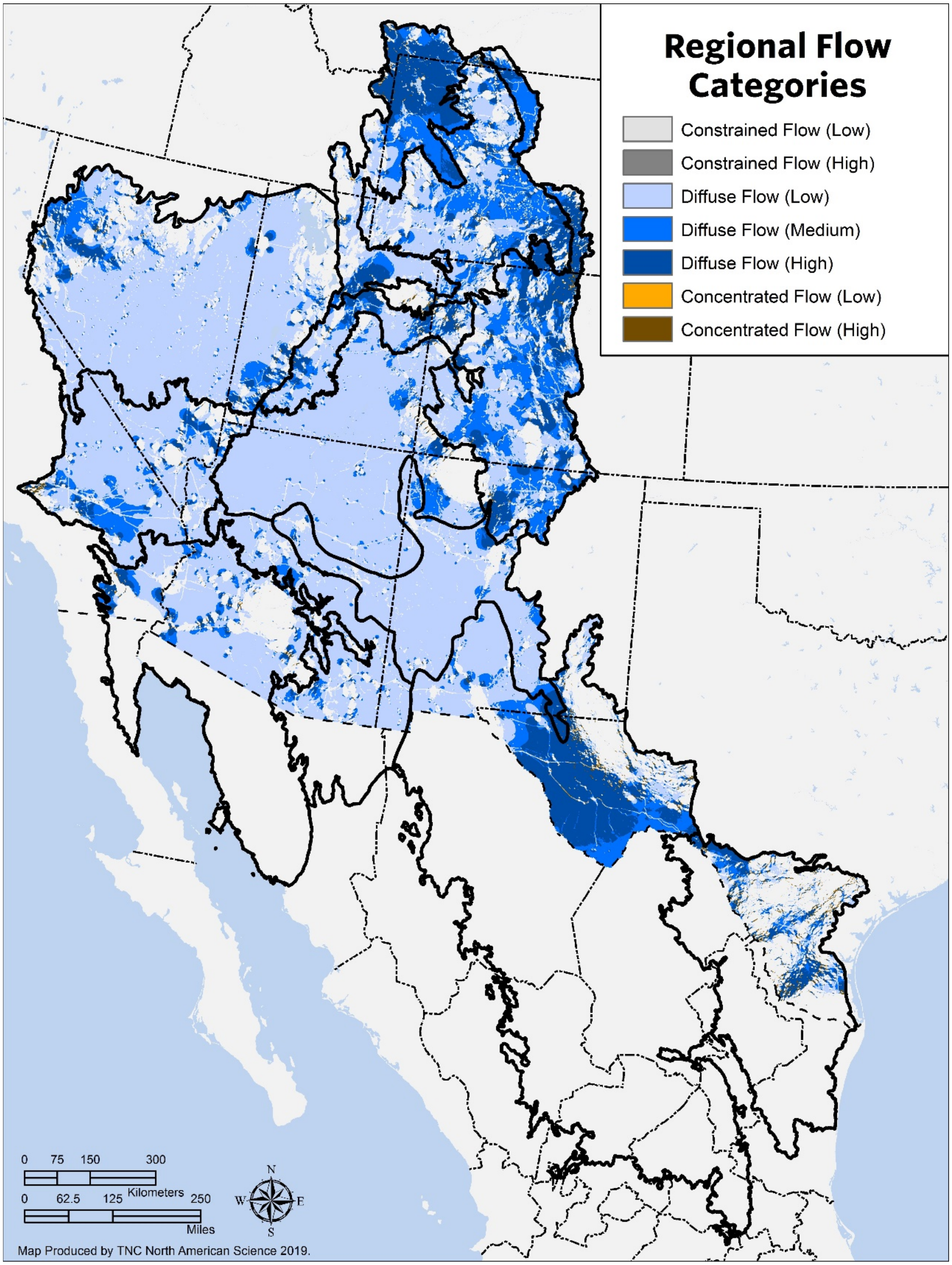


Figure 7.8: Categorized results of the wall-to-wall Circuitscape model applied to the anthropogenic resistance grid. Grey indicates areas with low permeability where movement is blocked. Green indicates areas of moderate flow; often highly natural settings where species movements are diffuse. Blue indicates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



Climate Flow

This section describes 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 litereature we focused our attention on four well documented responses of species movement 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 (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 7.9 and 7.10). 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.

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.

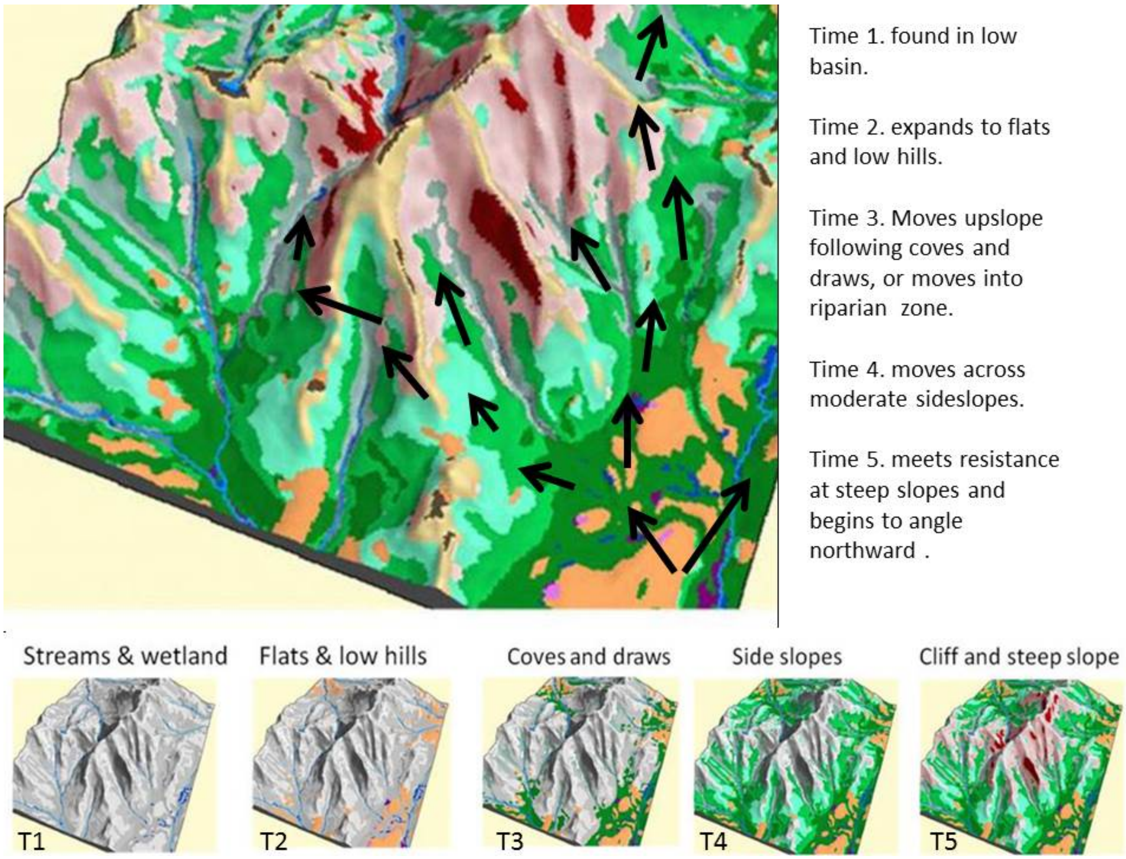
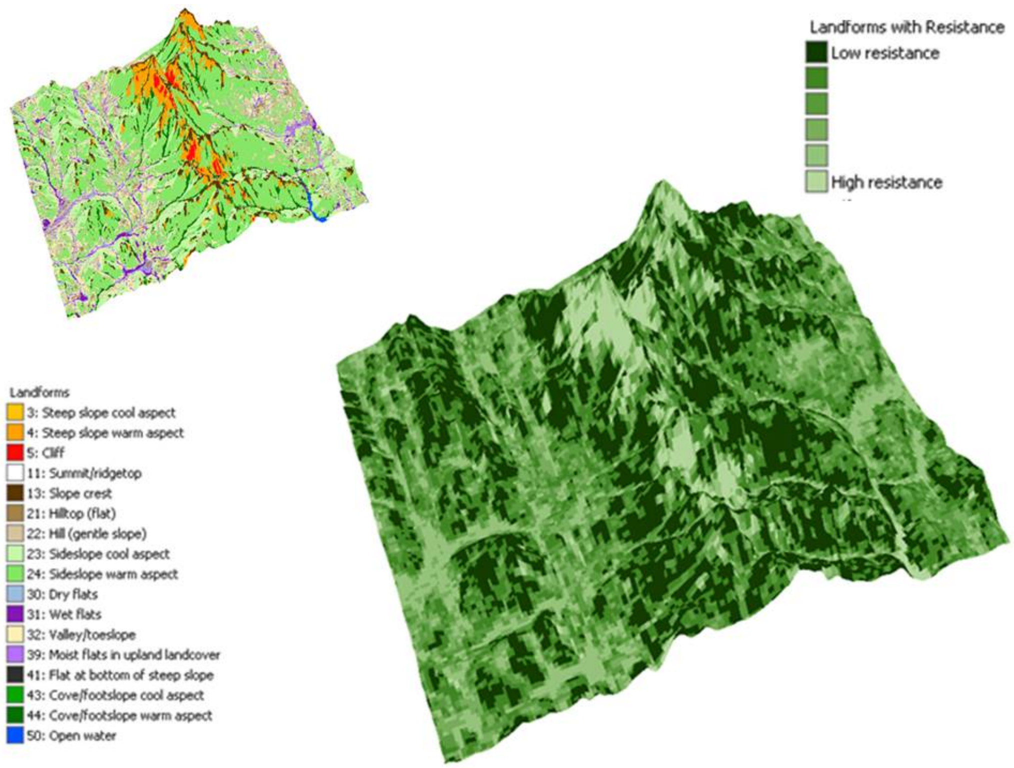


Figure 7.10: The resistance scores applied to the landform model. This picture shows a three-dimensional model of Mt Mansfield in Vermont. The left image shows the landform model. The second image shows the resistances where low resistance corresponds to areas with the most temperature gain for the least 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 and 7.12). The realistic effect of the local scaling (Figure 7.13) is to create a much more distributed picture of where upslope movements may be available to species for local climate relief. 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 7.14).

Figure 7.11: The Upslope Model applied to the Study area.

Figure 7.12: The Upslope Model applied to the West.

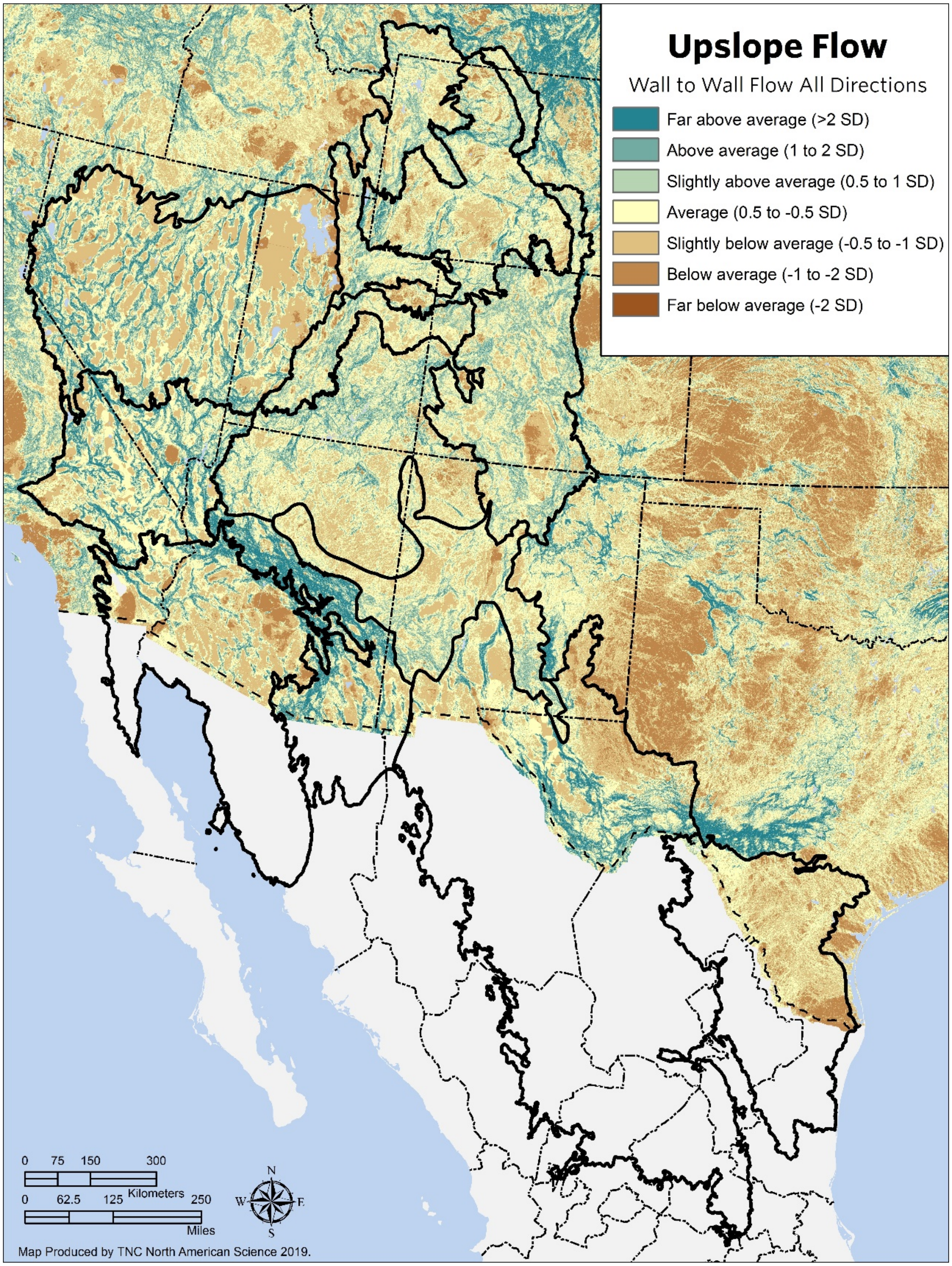


Figure 7.13: Zoom in of upslope model in Great Basin ecoregion. The map shows flow going upslope from the valleys to the uplifted mountain ranges.

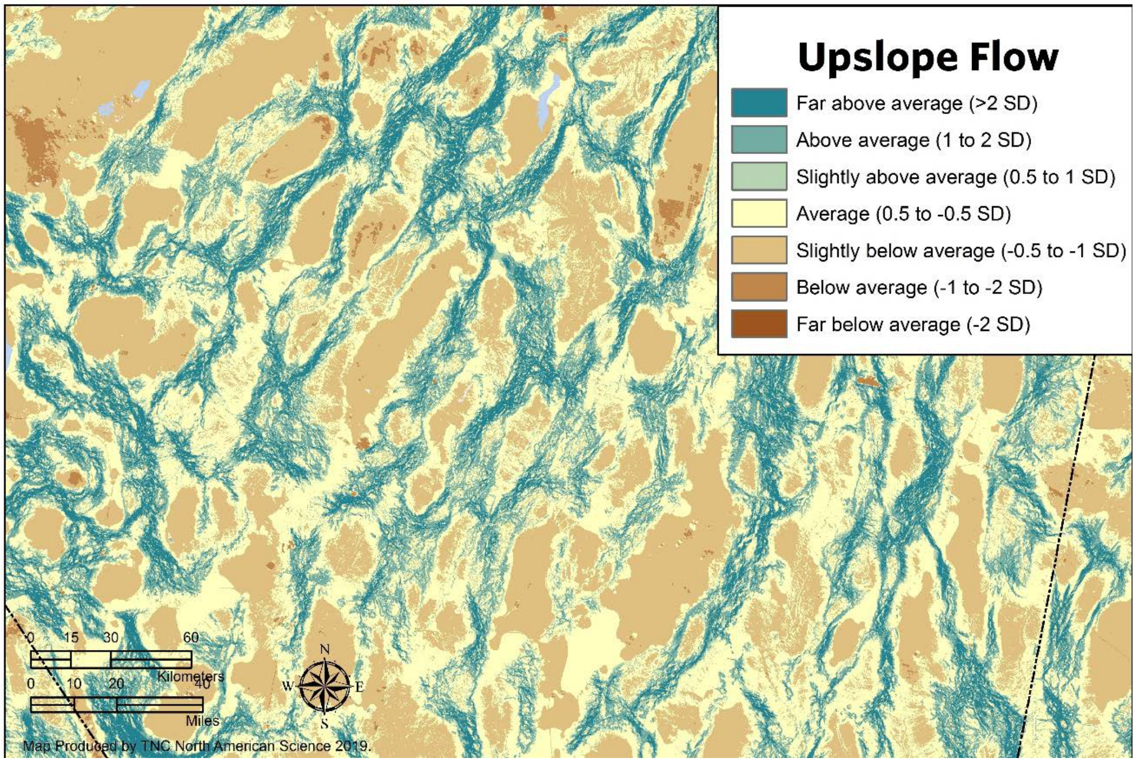
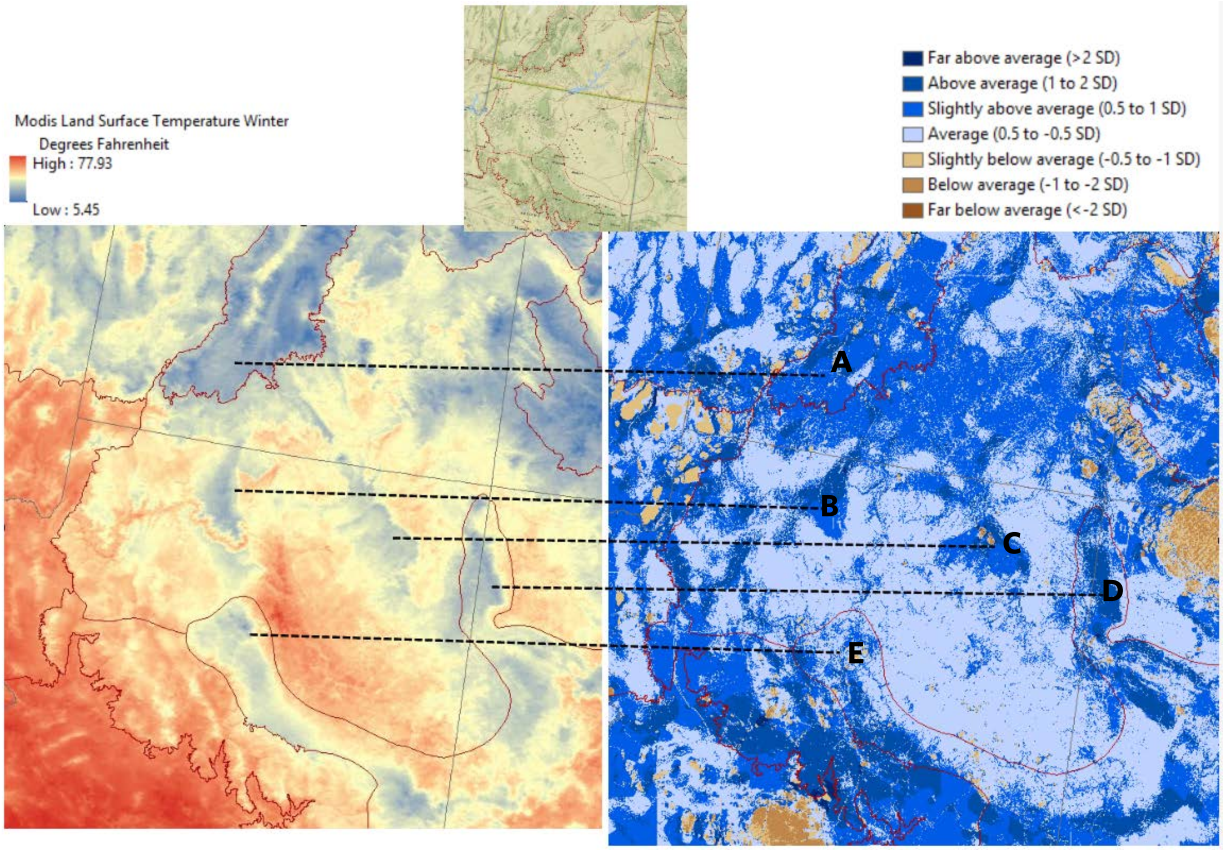


Figure 7.14: Comparison of upslope model with land surface temperature (LST) model for the Sandhills Region. This figure shows the correspondence between the topography and surface temperature in fall. The LST model is MODIS (MOD11A2.006) Terra Land Surface Temperature and Emissivity Winter mean at a 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.

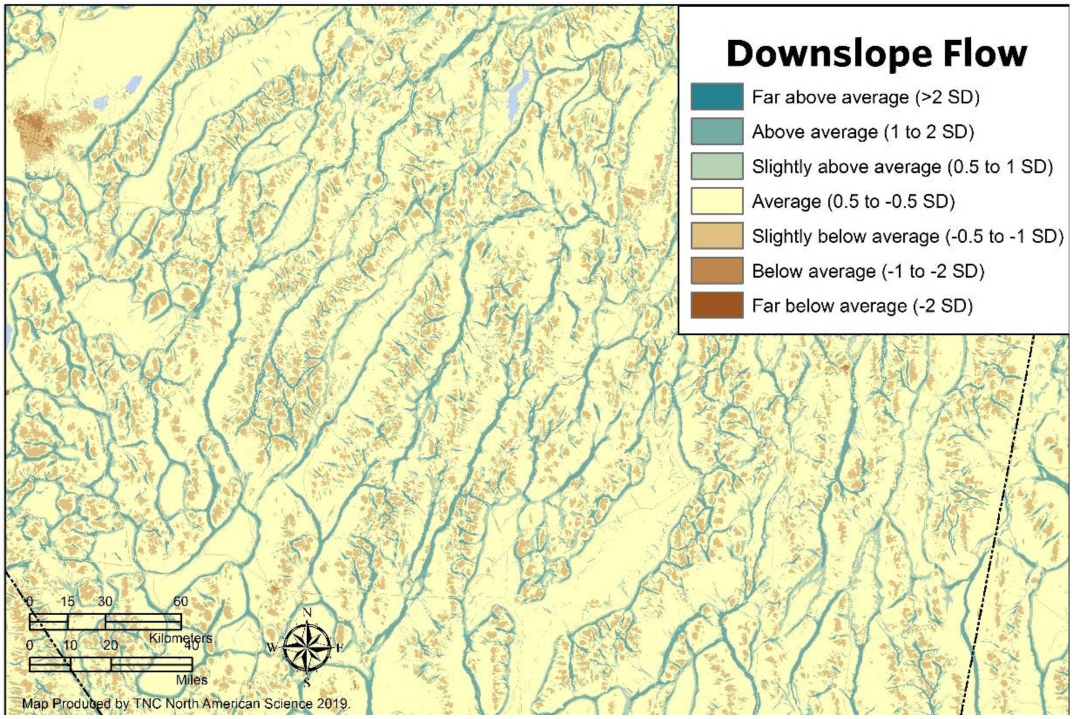
To create an integrated final downslope model that included human uses, we combined the downslope, moisture-enhanced resistance grid with the anthropogenic resistance grid to create a resistance surface that favored moving downslope but was sensitive to anthropogenic barriers. This was achieved with 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 7.15 -7.16).

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 the 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 7.15: 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 7.16: Zoom in of the Downslope Model. This map shows a zoom in of the same area as 7.12 for the Great Basin. Downslope flow clearly tracks valley bottoms.



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 (Figure 7.17 & 7.18).

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

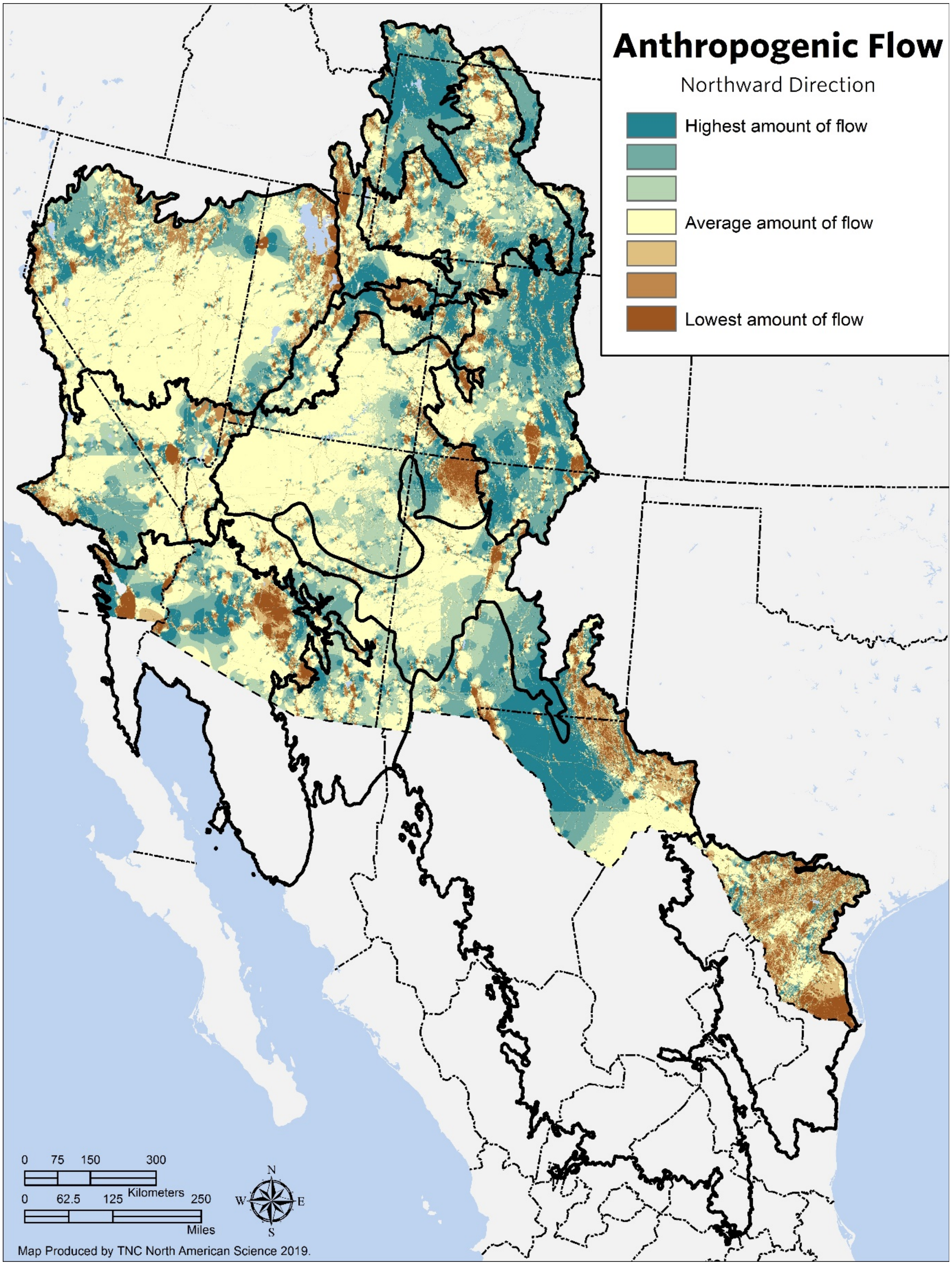
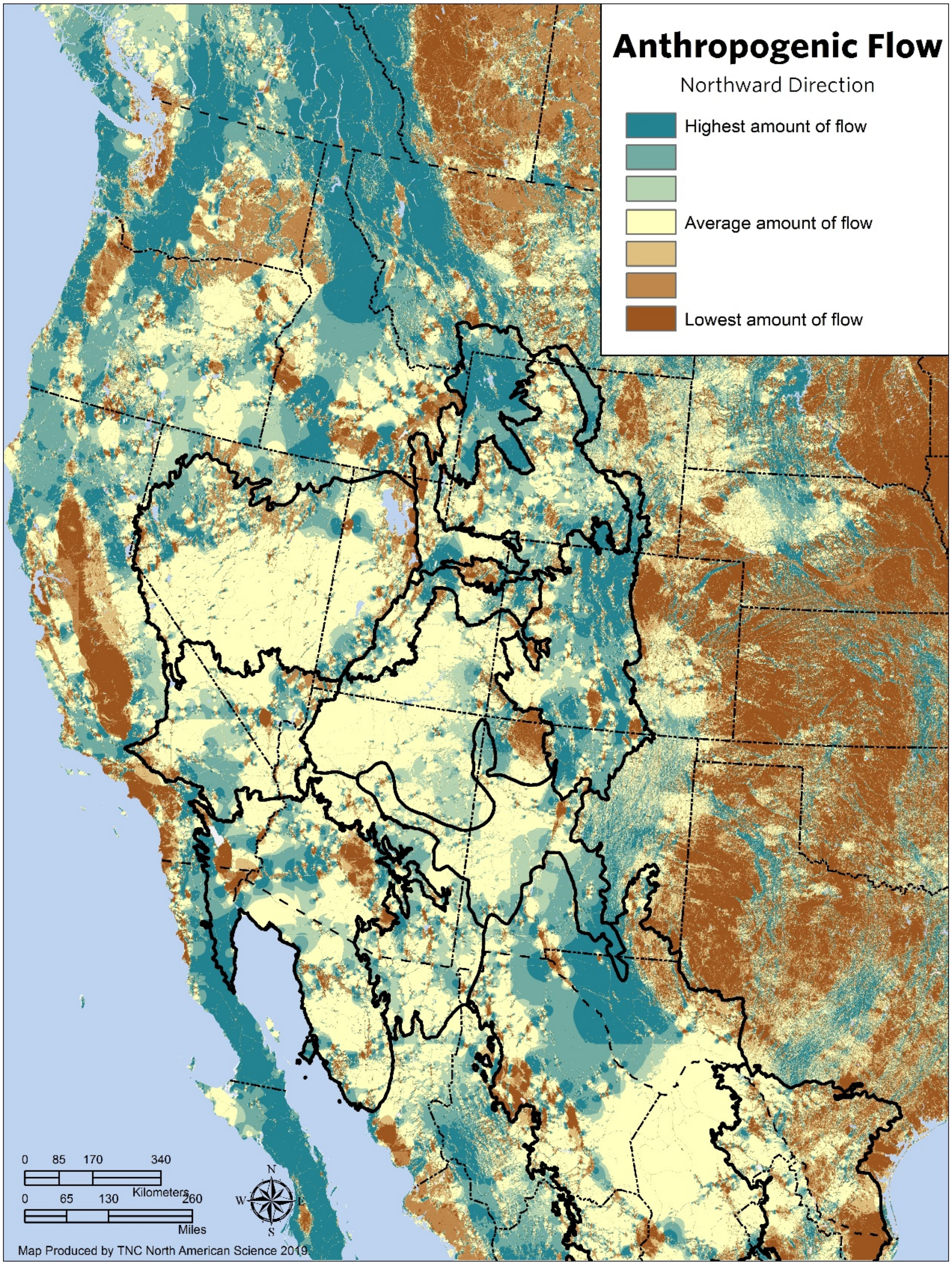


Figure 7.18: Northward model for West. This map shows regional flow model with north-south movements weighted 66% and east-west movements weighted 33%.



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 (Figure 7.19 - 7.21).

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 7.22 & Figure 7.23). 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 flow and identify key climate pathways within the relatively intact landscape.

Figure 7.19: 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

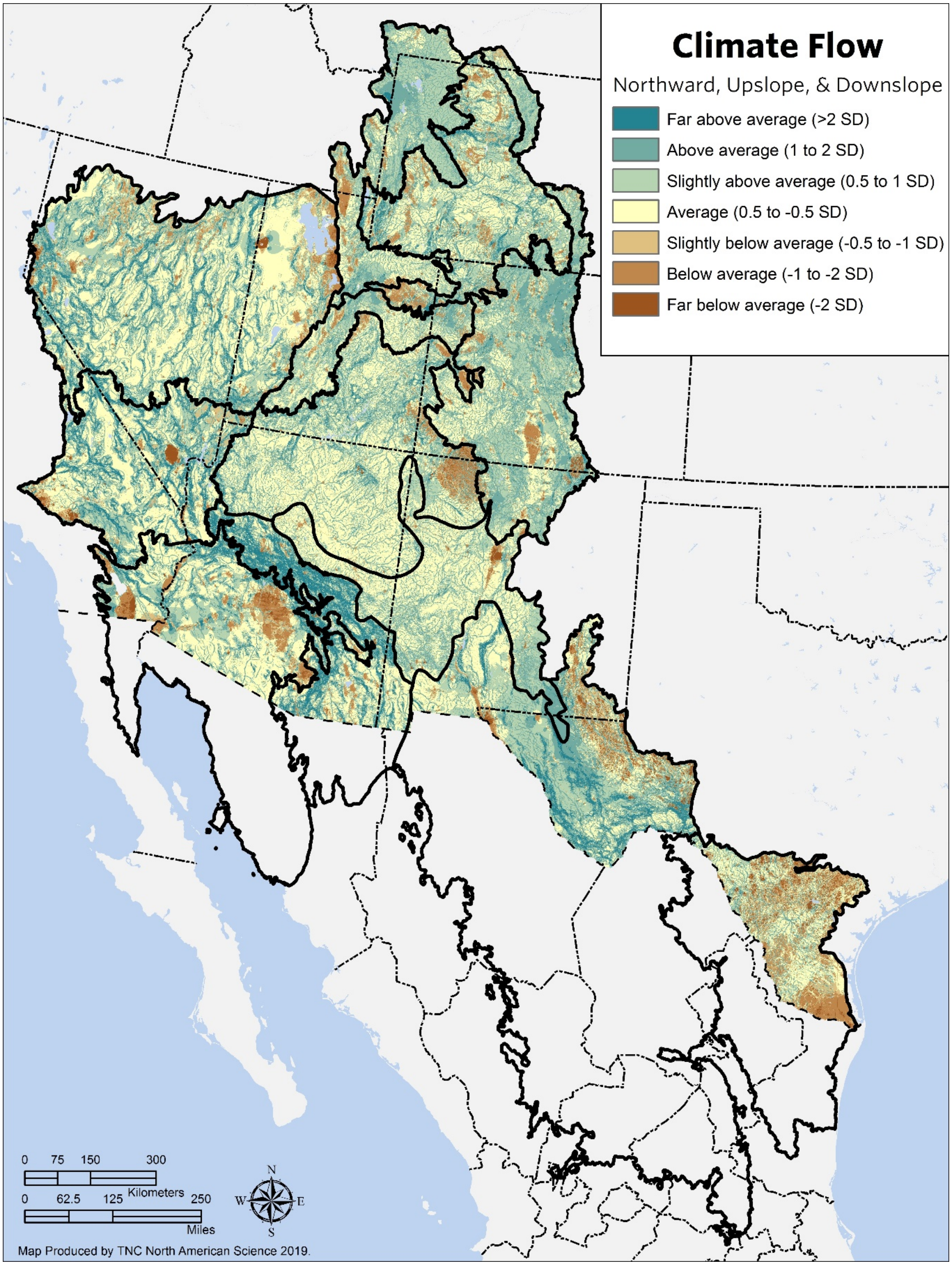


Figure 7.20: Climate flow model for West. The results of a Circuitscape analysis applied to the regional flow grid and weighted for above-average upslope flow, downslope flow or northward flow.

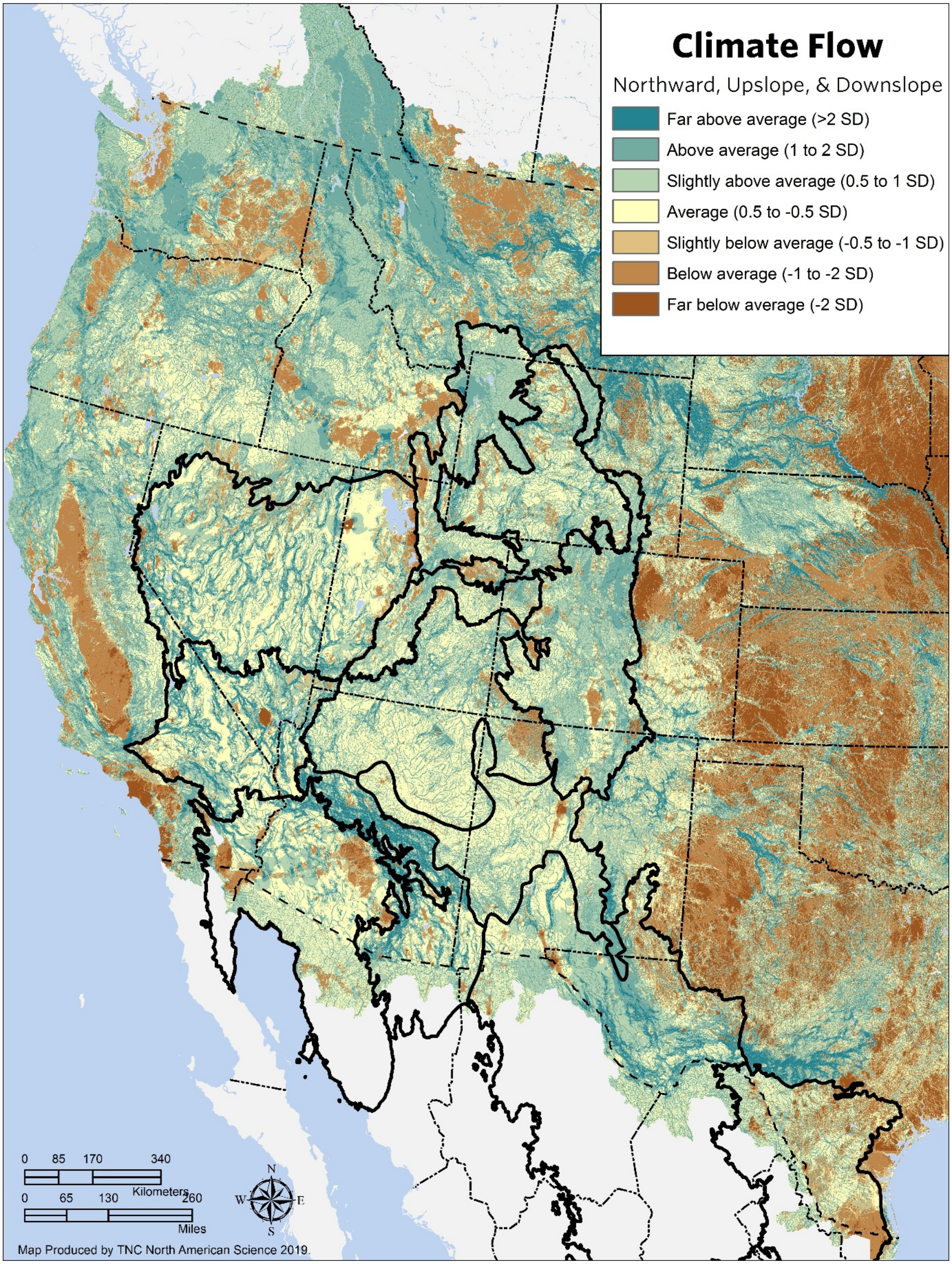


Figure 7.21: Comparision of results. These maps for the Canyonlands region of Utah compare the Circuitscape results for Regional Flow based on anthropogenic resistance only, with the enhanced versions that include upslope flow, downslope flow, northward flow and the integrated Climate Flow.

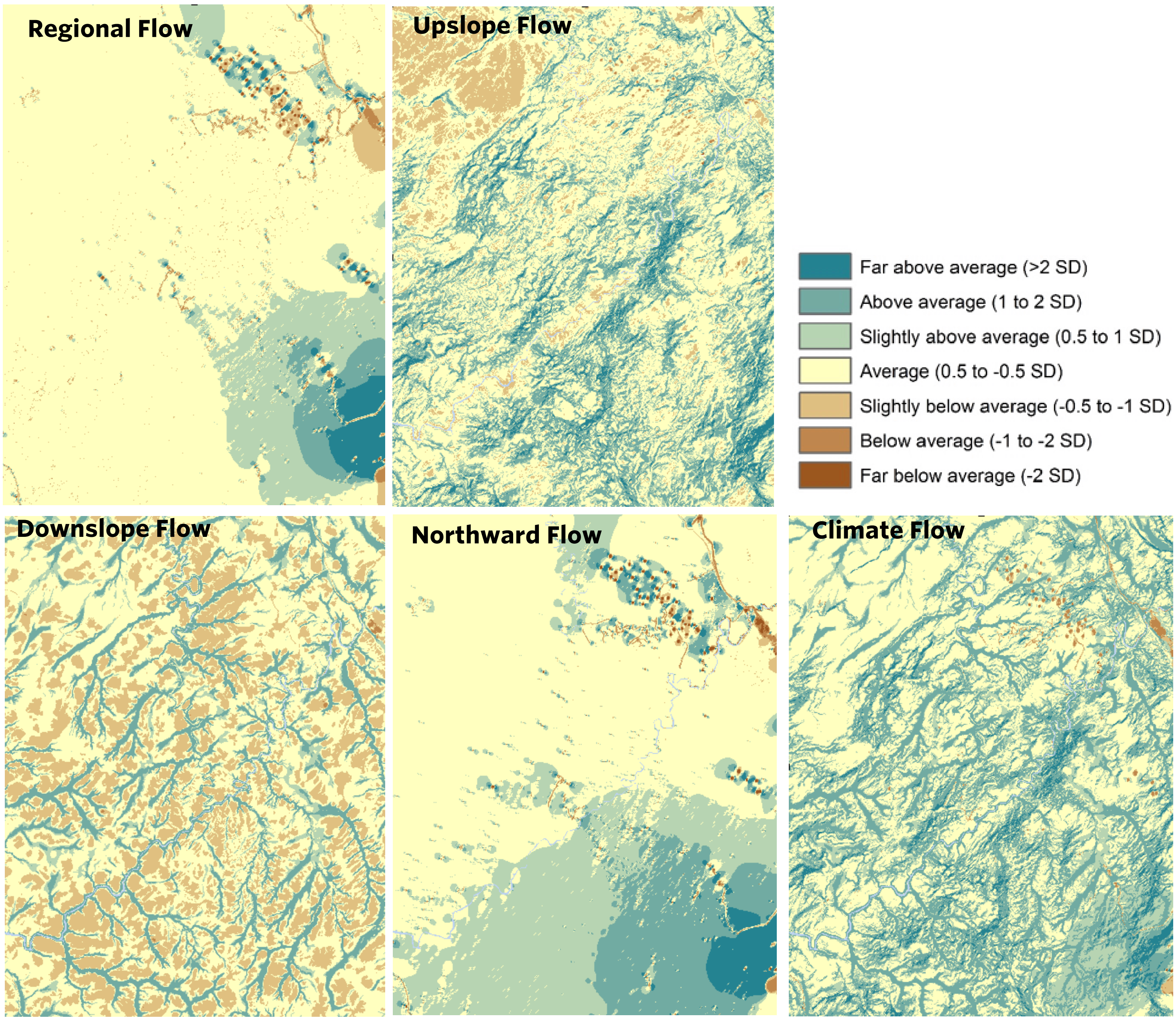


Figure 7.22. Classified Climate flow for Study Area. The results of classifying the climate flow map into 6 categories of flow density and spread.

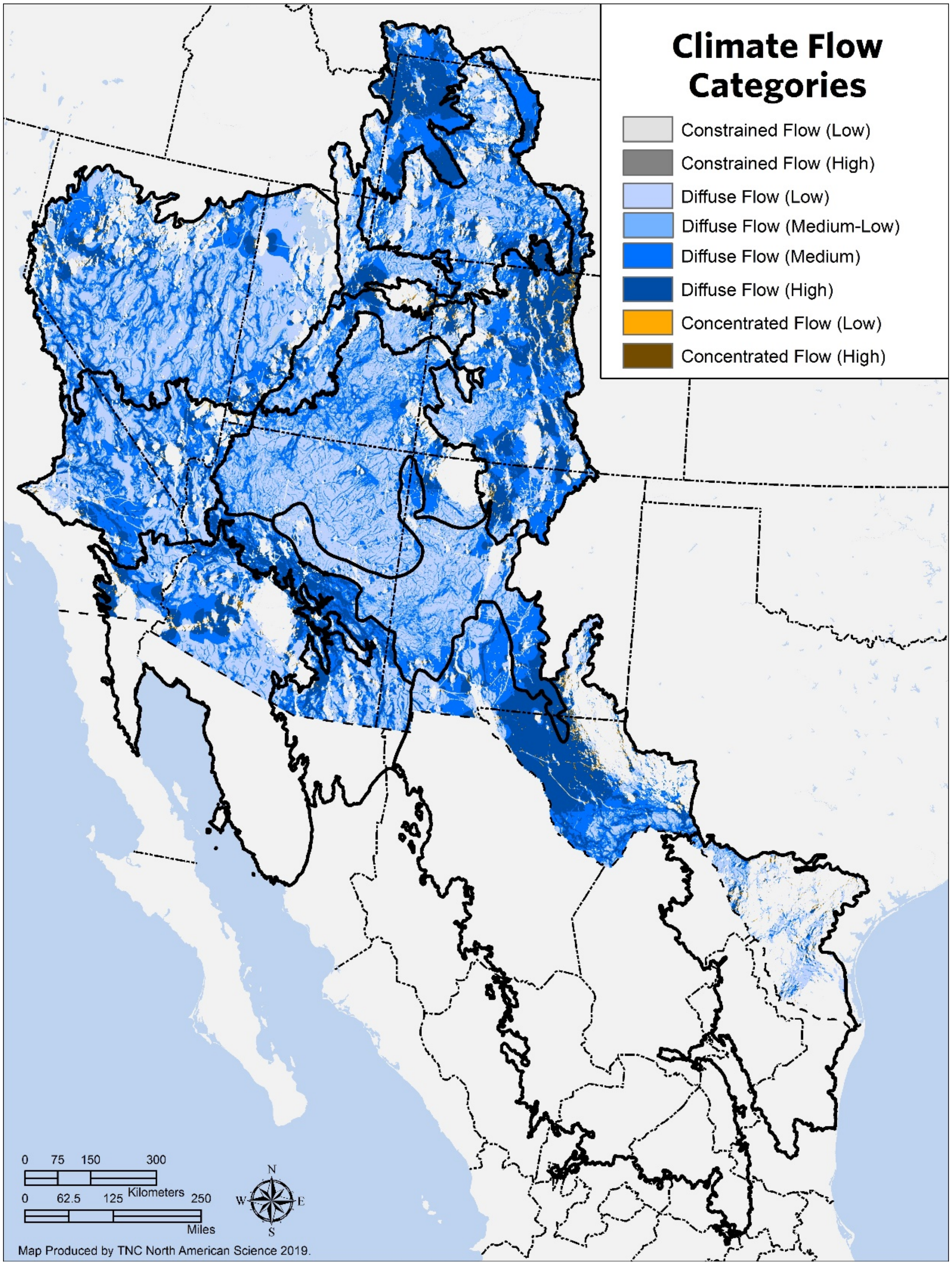
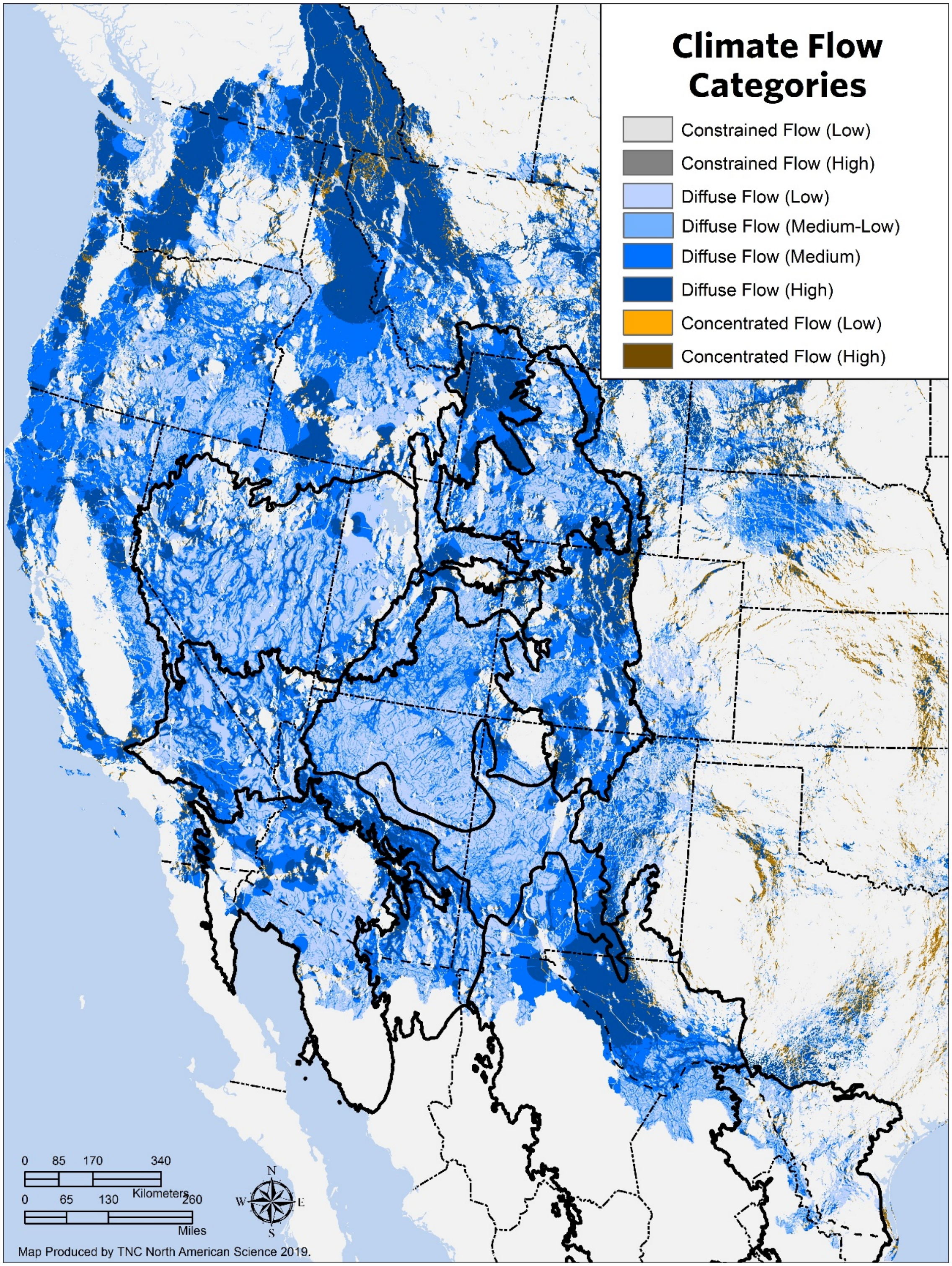


Figure 7.23. Classified Climate flow for Study Area. The results of classifying the climate flow map into 6 categories of flow density and spread



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 of climate resilience sites that contained the maximum amount of thriving biodiversity. Thus, in this section, we prioritized sites that scored high for resilience and contained intact habitat, 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 that mapped 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 81 terrestrial ecoregions in the U.S. 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 occurrence (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 or were selected as part of a site selection algorithm using wall-to-wall hexagons. 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 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

We also obtained the national "roll-up" version of the TNC ecoregional portfolios (TNC 2012) and updated Wyoming Basin 2012 Portfolio and Mojave Desert Update (Randall et al. 20010). The revised portfolio data was overlaid on the spatially continuous map of resilience scores.

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 almost two-thirds of the total portfolio area with 18% scoring "below-average. Across the study area 49% (105 million acres) of the 219 million acres of resilient land was identified as having confirmed diversity value from the TNC portfolios.

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 portfolios. 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.

Table 8.1. List of TNC Ecoregional Plans compiled for this study.

Ecoregion	Ecoregional Plan
Apache Highlands	Marshall, R.M., D. Turner, A. Gondor, D. Gori, C. Enquist, G. Luna, R. Paredes Aguilar, S. Anderson, S. Schwartz, C. Watts, E. Lopez, P. Comer. 2004. An Ecological Analysis of Conservation Priorities in the Apache Highlands Ecoregion. Prepared by The Nature Conservancy of Arizona, Instituto del Medio Ambiente y el Desarrollo Sustentable del Estado de Sonora , Agency and Institutional partners. 152.pp.
Arizona - New Mexico Mountains	Bell, G, J. Baumgartner, J. Humke, A. Laurenzi, P. McCarthy, P. Mehlhop, K. Rich, M. Silbert, E. Smith, B. Spicer, T. Sullivan, and S. Yanoff. 1999. Ecoregional Conservation Analysis of the Arizon-New Mexico Mountains. Arizona-New Mexico Ecoregional Conservation Team. The Nature Conservancy. Santa Fe, New Mexico.
Chihuahuan Desert	The Nature Conservancy, 2004. Ecoregional Conservation Assessment of the Chichuahan Desert. Second Edition Revised 2004. Pronatura In partnership with The Nature Conservancy and The World Wildlife Fund.
Colorado Plateau	Tuhy, J., P. Comer, G. Bell, D. Dorfman, B. Neely, M. Lammert, S. Silbert, H. Humke, L. Whitham, B. Cholvin, and B. Baker. 2002. A Conservation Assessment of the Colorado Plateau Ecoregion. The Nature Conservancy Colardo Plateau Ecoregional Planning Team. Moab. Utah.
Great Basin	Nachlinger, J., K. Sochi, P. Comer, G. Kittel, and D. Dorfman. 2001. Great Basin: an ecoregion-based conservation blueprint. The Nature Conservancy, Reno, NV. 160 pp + appendices.
Mojave Desert	Randall, J. M., S.S. Parker, J. Moore, B. Cohen, L. Crane, B. Christian, D. Cameron, J. MacKenzie, K. Klausmeyer and S. Morrison. 2010. Mojave Desert Ecoregional Assessment. Unpublished Report. The Nature Conservancy, San Francisco, California. 106 pages + appendices. Available at: http://conserveonline.org/workspaces/mojave/documents/mojave-desert-ecoregional-2010/@@view.html.
Sonoran Desert	Marshall, R.M., S. Anderson, M. Batcher, P. Comer, S. Cornelius, R. Cox, A. Gondor, D. Gori, J. Humke, R. Paredes Aguilar, I.E., Parra, S. Schwartz. 2000. An Ecological Analysis of Conservation Priorities in the Sonoran Desert Ecoregion. Prepared by The Nature Conservancy Arizona Chapter, Sonoran Institute, and Instituto del Medio Ambiente y el Desarrollo Sustentable del Estado de Sonora with support from Department of Defense Legacy Program, Agency and Institutional partners. 146 pp
Southern Rocky Mountains	Neely, B., P. Comer, C. Moritz, M. Lammert, R. Rondeau, C. Pague, G. Bell, H. Copeland, J. Humke, S. Spackman, T. Schulz, D. Theobald, and L. Valutis. 2001. Southern Rocky Mountains: An Ecoregional Assessment and Conservation Blueprint. Prepared by The Nature Conservancy with support from the U.S. Forest Service, Rocky Mountain Region, Colorado Division of Wildlife, and Bureau of Land Management.
Tamaulipan Thornscrub	The Nature Conservancy and Pronatura Noreste. 2010. A Conservation Blueprint for the Tamaulipan Thornscrub Ecoregion. Tamaulipan Thornscrub Ecoregional Planning Team, The Nature Conservancy, San Antonio, TX.
Utah High Plateaus	Comer, P., Tuhy, J. and R. Esselman, 2006. Scenario Building in the Utah High Plateaus Ecoregion. Case Study in Ecoregion Asessments and Biodiverity Vision Toolbox. The Nature Conservancy
Utah-Wyoming Rocky Mountains	Noss, R., Wuerthner, G, Vance-Borland, K., and Carroll, C. 2001. A Biological Conservation Assessment for the Utah-Wyoming Rocky Mountains Ecoregion: Report to The Nature Conservancy. Conservation Science, Inc. Corvallis, OR. USA.
Wyoming Basins	Sochi, K., M. Heiner, H. Copeland, A. Pocewicz, and J. Keisecker. 2013. Systematic Conservation Planning in the Wyoming Basins. The Nature Conservancy. Boulder, CO. 134pp.

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" (COA), 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. Details on the sources of data for each state are shown in Table 8.2.

Additional Biodiversity Sources

We supplemented the TNC ecoregional portfolio data and State Wildlife Action Plans (SWAPs) with a few additional sources of biodiversity data. We obtained all sage-grouse Priority Areas for Conservation identified in the 2013 Greater Sage-Grouse Conservation Objectives Team Report (USFWS, 2014). These are areas identified as essential for the long-term conservation of the sage-grouse in Montana, Idaho, Colorado, Wyoming, Utah, and Nevada. We also extracted polygons from the TNC

Table 8.2. Spatial data from State Wildlife Action Plan (SWAP)s or similar state assessments, to identify wildlife/biodiversity priority areas.

Note: Most datasets were obtained directly from SWAP coordinators (current contact info can be found on the web pages that we link to for each state), but in cases where these data are publicly posted, we have included the web link. Acronyms: SGCN = Species of Greatest Conservation Need; COA = Conservation Opportunity Area.

State & plan date, Title of map	Comments & link to the plan and dataset if publicly posted
Arizona	No Statewide SWAP available. Used portions of statewide grasslands study: http://azconservation.org/downloads/category/grassland_assessment A GIS data set depicting the results of a two-year study to delineate grasslands and evaluate their ecological condition in Arizona, southwestern New Mexico, and northern Mexico. This study was completed with the assistance of resource professionals from U.S. and Mexico universities and public agencies. We extracted class "A", "B", "A&B", these are native grasslands based on this statewide field survey. The Nature Conservancy. Arizona. 2004.
Colorado (2015): Crucial Habitat for Tier 1 Terrestrial Animal and Plant SGCN (Figure 21).	The state was mapped into 5 priority levels for crucial habitat for SGCN, and we incorporated the two highest levels into our composite SWAP map. Details on the map methodology are in Chapter 8 of the Colorado plan. http://cpw.state.co.us/aboutus/Pages/StateWildlifeActionPlan.aspx
Montana (2015): Tier 1 Terrestrial Focal Areas (Fig. 133)	The plan delineates habitat (plant communities) of most critical conservation need as well as SGCN, emphasizing SGCN with state ranks of S1 or S2. The plan notes differences in the process east and west of Continental Divide; the east focused more on intact landscapes, while teams in the west focused more on connectivity between protected areas. http://fwp.mt.gov/fishAndWildlife/conservationInAction/actionPlan.html
New Mexico (2016):	Defined as areas considered to have superior potential for conserving SGCN. Incorporates priority habitats from assessments with the New
Nevada (2017)	Focal areas identified in the Nevada Wildlife Action Plan (2012) as discrete landscape units that provide a framework for evaluating the WAP in a statewide context. Feature Layer by cvandellen Created: Mar 13, 2017 Updated: Mar 13, 2017
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.
Wyoming (2010): No map in the 2017 revision, but we incorporated SGCN priority areas from the 2010 plan.	Wyoming defined COAs in the 2010 SWAP based on a MARXAN analysis of priority habitats for SCGN for a suite of habitat types (input maps are shown in Figs 1-10 and 15 in the 2010 plan). This prioritization was not included in the 2017 SWAP revision, as stakeholders in Wyoming preferred access to input datasets on overlap in SCGN ranges, landscape intactness, etc., rather than the final prioritization product. We included this 2010 product but note that this is not a product that WY is currently using to guide implementation. Links to the 2017 and the 2010 plan: https://wgfd.wyo.gov/Habitat/Habitat-Plans/Wyoming-State-Wildlife-Action-Plan

secured lands layer which represented areas of high biodiversity management and value. This included all GAP 1 and 2 Land, National Park Service National Parks and Wilderness, USFS Research Natural Areas, Wilderness, Proposed Wilderness, and National Forest Roadless Areas; USFWS Wilderness, National Wildlife Refuge; BLM Wilderness areas, Research Natural Areas, National Monuments (geodiversity); and The Nature Conservancy fee and easement lands. This was an important step because in some of the TNC portfolios, existing biodiversity areas that were already protected (such as Yosemite National Park) were excluded from the portfolio map to focus on new protection.

Collectively the biodiversity data identified land with intact habitat, viable species populations, unique communities or sage grouse priorities. The SWAP lands and additional biodiversity sources areas added another 61 million acres beyond the TNC Portfolio Lands as confirmed biodiversity areas (Figure 8.1)

Biodiversity and Resilience

The biodiversity areas were intersected with the resilience map to estimate the amount of resilient land recognized for its current biodiversity values (Figure 8.2). The amount varied by ecoregion and ranged from a low of 46% in the Arizona-New Mexico Mountains to a high of 95% in the Mojave Desert. Over the entire study area, the confirmed biodiversity areas comprised 65% of the resilient area and 58% of the total land assessed (Table 8.3).

Figure 8.1. Biodiversity areas. Areas recognized for their biodiversity value in TNC portfolio, State Wildlife Action Plans and other sources

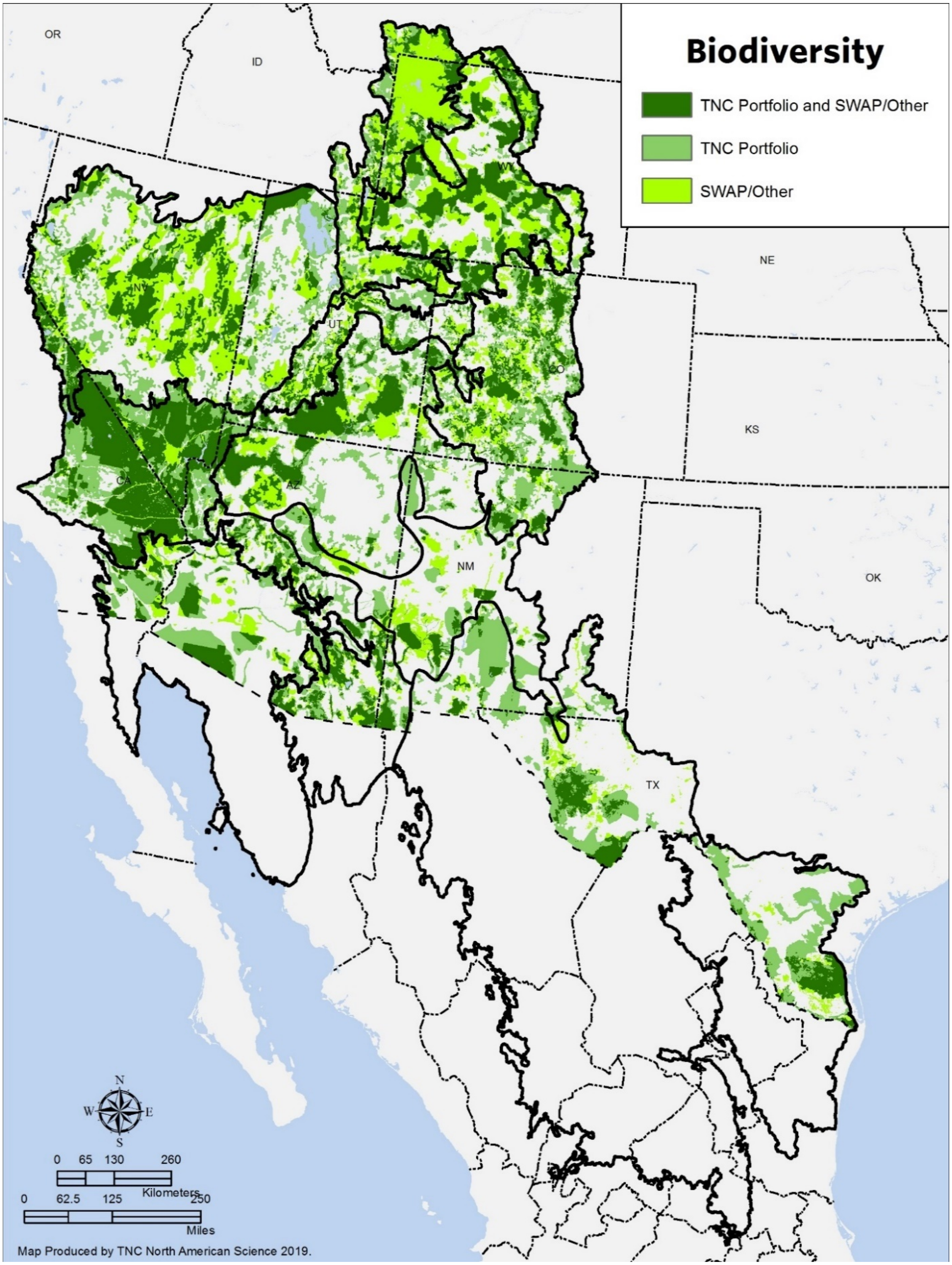


Figure 8.2. Biodiversity Areas by Site Resilience.

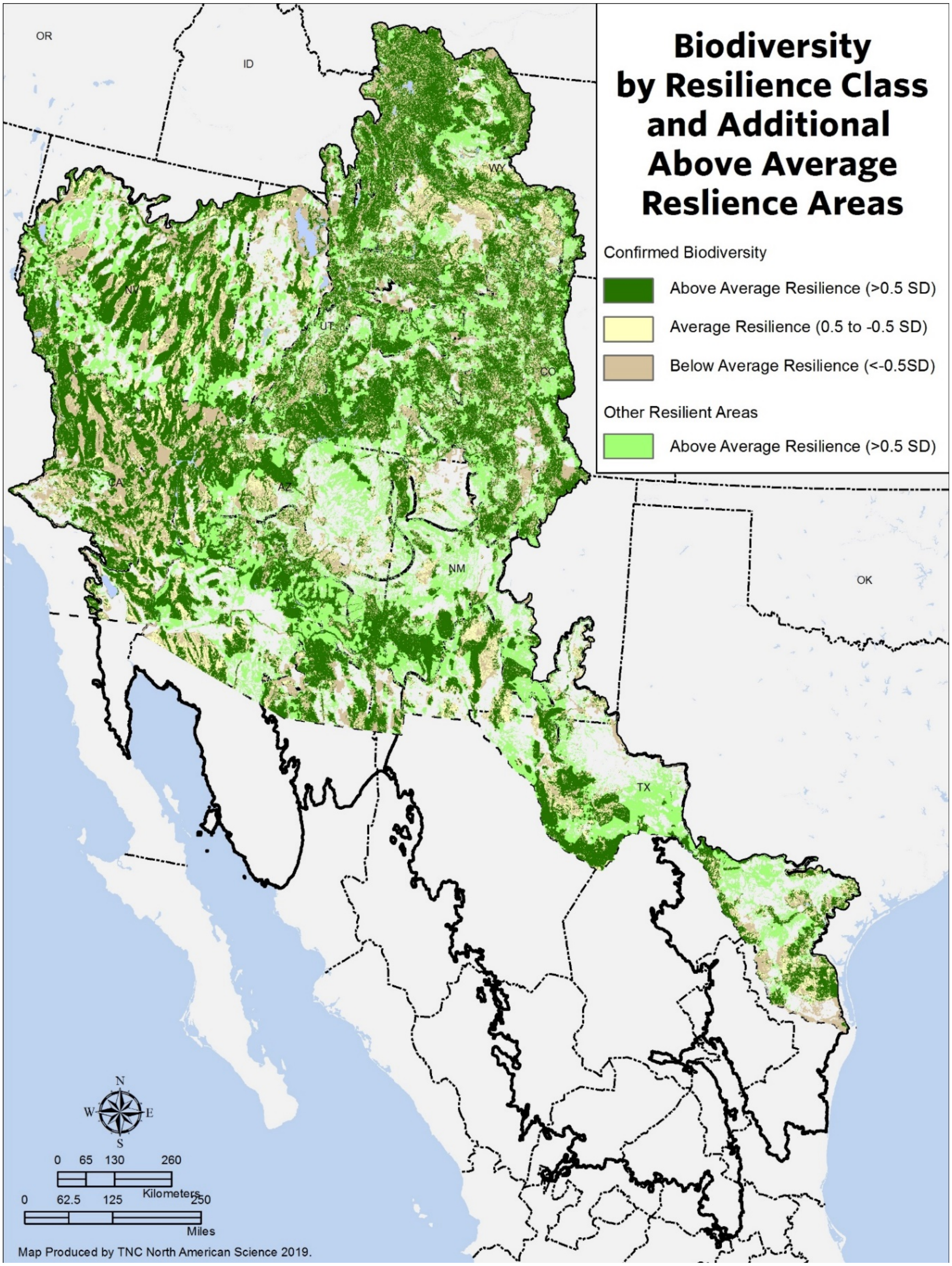


Table 8.3. Percent overlap of biodiversity areas with resilient sites. The final column is the proportion of resilient land identified as having confirmed biodiversity value. Resilient area indicates the amount of the ecoregion that scored above-average for resilience (>0.5 SD). % Biodiversity indicates the amount of the ecoregion that was confirmed for biodiversity by our biodiversity sources.

Region	Ecoregion	Total Acres	% Resilient	% Biodiversity	% Resilient Land that is Confirmed Biodiveristy
Mountains	Arizona-New Mexico Mountains	28,789,040	59%	38%	46%
	Southern Rocky Mountains	39,929,530	66%	63%	66%
	Utah High Plateaus	11,342,944	65%	61%	62%
	Utah-Wyoming Rocky Mountains	27,057,074	68%	86%	88%
Mountains Total		107,118,588	64%	62%	67%
Cold Deserts	Colorado Plateau	48,556,189	51%	46%	57%
	Great Basin	72,411,104	53%	60%	66%
	Wyoming Basins	33,027,171	52%	69%	72%
Cold Deserts Total		153,994,463	52%	57%	65%
Warm Deserts	Apache Highlands	20,644,528	65%	57%	61%
	Chihuahuan Desert	38,578,326	44%	38%	49%
	Mojave Desert	32,279,964	51%	89%	95%
	Sonoran Desert	28,668,985	49%	48%	58%
Warm Deserts Total		120,171,804	51%	58%	66%
Tamaulipan Thorn Scrub	Tamaulipan Thorn Scrub	19,645,427	37%	47%	53%
Grand Total		400,930,282	55%	58%	65%

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.

In this section we prioritize among the 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 see Figure 5.11). 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 52% of the study area is in some form of permanent securement, so the greatest challenges will be on sustainably managing the network.

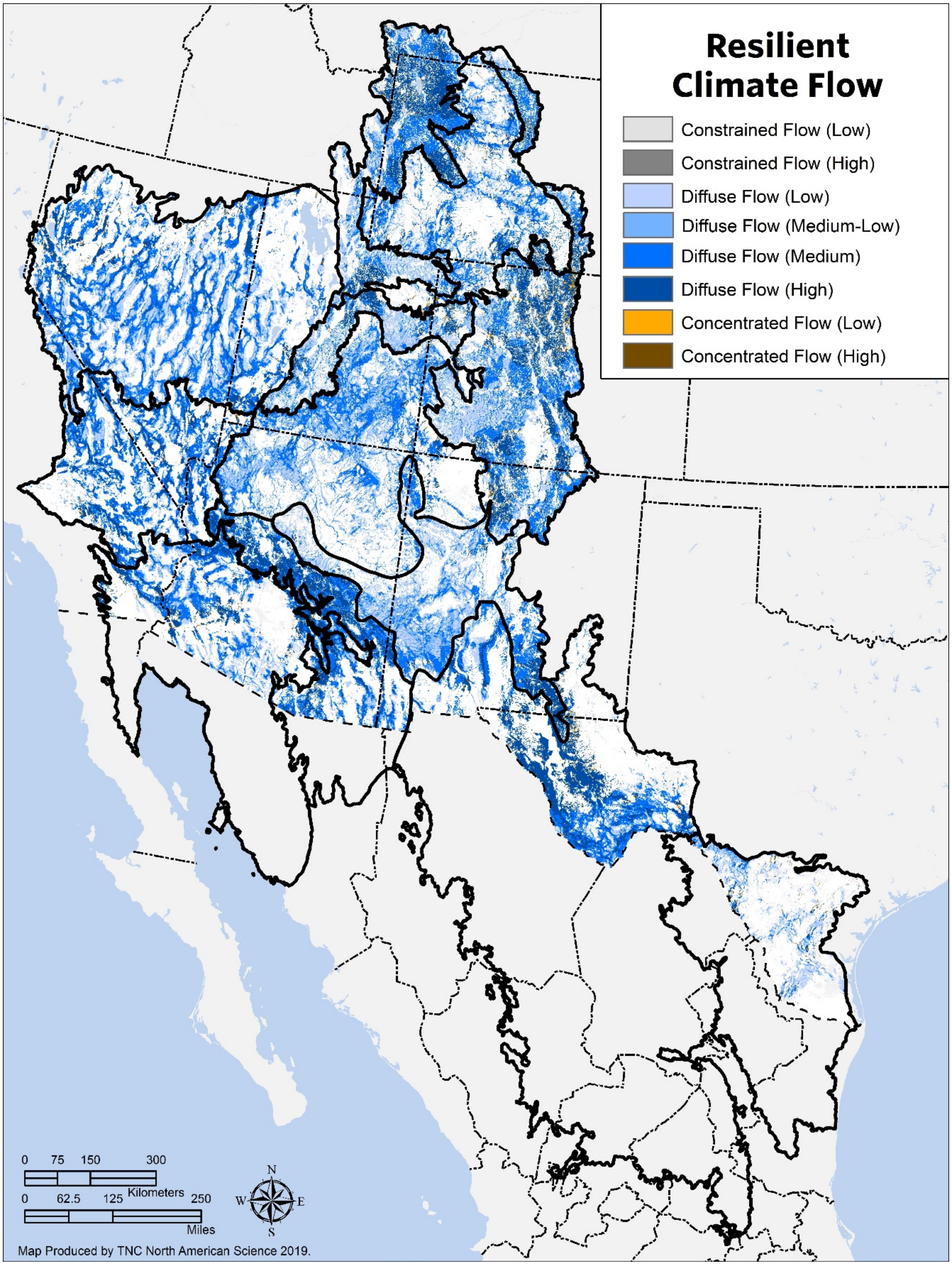
Site Prioritization: Resilience, Flow, and Diversity

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). We could also study and map any of the 42 possible combinations of resilience and flow: eight levels of resilience scores and seven types of flow based on pattern and intensity.

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 highlights potentially important areas of moderate upslope or downslope flow within the relatively intact landscape. Collectively the selected areas covered 38% 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

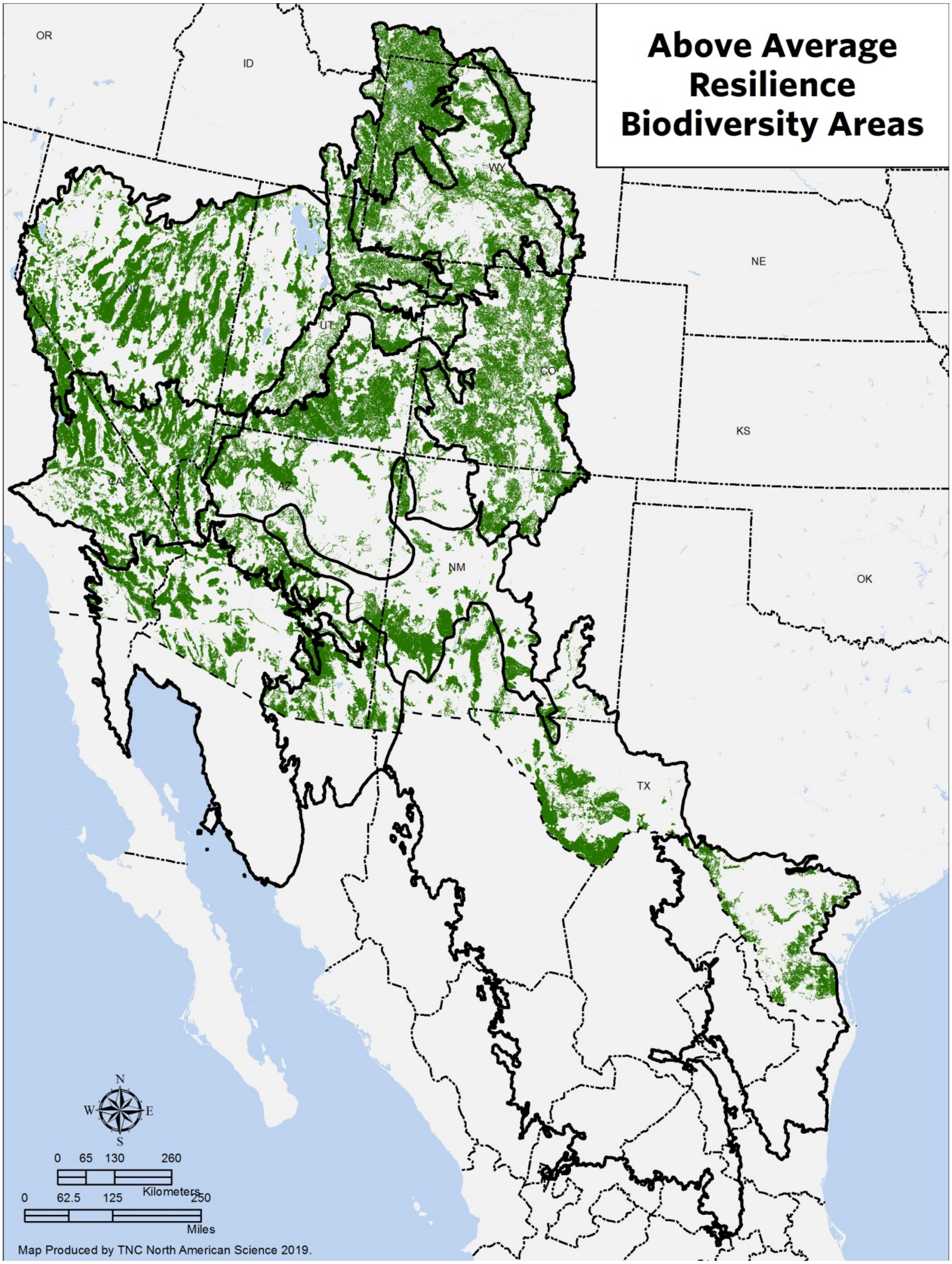
The biodiversity criteria identified the resilient portions of sites that have been recognized for their conservation value by other independent studies, namely the TNC ecoregional portfolio sites or the State Wildlife Action Plan sites (Figure 9.2). In total, the resilient biodiversity sites covered 37% of the study region, with most of them (26%) also overlapping with the flow network. The remaining 10% were 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 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 Network (RCN)

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 of all the characteristic environments of the region while maximizing the current biodiversity and climate flow contained within the network. By building the network around the natural flows that allow species populations to shift, and 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 50% (201 million acres) plus another 4% (17 million acres) of resilient land. Just under three quarters of the network (74%) met all three criteria: flow, confirmed diversity, and resilience. The rest of the area met at least two criteria: flow and resilience (12%) or confirmed diversity and resilience (10%). Only 2% 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** **50%**
    - Climate Corridor <1%
    - Climate Corridor with Confirmed Biodiversity <1%
    - Climate Flow Zone 12%
    - Climate Flow Zone with Confirmed Biodiversity 26%
    - Resilient w Confirmed Biodiversity 10%
    - Resilient Secured 2%

- **Resilient Only (not in Network)** 4%

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 prioritized resilient areas. This amount of each ecoregion's land identified by the respective network classes. The RCN covers 50% of the region (Ranged 66% to 24%).

	Outside of Network			Resilient and Connected Network							Grand Totals		
Ecoregions	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	Total Water Acres	Grand Total Acres
Apache Highlands	63,832	7,207,389	359,709	21,474	20,162	4,611,922	7,167,632	975,466	212,666	13,009,321	20,640,251	4,277	20,644,528
Arizona-New Mexico Mountains	133,248	11,772,620	2,270,838	37,375	31,332	5,589,243	5,365,416	2,444,753	1,129,414	14,597,532	28,774,238	14,802	28,789,040
Chihuahuan Desert	181,301	21,318,297	1,934,913	165,945	78,805	6,075,183	7,272,883	1,022,698	484,955	15,100,470	38,534,980	43,346	38,578,326
Colorado Plateau	123,564	23,297,520	2,774,668	44,866	51,119	6,985,903	10,275,453	3,831,354	1,005,369	22,194,065	48,389,817	166,371	48,556,189
Great Basin	366,914	32,362,174	1,273,764	129,202	159,781	8,854,885	16,892,355	8,572,259	2,745,483	37,353,964	71,356,817	1,054,287	72,411,104
Mojave Desert	288,241	15,355,742	233,597	17,323	96,068	433,768	12,895,646	2,748,571	74,554	16,265,930	32,143,509	136,455	32,279,964
Sonoran Desert	502,078	13,823,108	1,593,657	83,801	76,610	3,658,554	5,989,153	2,074,217	572,505	12,454,841	28,373,683	295,303	28,668,985
Southern Rocky Mountains	116,234	13,349,559	1,687,716	375,359	436,494	5,960,770	12,890,123	3,990,228	987,650	24,640,623	39,794,132	135,398	39,929,530
Tamaulipan Thorn Scrub	203,135	11,975,372	2,625,982	51,929	84,809	770,450	863,989	2,926,712	347	4,698,236	19,502,724	142,703	19,645,427
Utah High Plateaus	23,260	3,888,086	436,927	64,780	51,960	1,634,162	2,797,253	1,729,836	692,568	6,970,558	11,318,831	24,112	11,342,944
Utah-Wyoming Rocky Mountains	64,976	8,363,079	563,186	23,478	176,025	1,329,227	12,112,111	3,903,446	227,680	17,771,967	26,763,209	293,866	27,057,074
Wyoming Basins	95,976	15,434,911	1,122,084	128,038	225,108	2,755,998	7,901,626	4,241,452	821,479	16,073,700	32,726,670	300,500	33,027,171
Grand Total	2,162,757	178,147,856	16,877,041	1,143,568	1,488,276	48,660,063	102,423,640	38,460,991	8,954,670	201,131,207	398,318,862	2,611,420	400,930,282

Ecoregions	Outside of Network		Resilient and Connected Network							
	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	Network % Total Area
Apache Highlands	0%	35%	2%	0%	0%	22%	35%	5%	1%	63%
Arizona-New Mexico Mountains	0%	41%	8%	0%	0%	19%	19%	8%	4%	51%
Chihuahuan Desert	0%	55%	5%	0%	0%	16%	19%	3%	1%	39%
Colorado Plateau	0%	48%	6%	0%	0%	14%	21%	8%	2%	46%
Great Basin	1%	45%	2%	0%	0%	12%	24%	12%	4%	52%
Mojave Desert	1%	48%	1%	0%	0%	1%	40%	9%	0%	50%
Sonoran Desert	2%	49%	6%	0%	0%	13%	21%	7%	2%	43%
Southern Rocky Mountains	0%	34%	4%	1%	1%	15%	32%	10%	2%	62%
Tamaulipan Thorn Scrub	1%	61%	13%	0%	0%	4%	4%	15%	0%	24%
Utah High Plateaus	0%	34%	4%	1%	0%	14%	25%	15%	6%	61%
Utah-Wyoming Rocky Mountains	0%	31%	2%	0%	1%	5%	45%	15%	1%	66%
Wyoming Basins	0%	47%	3%	0%	1%	8%	24%	13%	3%	49%
Grand Total	1%	45%	4%	0%	0%	12%	26%	10%	2%	50%

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 50% of the region and captures 96% of all the resilient sites.

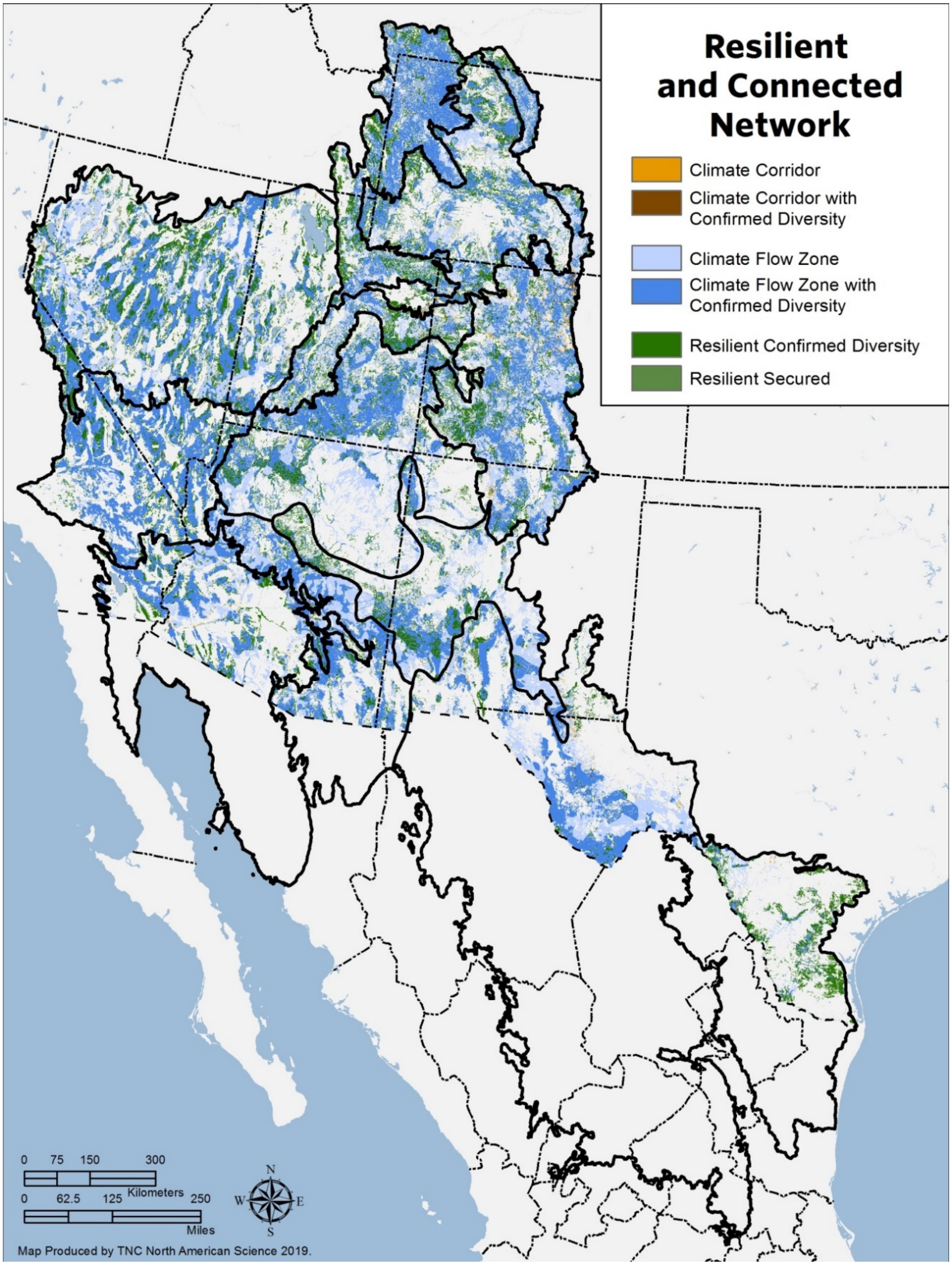


Figure 9.4: Resilient and Connected Network plus Other Resilient Land. This map shows the resilient and connected network (50%) plus other resilient areas (4%) that did not meet the criteria for confirmed biodiversity or climate flow.

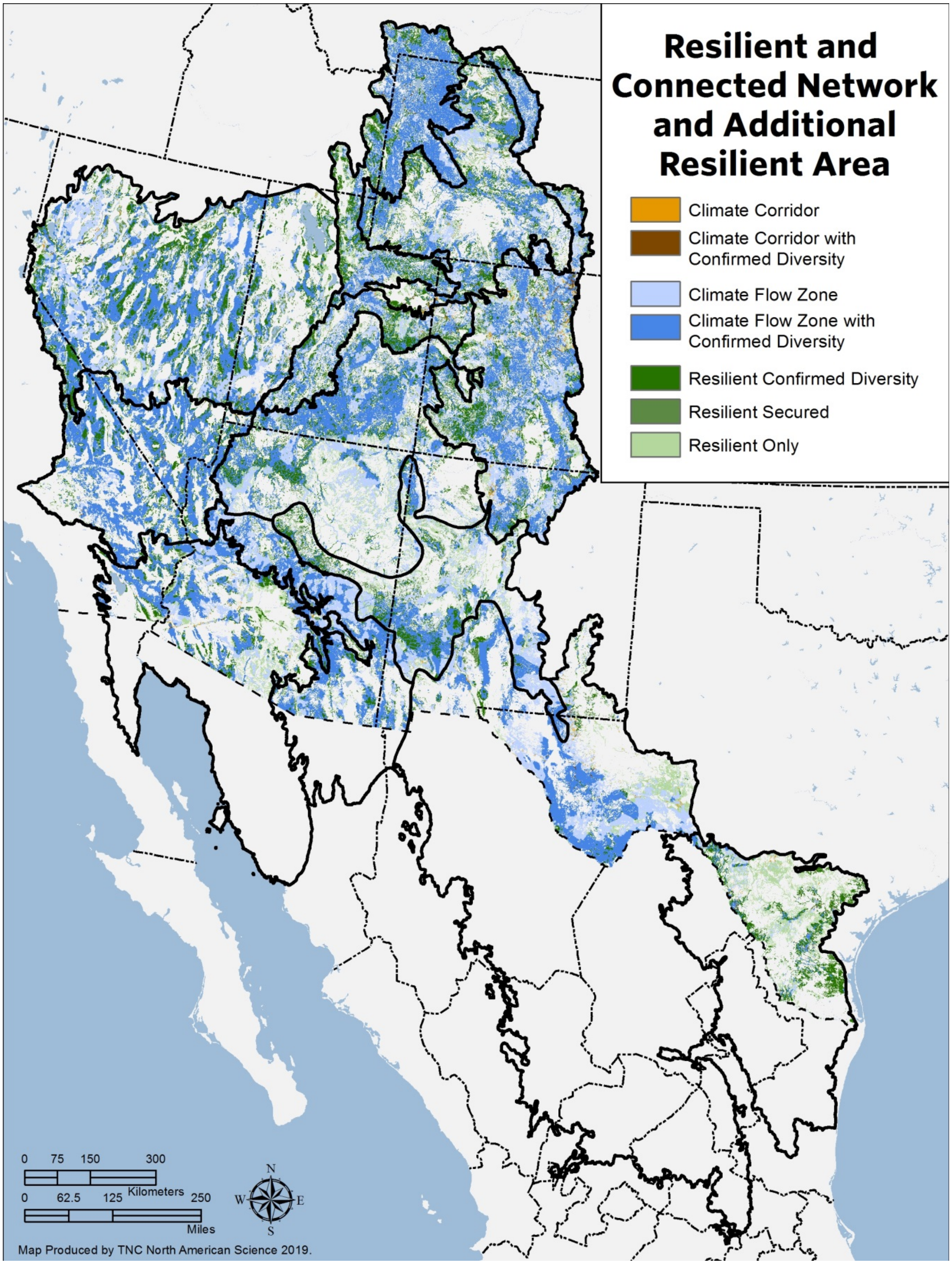


Figure 9.5: Continuous Map of Resilient and Connected Sites. This wall-to-wall map shows the resilient and connected network (50%), plus all other resilient sites (4%), plus all other categories of average, vulnerable or developed land (46%).

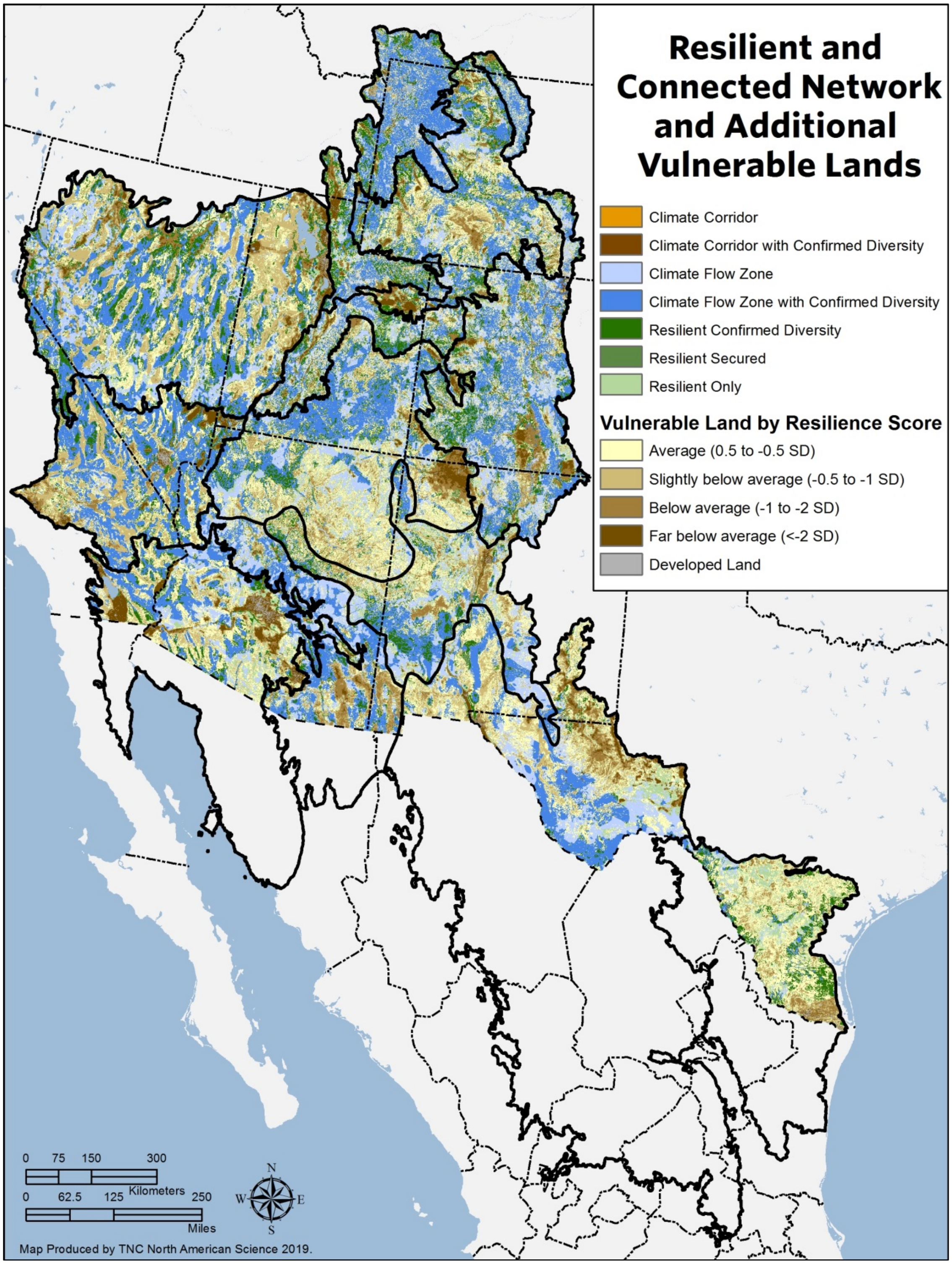
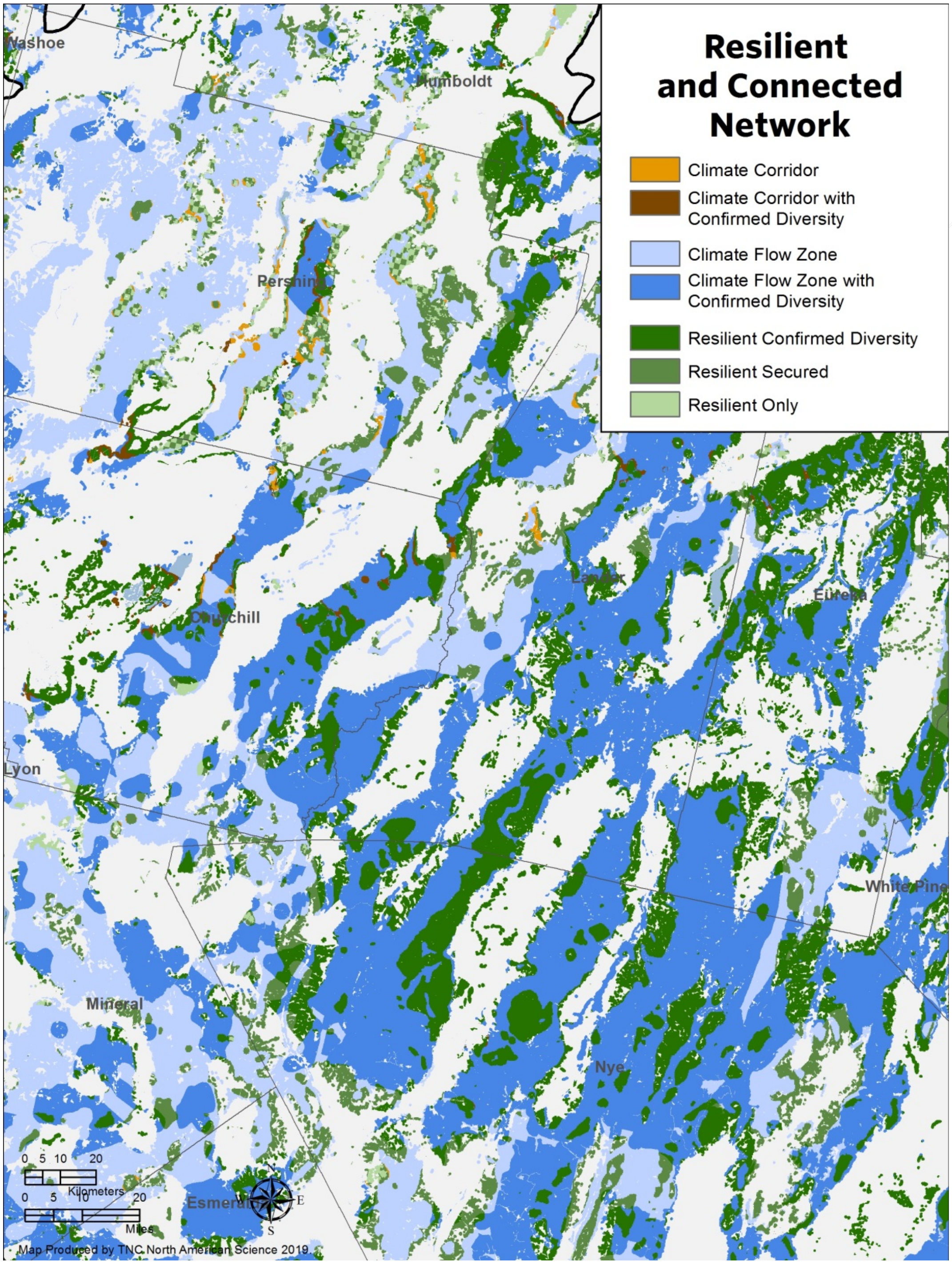


Figure 9.6: Zoom-in Great Basin Ecoregion. This map shows the resilient and connected network and other resilient land in parts of Nevada counties of Pershing, Churchill, Mineral, Nye, Lander, Eureka and their environs. Climate corridors and flow zones with confirmed diversity are in darker colors.



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 several settings were under-represented in the network. These settings may require further protection or restoration and sustained management to ensure that they retain their natural diversity into the future.

Estimated of the percent representation of each setting in the resilient and connected network show wide variation (Table 9.2 Figure 9.7). High elevation life zones are well represented: Alpine (82%), Subalpine (71%), Upper Montane (67%), Lower Montane (79%). Lower elevation lowlands and basins have lower representation (46%-47%) and the Tropical Lowlands have the lowest (24%).

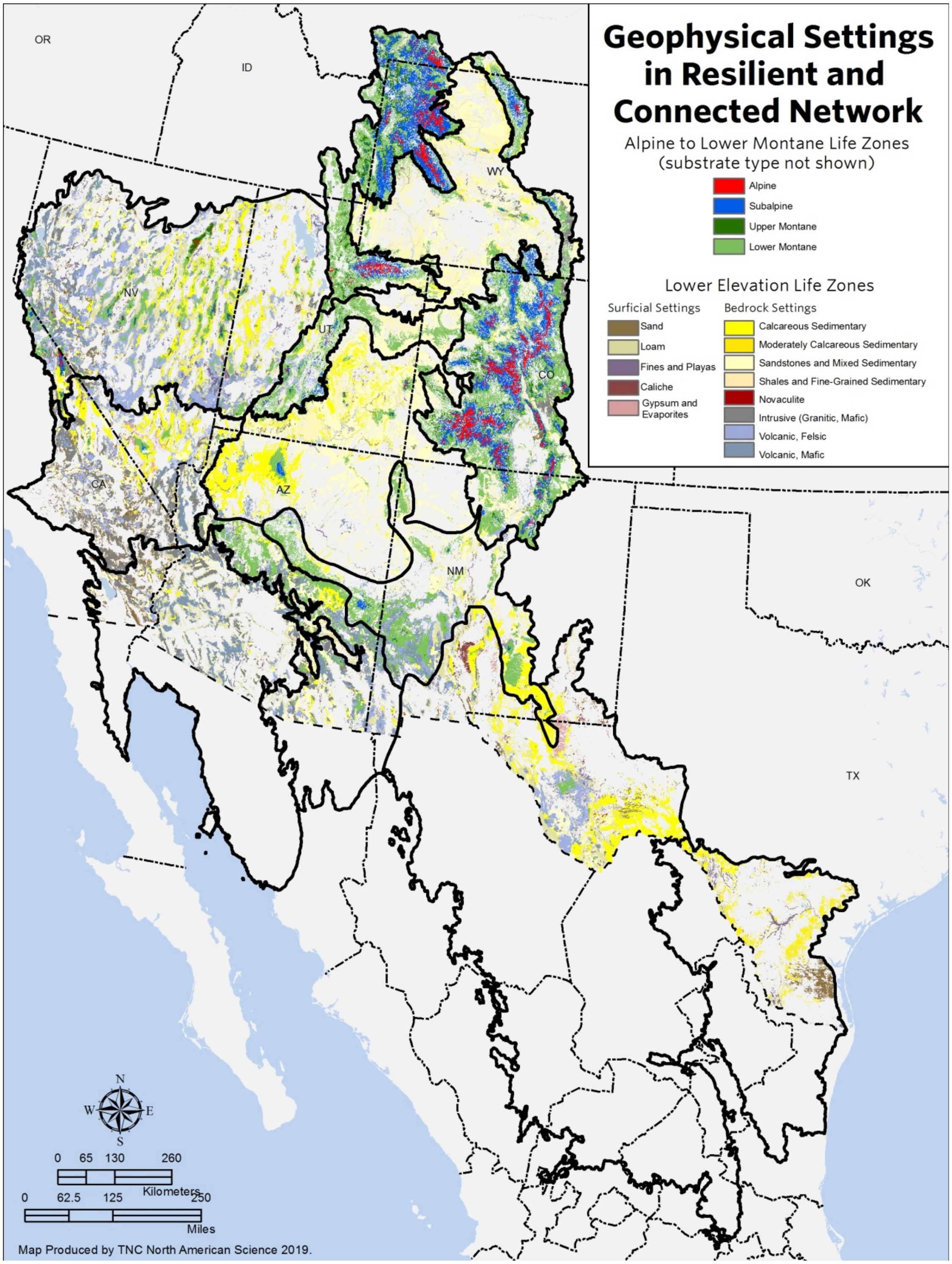
Among the low elevation settings, Fine sediment and playa settings have the lowest representation in the network (16%-17%). Other less well represented soil types in the lowland regions include sand (15%-37%) and loam (21%-32%). Bedrock settings are well represented ranging from 32%-93%.

Table 9.2: Representation of Geophysical Settings in Network.

		RCN		Distribution Across RCN						Not in RCN		
Geological Setting	Total Land	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
ALPINE	4,089,464	3,356,514	82%	0%	0%	3%	60%	18%	1%	1%	17%	0%
Calcareous Sedimentary	211,420	159,678	76%	0%	0%	3%	51%	21%	0%	0%	24%	0%
Fines and Playas	1,154	985	85%	0%	0%	14%	30%	42%	0%	0%	15%	0%
Intrusives (Granitic, Mafic)	1,901,247	1,582,167	83%	0%	0%	3%	68%	11%	0%	0%	17%	0%
Loams	197,396	153,935	78%	0%	0%	3%	50%	23%	1%	1%	21%	0%
Sandstones and Mixed Sedimentary	566,535	437,180	77%	0%	0%	3%	41%	33%	1%	1%	22%	0%
Shale and Fine-Grained Sedimentary	21,646	16,537	76%	0%	0%	3%	61%	10%	3%	0%	24%	0%
Volcanic, Felsic	302,787	249,504	82%	0%	0%	4%	38%	38%	2%	0%	17%	0%
Volcanic, Mafic	887,279	756,528	85%	0%	0%	2%	65%	14%	3%	1%	13%	0%
SUBALPINE	17,215,654	12,215,140	71%	0%	0%	9%	53%	6%	1%	0%	28%	0%
Calcareous Sedimentary	1,699,207	1,233,301	73%	0%	0%	10%	53%	8%	1%	0%	27%	0%
Fines and Playas	64,216	42,418	66%	0%	0%	17%	19%	18%	11%	0%	34%	0%
Intrusives (Granitic, Mafic)	5,094,871	3,730,703	73%	0%	1%	10%	56%	5%	1%	0%	26%	0%
Loams	2,503,463	1,640,299	66%	0%	1%	8%	50%	6%	1%	1%	33%	0%
Sandstones and Mixed Sedimentary	2,972,703	2,002,130	67%	0%	0%	9%	47%	8%	2%	1%	32%	0%
Shale and Fine-Grained Sedimentary	436,177	277,793	64%	0%	0%	11%	48%	4%	0%	1%	36%	0%
Volcanic, Felsic	1,524,066	990,549	65%	0%	0%	11%	42%	9%	3%	0%	35%	0%
Volcanic, Mafic	2,920,950	2,297,947	79%	0%	0%	7%	65%	6%	1%	0%	21%	0%
UPPER MONTANE	6,883,586	4,644,411	67%	0%	1%	12%	43%	10%	2%	1%	31%	0%
Calcareous Sedimentary	682,012	515,815	76%	0%	0%	12%	42%	19%	2%	1%	23%	0%
Fines and Playas	107,723	51,021	47%	0%	0%	16%	28%	3%	1%	1%	51%	0%
Intrusives (Granitic, Mafic)	936,811	761,528	81%	0%	0%	13%	55%	12%	1%	1%	18%	0%
Loams	978,381	628,365	64%	0%	3%	8%	43%	10%	1%	1%	35%	0%
Sand	1,309	772	59%	0%	0%	33%	26%	0%	0%	0%	39%	2%
Sandstones and Mixed Sedimentary	1,868,979	1,196,608	64%	0%	0%	13%	39%	9%	3%	2%	34%	0%
Shale and Fine-Grained Sedimentary	593,247	354,433	60%	0%	0%	15%	38%	6%	1%	2%	38%	0%
Volcanic, Felsic	950,049	632,787	67%	0%	1%	9%	49%	7%	1%	0%	33%	0%
Volcanic, Mafic	765,074	503,082	66%	0%	0%	17%	39%	8%	2%	1%	33%	0%
LOWER MONTANE	50,919,086	35,731,899	70%	1%	1%	16%	36%	15%	3%	4%	26%	0%
Calcareous Sedimentary	8,763,290	6,827,828	78%	0%	0%	18%	37%	19%	3%	2%	20%	0%
Fines and Playas	431,044	172,830	40%	0%	0%	6%	17%	15%	2%	5%	55%	0%
Intrusives (Granitic, Mafic)	6,688,340	5,354,653	80%	2%	1%	23%	41%	11%	2%	4%	16%	0%
Loams	4,490,440	2,226,582	50%	0%	1%	7%	25%	15%	1%	4%	46%	1%
Sand	49,251	18,917	38%	0%	0%	1%	14%	23%	0%	1%	59%	1%
Sandstones and Mixed Sedimentary	14,645,639	9,701,342	66%	1%	1%	16%	32%	14%	3%	5%	29%	0%
Shale and Fine-Grained Sedimentary	4,024,858	2,670,017	66%	0%	1%	18%	31%	14%	3%	6%	28%	0%
Volcanic, Felsic	4,254,545	3,567,554	84%	0%	1%	9%	54%	18%	1%	1%	15%	0%
Volcanic, Mafic	7,571,678	5,192,176	69%	0%	0%	17%	35%	11%	4%	4%	27%	0%
MOUNTAIN LOWER BASIN	41,120,316	19,336,359	47%	1%	1%	16%	16%	11%	3%	8%	45%	1%
Calcareous Sedimentary	5,620,813	3,241,758	58%	0%	0%	27%	21%	7%	2%	5%	37%	0%
Fines and Playas	937,180	186,505	20%	0%	0%	8%	4%	7%	0%	7%	71%	1%
Gypsum and Evaporite	99,386	22,530	23%	0%	0%	18%	3%	2%	0%	1%	76%	0%
Intrusives (Granitic, Mafic)	1,899,492	1,400,657	74%	2%	5%	22%	31%	13%	2%	5%	20%	0%
Loams	7,810,291	2,141,894	27%	0%	0%	8%	7%	10%	2%	7%	64%	1%
Sand	937,979	145,089	15%	0%	1%	5%	6%	3%	0%	10%	73%	2%
Sandstones and Mixed Sedimentary	12,943,135	6,473,692	50%	1%	1%	15%	17%	12%	5%	10%	39%	0%
Shale and Fine-Grained Sedimentary	3,399,845	1,857,762	55%	1%	1%	16%	17%	16%	5%	7%	38%	0%
Volcanic, Felsic	2,014,048	1,434,220	71%	0%	0%	20%	31%	16%	4%	4%	25%	0%
Volcanic, Mafic	5,458,147	2,432,253	45%	0%	0%	16%	17%	8%	3%	7%	48%	0%
COLD DESERT BASIN	143,390,207	68,022,915	47%	0%	0%	12%	21%	10%	3%	3%	49%	0%
Calcareous Sedimentary	15,469,852	10,983,898	71%	0%	0%	18%	36%	14%	3%	3%	26%	0%
Fines and Playas	10,056,212	1,740,852	17%	0%	0%	2%	4%	9%	2%	2%	80%	1%
Intrusives (Granitic, Mafic)	2,639,782	2,355,463	89%	0%	0%	28%	39%	17%	4%	2%	8%	0%
Loams	38,272,075	12,181,848	32%	0%	0%	6%	11%	10%	4%	3%	65%	1%
Sand	4,429,621	1,128,610	25%	0%	0%	6%	9%	7%	3%	3%	71%	1%
Sandstones and Mixed Sedimentary	40,706,720	20,132,372	49%	0%	0%	14%	23%	10%	2%	5%	45%	0%
Shale and Fine-Grained Sedimentary	15,779,490	6,651,275	42%	0%	0%	9%	21%	9%	3%	4%	54%	0%
Volcanic, Felsic	9,690,243	8,136,134	84%	0%	0%	24%	45%	10%	5%	2%	14%	0%
Volcanic, Mafic	6,346,211	4,712,462	74%	0%	0%	27%	31%	10%	4%	3%	22%	0%
WARM DESERT BASIN	115,197,825	53,125,733	46%	0%	0%	12%	27%	6%	1%	4%	49%	1%
Calcareous Sedimentary	14,270,402	8,662,994	61%	0%	0%	21%	34%	5%	1%	7%	32%	0%
Caliche	1,726,182	439,908	25%	0%	0%	4%	4%	9%	8%	7%	67%	0%
Fines and Playas	6,090,831	1,146,900	19%	0%	0%	6%	7%	4%	0%	7%	73%	2%
Gypsum and Evaporite	2,583,535	680,944	26%	1%	1%	9%	11%	4%	1%	2%	69%	2%
Intrusives (Granitic, Mafic)	9,729,764	7,913,596	81%	0%	0%	17%	55%	8%	1%	2%	16%	0%
Loams	39,660,835	10,231,319	26%	0%	0%	7%	12%	5%	1%	4%	69%	2%
Moderately Calcareous Sedimentary	15,763	9,118	58%	0%	0%	58%	0%	0%	0%	9%	33%	1%
Novaculite	23,586	21,869	93%	0%	0%	0%	91%	2%	0%	0%	7%	0%
Sand	13,990,402	3,597,565	26%	0%	0%	2%	14%	7%	1%	2%	71%	1%
Sandstones and Mixed Sedimentary	10,831,426	7,476,856	69%	0%	0%	18%	43%	6%	1%	2%	28%	0%
Shale and Fine-Grained Sedimentary	2,731	2,369	87%	0%	0%	87%	0%	0%	0%	0%	13%	0%
Volcanic, Felsic	6,009,626	5,060,391	84%	0%	0%	13%	66%	5%	0%	1%	15%	0%
Volcanic, Mafic	10,262,742	7,881,903	77%	0%	0%	20%	50%	6%	1%	2%	21%	0%
TROPICAL LOWLAND	19,502,724	4,698,236	24%	0%	0%	4%	4%	15%	0%	13%	61%	1%
Calcareous Sedimentary	844,975	580,049	69%	0%	1%	24%	29%	15%	0%	15%	16%	1%
Fines and Playas	3,124,150	544,658	17%	0%	0%	5%	3%	8%	0%	18%	63%	1%
Loams	3,394,761	707,068	21%	0%	1%	3%	5%	12%	0%	14%	63%	2%
Moderately Calcareous Sedimentary	9,840,361	2,026,593	21%	0%	0%	3%	3%	14%	0%	14%	64%	1%
Sand	2,226,289	815,334	37%	0%	0%	0%	3%	33%	0%	2%	62%	0%
Sandstones and Mixed Sedimentary	69,343	22,034	32%	0%	1%	0%	0%	31%	0%	3%	65%	1%
Volcanic, Mafic	2,846	2,500	88%	0%	0%	0%	42%	46%	0%	0%	12%	0%
Grand Total	398,318,862	201,131,207	50%	0%	0%	12%	26%	10%	2%	4%	45%	1%

Note water is excluded from this summary table

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



Secured Lands and the Resilient and Connected Network

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 The Nature Conservancy. 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 in operation 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).

The majority of the network is secured against development (52%). Climate Corridors had the lowest amount of securement (35%) and Climate Flow Zones with Confirmed Diversity had the highest amount of securement (75%) (Table 9.3 Figures 9.8-9.9). This region has the highest amount of secured network in the U.S. suggesting that effective management of the secured public and private lands will be a critical tool for conservation of the network.

Table 9.3: Land securement across the Resilient and Connected Network.

Resilient and Connected Network	Acres	% Secured	% GAP 1	% GAP 2	% GAP 3
Climate Corridor	1,143,568	35%	0%	0%	35%
Climate Corridor with Confirmed Diversity	1,488,276	54%	9%	15%	29%
Climate Flow Zone	48,660,063	47%	0%	0%	47%
Climate Flow Zone with Confirmed Diversity	102,423,640	75%	23%	21%	31%
Resilient Confirmed Diversity	38,460,991	63%	15%	17%	31%
Resilient Secured	8,954,670	100%	0%	0%	100%
Not in the Network	201,131,207	67%	15%	14%	38%
Resilient Only	16,877,041	0%	0%	0%	0%
Average or Vulnerable	178,147,856	42%	5%	6%	30%
Developed	2,162,757	13%	0%	2%	11%
Water	2,611,420	-	-	-	-
Grand Total	400,930,282	52%	10%	10%	33%

Figure 9.8: Secured lands. This map shows the secured lands in the region by Gap status (see Table 9.3)

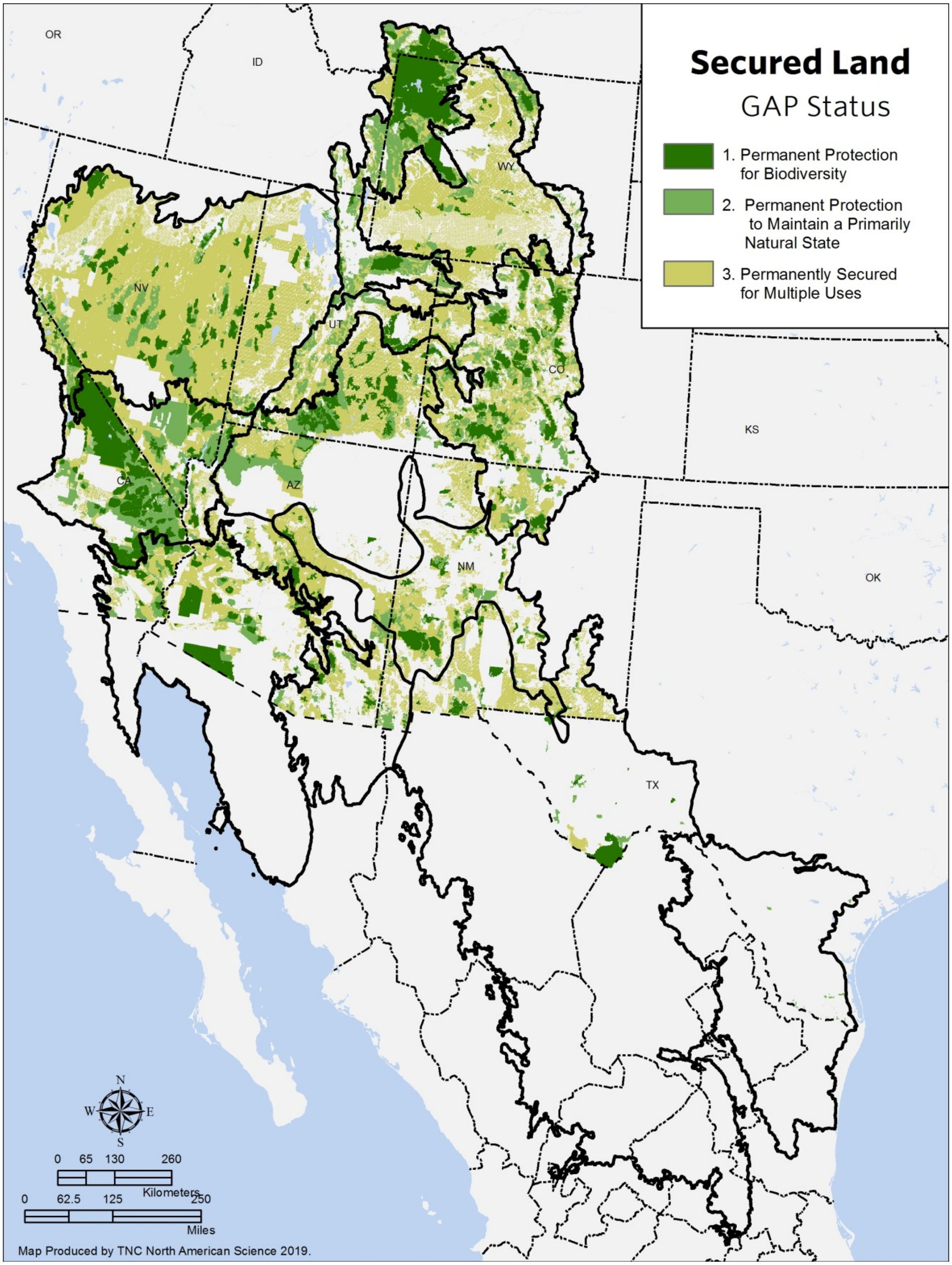
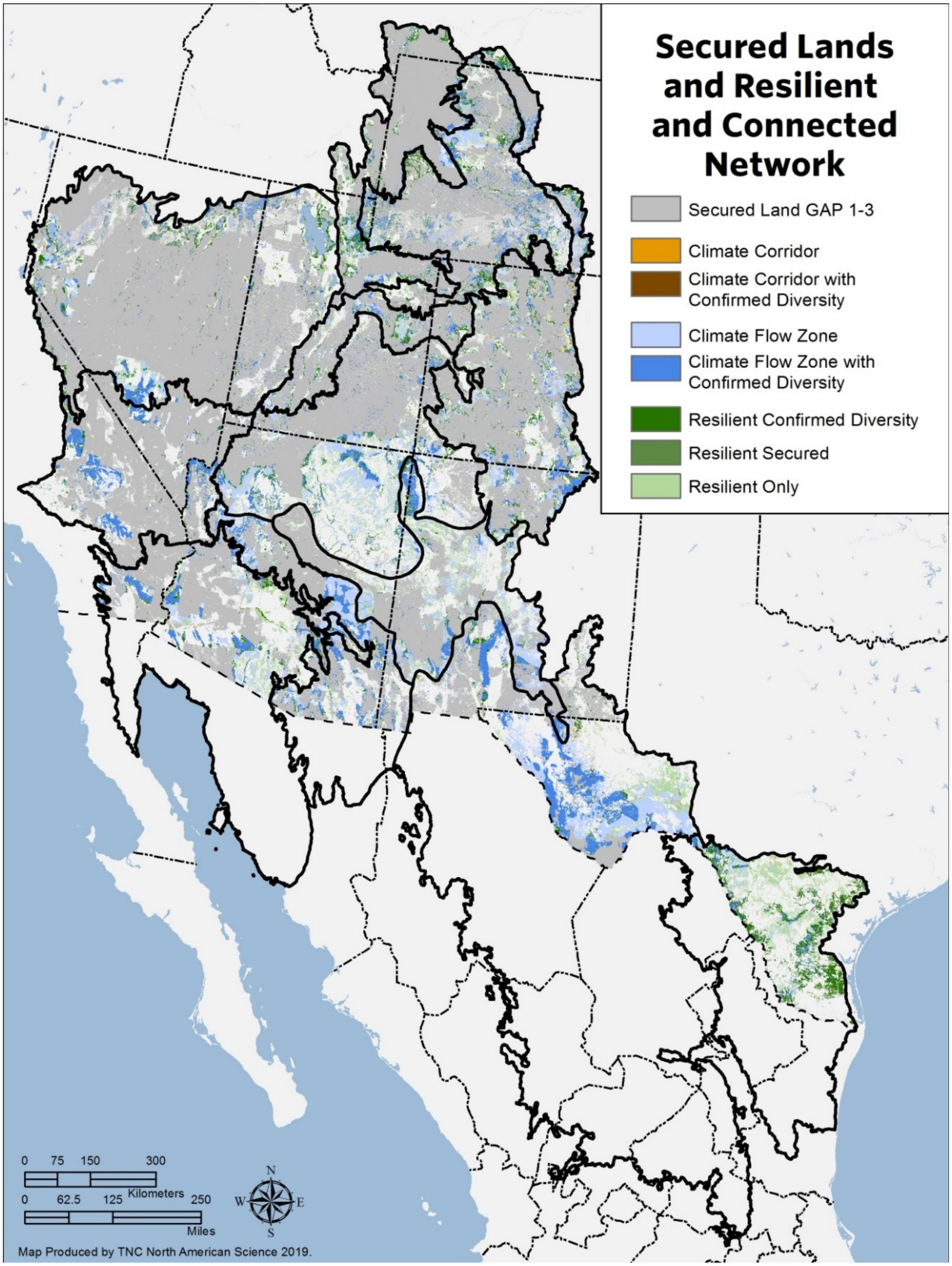


Figure 9.9: Secured land with the Resilient and Connected Network . The map shows the secured lands in gray on top of the resilient and connected network. In sum the network is 67% secured by conservation land in Gap 1-3 status and 33% is unsecured.



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