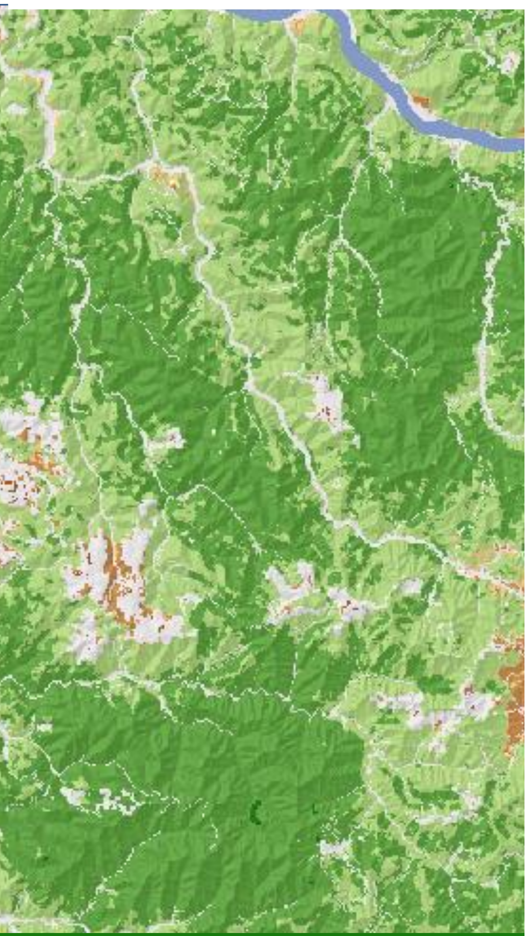
Resilient *and* Connected Landscapes

for Terrestrial Conservation

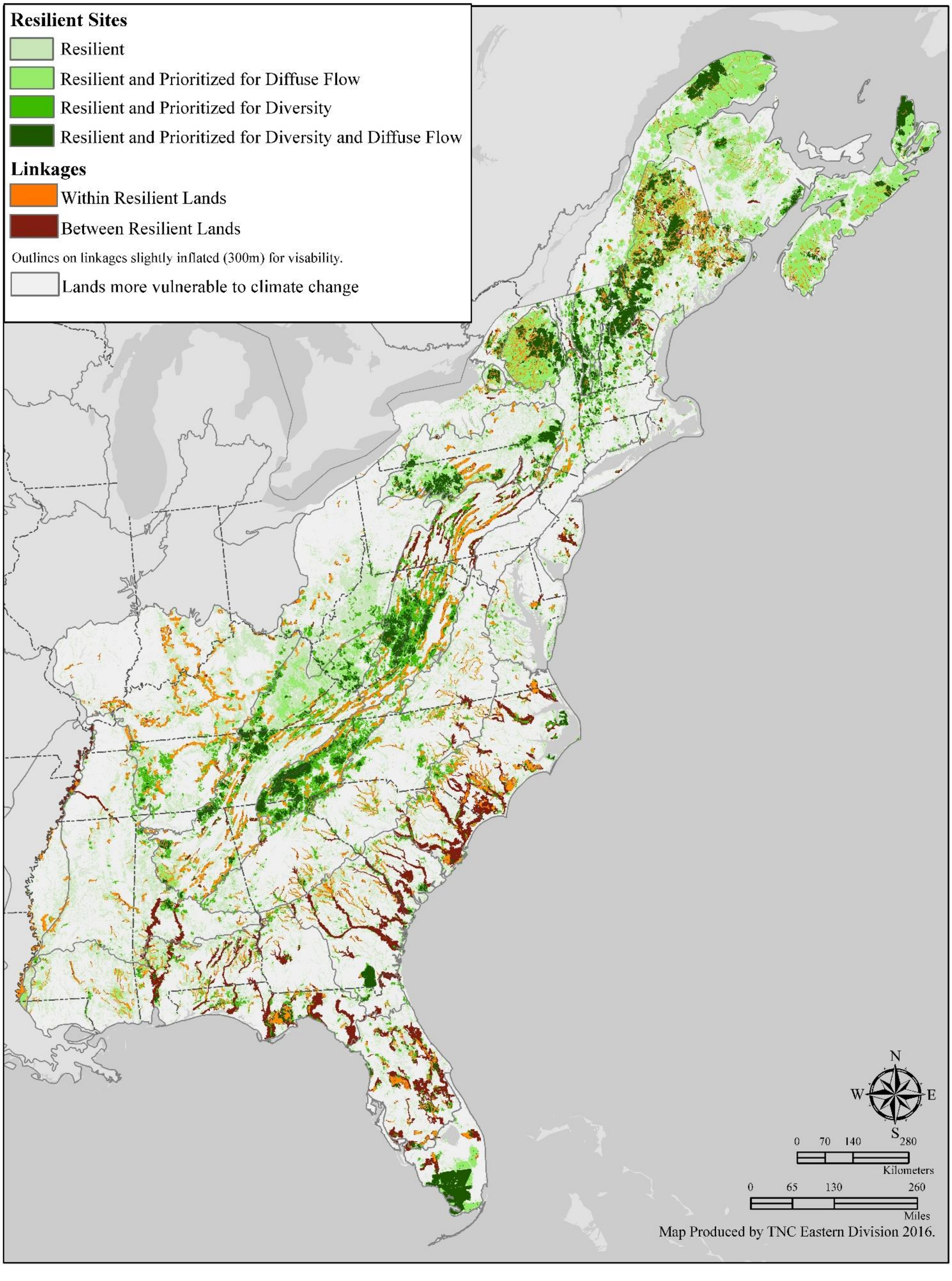
The Nature Conservancy
Eastern Conservation Science



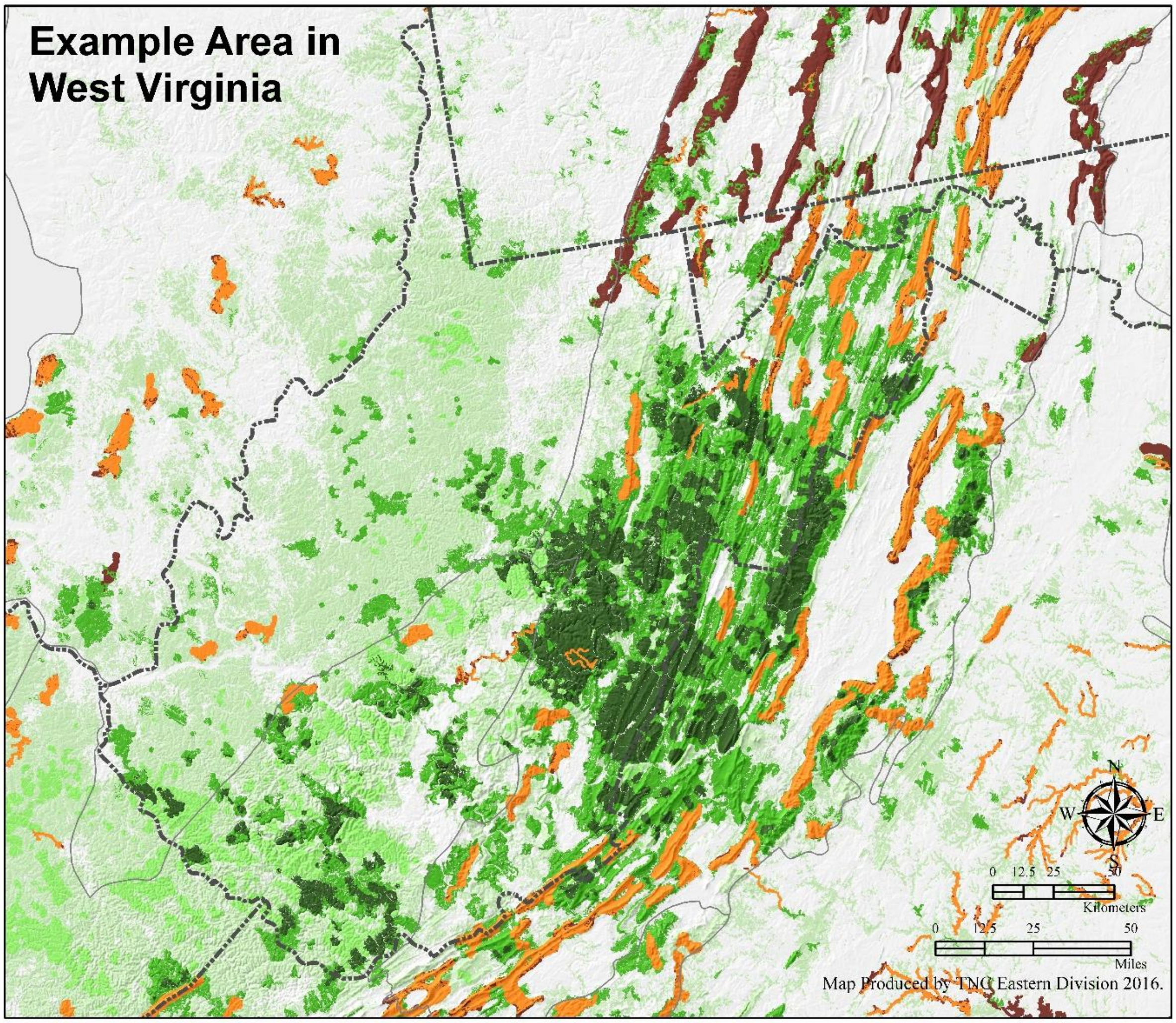
RESILIENT LANDS

CONNECTED LANDSCAPES

CONSERVATION STRATEGIES



Map Produced by TNC Eastern Division 2016.



🟩 **RESILIENT**	Areas of above average resilience, but do not fall into any of the prioritization categories.
🟩 **RESILIENT & DIFFUSE FLOW**	Resilient areas of high or medium diffuse flow. Diffuse flow areas are extremely intact and consequently facilitate high levels of dispersed flow.
🟩 **RESILIENT & HIGH DIVERSITY**	Resilient areas that have confirmed rare species and natural communities, or are large resilient examples of each geophysical setting.
🟩 **RESILIENT & DIVERSITY & FLOW**	Resilient areas that are high in diversity and have high or medium diffuse flow
🟧 **Linkage within Resilient Land**	Resilient areas that are either pinch points of concentrated regional flow or are in a Riparian Climate Corridors.
🟫 **Linkage between Resilient Land**	Areas that connect areas of prioritized resilience that are either pinch points of concentrated regional flow or Riparian Climate Corridors.

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About the Cover:

1. © Kent Mason. Sunrise as seen from The Nature Conservancy's Bear Rocks Preserve in West Virginia. High above Canaan Valley, in Dolly Sods, where a flat, windswept expanse of subalpine heath barrens opens up to the sky. Stunted red spruce, ancient bogs and forlorn boulders define this haunting landscape, where creatures typically found in more northern environs roam oblivious to their geologic isolation.
2. © Kent Mason. Westland area in Canaan Valley. Canaan Valley is an oval, bowl-like upland valley nestled among the higher ranges of the Allegheny Mountains in northeastern Tucker County, West Virginia. Canaan Valley supports the largest area of wetlands in all of the Central Appalachians, providing critical habitat for wildlife that is irreplaceable.
3. © Kent Mason. Wind farm turbines situated on a ridge top in the Appalachian mountains of West Virginia.

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Table of Contents

Figure and Table List

CHAPTER

1

INTRODUCTION

Objective and Background

The climate is changing. Insurance company records indicate that the last four decades have seen an increasing number of billion-dollar storms, droughts, floods, and fires. People pay these costs and adjust to the changes by regulating their direct environment, heating or cooling their homes, and preparing their communities. Nature also pays a cost, but unlike people, plants and animals must relocate.

To track a changing climate, plants and animals shift their distributions by colonizing and establishing in new territory, finding suitable microclimates that allow 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, dams, development, and other barriers to movement.

How do we ensure that the Eastern North American landscape will continue to support its vast botanical diversity and iconic wildlife? That nature will continue to provide the wealth of materials, food, medicines, and clean water we depend on? And, that our grandchildren will experience places still directly linked to distinctive American ecosystems like spruce-fir forests in the Northeast, rich cove forests in the Central Appalachians, and longleaf pine forests in the Southeast?

To address this problem, a team of 60 scientists led by The Nature Conservancy (TNC), have identified the places where nature’s own natural resilience is the highest. Thanks to the land’s diverse topography, bedrock, and soil, these climate-resilient sites are more likely to sustain native plants, animals, and natural processes into the future, becoming natural strongholds for diversity. To map their locations, The Nature Conservancy-led team used over 70 new and comprehensive datasets to find places that are buffered from the effects of climate change because the site offers a wide range of micro-climates within a highly connected area. In 2015, the results were published in a leading conservation science journal (Anderson et al. 2014). Now, in 2016, the map has been revised and expanded to cover 20 ecoregions, and new mapping approaches have been used to improve the accuracy and utility of the data, especially in the flatter and wetter parts of the region (Anderson et al. 2016a).

The resilience map identifies areas best able to support plants and animals in a changing climate, and represents the diversity of environments up and down Eastern North America. The analysis complements other conservation tools that assess species and habitats because this analysis focuses on the properties of the land itself. It helps decision-makers ensure that the places we conserve today will support a diversity of plants and animals tomorrow. In addition to sustaining a diversity of plants, animals, and wildlife habitat, the public benefits of conserving resilient places include improved air and water quality, carbon sequestration, and soil health. It makes good fiscal sense to invest in areas with high natural resilience to ensure that these benefits last. Resilience science can guide land acquisition, restoration, and management practices.

Connected Landscapes: The resilience analysis focused on sites, but scientists have long understood that the *connections between and among sites are critical to sustaining diversity under a changing climate.* How populations move across the region, and where the critical connectors are, is the topic of this report. It is divided into five sections:

Site Resilience: This section briefly describes the counterpart report *Resilient Sites for Terrestrial Conservation in Eastern North America*. (Anderson et al. 2016 a) which contains the concepts and metrics for estimating the relative resilience of a site. The report presents the results of a region-wide analysis of site resilience across 62 geophysical settings from Nova Scotia to Louisiana. Here, we review the concepts to provide context for understanding how we integrate site resilience with landscape permeability. Users familiar with the resilient sites report can skip this section.

Landscape Permeability: This section describes our efforts to understand and map landscape permeability. It begins with an extensive review of the literature on range shifts and extracts the key lessons needed to guide conservation planning that aims to sustain diversity and facilitate range shifts under a changing climate. The second section presents a continuous wall-to-wall method for mapping and understanding landscape permeability, and then applies the method to the region. The results are compared with 30 smaller-scale studies on connectivity conducted within this region and found to compare favorably, particularly with species-based studies. The third section introduces methods to incorporate climate change into the permeability models following the evidence collected from the literature.

Biodiversity: This section describes our methods for prioritizing resilient areas that contain rare species, or have extraordinary taxa diversity. It also explains how we identified places that encompass the largest contiguous resilient example of each geophysical setting, especially those settings that are poorly represented in the current set of public and private conservation lands.

Resilient and Connected Conservation Networks: This section integrates resilience, permeability, 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.

Conservation Strategies: In this section we give examples of how the results can be incorporated into conservation strategies like energy siting, carbon storage, road crossing mitigation, and land management or acquisition.

CHAPTER

2

SITE RESILIENCE

Climate change is expected to alter species distributions, modify ecological processes, and exacerbate environmental degradation (Pachauri & Reisinger 2007). To offset these effects, the need is greater than ever for strategic land conservation. Conservationists have long prioritized land acquisitions based on rare species or natural community locations (Groves 2003). Now, they need a way to set priorities that will conserve biological diversity and maintain ecological functions, despite climate-driven changes in community composition and species locations (Pressey et al. 2007). We devised such an approach to identify potential conservation areas based on geophysical characteristics that influence a site's resilience to climate change.

Geophysical Settings

Geology defines the available environments and determines the location of specialist species. In Eastern North America, for example, limestone valleys support fen plants, mussels, and cave fauna, whereas inland sand plains support species adapted to dry acidic soils and fire. Geophysical variables (geology, latitude, and elevation) explain 92% of the variation in the species diversity of the eastern states and provinces, far more than climate variables do (Anderson & Ferree 2010). Because biodiversity is so strongly correlated with the variety of geophysical settings, conserving the full spectrum of geophysical settings offers a way to maintain both current and future biodiversity, providing an ecological stage for a different set of species, which turnover through time (Beier & Brost 2010).

Geophysical diversity as a surrogate for species diversity has a long history in conservation planning (e.g., Hunter et al. 1988, Faith & Walker 1996, review in Rodrigues and Brooks 2007), and recently it has been recognized for its potential role in conservation planning under climate change (Schloss et al. 2011, Lawler et al. 2015, Anderson et al. 2015). We used different aspects of geophysical diversity for different purposes: geological representation to capture species diversity, and topographic and elevation diversity to identify places that have the maximum resilience to climate change.

Characteristics that Impart Resilience

Our use of the term site resilience is distinguished from ecosystem or species resilience because it refers to the capacity of a geophysical site to maintain species diversity and ecological function as the climate changes (definition modified from Gunderson 2000). Because neither the site's species composition nor the range of variation of its processes are static under climate change, our working definition of a resilient site was a structurally intact geophysical setting that sustains a diversity of species and natural communities, maintains basic relationships among ecological features, and allows for adaptive change in composition and structure. Thus, if adequately conserved, resilient sites are expected to support species and communities appropriate to the geophysical setting for a longer time than less resilient sites.

We developed a method to estimate site resilience as the sum of two quantitative metrics: landscape diversity (i.e., diversity of topography and range of elevation in a site and its surrounding neighborhood) and local connectedness (i.e., permeability of a site's surrounding land cover). Using a geographic information system (GIS) we calculated these metrics for every 30-m cell in the Northeast United States and Atlantic Canada and used the results to estimate the site resilience of specific places.

Landscape diversity, the variety of landforms created by an area's topography, together with the range of its elevation gradients, increases a site's resilience by offering micro-topographic thermal climate options to resident species, buffering them from changes in the regional climate (Willis & Bhagwat 2009, Dobrowski 2010, Ackerly et al. 2010) and slowing down the velocity of change (Loarie et al. 2009). Under variable climatic conditions, areas of high landscape diversity are important for the long-term population persistence of plants, invertebrates, and other species (Weiss et al. 1988, Randin et al. 2008). Because species shift locations to take advantage of microclimate variation, extinction rates predicted from coarse-scale climate models that fail to account for topographic and elevation diversity have been disputed (Luoto & Heikkinen 2008, Wiens & Bachelet 2010).

Local connectedness is a measure of the permeability of an organism's local surroundings, defined as the degree to which the surroundings are conducive to movement, dispersal, and the natural flow of ecological processes (definition modified from Meiklejohn et al. 2010). A highly permeable landscape promotes resilience by facilitating local movements, range shifts, and the reorganization of communities (Krosby et al. 2010). Accordingly, measures of permeability such as local connectedness are based on landscape structure: the hardness of barriers, the connectedness of natural cover, and the arrangement of land uses.

A climate-resilient conservation portfolio includes sites representative of all geophysical settings selected for their landscape diversity and local connectedness. We developed a method to identify such a portfolio. First, we mapped geophysical settings across the entire study area. Second, within each geophysical setting we located sites with diverse topography that were highly connected by natural cover. Using this information, we identified places that could serve as strongholds for diversity both now and into the future (Figure 2.1, from Anderson et al. 2016a).

Figure 2.1. The highest scoring areas for estimated resilience. Areas in yellow are comprised of cells with an average estimated resilience score based on their geophysical setting, landscape diversity and local connectedness as compared to others in their geophysical setting and ecoregion. Areas in green score above average and are estimated to be more resilient. Areas in brown are below average and are estimated to be vulnerable to climate change (from Anderson et al. 2016a).

CHAPTER

3

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 in spite of 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 Eastern North America 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, most of Eastern 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 Eastern North America.

Climate Change and Range Shifts

Range Shifts

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

The other way that species may respond to climate changes is that 3) *populations and species shift their distributions*. This can occur when climate change leads to previously unsuitable habitat becoming suitable for population persistence allowing colonization of new habitat patches outside of the current range of a species. It can also result from differential survival of individuals at the range edge leading to a more gradual redistribution, for instance individual propagules surviving preferentially in shadier or moister areas causing a local population to shift in elevation or to a more shaded aspect. It is likely that components of all three mechanisms occur for most species. Range shifts may be essential for species with narrow climatic tolerances experiencing rapid and extreme climatic changes in their current ranges, or for species that depend on naturally patchy landscape features, such as amphibians that breed in isolated wetlands.

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

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

Dispersal and Dispersal Pressure

Whether species arrive in a new location that may be suitable for colonization depends on the population size and the build-up of dispersal pressure, their dispersal ability, and the proximity, relative abundance, and size of patches of suitable habitat (Primack

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

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

Landscape Permeability: the influence of the medium through which 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 Eastern 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 Eastern 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 3.1, 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 3.1. 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 3.1). 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.

<u>Northward Expansions:</u> Northward movements are also well documented for 754 species across five taxa groups, and they appear to be ubiquitous across the northern hemisphere (Table 3.1, 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.

<u>Riparian Climate Corridors:</u> Although the evidence for upslope and northward movements is strong, there is substantial variation in how species respond to climate change, and a third alternative for many species is to move downslope towards the cooler and moister temperatures of riparian environments. Riparian areas are the zones along waterbodies that serve as interfaces between terrestrial and aquatic ecosystems. Although they comprise a minor proportion of the landscape, they are typically more structurally diverse and more productive in plant and animal biomass than adjacent upland areas, and they supply 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).

With respect to climate change, riparian areas feature microclimates that are significantly cooler and more humid than immediately surrounding areas (Olsen et al. 2007), and are expected to provide microclimatic refugia from warming and drought for many species, particularly wetland species (Seavy et al. 2009). Species showing downslope shifts have been well documented (Archaux 2004, Popy et al. 2010), and an illustrative, non-comprehensive survey of such 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). A spatially explicit climate resilience analysis based on microclimates and connectedness identified many riparian corridors as key landscape features because of the many climate options they provide, especially in relatively flat landscapes (Anderson et al. 2014).

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 modeled temperature gradients within most riparian or floodplain corridors is extremely small, ranging from an average 0.14 C on the Coastal Plain to an average of 1.3 C in the Central Appalachian mountains, suggesting little temperature relief in moving along a riparian corridor except in the mountains where the gradients are steep (Anderson et al. 2015). This is in contrast to the temperature and moisture differences between riparian corridors and their surrounding landscapes, which are much larger (5-20^{0}C cooler) and 10-15% higher in soil moisture (Yeakley et al. 2008, Bennie et al. 2008). These differences provide ample incentive for species to move into riparian areas, even if less reason to move in a directional way along the corridor. Temperature gradients and directionality aside, riparian areas are cooler and moister than the surrounding landscape, and they naturally connect many landscape features. These unique attributes 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).

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, which are an exception in much of the Eastern US.

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 very likely that many wildlife species would use a riparian corridor for dispersal if that is the only safe natural cover in the wider landscape (Fremier et al. 2015). Such corridors may allow multi-generational dispersal to occur between larger heterogeneous areas of protected habitat if the corridors include appropriate breeding habitat, and this may be particularly important for species with limited dispersal abilities. Further, it is postulated that ensuring riparian corridors right up to headwaters can provide critical over-the-ridge links for dispersal across watersheds (Olson & Burnett 2013). It is less clear in a landscape were the riparian areas occur within intact natural land cover whether upland terrestrial species would preferentially disperse along a river valley rather than along ridge lines or contour lines that have their preferred cover or food sources.

Microclimates and Rates of Change: The fourth and perhaps most common alternative for species is to find suitable habitat nearby, moving a small distance to take advantage of a local microclimate. Species experience climate at extremely local scales (cm to meters) and the available moisture and temperature in the near-ground "boundary layer" can differ greatly from the local average (Geiger et al. 2009). Thus, a topographically diverse landscape is experienced by its resident species as a heterogeneous mix of microclimates many of which might be suitable for persistence even where the average background climate appears unsuitable. Landscape-based climatic variation can be substantial, on par with or greater than the 1.5^{o}C warming expected for the future. Studies where climate data loggers are placed across gradients of slope, aspect and elevation have found maximum temperature differences over 20^{0} C (Surgett et al. 2010, Dobkin et al. 1987) and 15-20 % fractional soil moisture differences (Yeakley et al. 1998, Bennie et al. 2008). In Southern Appalachian watersheds, topography explains 40% to 72% of the variation in near-surface soil moisture (Yeakley et al. 1998). Even microscale patches of suitable climate may allow persistence of species over long 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 eastern 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.

Conclusion: The evidence for contemporary range shifts provide 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 under the headings of facilitating dispersal, and facilitating dispersal under climate change, and where possible linked to the resilience analysis (Anderson et al. 2016) completed for the Eastern US.

Facilitating Dispersal

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 such 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.

Facilitating Dispersal in Response to Climate Change

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 in the Eastern US 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. 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 riparian corridors 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 than their surroundings (e.g., bottomland forests in the Southeast Coastal Plain).

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 identified as having 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 microtopogaphy or attributes that make their climates intrinsically more stable, such as the eastern coast of Maine cooled by cold ocean currents. 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, 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, and especially if they are source areas 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.

Mapping Landscape Permeability

The Nature Conservancy’s analysis of resilient sites for terrestrial conservation (Anderson et al. 2016a) addresses many of the recommendations summarized in the previous section. This includes recommendations to: 1) identify source areas for all species; 2) represent all geophysical settings in a variety of climate zones; 3) identify microclimate refugia in areas with higher landscape diversity; and 4) ensure a portfolio of conservation sites includes geographic distribution, stratification by ecoregion, and geophysical representation. The resilience analysis stops short, however, of identifying a connected network of sites that includes the types of linkages and confirmed biodiversity features identified as important to facilitate range shifts. We address these issues in the next part of this report. Specifically, we develop methods to map and assess the permeability of the landscape as influenced by anthropogenic features, we examine where upslope and northward movements are likely to concentrate, we identify which riparian areas are situated to collect and facilitate movements, and we locate sites with confirmed rare species taxa or exemplary communities. The final section integrates these components with the resilient sites to produce maps that answer specific conservation questions.

Introduction

The permeability of a landscape is a function of the resistance of its major elements and their spatial arrangement: the types and resistance of barriers, the connectedness of natural cover, and the arrangement 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). Our goal in understanding landscape permeability was to map it 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 including: 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). Of these, 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 travel across large regions. The resulting mosaics provide a continuous view of connectivity across the study area at the full original resolution and they highlight pinch points, narrow corridors where organisms appear to be required to traverse when moving through the landscape (Pelletier et al. 2014).

To create a wall-to-wall surface of landscape permeability we used 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 and these colonize new habitat at a distance from their source point. Juvenile animals can walk, climb, fly, swim, glide, crawl or burrow their way into new locations, and plants have evolved a host of mechanisms for dispersing their propagules by taking advantage of wind, water, animals, and people. If the current habitat becomes unsuitable, but available suitable habitat exists nearby, the constant flow of dispersers helps ensure that the new habitat will be discovered and colonized.

Current climate change differs from historic climate change 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 a range constriction. Our goal in modeling range shifts was to understand how species in the Eastern North America move in response to the modified and developed landscapes, identifing where the pinch points, blockages, or flow concentration areas occur. We compared our results against smaller scale studies to determine if we were getting similar results and build confidence in our methods. The results of the comparison are presented in section called "Comparisons and Confirmation" and more completely in Appendix 1 so readers can make their own judgements.

Once we had modeled flow based on current anthropogenic resistance and compared the results with others, our next step was to incorporate climate change directly into the model. This is presented in the section called "Permeable Climate Pathways" and is based on evidence on how species are already repsonding to climate change. Accordingly, we modeled species range shifts in response to climate change in three compounding ways (understanding that actual range shifts are probably integrated across these options): Anthropogenic resistance only, Anthropogenic resistance weighted by upslope and northward gradients, and Anthropogenic resistance concentrated in riparian climate corridors

The anthropogenic model is based solely on human-modified barriers such as roads and development and the resistance they create. The anthropogenic, northward, and upslope model uses local neighborhood land position and slope to simulate where species will move to get the greatest temperature change with the least amount of effort. The northward model uses the anthropogenic model but gives more weight to north-south flows than to east-west flows. The riparian climate corridors look at where flow based on the anthropogenic model becomes concentrated in valley bottoms.

Circuitscape Model

All modeling of landscape permeability 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 rills, gullies, braided channels, eddies, and main channels associated with flowing water. The program's ability to highlight flow concentration areas and pinch-points makes it particularly useful for identifying key linkages for permeability. Concentration areas are easily recognized in the Circuitscape output by their high current density.

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 grid we used for anthropogenic resistance was land cover, but in theory resistance can be any factor that impedes movement (in later examples 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 or low intensity development, were considered less permeable because of differences in structure, surface texture, chemistry, temperature, or exposure. Wildlife and plants do cross various landscape elements, but sharp contrasts such as forest adjacent to a farm field or development disrupts movement because an animal may prefer to avoid the risk inherent in crossing the more exposed habitat or a 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.

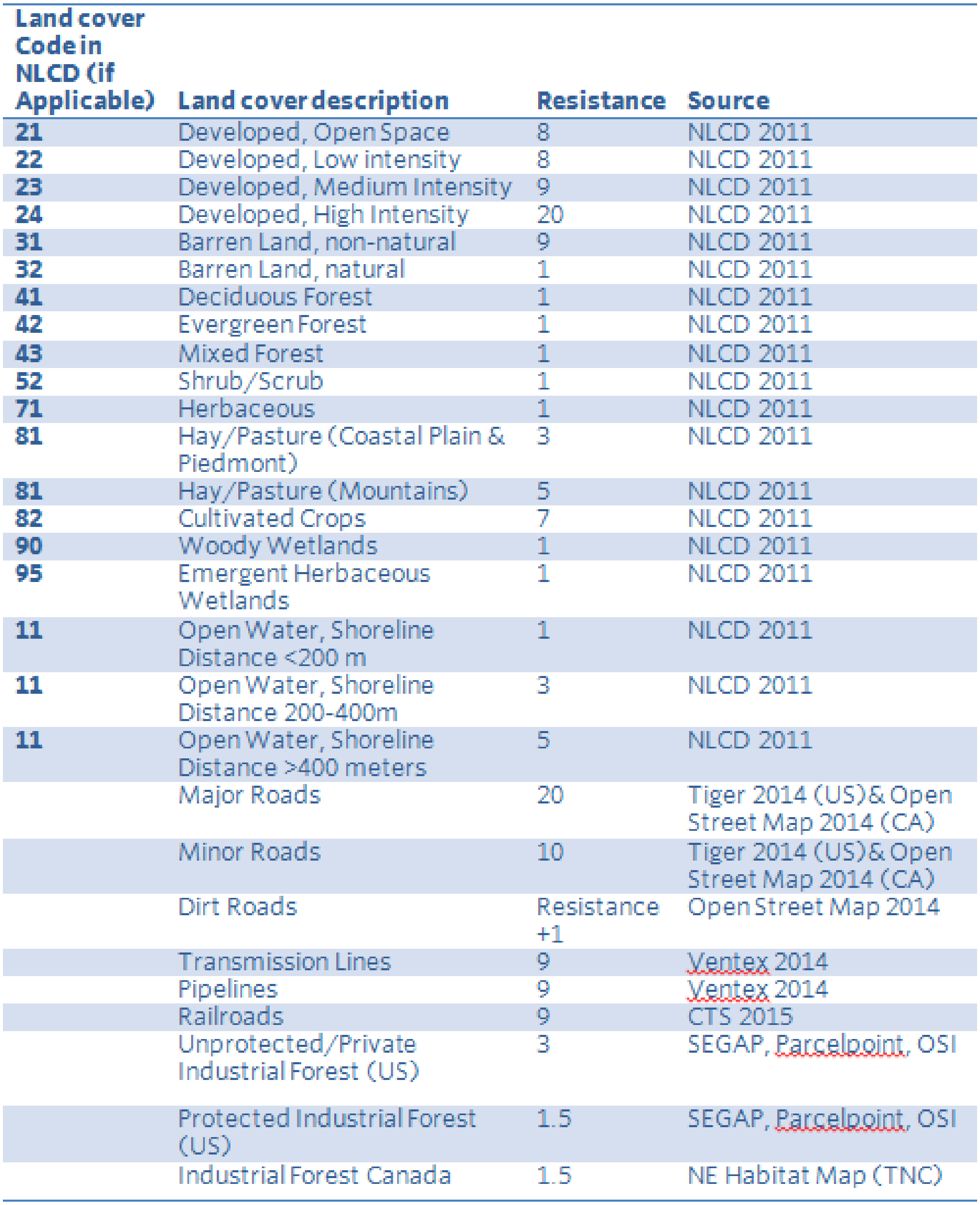
Agricultural or modified lands: landscape elements where natural processes are modified by direct, sustained, and intentional human intervention. This usually involves modifications to both the structure (e.g., clearing and mowing), and ecological processes (e.g., flood and fire suppression, predator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

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

In developing an anthropogenic resistance grid, we applied a weighting scheme to the 2011 National Land Cover Database (NLCD, Jin et al. 2013) such that natural lands had the least resistance, agriculture, or modified lands had more resistance and developed lands had the highest resistance (Table 3.2). The NLCD is the most recent national land cover database for the United States and it is mapped at a 30-m scale. For Canada we used Provincial land cover datasets (Ministère des Ressources naturelles 2014, New Brunswick Forest Inventory Database 2012, New Brunswick Wetlands Inventory 2006, Prince Edward Island Corporate Land Use Inventory 2010, Nova Scotia Forest Inventory and Wetlands Inventory 2014). We visually compared provincial datasets with current aerial photos and older land use data to confirm their accuracy, and we matched the resistance weights in Canada with those in the US (Table 3.2).

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).

Table 3.2. Land cover types and assigned resistance values. This table shows the available attributes and the resistance score assigned to the land cover category. Resistance scores range from "1," no resistance, to "20," very high resistance.



Land cover Code in NLCD (if Applicable)	Land cover description	Resistance	Source
21	Developed, Open Space	8	NLCD 2011
22	Developed, Low intensity	8	NLCD 2011
23	Developed, Medium Intensity	9	NLCD 2011
24	Developed, High Intensity	20	NLCD 2011
31	Barren Land, non-natural	9	NLCD 2011
32	Barren Land, natural	1	NLCD 2011
41	Deciduous Forest	1	NLCD 2011
42	Evergreen Forest	1	NLCD 2011
43	Mixed Forest	1	NLCD 2011
52	Shrub/Scrub	1	NLCD 2011
71	Herbaceous	1	NLCD 2011
81	Hay/Pasture (Coastal Plain & Piedmont)	3	NLCD 2011
81	Hay/Pasture (Mountains)	5	NLCD 2011
82	Cultivated Crops	7	NLCD 2011
90	Woody Wetlands	1	NLCD 2011
95	Emergent Herbaceous Wetlands	1	NLCD 2011
11	Open Water, Shoreline Distance <200 m	1	NLCD 2011
11	Open Water, Shoreline Distance 200-400m	3	NLCD 2011
11	Open Water, Shoreline Distance >400 meters	5	NLCD 2011
	Major Roads	20	Tiger 2014 (US)& Open Street Map 2014 (CA)
	Minor Roads	10	Tiger 2014 (US)& Open Street Map 2014 (CA)
	Dirt Roads	Resistance +1	Open Street Map 2014
	Transmission Lines	9	Ventex 2014
	Pipelines	9	Ventex 2014
	Railroads	9	CTS 2015
	Unprotected/Private Industrial Forest (US)	3	SEGAP, Parcelpoint, OSI
	Protected Industrial Forest (US)	1.5	SEGAP, Parcelpoint, OSI
	Industrial Forest Canada	1.5	NE Habitat Map (TNC)

Improvements to the Land Cover Datasets

Although the 2011 NLCD and the Canadian Provincial datasets are the most current datasets available, we made several adjustments to them that substantially improved their performance as resistance grids. These included: 1) updating the roads and railroads, 2) adding dirt roads, 3) adding transmission line data, 4) reclassifying barrens as natural or developed, 5) adding plantation forests, 6) differentiating between hay/pasture and cropland and 7) reclassifying water polygons.

Roads: All of the NLCD products (2011, 2006, and 2001) have older and inaccurate road data burned into them from the Bureau of Transportation Statistics. These roads do not align with the more commonly used and more accurate Tiger Road dataset (US Census 2014). To address this issue, we removed the older roads from the 2011 NLCD and replaced them with roads from the newer Tiger 2014 dataset, greatly improving the spatial accuracy of the roads component. First, cells in the 2011 NLCD's "developed open space" class (which contains the roads) were shrunk by one pixel, effectively removing linear road pixels but not the larger actual developed open space areas. Values for these cells were replaced with the majority value of the surrounding pixels. Next, the 2014 Tiger roads were "burned in" on top of the 2011 NLCD to replace the old roads with the more accurate data.

The compiled Canadian land use data did not contain information on roads except for some of the major highways, so we "burned in" road data from the National Road Network (National Road Network 2015). The latter was the most comprehensive information available, but it was uneven in its representation of minor roads across the provinces, being most complete in Nova Scotia and least complete in Quebec. We supplemented the National Road Network data with a detailed provincial roads dataset available for New Brunswick.

Dirt roads: Dirt roads or unpaved forest management roads are unevenly mapped in both the US and Canadian land use datasets, even though they may create substantial road networks in some parts of the region. To map unpaved roads, we used data from OpenStreetMap (2014) which is an open-source global dataset built by a community of mappers that contribute and maintain data about roads and trails. We extracted roads tagged as "track" which includes roads used primarily for agriculture, forest tracks, etc. This class of roads is usually unpaved but may include paved roads suitable for two-track vehicles such as tractors or jeeps. Trails and paths that are not wide enough for a two-track vehicle are excluded from this class. Although the quality and consistency of this dataset is variable, visual inspection suggested that it was more comprehensive than any other available dataset for mapping unpaved roads. In the resistance grid, cells were assigned an additional resistance point if they contained one or more unpaved roads. For example, the resistance of hay/pasture cells with track roads increased from a "3" to a "4."

Transmission Lines: We added the location of transmission lines to the land use datasets. For this step, we obtained access to power industry GIS data (Ventyx 2014), which was used with permission through a TNC agreement. We selected all transmission lines in service by voltage class, and all in-service natural gas pipelines. These were incorporated into the land cover dataset using power industry standard right of way widths: transmission lines less than 230 volts = 30 m width, greater than 230 volts = 180 m width, and all pipelines = 30 m width (Duke Energy 2014). We compared the dataset to aerial photos to confirm that these widths were reasonable and to ensure that we added only features that made a distinguishable footprint on the ground.

Barrens: In the US land cover dataset (NLCD 2011), the category "barrens" often included misclassified developed lands such as oil and gas wellheads or airport runways. To distinguish natural barrens (e.g., beaches and summits) from highly developed barrens (e.g., airport runways), we used a spatial analysis of the land cover types in a 100 m buffer surrounding each barren cell to distinguish barrens associated with industry or commercial development from barrens associated with bare rock, exposed beach, lake shorelines, and other natural settings. All barren areas greater than 300 acres were visually inspected to make sure that they were in the correct class. Also, all barrens on military lands (determined from an overlay of a secured lands database) were assumed to be non-natural barrens such as bombing ranges and runways. For Florida, we used the "Extractive" class in the Florida Cooperative Land Cover dataset (FNAI 2015) to identify barren land used for mines, quarries, gas fields, and other industrial activities.

Plantation Forest: In the US, industrial plantation forests dominate much of the Southeast Coastal Plain but they are lumped together with natural forest in the NLCD 2011 land cover dataset. To separate plantation from natural forest, we used information on the locations of plantations from four data sources. The first was the Southeast GAP land use dataset (Southeast GAP Land Cover Dataset 2010) which classified plantation forests from aerial imagery and spatially mapped three classes: deciduous plantation, evergreen plantation, and clear cut. The second data source was a proprietary dataset of land ownership with parcel shapes and ownership information for most of the Southeast (ParcelPoint 2013). We conducted queries on the parcel data to identify and map major industrial forest/timber ownership that occurred on land cover classes compatible with commercial forest operations. The third data source was an Industrial Forest Classification developed by the Open Space Institute (Open Space Institute 2009) using information from landowners and third party sources. The fourth dataset was a Global Forest Change dataset (Hansen et al 2013). From this dataset we compiled both the global forest loss (2000 – 2014) and the global forest gain (2000 – 2012), and we identified areas that were experiencing the rapid turnover indicative of industrial forest management. We used the Global dataset only where ParcelPoint (2013) ownership data was not available or where the majority of industrial timber lands were in small holdings and therefore difficult to identify by owner. The latter included all of the Chesapeake Bay ecoregion and the Illinois portion of the Interior Low Plateau ecoregion. We merged the four compiled datasets of plantation / industrial forest with the 2011 NLCD. Where industrial forest cells overlapped with the NLCD cells classified as "forest" or "shrub-scrub" (NLCD classes 40,41,42, and 52) we overrode the cell as "plantation/industrial forest" except in the Western Allegheny Plateau and the Interior Low Plateau where state experts recommended we only use the industrial forest data on conifer forest (NLCD 42), shrub/scrub (NLCD 52), and grassland/ herbaceous (NLCD 71), because pine plantations dominate these ecoregions and there are no known hardwood plantations.

We assigned industrial forests a resistance score of "3" as this land use is subject to frequent cutting, road development and other anthropogenic disturbances, and typically has less groundcover. An exception was when the industrial forests were on land that was permanently secured against conversion (GAP Status 1 – 3). Because these lands, by definition, are being managed for natural values we assigned them a lower resistance score of "1.5."

Industrial forests are well mapped and classified in the Canadian Terrestrial Habitat Map (Ferree & Anderson 2015), which was developed using the provincial forestry datasets. We assigned the classes "plantation forest" and "early seral forest" to the industrial forest class. Because Canadian plantations are cut more lightly and selectively than the Southeastern US plantations we scored them with a lower resistance value of "1.5."

Pasture: The differences between pasture/hay and cultivated agriculture were discussed extensively in our advisory committee meetings and it was agreed that cultivated cropland creates more resistance than pasture due to the heavy management and common use of pesticides in the latter. Thus, we assigned cropland a resistance value of "7." The resistance score of pasture varied depending on how much it contrasted with the dominant land cover in each subregion. A resistance value of "3" was assigned to pastureland in the Coastal Plain and Piedmont subregions which are largely comprised of open forest and agricultural land, and a resistance value of "5" was used in the Mountain subregion where the landscape is generally covered by closed canopy forest.

Waterbodies: We adjusted the resistance score of waterbodies to reflect their size because very large waterbodies can impede the movement of terrestrial species more so than small streams or ponds. To quantify the effect of waterbody size, we selected all water pixels in the NLCD, converted the pixels to polygons, and buffered them inward 200 and 400 m. We assigned water within 200 m of a shoreline a resistance value of "1" (natural), 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” because of the barrier it presents to movement (Figure 3.1).

All improvements to the land cover grid were performed on the 30-m grid cells and integrated with the NLCD, Provincial Canadian datasets, and other source data into one dataset (Figure 3.2). For the Circuitscape analysis, processing limitations required us to coarsen the data to 180-m cell resolution which we did using the “aggregate” function by mean in ArcGIS.

Figure 3.1. Waterbodies and the zones used in the resistance weighting. Waterbodies are shown in blue on the right, with darker blues indicating higher resistance at 0-200, 200-400, and 400+ meters.

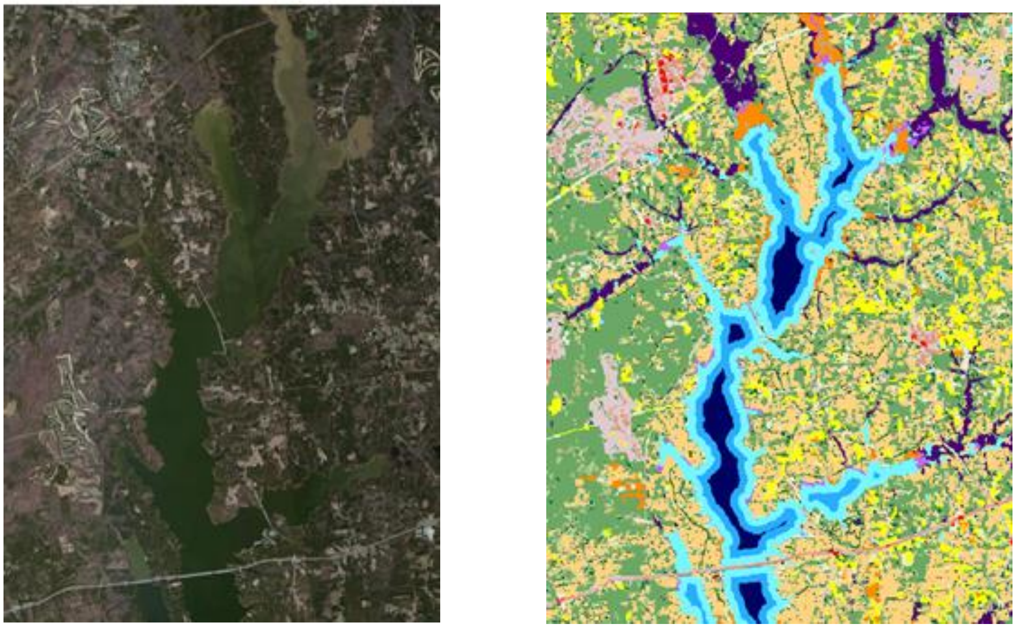
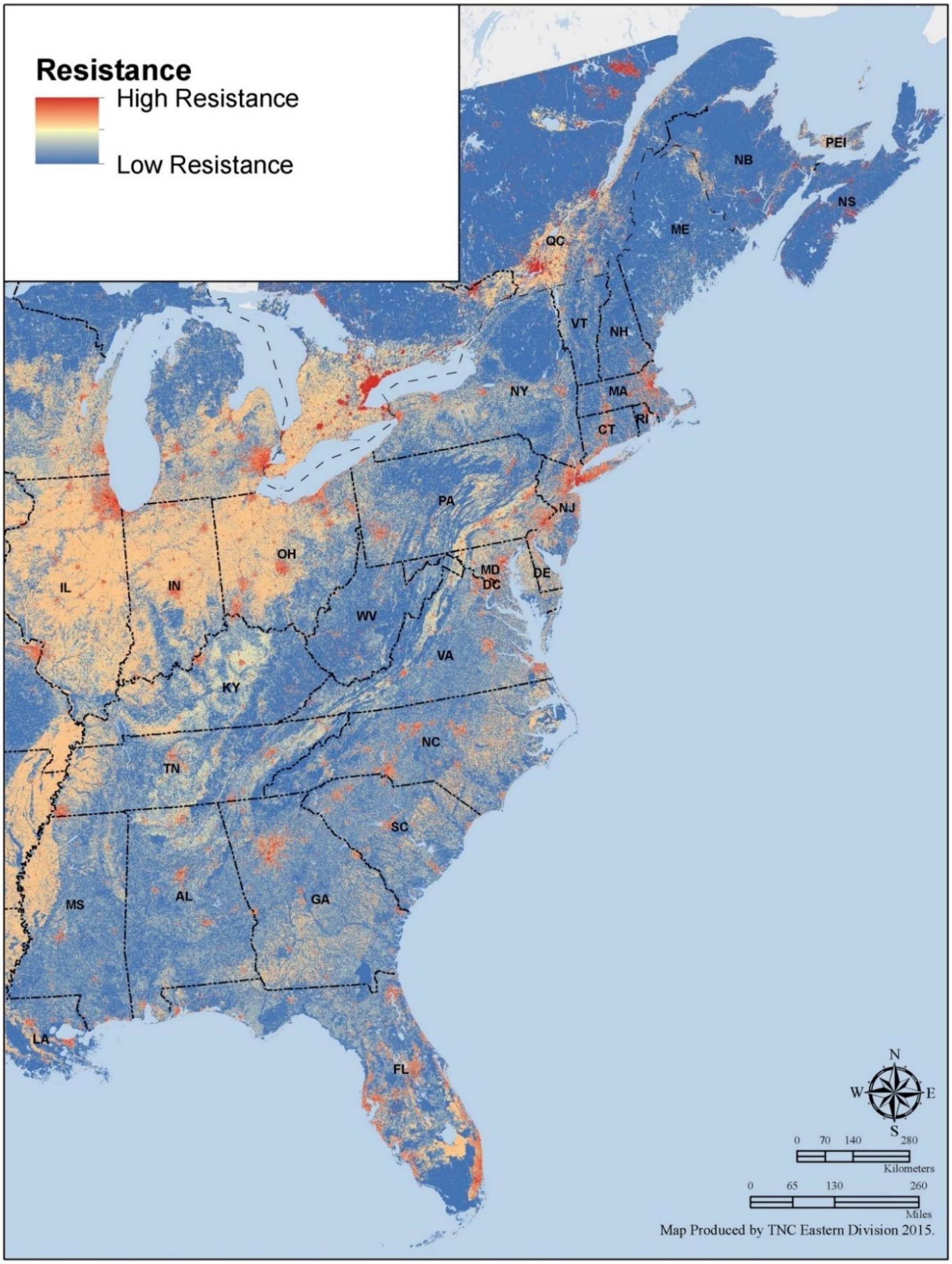


Figure 3.2. Anthropogenic resistance grid used in the Circuitscape analysis. The figure shows the improved and integrated land cover map with each cell reclassified to its assigned resistance score.



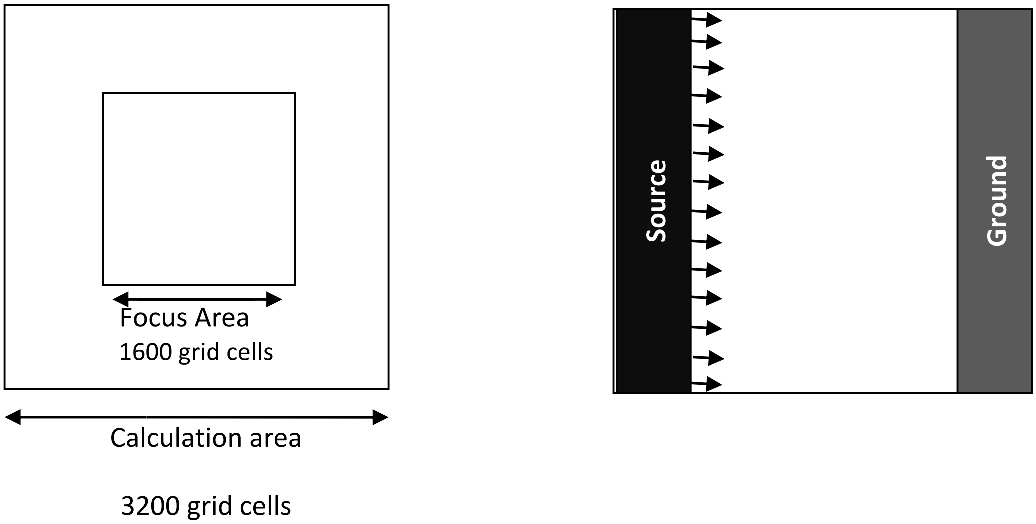
Mapping Regional Flow based on Anthropogenic Resistance

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 habitat needs of a particular 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 are described in Anderson et al. (2013) and Pelletier et al. (2014).

Briefly, to obtain complete 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 revealing the flow pathways across the landscape and highlighting 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 3.3) 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 (4.0) 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 3200 cells by 3200 cells or roughly 480 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).

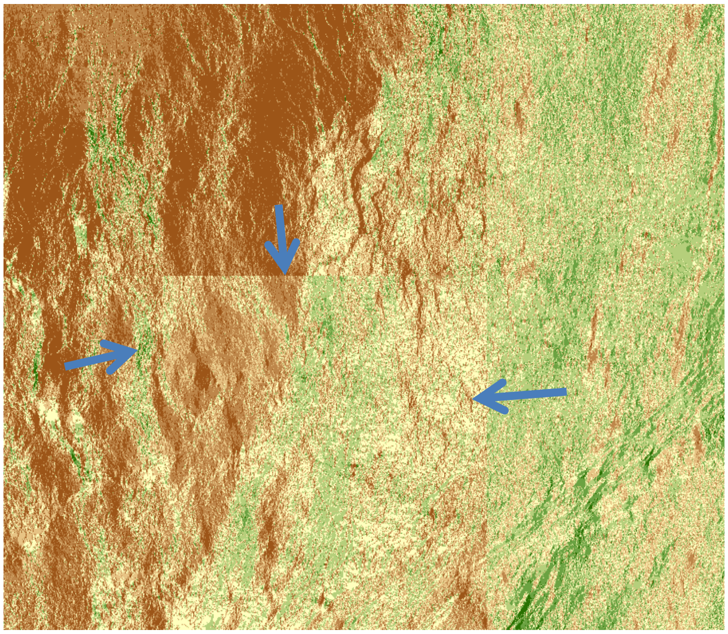
Figure 3.3. Diagram of tiles used in the Circuitscape analysis.
The image on the left shows the focus area in comparison to the calculation area. The image on the right shows how current is injected from every cell on the source (on the left) and can flow to any cell in the ground (right).

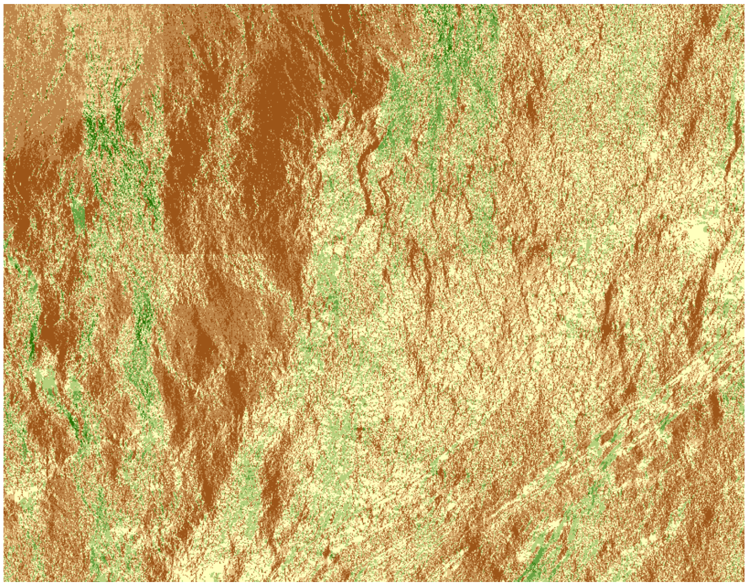


To inject current in the tile with coastal regions, where a proportion of the tile was filled by ocean or the Great Lakes we used a new method developed by Jeff Cardille of McGill University (personal communication, December 2015). We created a random raster with the same mean and standard deviation as the land resistance and replaced the large waterbodies (ocean and Great Lakes) 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. In earlier runs (Anderson et al. 2012) we had assigned the two waterbodies a resistance weight slightly higher than the average land average. This encouraged current to follow from the oceans onto the land, but there was still a slight preference for the current to enter the land in the closest point possible. The new method corrected this problem.

Lastly, the focus area was clipped out of each tile and joined together to create a single continuous coverage for the region. To standarize 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 3.4). 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 3.4. 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.





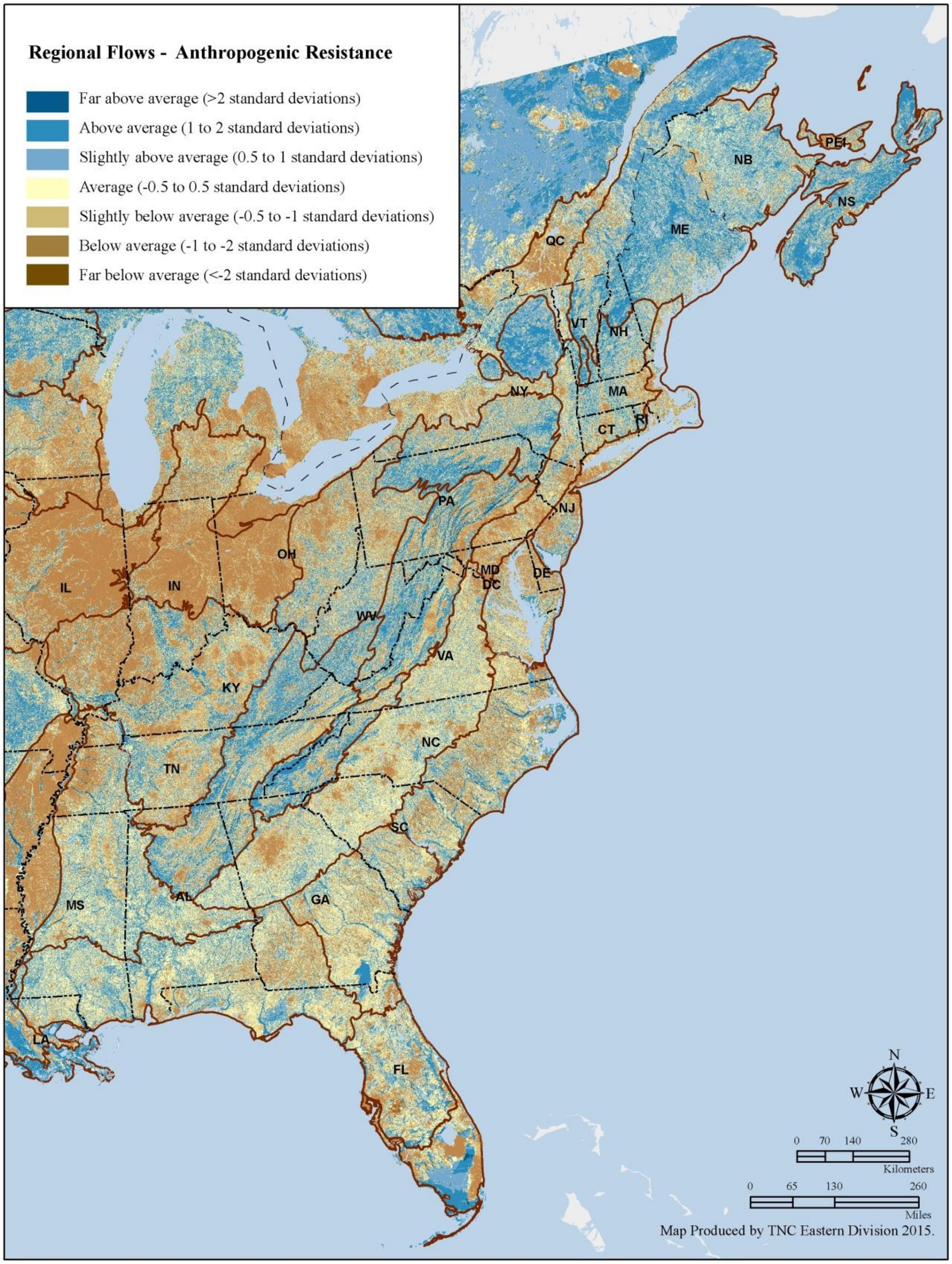
Regional Flow Results and Patterns

The final map of wall-to-wall regional flow applied to anthropogenic resistance grid highlights has areas of highest flow in dark blue, areas of moderate flow in medium blue, and areas of blocked or low flow in brown (Figure 3.5). A particularly useful feature of the wall-to-wall permeability results is that they reveal basic patterns in current flow that reflect how the human-modified landscape is spatially configured (Figure 3.6). Thus you can 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 results can be used to identify important pinch points where movements are predicted to concentrate, or diffuse intact areas that allow for more random movements. The four prevalent flow types each suggest different conservation strategies:

- <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. The conservation strategy is 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.

To create a categorical classification of flow patterns, we first converted the raster data into points and then ran a point density function on a small neighborhood (1000 acres) to calculate the flow density in the local neighborhood (Figure 3.7). Then the wall-to-wall grid results were compared to the neighborhood results to extract areas where the current flow was significantly different or similar. Areas that were different from their neighborhood and had high flow were classified as concentrated flow. Areas that were different from their neighborhood and had low to medium flow were classified as constrained flow. Areas that were similar to their neighborhood and had flow were classified as diffuse flow.

Figure 3.5. Results of the wall-to-wall Circuitscape model applied to the anthropogenic resistance grid. Brown indicates areas with low permeability where movement is blocked. 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.



Map Produced by TNC Eastern Division 2015.

Figure 3.6. 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.

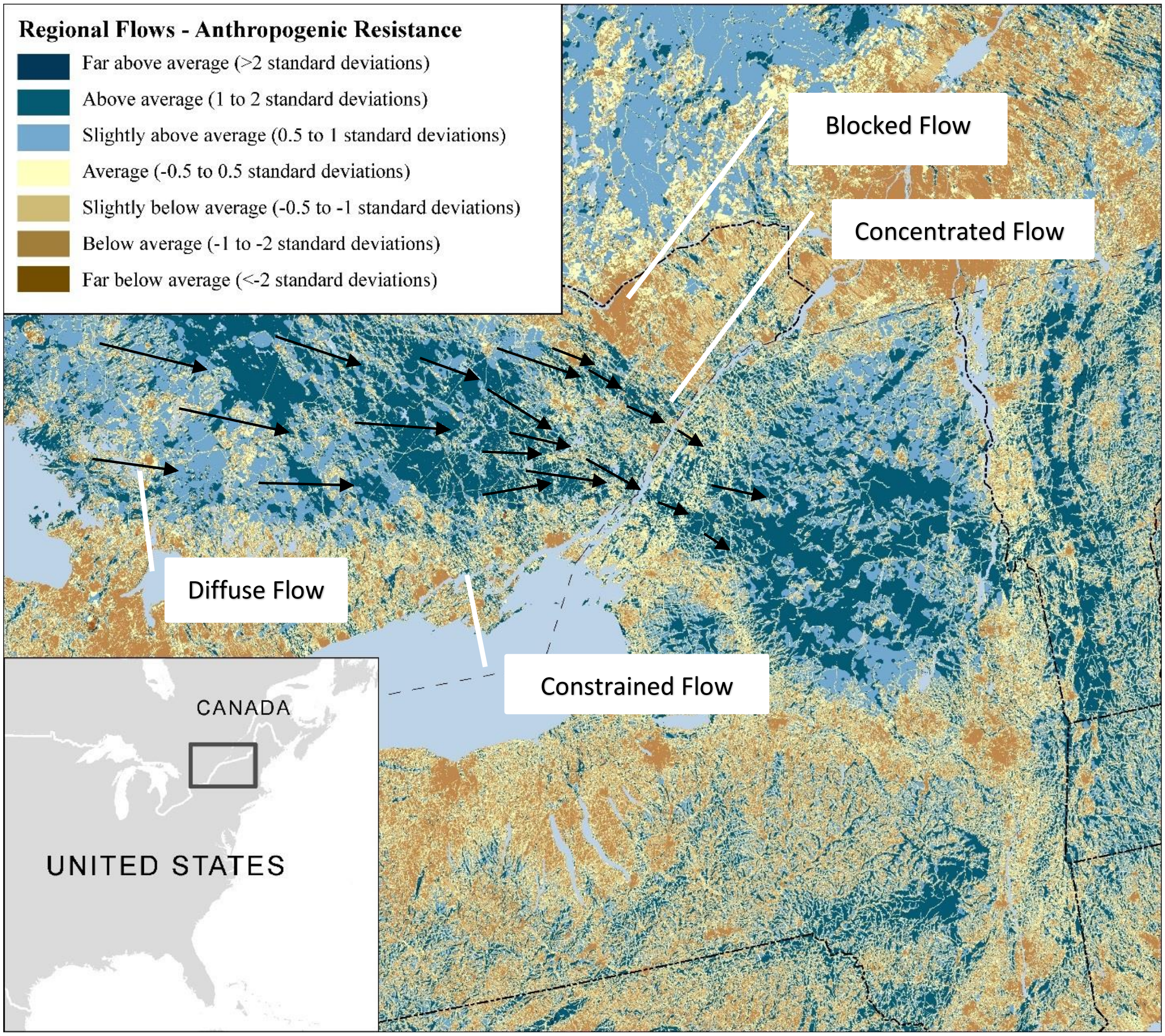
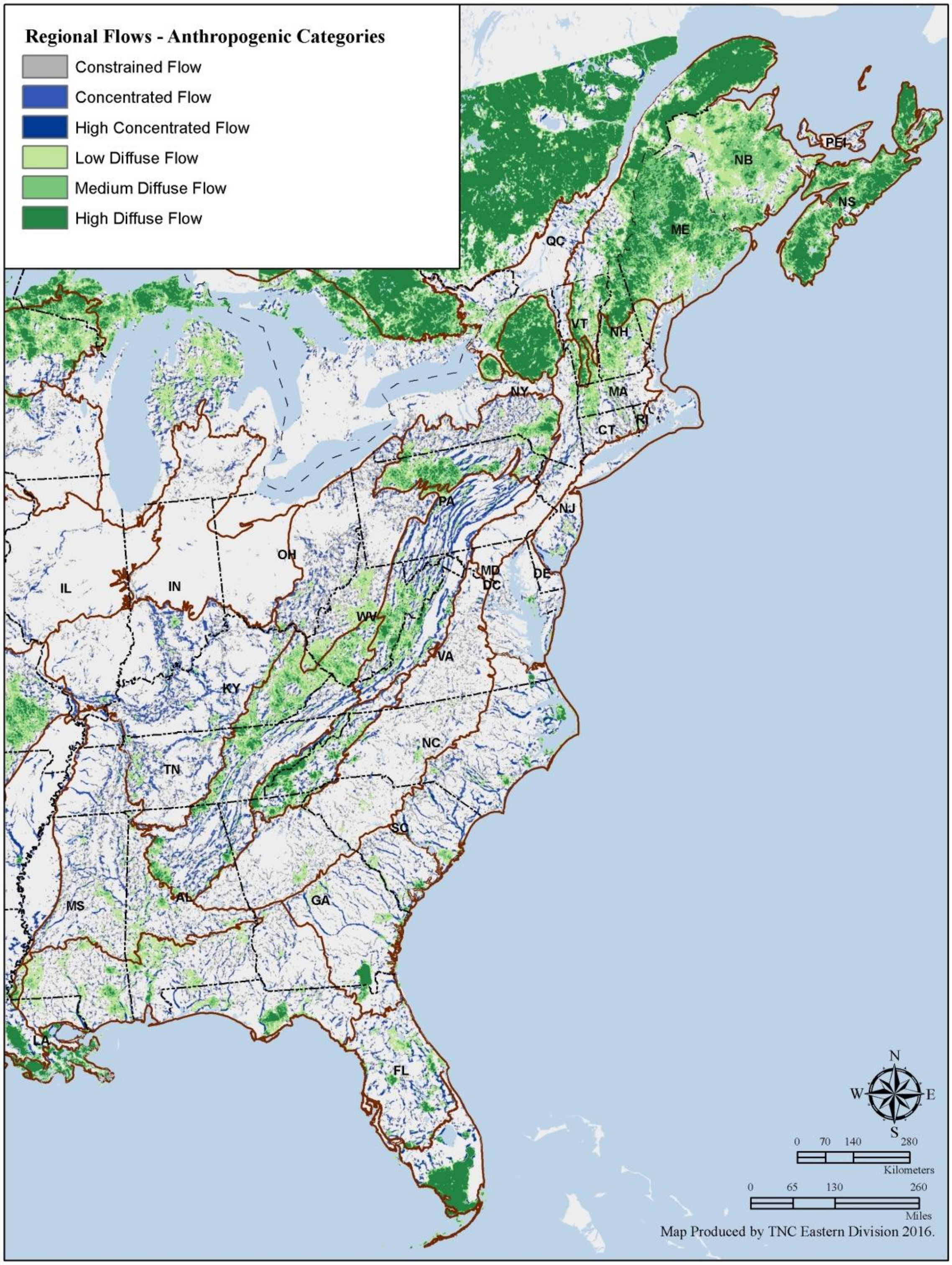


Figure 3.7. Categorized results of the wall-to-wall Circuitscape model applied to the anthropogenic resistance grid. Grey indicates areas with low permeability where movement is blocked. Green indicates areas of moderate flow; often highly natural settings where species movements are diffuse. Blue indicates areas of concentrated flow where movements will accumulate or be channeled through a pinch point.



Map Produced by TNC Eastern Division 2016.

Comparisons and Confirmation

The goal of this analysis was to understand the utility and limits of the region-wide permeability analysis ("regional flow" based on wall-to-wall Circuitscape with anthropogenic resistance, Anderson et al. 2012, 2014) by comparing the results to independent connectivity studies that were conducted across a range of scales and that used a variety of methods. Increased threats from climate change and other anthropogenic disturbances coupled with advances in analytical techniques have led to the development of many approaches to assess landscape and species habitat connectivity. The techniques can generally be grouped into two main types: 1) focal species and 2) "naturalness" modeling (Krosby et al. 2015). Approaches centered on focal species (i.e., fine-filter) seek to identify movement networks for a suite of species with the assumption that these areas will be important for other species that were not included in the study. A limitation of focal species approaches is the large amount of resources (i.e., time, funds, data, etc.) required to apply them across large geographic scales. Consequently, techniques such as Circuitscape, have been developed to delineate movement networks based on areas with minimal human impact (naturalness) and using readily available land use data (i.e., NLCD 2011). Naturalness analysis typically aims to identify linkages between pre-identified places, usually patches of good habitat or natural landscape blocks (Beier et al. 2011) to model the capacity of individual species to move between the core areas of habitat via corridors or linkage zones (Lindenmayer & Fischer 2006). Despite the increased use of naturalness approaches in conservation science, Krosby et al. (2015) appear to be the first study to quantitatively assess how effectively naturalness-based networks serve as a proxy for focal species analysis. Rather than compare the merits of connectivity modeling approaches, we instead sought to compare the regional flow results, which modeled landscape permeability as a continuous surface, with a variety of connectivity studies that included both naturalness and species-based techniques at a variety of spatial scales. We had no expectation that the studies would necessarily agree with the regional flow analysis, but we wanted to know if the regional study results were dramatically different, somewhat related, or very similar to other independently conducted studies.

Methods

We compiled 58 connectivity studies completed in Eastern North America that included areas from maritime Canada to Florida (Figure 3.8). The studies were diverse and included radio collar tracking of black bears, modeled habitat for a suite of terrestrial species based on expert opinion, and least-cost path analysis between a set of large forest blocks. In contrast to the approach used by Krosby et al. (2015) to compare naturalness and species-based connectivity studies using the same base datasets, the studies we collected differed greatly in their objectives, methods, data sources, time frame, and spatial scales. Thus, we decided to use straightforward visual comparisons and simple spatial overlays to compare the results. First, we identified studies that had spatially explicit results and were appropriate for comparison with the regional flow analysis. We excluded studies that focused on aquatic species (e.g., otter) as well as those conducted at very fine scales (e.g., box turtle movements). We categorized studies that encompassed an entire state or larger geographic area as large scale and considered all others to be small scale. We noted whether the study used a naturalness or species-based approach.

We further characterized both naturalness and species-based studies as to whether they restricted the analysis to *a priori* habitat blocks or specific locations (cores). For species-based studies, we noted those that used actual species data (radio-tags, GPS, mark recapture studies, etc.). Next, we compiled and processed the spatially explicit results for the selected studies. For studies where the results were only available as map images, we georeferenced the images, loaded them in a GIS with the regional flow results, and visually assessed the overlap between the study results and the regional flow data. As the visual overlay assessment was subjective, we had multiple individuals visually assess each study and submit their responses anonymously so that the predominant assignment was used. For studies with accompanying spatial data, we used simple spatial analysis to quantify spatial concordance with the regional flow data. Finally, for each study, we assigned the level of agreement with the regional analysis into one of three categories based on a simple set of rules (Box 1). The accompanying Supplementary Materials describe each study, provides details on how the comparison with the regional flow data was performed, and displays the results of each comparison.

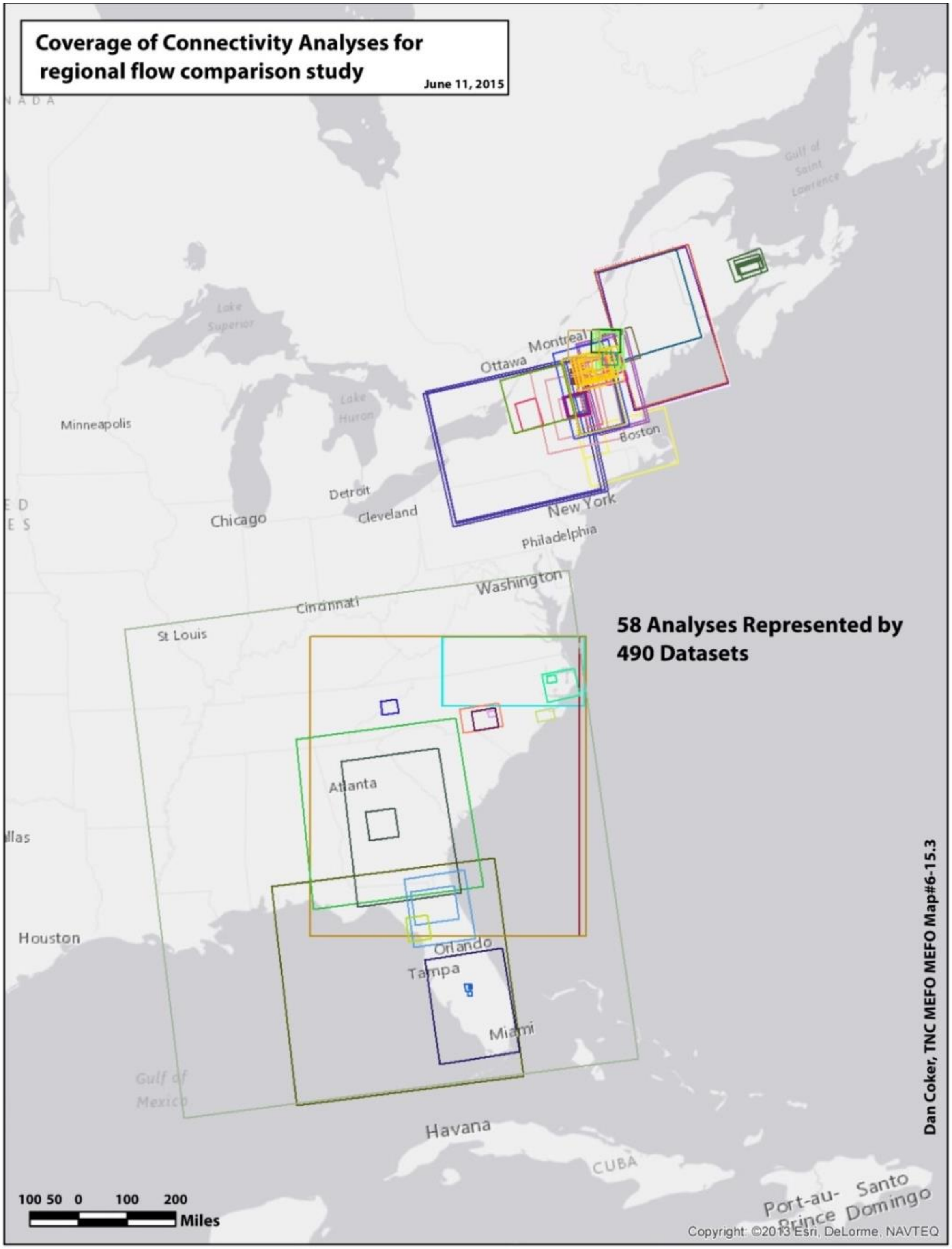
Box 1. Simple set of rules used to categorize the level of agreement between each connectivity study and the regional flow analysis.

Good Agreement
Majority ($\geq$ 80%) of the important areas identified in the study are captured as “Slightly Above Average” or higher in the regional flow assessment.

Moderate Agreement
Half to more than half ($\geq$ 50 - < 80%) of the important areas identified in the study are captured as “Slightly Above Average” or higher in the regional flow assessment.

Poor Agreement
Less than half (< 50%) of the important areas identified in the study are captured as “Slightly Above Average” or higher in the regional flow assessment.

Figure 3.8. Distribution and scale of the 58 compiled studies.



Results

Of the 58 studies collected, 23 were readily comparable (Table 3.3 and Supplementary Materials). As a handful of the studies had multiple locations (e.g., Cook 2007), there was a total of 30 sites for comparison. The studies we collected were predominantly small in geographic scale with only 20% of the sites considered large scale. The majority of studies (90%) used a species-based approach rather than a "naturalness" technique based solely on natural land cover. Of the species-based studies, 56% restricted the analysis to specific habitat blocks or locations (i.e., cores) and 52% incorporated actual species data. A large number of the species-based studies focused on wide- ranging mammals such as black bear, moose, and Florida panthers but there were a few that examined more locally-dispersed species such as red-cockaded woodpeckers (Breckheimer 2012, Simon 2009, and Trainor 2011). For the comparison methods, 57% of the studies did not have readily available spatial data and were assessed using a visual overlay. The remaining studies had accompanying spatial data and agreement with the regional flow analysis was quantified using simple spatial analysis.

Of the 30 site results tested, 57% had good agreement with the regional flow results and 43% had moderate agreement. No study had poor agreement (Table 3.3 and Figure 3.9). While there were more "good" agreements for the visual overlay comparison method than the spatial quantification approach, there was universal agreement by all who anonymously reviewed the visual overlay assessments which suggests subjective bias was not a factor. Highest agreement was found between the regional flow results and species movement studies that did not start with *a priori* cores.

Discussion

While we wanted studies that were independent of the regional flow analysis, a primary challenge of this effort was that those studies were not designed to be compared with the regional flow analysis. As such, there were numerous incongruities between the regional flow analysis and each study including overall objective, scale, method, land cover data, and time frame. With regard to objectives and scale, many of the studies focused on identifying the best corridors between specific locations and thus constrained linkages to occur in specific areas. For example, Hawk et al. (2012) identified the best locations to cross roads between already identified large forest blocks in the northern Green Mountains while Brown et al. (2009) focused on the best linkage area between the Adirondack Mountains and Tug Hill across the Black River Valley. As these and several of the other studies forced the identification of pathways between specific locations, the results may not represent all the potential corridors in the larger landscape that encompassed the specific locations. After removing the restriction of connecting these specific locations, there may be other pathways that are as, or more, intact and ecologically significant. These types of studies with *a priori* habitat blocks generally did not align as well with the regional flow analysis compared to other types of studies that examined actual animal movement and/or connectivity within a specific landscape. This is not surprising as the regional flow analysis is not restricted to specific patches to be connected but rather considers movement across the whole landscape. It is also worthwhile to consider the impact of comparing sub-regional and small scale analyses to the much larger regional flow analysis. By necessity and through the use of z-scores and stratification, the regional flow analysis forces the entire Eastern US landscape into one of seven flow categories ranging from Far Above Average to Far Below Average. An area that might be outstanding for connectivity at a small or sub-regional scale may only be Average at the much larger regional scale due to bigger more intact areas of flow elsewhere at the regional scale.

In addition to variation in project objectives and spatial scale, the selected studies used a range of methods to identify linkages including least-cost pathways, focal species modeling, animal movement data, corridor delineation programs, and circuit theory. Different methods represent both an opportunity and a hindrance in comparing these studies with the regional flow analysis. Confidence is inspired when multiple methods identify a similar area. On the other hand, it can be difficult to compare results if one analysis identifies a pathway for a single and locally-dispersed species while another analysis in the same geography delineates multiple corridors based on habitat intactness or a suite of wide-ranging large mammals. In their analysis, Krosby et al. (2015) concluded that naturalness approaches had better agreement with species approaches that were focused on large and wide-ranging animals. In our small sample and in contrast to Krosby et al. (2015), we found good agreement between the regional flow analysis and independent studies of both large (i.e., Cook 2007, Guthrie 2012) and local dispersing species (i.e., Trainor 2011, Simon 2009).

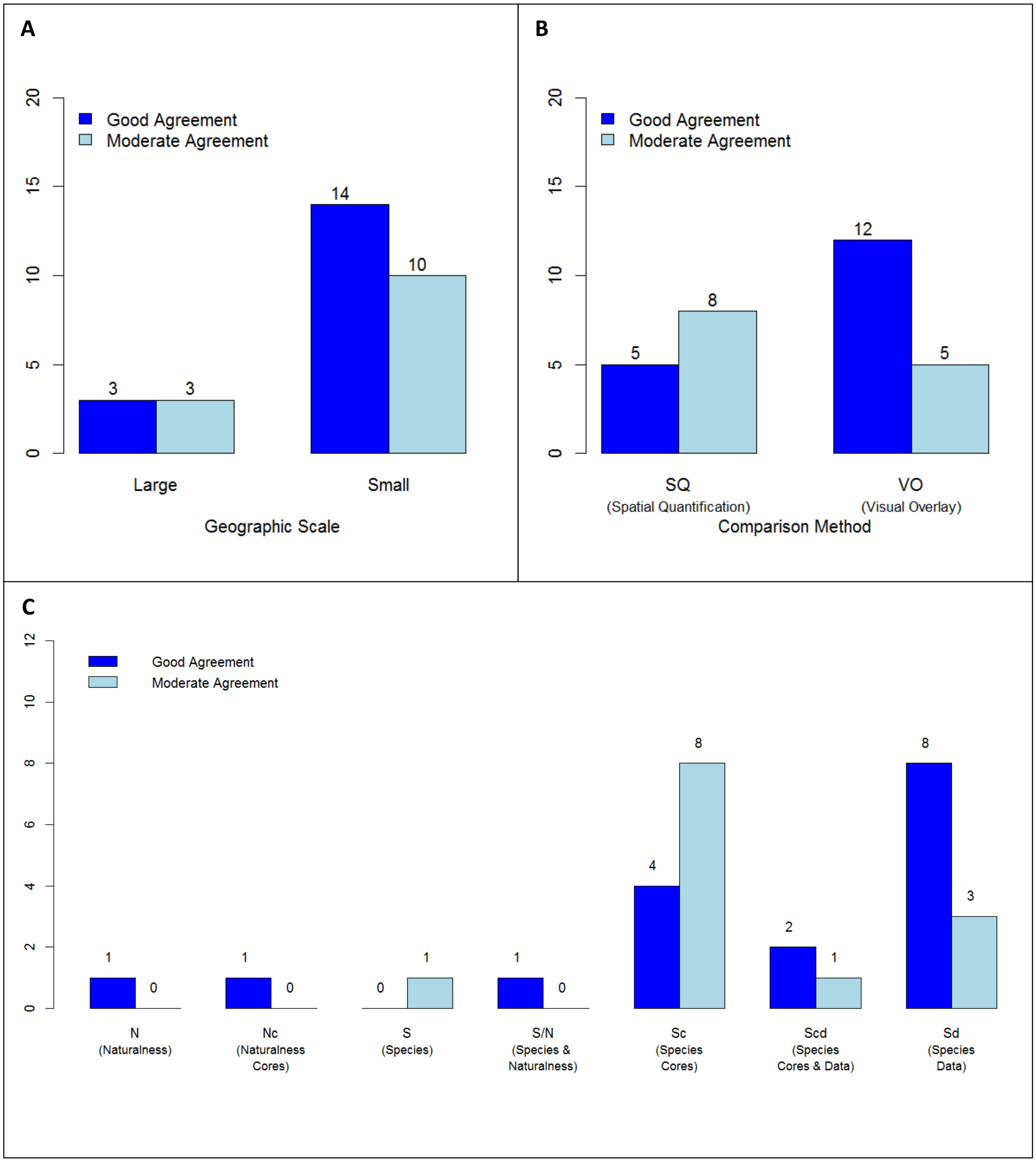
Land cover is the foundation dataset for all connectivity analyses. The regional flow analysis used the 2011 National Land Cover Dataset (NLCD) after several adjustments had been made to it including incorporating major and minor roads and distinguishing between natural and non-natural barren lands. However, most of the studies we collected used different sources and vintages of land cover data. For example, Kindall and van Manen (2007) used the 1992 National Land Use Land Cover (1992 NLCD) dataset while Noseworthy (2014) used a much more detailed land cover dataset with 35 classes compared to the 16 classes found in the NLCD.

Table 3.3. Summary of agreement between the regional flow analysis and several independent connectivity studies. Type refers to the focus of the study where "S" denotes a species-based approach and "N" indicates naturalness; a subscript of "c" specifies that the analysis was restricted to *a priori* habitat locations and "d" indicates actual species data was used. Comparison method identifies the approach used to compare the study to the regional flow analysis with "VO" referring to visual overlay and "SQ" indicating spatial quantification for those studies where spatial data was readily available.

Study	Geography	Scale	Type	Comparison Method	Agreement		
					Good	Moderate	Poor
Anco 2011	Georgia	Large	S_c	VO		X	
Breckheimer 2012	North Carolina	Small	S_d	VO		X	
Brown et al. 2009	New York	Small	S_c	SQ		X	
Cook 2007: Site 1	Georgia	Small	S_d	VO	X		
Cook 2007: Site 2	Georgia	Small	S_d	VO	X		
Dixon 2004: Site 1	Florida	Small	S_d	VO		X	
Dixon 2004: Site 2	Florida	Small	S_d	VO	X		
Gruber 2009	Florida	Small	S_c	VO		X	
Guthrie 2012: Site 1	Florida	Small	S_d	VO	X		
Guthrie 2012: Site 2	Florida	Small	S_d	VO	X		
Guthrie 2012: Site 3	Florida	Small	S_d	VO	X		
Hawk et al. 2012	Vermont	Small	S_c	SQ		X	
Hoctor et al. 2013	Florida	Large	S/N	SQ	X		
Jones 2008	North Carolina	Small	S_d	VO	X		
Kindall & van Manen 2007: Site 1	North Carolina	Small	S_{cd}	VO		X	
Kindall & van Manen 2007: Site 2	North Carolina	Small	S_{cd}	VO	X		
Marangelo 2013: Site 1	Vermont	Small	S_c	SQ		X	
Marangelo 2013: Site 2	Vermont	Small	S_c	SQ		X	
Noseworthy 2014	Chignecto Isthmus	Small	S_c	SQ	X		

Richardson et al. 2013	United States	Large	N	SQ	X	
Robidoux 2010	Appalachian Corridor (Quebec)	Small	N_c	SQ	X	
Shaffer 2007	North Carolina	Small	S_c	VO	X	
Simon 2009	North Carolina	Small	S_c	VO	X	
Staying Connected Initiative	Northeast	Large	S	SQ		X
Steckler & Bechtel 2013	Northeast Kingdom to New Hampshire	Small	S_c	SQ		X
Sutherland et al. 2014: all species	Southeastern US	Large	S_c	SQ		X
Sutherland et al. 2014: two species	Southeastern US	Large	S_c	SQ	X	
Thatcher et al. 2009	Florida	Small	S_{cd}	VO	X	
Trainor 2011	North Carolina	Small	S_d	VO	X	
VT Fish and Wildlife	Vermont	Small	S_d	SQ		X

Figure 3.9. Visual summary of agreement between the regional flow analysis and the connectivity studies collected for the Eastern US by A) Geographic Scale, B) Comparison Method, and C) Connectivity Study Focus. For the latter, "cores" refers to studies that started with pre-identified core areas, "species data" refers to actual observation or radio-collared tracking, "species experts" refers to models based on expert opinion relative to a particular species, and "naturalness" refers to methods based on degree of human modification.



Despite all these challenges, the studies that used actual species data and were not restricted to *a priori* habitat blocks were particularly encouraging as almost all of these aligned well with the regional flow analysis and reflect how animals are truly using the landscape. For example, Cook (2007) used telemetry data from radio-tagged black bears in central Georgia to create probability models of black bear annual habitat use. The high probability areas at multiple scales overlapped very well with the regional flow analysis. Similarly, Guthrie (2012) used GPS data of black bears to identify movement corridors at a small scale in south-central Florida. The fast and direct movement corridors had high spatial agreement with the regional flow analysis results. The agreement with animal movement data was not limited to black bears as studies on Florida panthers (Thatcher et al. 2009), red wolves (Shaffer 2007), and red-cockaded woodpeckers (Trainor 2011) had high spatial concordance with the regional flow analysis. Studies that incorporated animal data but only had moderate agreement with the regional flow analysis were almost always those that restricted movement to specific locations; an approach that is problematic when comparing to the regional flow analysis for the reasons previously discussed.

This analysis was not an attempt to compare connectivity modeling approaches, but rather to assess the kinds of information the regional flow analysis reliably captures as well as the type of information it omits. Given all the challenges inherit in this analysis, it was encouraging that almost 60% of the sites had good agreement with the regional flow analysis and that none had poor agreement. Most importantly, the regional flow analysis corresponded well with those studies that incorporated actual species data regardless of the type of species (i.e., wide-ranging or locally dispersed). In almost all cases of moderate agreement, the studies were restricted to generating connections between an *a priori* set of locations rather than considering the entire landscape. Based on this analysis, we are confident that the regional flow analysis does a good job of identifying important landscape connections at multiple spatial scales and for a range of species. In addition, this analysis shows that the regional flow analysis will likely not be as useful for applications or projects that are focused on linkages between specific locations, but it could still provide insight on how the surrounding landscape relates to these specific pathways.

Permeable Climate Pathways

In this section we modify the regional flow model to specifically highlight connections that provide climate relief. Our goal is to evaluate the capacity of the landscape to allow species range shifts in the face of dynamically shifting climate and to identify the places that promote climate connectivity and could potentially allow for such movements. Models that project species movements in response to climate change have often not examined where or how fragmentation will limit those movements, nor did our own analysis of resilient sites based on geophysical settings examine how species will move between resilient sites.

Recently, new approaches to incorporate climate gradients into connectivity models have been developed with the most straightforward being 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 coarser). These modesl don't contain the fine-scale microclimates and topographic 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.

Evidence for contemporary range shifts in response to climate has now been documented for over 1000 species. The evidence for upslope and northward movements is strong and consistent across many taxa groups and across several continents, and there is also rapildy growing evidence for the important role of riparian areas and local microclimates in facilitating species persistance (see introduction to section III). Following the findings presented in the introduction, we focused our attention on the four most common and mappable patterns of species response to climate change:

1) **Upslope** toward higher elevations,
2) **Northward** toward cooler latitudes,
3) **Downslope** toward moist **riparian** areas, and
4) **Locally** toward suitable microclimates.

As we model the range shift patterns expected from these four responses, keep in mind that a variety of ecological factors may create variation in a species response to climate including: 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).

Upslope and Northward Model for Range Shifts

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 3.1). Theoretically, a plant or animal population with a leading edge ending on the banks of the Charles River in Boston might appear on top of Beacon Hill or northward halfway to the New Hampshire border in just 20 years. In one century, the same populations could occur north of Portland, Maine, or have already topped the summit of Mount Agamenticus. Of course, there are other factors besides temperature and moisture that determine where a species occurs. For example, a species inhabiting rich and fertile river floodplains might not be able to tolerate the thin rocky soils of a mountaintop. However, temperature is a well-documented and understood factor limiting the northward expansion of many species, even if other factors such as moisture and soil type determine where exactly a species is found within its range. Paleoecological studies show that movement was a near universal response to past changes in climate (Pardi and Smith 2012).

Here we explore the implications of human modification of the landscape on directional movement driven by climate change. Our essential question was: If species populations are tracking temperature changes by moving upslope and northward, then how and where does the fragmented human-dominated landscape impede such movement and where are the places that facilitate such movement? Our approach was to first model upslope and northward movements as if there were no human modification, then integrate the resistance layer and re-run the model to identify pinch points, barriers, flow concentration areas, and facilitating landscapes.

The wall-to-wall Circuitscape approach is well suited to exploring this question because it assumes that every cell in the region is a starting point for some species and the directional movement upslope (short term climate relief) could be conceived in terms of resistance and northward (long-term climate relief) as source-ground flow. To simulate population movements over time, we first developed a fine-scale model to estimate upslope movement, and then we added latitudinal direction to the anthropogenic model by setting the “sources” and “grounds” to a north-south direction. We added the anthropogenic resistance grid to identify how flow across the directional pathways intersect with human uses. “Flow” refers to the gradual movement of populations tracking a set of changing conditions over time.

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 3.4).

For example, moving upward along a gentle slope is easy but provides little gain in temperature differences (moderate resistance), moving upward along a moderate slopes provides larger gains in temperature differences for moderate effort (low resistance), moving upward along a steep slope is too difficult for most species in spite of the temperature gains (high resistance) (Figures 3.10 and 3.11). We combined the land position and slope values into one resistance score that scales the model such that a theoretical species would move upslope preferentially along areas of moderate slope where they would experience the greatest temperature differences relative to effort.

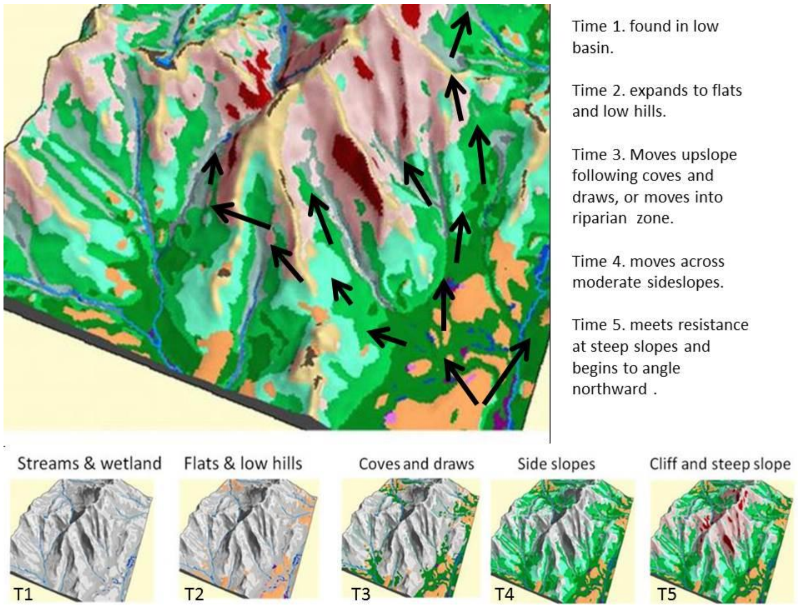
Although mountainous areas may produce the highest amount of pure relief, species experience temperature relief from slopes relative to their local landscape (a 10-m slope in a flat landscape may provide more relief to nearby species than a 10-m slope in an already mountainous landscape). To ensure that the model was scaled to local relief we calculated the landform resistances in a local neighborhood (3 km) around each cell. To do this in ArcGIS, we used the focal statistic algorithm to calculate the mean and standard deviations for a 3 km radius. This is the same processing radius we used for local connectedness in the resilience analysis. We used the mean and standard deviation to calculate a Z-score for each cell based on the neighborhood statistics. The results provide a fine-grained estimate of the location and amount of available climate relief from local slopes (Figure 3.12).

The Circuitscape analysis on the landform-based upslope resistance grid shows how the areas with high potential for upslope range shifts are arranged locally and across the region, and how they intersect with anthropogenic resistance (Figures 3.12 and 3.13). The realistic effect of the local scaling (Figure 3.13) 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 in the Coastal Plain, Piedmont, and North Atlantic Coastal ecoregions where these features might play a large role in providing local climate relief. The high flow areas on the map are important because the rate of current climate change is faster than the historic rate and the moderate slopes offer the easiest access to meaningful temperature gradients (Corlett & Westcott 2015).

Table 3.4. Resistance scores applied to the landform model. Land position ranks (LP rank) were ordered so they decrease towards higher land positions. Slope ranks (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 (most gain for least effort.).

Landform	code	Slope	Position	LP rank	S rank	Sum	Weight
Slope crest	13	3mod	highest	1	1	2	1
Ridgetop	12	2gentle	highest	1	4	5	2.5
N-sideslope	23	3mod	high	4	1	5	2.5
S-sideslope	24	3mod	high	4	1	5	2.5
Flat summit	11	1flat	highest	1	7	8	4
hill/gentle slope	22	2gentle	high	4	4	8	4
Lower side	33	3mod	low	7	1	8	4
Hilltop flat	21	1flat	high	4	7	11	5.5
Valley/toeslope	32	2gentle	low	7	4	11	5.5
N-cove	43	3 mod	lowest	10	1	11	5.5
S-cove	44	3 mod	lowest	10	1	11	5.5
Dry flat	30	1flat	low	7	7	14	7
Wet flat	31	1flat	low	7	7	14	7
Slopebottom	42	2gentle	lowest	10	4	14	7
Slopebottom flat	41	1flat	lowest	10	7	17	8.5
Steep slope	4	4 High	any	NA	9	18	9
Cliff	5	5 Highest	any	NA	10	20	10

Figure 3.10. Conceptual model of how a species population (black arrows) might move upslope and northward over five generations.



Time 1. found in low basin.

Time 2. expands to flats and low hills.

Time 3. Moves upslope following coves and draws, or moves into riparian zone.

Time 4. moves across moderate sideslopes.

Time 5. meets resistance at steep slopes and begins to angle northward .

Figure 3.11. 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 with the low land position flats in purple and blue, mid land position and moderately sloped sideslopes in green, and high position and steep slopes and cliffs in orange and red. 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.

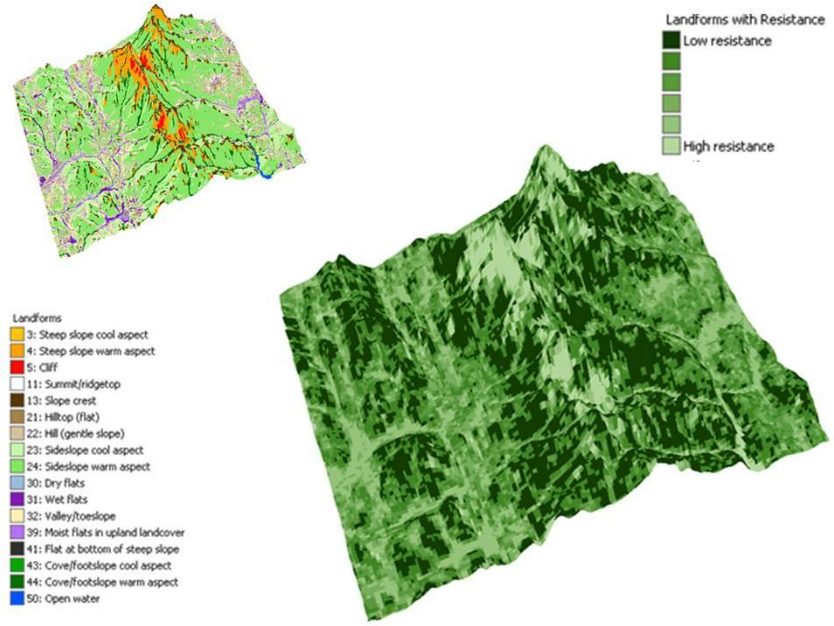


Figure 3.12. Zoom-in of the upslope results for the Mohawk Valley between the Adirondacks and Catskills, NY. Areas of high current flow are expected to be important channels of upslope movement.

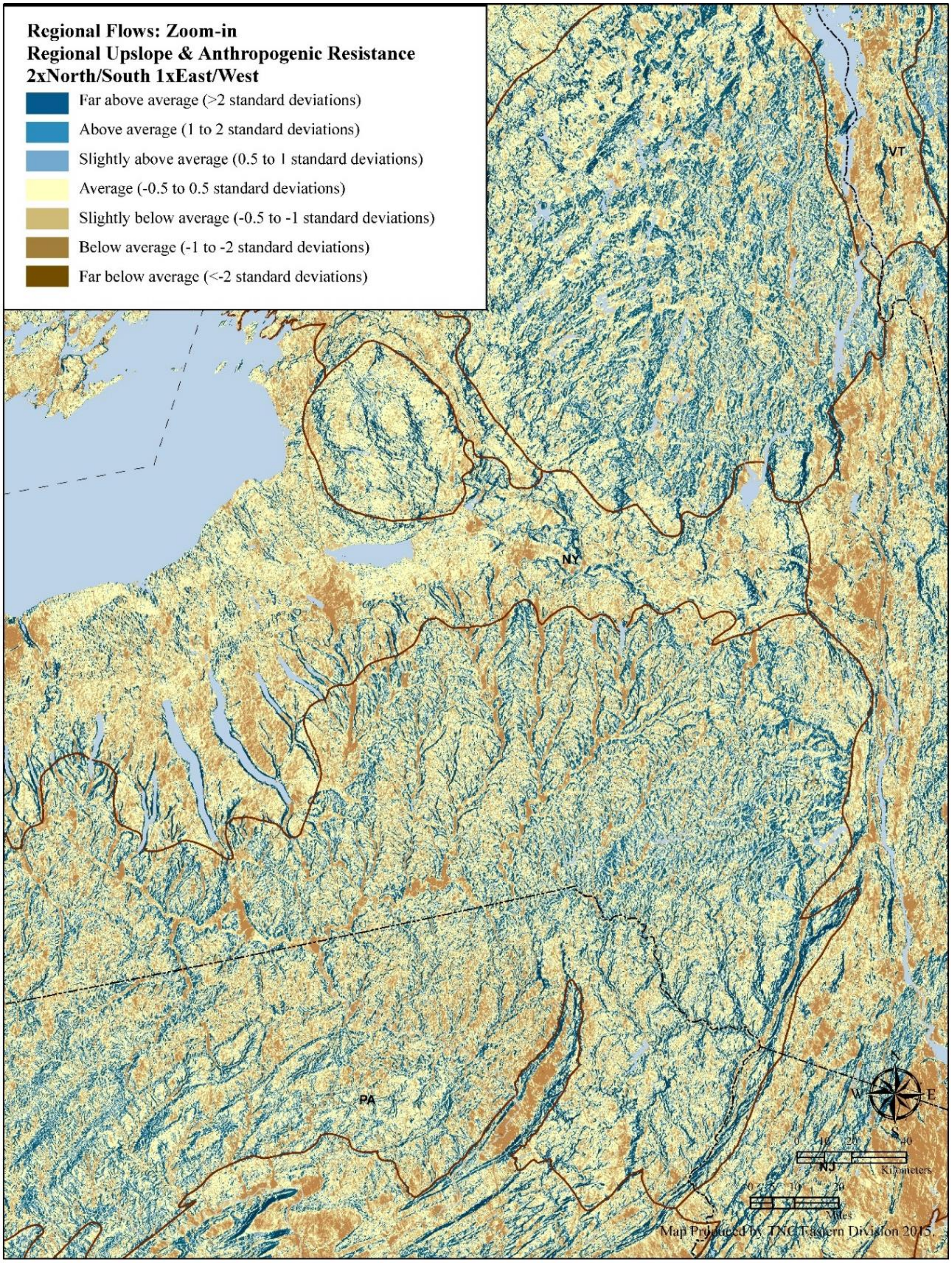
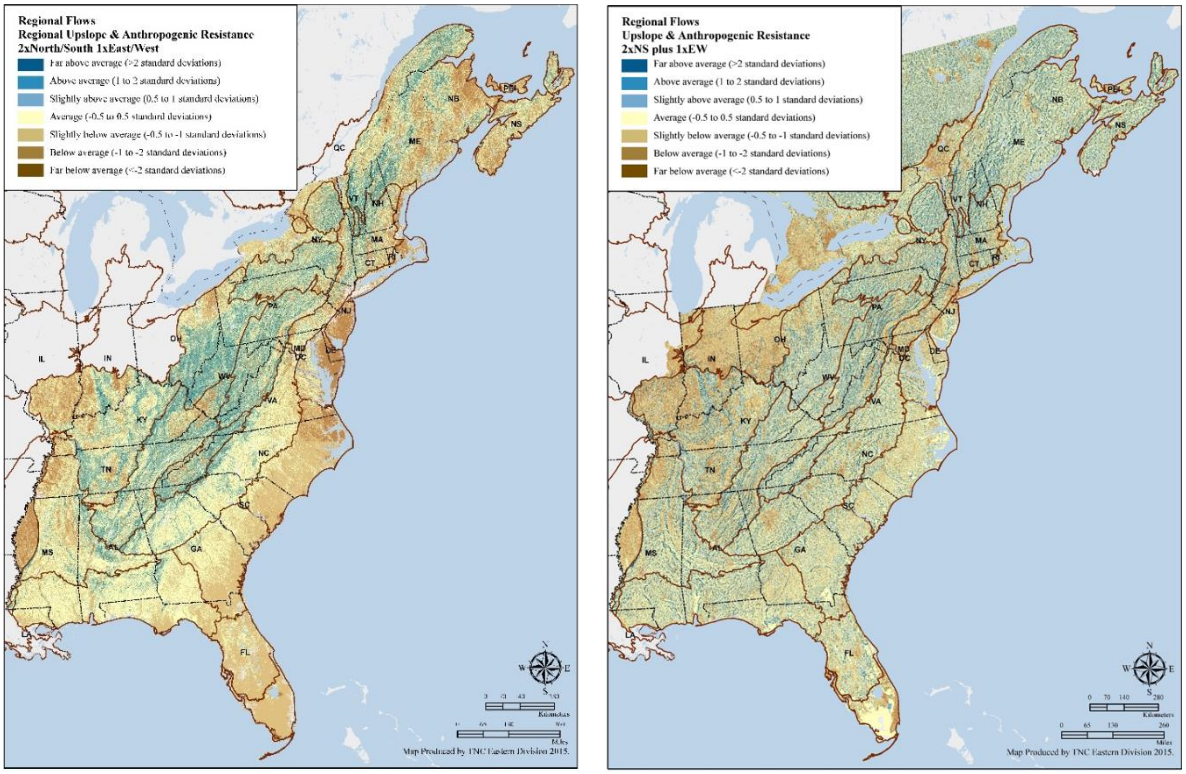
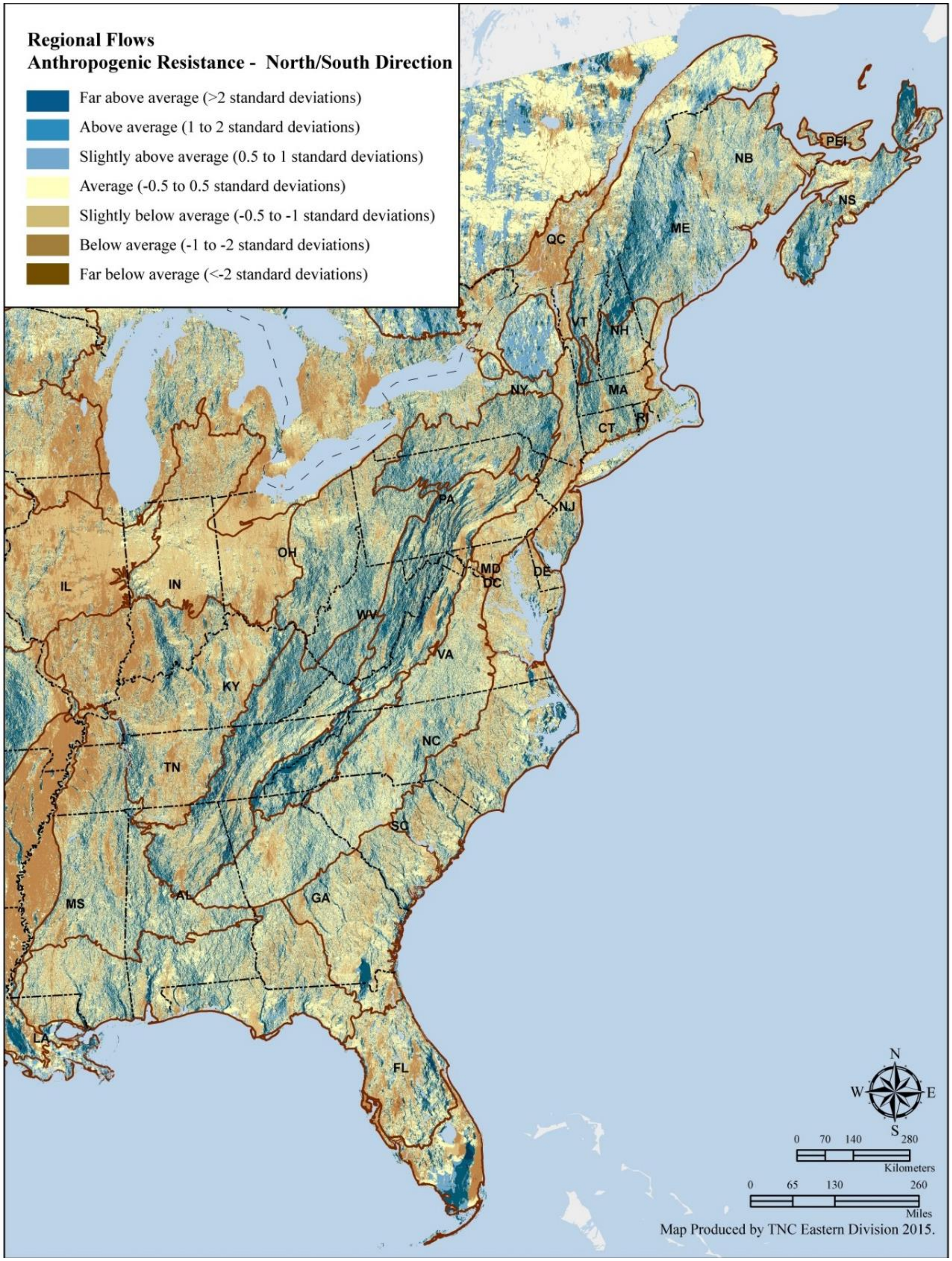


Figure 3.13. The effect of scaling on the upslope model. The map on the left shows the regional flow pattern based on the unscaled upslope model. The map on the right shows the regional flow patterns after scaling the upslope model to the local 3-km landscape.



We added latitudinal direction of the results in order to simulate both short term (upslope) and long-term (northward) climate relief. We did this by modifying the four directional runs we used to develop the wall-to-wall anthropogenic 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. Initially we omitted the east-west runs and combined the north-souths runs to create results just along the south to north axis. The results of this approach strongly highlight the mountainous sections of the region (Figure 3.14). We used these results to classify the mapped anthropogenic flow concentrations by their directionality (Figure 3.15). This analysis revealed that while the vast majority of flow concentrations resulted in pinch-points oriented in a north-south direction there were also key east-west pinch points in many of the low elevation ecoregions such as the Coastal Plain or Interior Low Plateau. If the east-west pinch point ran along an upslope gradient it could provide important linkages for climate connectivity and thus in the final integration described below we did not omit the east-west axis but simply gave more weight to the north-south axis.

Figure 3.14. The northward model. This figure shows the results of a wall-to-wall Circuitscape analysis applied to the anthropogenic resistance grid with source-ground flow limited to the north-south axis.



Map Produced by TNC Eastern Division 2015.

Figure 3.15. Flow concentrations classified by direction. This figure shows the concentrated flow areas by their directionality. The vast majority of pinch points run along the north-south axis and are likely important for facilitating northward range shifts.

Map Produced by TNC Eastern Division 2016.

Final Integration of Upslope, Northward, and Anthropogenic

For our final model, we combined the anthropogenic resistance and the landform resistance to model where species could flow through the natural landscape finding climate refuge both by moving upslope and mostly in the northward direction. The goal was to approximate a species population expanding locally upslope 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 (anthropogenic resistance, upslope resistance, north-south flow and east-west flow) in a way that most closely approximates the real world. In our initial analysis we gave the same weight to the anthropogenic and upslope resistances, and twice the weight to north-south flows over east-west flows when combing the results (Figure 3.16). We wanted to keep the emphasis on the areas that are important for anthropogenic flow, while incorporating the upslope flow, so we used the anthropogenic flow map as a base map and overrode the anthropogenic scores with the upslope scores where the upslope values are above average and greater than the anthropogenic values. The results emphasize the prevalence of local slopes across the region, effectively creating a much more dispersed picture of climate adaptation. This makes sense because in the short term, local upslope range shifts are more likely than latitudinal shifts as elevational temperature gradients are steep and much greater than the latitudinal gradients (Colwell et al. 2008). If this is the case, then the model of upslope with anthropogenic resistance may give a more accurate picture of important linkages. When the maps are compared with the purely anthropogenic model (Figure 3.17) the differences are immediately obvious. Smaller complexes of slopes, for example in the High Allegheny and Cumberland Mountains, have more flow, while the very high scores of the Central and Northern Appalachians are muted. A zoom-in of the Mohawk Valley between the Catskills and the Adirondacks (Figure 3.17) is instructive. In the anthropogenic model (upper left) the valley, which is heavily agricultural, scores poorly with flow concentrated only in a few relatively intact regions. In the full model (bottom right) the importance of the many sloped landforms crossing the valley is emphasized as they likely offer the most temperature change to species in the flat regions.

Weighting can be adjusted relatively easily to test for sensitivity or influence of a factor. We performed the weighting by converting the individual resistance grids (anthropogenic and upslope) to Z-scores so the two grids each had a mean of 0 and a standard deviation of 1. This ensures absolutely equal influence of each grid and also makes it possible to control the weighting by using a multiplier. To limit the weight of outliers, scores were capped at above +3.5 SDs or below -3.5 SD. A constant was used to make all values positive, which is required for Circuitscape.

Figure 3.16. The upslope, northward and anthropogenic model. The results of a wall-to-wall Circuitscape analysis applied to a resistance grid derived from landforms and anthropogenic resistance, with northward flows given twice the weight of east-west flows. Areas of high current flow are predicted to be important for upslope range shifts and because human fragmentation patterns also channel flow through these areas.

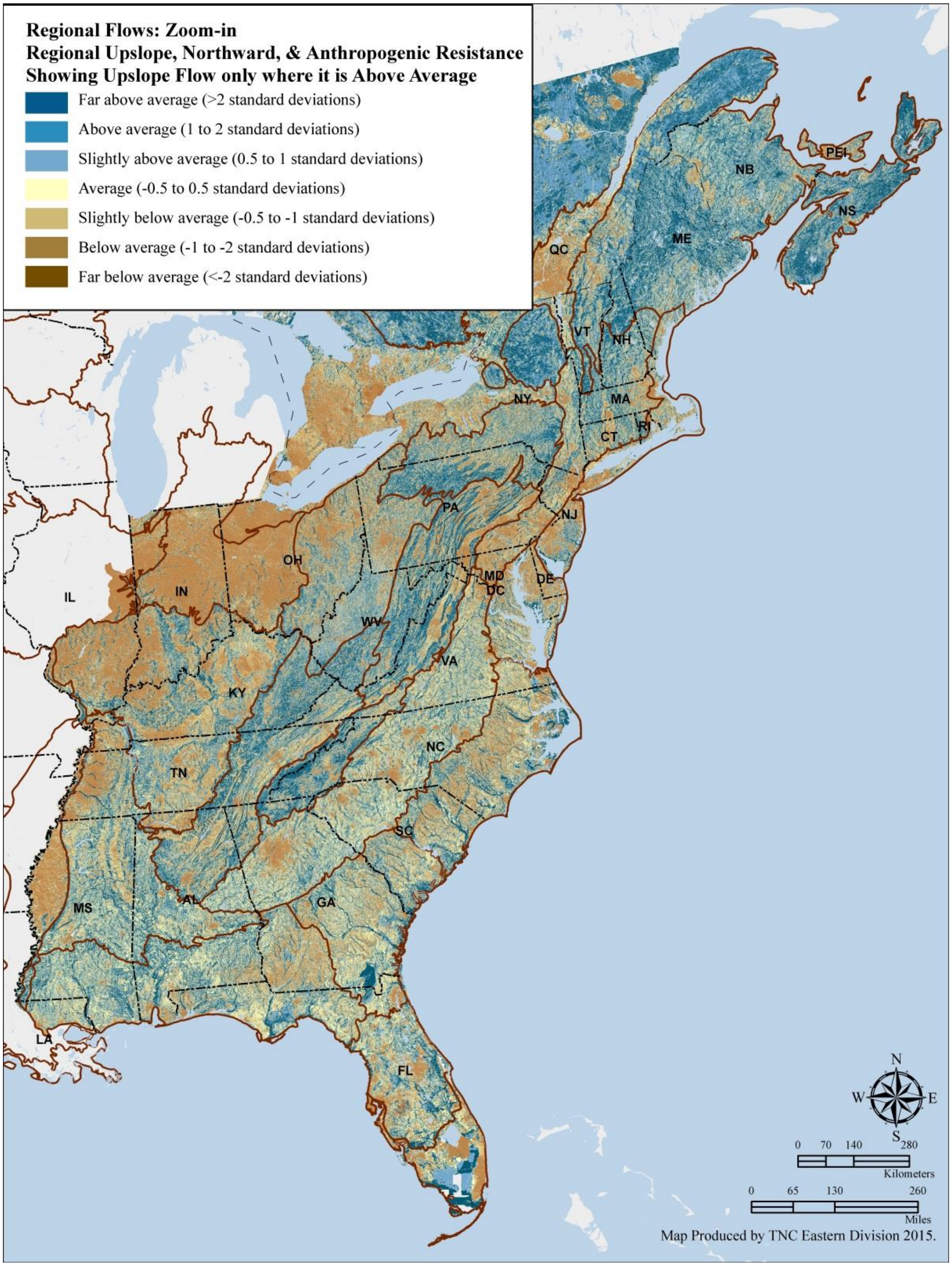
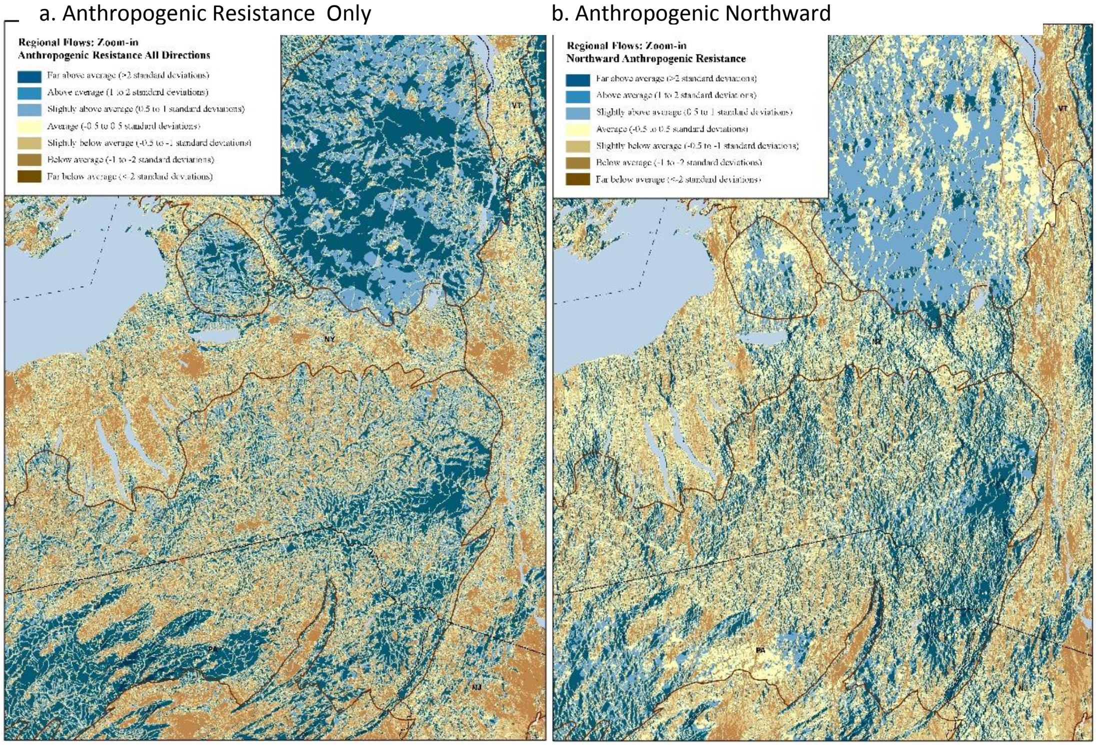
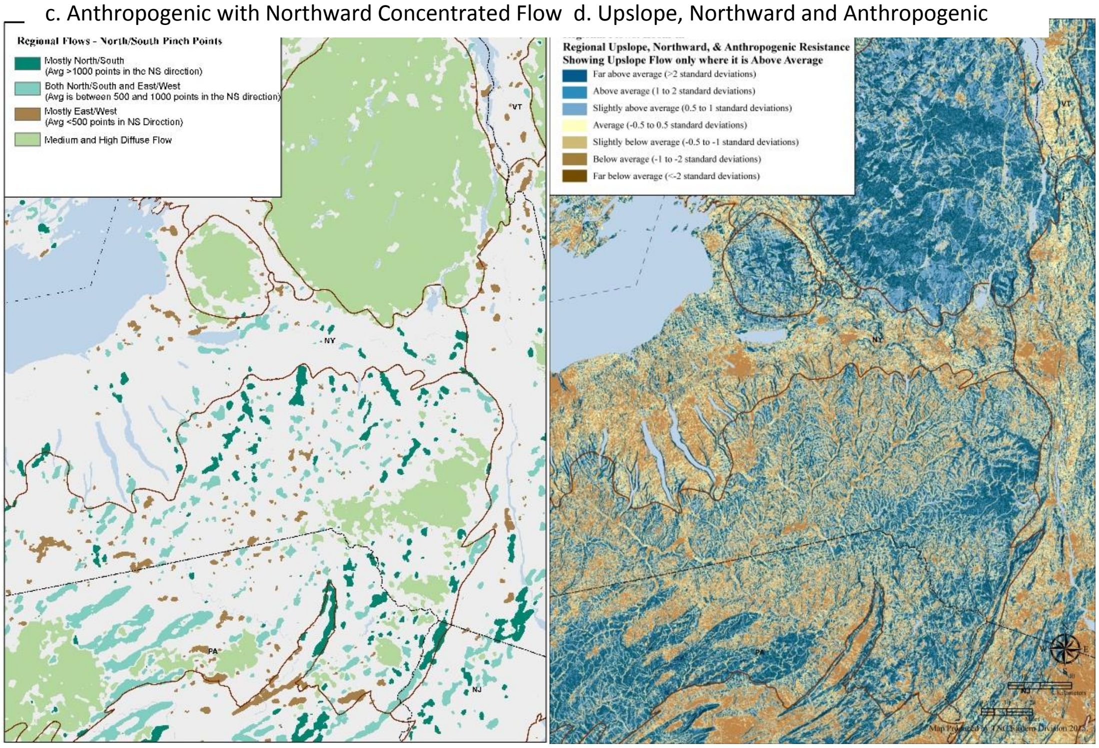


Figure 3.17. Comparison of results. This map compares the various Circuitscape runs for the Mohawk Valley region between the Adirondack and Catskill mountains in New York.



a. Anthropogenic Resistance Only

b. Anthropogenic Northward



c. Anthropogenic with Northward Concentrated Flow

d. Upslope, Northward and Anthropogenic

Riparian Climate Corridors

Introduction and Background

Riparian areas are the zones along waterbodies that serve as interfaces between terrestrial and aquatic ecosystems. Although they compose a minor proportion of the landscape, they are typically more structurally diverse and more productive in plant and animal biomass than adjacent upland areas. Riparian areas supply food, cover, and water for a large diversity of animals, and serve as migration routes and connectors between habitats for a variety of wildlife, particularly within highly modified landscapes (Hilty & Merenlender 2004). With respect to climate change, riparian areas feature microclimates that are significantly cooler and more humid than immediately surrounding areas (Olsen et al. 2007), and are expected to provide microclimatic refugia from warming (Seavy et al. 2009). Indeed, our own climate resilience analysis based on microclimates and connectedness coincidently identified many riparian corridors as key landscape features in providing climate options (Anderson et al. 2014). Riparian areas that span climatic gradients and provide natural corridors that species may use to track shifting areas of climatic suitability have been called Riparian Climate Corridors or RCCs (Krosby et al. 2014).

In addition to their connectivity functions, riparian areas offer many other conservation values. They 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). Riparian areas typically contain high levels of species richness (Naiman et al. 1993).

Krosby et al. (2014) proposed a method for identifying priority riparian areas for climate adaptation. Their analysis, performed in the Pacific Northwest at a 90-m scale, identified potential riparian areas that span large temperature gradients, have high levels of canopy cover, are relatively wide, have 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. We were inspired by this work and aimed to develop a counterpart for the Northeast.

After considerable experimentation, our final method of assessing riparian areas differed in several ways from Krosby et al. (2014). First, we focused on the riparian floodplain areas of creeks to large rivers, and we omitted small headwater streams because the riparian area of headwater streams in the Eastern US is not easily differentiated nor particularly distinct from the surrounding forest. Second, we developed the analysis at a 30-m scale, because we wanted a fine-scale analysis. Third, because the Northeast is largely forested we found that the available canopy cover and solar radiation datasets provided little if any differentiation among riparian units, and for those riparian areas that did have very different values, further examination suggested that the data was in error. Fourth, we were unable to find a downscaling method that could accurately convert the measures of temperature modeled at the 800-m scale to the 30-m riparian corridors. Moreover, after we created and applied a 90-m downscaled temperature model using PRISM data we discovered that most of the riparian corridors had less than one-degree C difference within them (Table 3.5). Riparian areas with greater than one-degree C difference were located in very sloping mountainous regions and the coarse-scale temperature unit sometimes picked up elevation outside the floodplain in adjacent mountain slopes.

What we learned from our testing was that in the flatter portions of our region, such as the Coastal Plain, the riparian floodplain areas are indeed cooler and moister but they have little temperature variation within them. Species traveling along the riparian area are unlikely to encounter progressively cooler temperatures unless they follow a tributary that runs upslope or move slightly northward while staying within the floodplain. In fact, elevation change and latitude appeared to be more sensitive measures of potential temperature change than the downscaled climate model.

Table 3.5. Temperature variation within riparian units. This table shows the mean and standard deviation (SD) of the mean annual temperature in degrees celcius within riparian units of any size.

Ecoregion	Mean Annual Temperature Range	SD of Mean Annual Temperature Range
Mid-Atlantic Coastal Plain	0.14	0.04
Chesapeake Bay Lowlands	0.22	0.07
North Atlantic Coast	0.25	0.09
Piedmont	0.42	0.16
St. Lawrence – Champlain Valley	0.45	0.21
Western Allegheny Plateau	0.59	0.17
Great Lakes	0.72	0.34
Lower New England / Northern Piedmont	0.77	0.33
High Allegheny Plateau	1.03	0.42
Cumberlands Southern Ridge and Valley	1.11	0.33
Southern Blue Ridge	1.11	0.42
Northern Appalachian / Acadian	1.23	0.60
Central Appalachian Forest	1.32	0.46

Mapping Riparian Climate Corridors

We based our measurements of the importance of a riparian floodplain to species movements primarily on the degree to which regional flow from our Circuitscape analysis was concentrated in the riparian units. Modeled "flow," as discussed in the previous chapter, is already an integrated variable that takes into account the resistance of the landscape as well as how the spatial configuration of anthropogenic resistance serves to concentrate species movement into pinch points. The degree to which flow is channeled into or along a particular riparian corridor provides an excellent quantitative measure of its relative value to species movement. Further, our experimentation suggested that many of our original ideas for attributes to collect were either redundant or did not provide the fine resolution and detail needed to make choices among riparian areas. We did, however, calculate a few other metrics which, although somewhat correlated with flow, could be used to help distinguish among riparian areas. These include measures of how much the local connectivity score within the unit varied from surrounding buffer connectivity, and the amount of secured land within each.

Our objective was to identify contiguous units of riparian floodplain that would facilitate movement of plants and wildlife. In contrast to the upslope model of the previous section where populations were presumed to traverse the landscape starting at any point, here we assumed that the species of interest would move into the floodplain and stay within the floodplain, traveling linearly along it to take advantage of the cooler moister environment.

Riparian Units

Our riparian model was based on the Active River Area (ARA) model previously developed to map the floodplain and other zones of rivers in the Eastern US (Eastern Conservation Science 2009). The ARA includes the meander belt, riparian wetlands, and the 100-year floodplain associated with each stream. The mapped area accommodates the natural ranges of variability of flooding, sediment transport, processing of organic materials, and other key biotic interactions necessary to maintain riparian habitat types and conditions in and along rivers and streams. Our model is based on a 10-m DEM in the Appalachian and Southeast region (Olivero and Anderson 2015, Barnett 2014) and a 30-m DEM elsewhere (Olivero 2009), along with a 1:100,000 hydrography dataset and FEMA 100-year floodplain maps where available to model the floodplain and riparian lands (Smith et al. 2008).

The ARA maps a continuous zone along rivers and streams. In order to partition it into individual units, we used the stream size classes adopted from the Northeast and Appalachian stream classification (Olivero and Anderson 2013, Olivero et al. 2015). This separates the floodplain areas associated with six different stream sizes based on watershed area: creeks, small rivers, medium tributary, medium mainstem, large river, and great rivers. The ARA areas associated with creeks and small rivers were then further divided by HUC10 watersheds, while the floodplains of the medium and larger rivers were divided by larger HUC8 watersheds and/or Canadian Subdivision-level watersheds. The resultant final riparian units were composed of connected ARA cells associated with a given river or stream size within a watershed (Figures 3.18 and 3.19).

After creating and mapping the units, we simplified the classification to four classes: creek, small river, medium tributary, and large (medium mainstem, large, and great rivers).

Riparian Unit Attributes

All riparian units greater than 100 acres in size were attributed with the following information: size, mean regional flow, and contrast (the difference in mean local connectedness within the unit versus the mean within a buffer area). Other basic statistics calculated for each unit included: amount of secured lands, mean terrestrial resilience score, and name of the associated river if available.

Size: For each unit, we calculated its total area in acres. Our assumption was that the larger the size of the unit, the longer species could persist within it and the more likely it was to facilitate movement through large geographic areas. When further querying this dataset we often used size cutoffs to focus our analysis on the larger units. As in Krosby et al. (2014), size also provided the closest approximation of length and width, as these characteristics proved difficult to summarize into a single value due to the complexity of some of the longer networks.

Regional Flow: High regional flow in a riparian unit suggests that species movements are concentrated into these corridors, making them critical to the permeability of the regional landscape. As species move through the surrounding landscape these areas are the most natural and connected option available. To measure this, we overlaid the regional flow dataset (anthropogenic resistance only) on the riparian units and calculated the percent of each unit covered by high regional flow (i.e., regional flow > 0.5 SD above the mean score for the region, Figure 3.20). This served as a measure of overlap and correspondence between high flow and the riparian units. By calculating the degree of flow in each riparian unit we effectively eliminated flow that occurred along ridgelines or mountaintops, and focused the analysis on flow that concentrated on valley bottoms. In order to compare across ecoregions (Figure 3.21) and size classes (Figure 3.22) we transformed the values for each riparian unit using a logit transformation, and we then transformed them again into a standard normal distribution (Z-scores) based on the mean and SD of the variable within each size class.

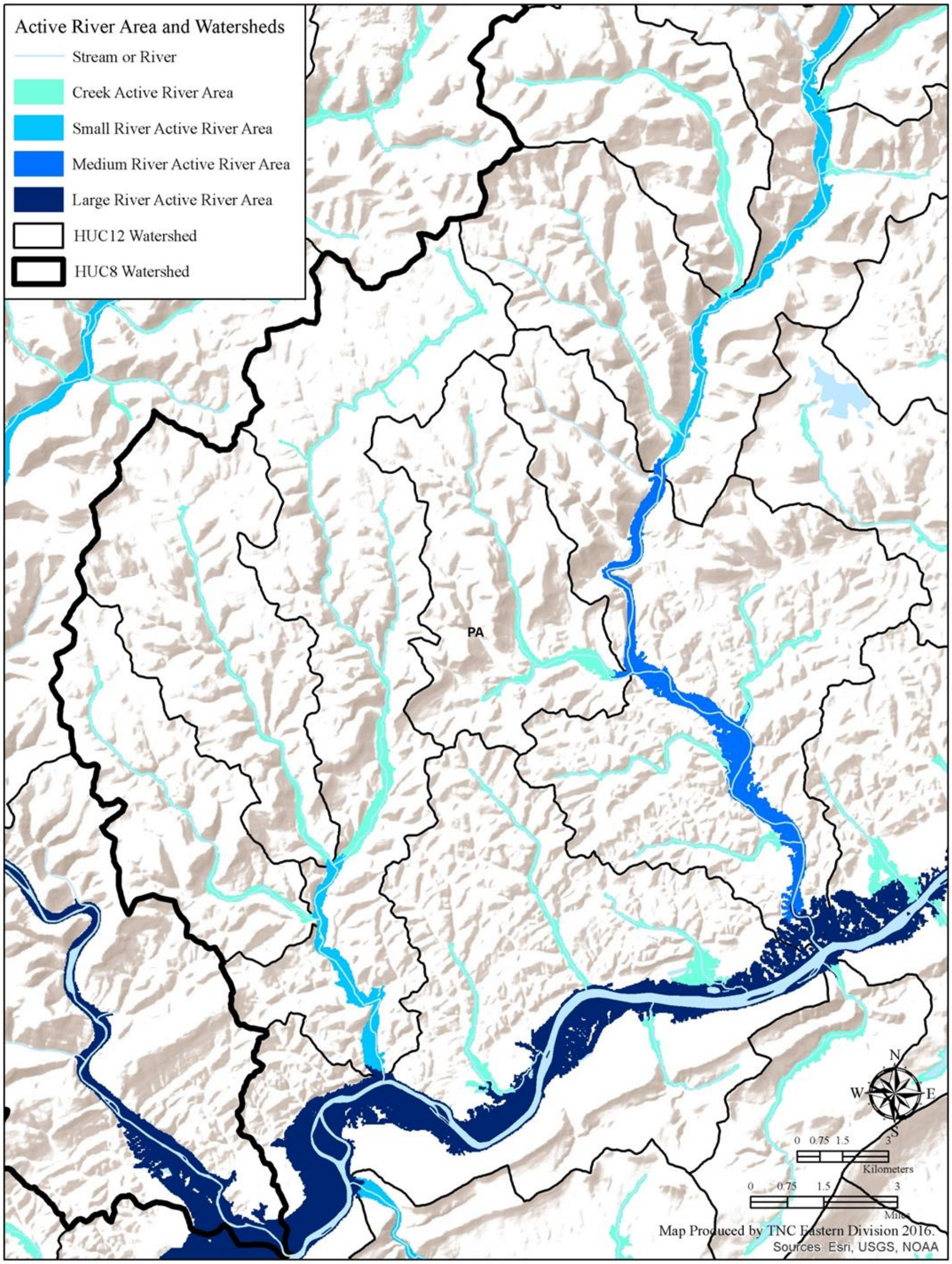
Based on visual inspection, our methods appeared to do a good job of transferring the regional flow data to the riparian areas. However, some cases required special attention. Exceptionally wide riparian units often had large contiguous stretches of high flow along the mainstem, but received low scores because the flow accounted for a small proportion of the total area. Because these areas could potentially serve the same function as the narrower units, we added a separate query to identify and score them. To identify these kinds of riparian corridor units, we calculated the largest size of high permeability (> .5 SD flow score) in a contiguous area within each riparian unit. We normalized the maximum size value using a logit transformation and then transformed it again to a standard normal distribution (Z-scores) by size class.

Contrast: Local Connectedness / Human Modification: We overlaid the local connectedness dataset (described in Anderson et al. 2016a) and calculated the mean connectedness score for each unit as an indication of the degree to which the corridor has been impacted by human activity. We also calculated the mean connectedness score for a buffer area around each unit. Creek and small river associated units were buffered by 2.5 km. Medium and larger rivers were buffered by 5 km. The difference between the buffer and internal local connectedness score was then calculated to develop a measure of "contrast" between the unit and its surroundings. Riparian units that scored higher in local connectedness than their buffer areas could then be queried to highlight those units that might provide greater refuge and connectivity. In these units, the more disturbed and disconnected surrounding area might drive species looking for connectivity and intact habitats disproportionately more into the riparian areas given the lack of other connectivity options or pathways outside the riparian area. For each unit, we transformed the values to a standard normal distribution (Z-scores) based on the mean and SD of the variable within a given geographic stratification: whole region, within ecoregion, and within ecoregion by size class. Although this attribute was not used in final selection of the riparian climate corridors, we felt in some parts of the region this attribute is a particularly useful secondary variable for further refinement of the prioritization results.

Securement: We overlaid the secured lands dataset and calculated percent of the riparian unit in GAP status 1, 2, and 3.

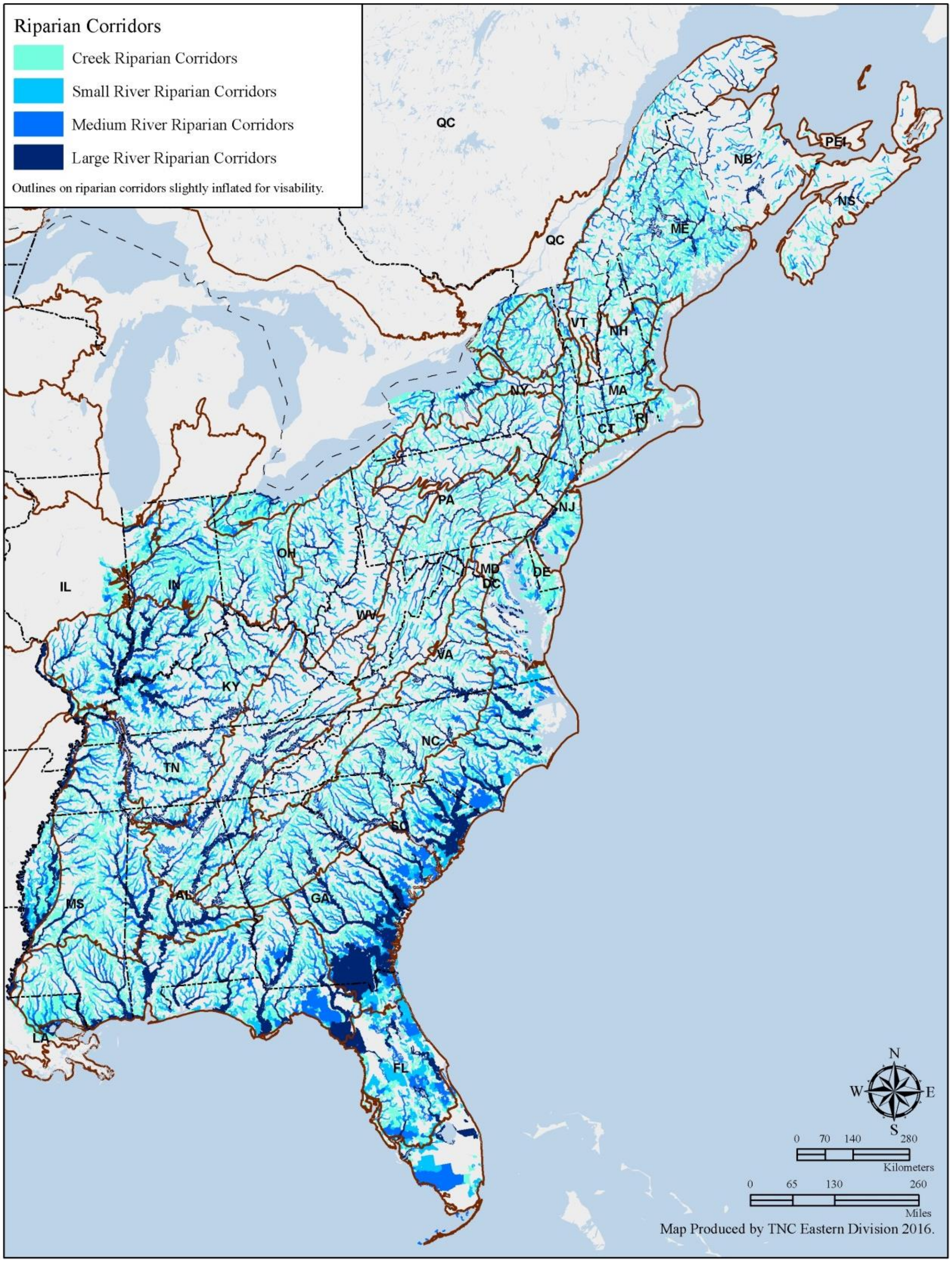
Resilience: We overlaid the above average resilience (Z > 0.5 SD) dataset and calculated percent of the riparian unit with above average resilience.

Figure 3.18. Riparian units. This map shows the Active River Area (ARA) associated with each stream class and the watershed boundary within which the unit was clipped. The riparian area is the colored region surrounding each stream line. In general, larger streams have larger and longer riparian areas.



Map Produced by TNC Eastern Division 2016.
Sources: Esri, USGS, NOAA

Figure 3.19. All riparian units by size class. This map shows all the riparian units assessed in this study colored by their size class.

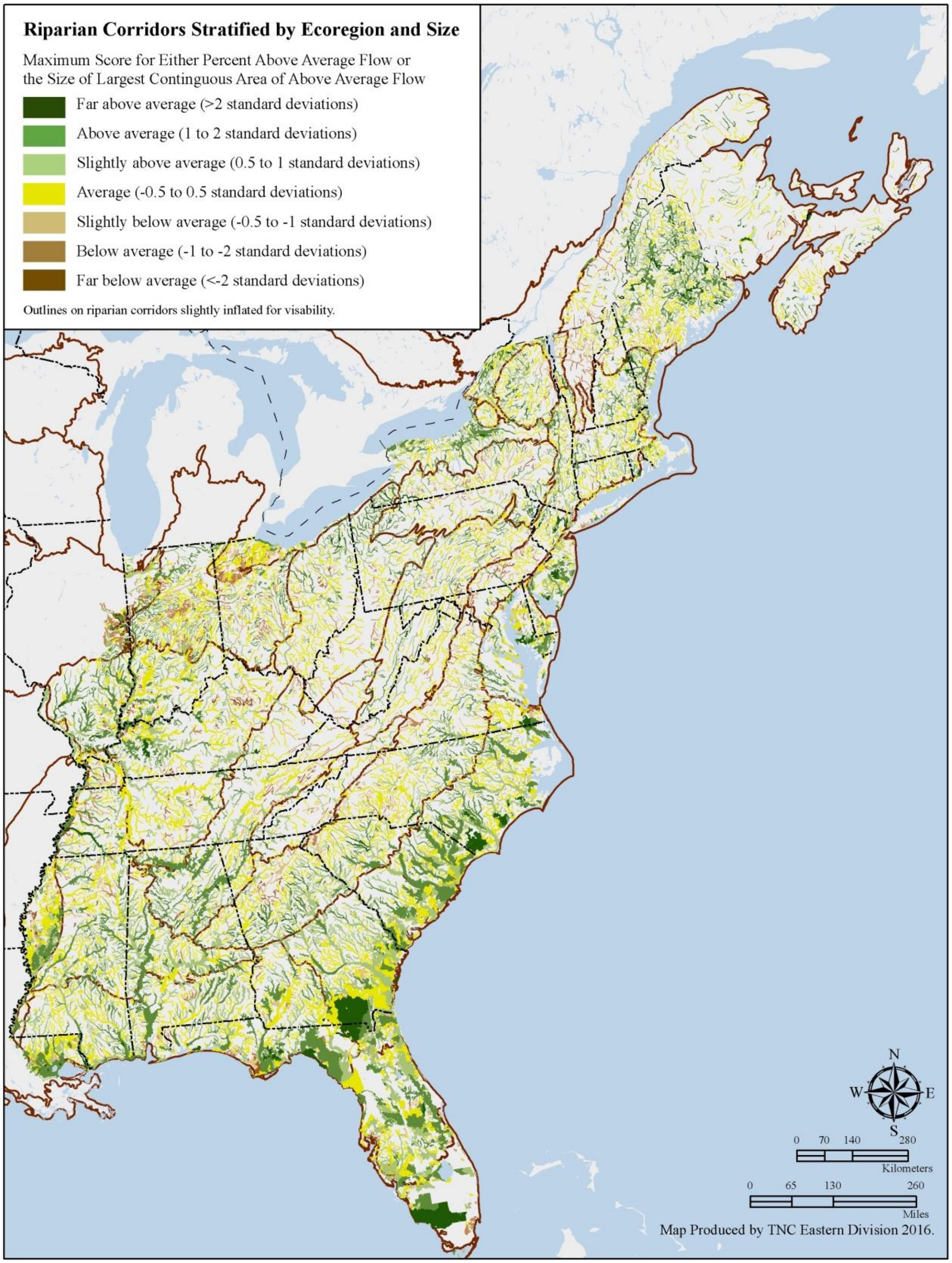


Map Produced by TNC Eastern Division 2016.

Figure 3.20. Regional flow within riparian climate corridors. This map shows the relative amount of regional flow within each riparian unit compared to the whole study area.

Figure 3.21. Regional flow within riparian climate corridors stratified by ecoregion. This map shows the relative amount of regional flow within each riparian unit compared to its ecoregion.

Figure 3.22. Regional flow within riparian climate corridors stratified by ecoregion and size. This map shows the relative amount of regional flow within each riparian unit compared to its ecoregion and size class.



Map Produced by TNC Eastern Division 2016.

Riparian Climate Corridor Query

To understand how the regional flow was distributed across the riparian units we queried the data within several geographic areas. At the scale of the whole region (Figure 3.20), the results highlighted several relevant issues. Riparian areas with high flow are concentrated geographically in the Southeast Coastal Plain and to a lesser extent in the Northern Appalachian ecoregion. In the South this is likely due to the prevalence of large bottomland forests that are more intact than the surrounding landscape and tend to channel concentrated flow. The absence of high flow in the Central Appalachian region may reflect the opposite (i.e. the ridges are in better shape than the floodplains and flow is channeled much more terrestrially). High flow in the Northern Appalachians mostly represents smaller rivers and streams in an area with large amounts of diffuse flow. Stratifying the maps further by ecoregion and size, highlights smaller-scale patterns that may be useful to users working within states or counties (Figures 3.21 and 3.22).

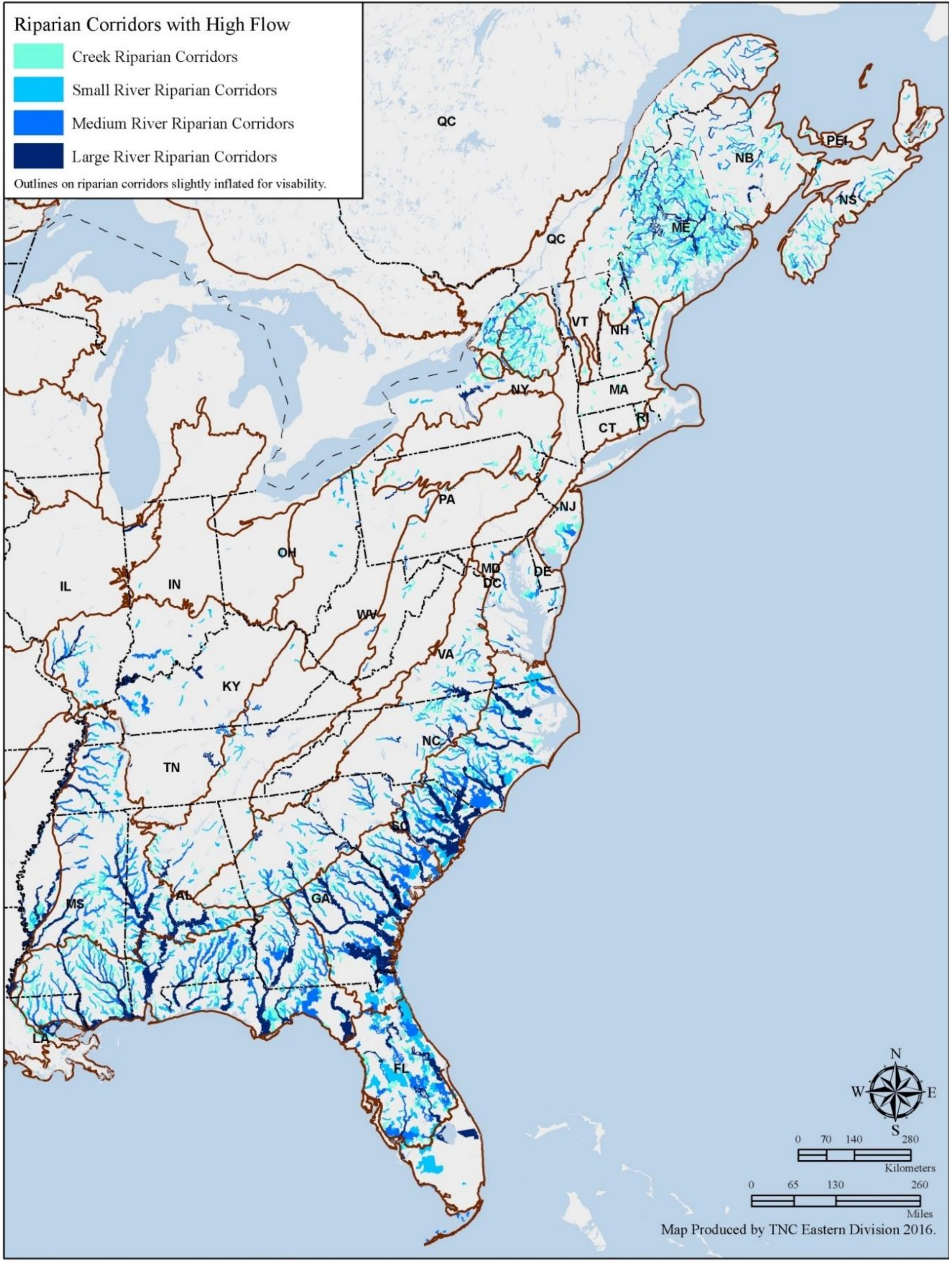
We developed a final query to identify a set of the most permeable riparian corridors distributed across stream and river size classes. Units meeting these criteria were used in the final section of this document to identify regionally significant riparian corridors that connect other resilient areas or important biodiversity features. We limited this selection to riparian units greater than 1000 acres in size, not predominantly in the tidal zone, and not restricted to a narrow strip dominated by a large reservoir or lake (Figure 3.33). From this limited selection we extracted units that had a high percentage of area in above average regional flow or that contained a large contiguous area of high regional flow.

The specifics of the queries were as follows:

1) limit to riparian units with <80% water and <60% coastal elevation zone that are >= 1000 acres in size.
2) extract units with higher percent of total area above average permeability
    - For small, medium and large rivers, Z-score over 0.5 SD (percent of the unit >= 0.5 SD)
    - For creeks, Z >= 0.66 SD. We used a slightly higher criteria (>2/3rds above the mean) because of the larger number of creek units in the region and the need to narrow the prioritization among this large set.
3) extract units with large chunks of contiguous above average permeability
    - For small, medium and large rivers, the maximum contiguous acres of high flow Z >= 1 SD.
    - For creeks, the maximum contiguous acres of high flow Z >= 1.5 SD.

We did not use local connectedness, contrast, or securement in our final query, but provide them in the distributed dataset. We anticipate that they will be useful in state and local analysis.

Figure 3.23. Regionally significant riparian climate corridors. This map shows the riparian units with above average regional flow based on either the percent of the unit with high flow, or the size of the largest contiguous stretch of high flow.



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 the majority of 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. 2016a), 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
4

BIODIVERSITY

Geology and Species

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 (Anderson & Ferree 2010, 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 (Hunter et al. 1988). The climate resilience analysis (Anderson et al. 2016) was designed to represent the most resilient portion of 61 geophysical settings, thus ensuring comprehensive representation of every setting. Specifically, we identified the portion of each setting that scored >0.5 SD above the mean score with respect to the number of microclimates and the degree of connectedness, which results in roughly 30% of each setting. The actual amount selected varies in proportion to the actual amount available in each ecoregion.

In this section we compile the data and tools necessary to prioritize among the resilient areas based on the confirmed presence of rare species, exemplary natural communities, or the identification of geophysical settings that are underrepresented in the current set of public and private areas secured for conservation.

The term "sites" in this section refers to 1000-acre hexagons, which was the analysis unit used to integrate information across datasets. We chose this unit because the size allowed assessment of relatively fine-scale detail, and because the hexagon shapes match edge-to-edge to perfectly tessellate the entire 18-state and three-province region. Additionally, the size of the unit allowed us to maintain the sensitivity of the exact location of the rare species ("element occurrences") and allowed for some spatial error in those locations. The use of hexagons is discussed further in the later section on integration.

Rare Species and Natural Communities

We compiled 234,576 point locations of rare species and natural communities for this study. The data came from NatureServe and the State Natural Heritage programs and was used with their permission. Each location, called an element occurrence or "EO" represented an area of land and/or water where a species is, or was present, and which has practical conservation value. Element occurrences are the basic unit of record for documenting and delimiting the presence and extent of a species on the landscape and typically reflect populations or subpopulations.

The Natural Heritage programs generally create element occurrences for native species that are considered at-risk within their jurisdictions, with an emphasis on the most imperiled species. Species that are assessed by NatureServe as critically imperiled or imperiled globally (G1 or G2) generally have EOs throughout their range because, by definition, these species are imperiled in every jurisdiction in which they occur. The data are more complete for vertebrates and vascular plants, but include selected species of invertebrates from groups such as freshwater mussels, freshwater and terrestrial snails, crayfishes, butterflies, underwing and Papaipema moths, dragonflies and damselflies. There is great variation in information on other invertebrate groups and non-vascular plants.

The mapped location of an element occurrence usually has a recorded level of mapping accuracy. This can range from highly precise, where the locality is very well understood and documented, to very low precision, which is used to identify older records that may have been vague as to the exact locale.

Species point locations were provided by US State Natural Heritage programs in 2013 and used with permission. We focused on all species, subspecies, and varieties that were ranked as critically imperiled, imperiled, vulnerable, or apparently secure (Table 4.1). This translated to all vertebrates, invertebrates, and plants ranked G1-G4 or T1-T4. This set of 7707 taxa is surveyed relatively consistently among states and within regions. More common species (G4 and G5) were excluded from most analyses due to inconsistent survey effort.

Table 4.1. NatureServe Global Rank definitions (NatureServe Explorer 2015).

Rank	Definition
GX	**Presumed Extinct** (species): Not located despite intensive searches and virtually no likelihood of rediscovery.
GH	**Possibly Extinct** (species): Missing; known from only historical occurrences but still some hope of rediscovery.
G1	**Critically Imperiled:** At very high risk of extinction due to extreme rarity (often 5 or fewer populations), very steep declines, or other factors.
G2	**Imperiled:** At high risk of extinction due to very restricted range, very few populations (often 20 or fewer), steep declines, or other factors.
G3	**Vulnerable:** At moderate risk of extinction due to a restricted range, relatively few populations (often 80 or fewer), recent and widespread declines, or other factors.
G4	**Apparently Secure:** Uncommon but not rare; some cause for long-term concern due to declines or other factors.
G5	**Secure:** Common; widespread and abundant

We developed a simple taxa index to indicate whether a site (1000-acre hexagon) had more types of rare species than expected given its geophysical setting. For each setting we calculated the average number of rare taxa found across all sites and then we compared each individual site to the expected average. This was done with rank-based Z-scores as the distributions were usually highly skewed towards zero. The results varied with the abundance and diversity of each geophysical setting. For example, in very common settings with few rare species, a single confirmed occurrence was above average, whereas in uncommon settings with many rare species the site might need to have two or three rare taxa to score above average. In all cases, we counted the number of unique species not the number of occurrences. For instance, a site with three occurrences of Indiana bat and six occurrences of Tennessee cave salamander would get a score of two because it had two unique species.

Natural communities are repeating assemblages of species that occur within a distinct set of environmental parameters such as a unique geophysical setting (e.g., sandstone pavement barren, calcareous cliff), a setting combined with a process (e.g., fire-dependent longleaf pine woodlands on sand, or hydro-dependent alkaline fen on limestone), or a climatically driven dominant vegetation type (e.g., northern hardwood forest, dry oak-heath forest). Each state has developed its own classification of the natural communities found within the state and the rarer ones are inventoried, mapped and described in a manner analogous to mapping the extent of a species population. Canadian provinces do not currently track communities.

The quality of each community occurrence is ranked by the field biologist based on the size, condition, and landscape context of the occurrence. For example, the VT NHP uses the following criteria (Vermont F&W 2009), and summarizes it into an overall rank for each occurrence:

Current Condition:

- A: mature example of the community type (forests with trees generally >150 years old); natural processes intact; no exotics
- B: some minor alteration of vegetation structure and composition, such as by selective logging; minor alterations in ecological processes; exotics species present in low abundance
- C: significant alteration of vegetation structure and composition, such as by heavy logging; alteration of ecological processes are significant, but community recovery/restoration is likely; exotic species are abundant and control will take significant effort
- D: ecological processes significantly altered to the point where vegetation composition and structure are very different from A-ranked condition and restoration/recovery is unlikely; exotic species are abundant or control will be difficult

Landscape Context:

- A: highly connected; area around EO (>1,000 acres) is largely intact natural vegetation, with species interactions and natural processes occurring across communities; surrounding matrix forest meets at least B specifications for Condition.

- B: moderately connected; area around EO (>1,000 acres) is moderately intact natural vegetation, with species interactions and some natural processes occurring across many communities, although temporary disturbances such as logging have reduced condition of the landscape; surrounding matrix forest meets at least C specifications for Condition
- C: moderately fragmented; area around EO is largely a combination of cultural and natural vegetation with barriers to species interactions and natural processes across communities; surrounding land is a mix of fragmented forest, agriculture, and rural development
- D: highly fragmented; area around EO is entirely, or almost entirely, surrounded by agriculture or urban development

<u>Size:</u> No Generic ranking applicable. Record actual size of community.

We created an index of natural community value for each hexagon using the formula: *Community Index = 3*#A-ranked EOs + 2*#B-ranked EOs + 1*# C-ranked, Extant, or Unranked EOs*

This ensured that areas with many high quality natural communities would receive a correspondingly high score but that areas with many confirmed but unranked occurrences could also score well.

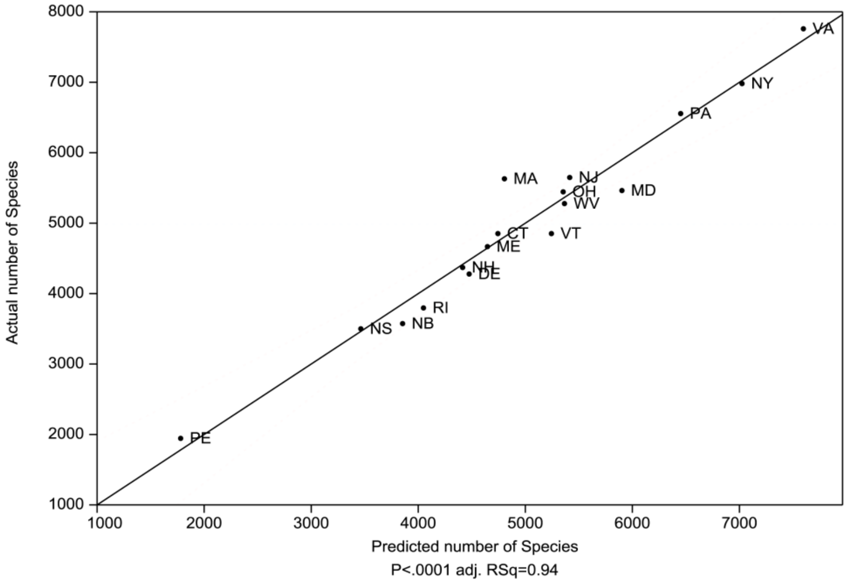
Geophysical Settings

Geophysical settings are the geological environments found within a given elevation zone (e.g., low elevation limestone, high elevation acidic granite). The elevation zones and geology class thresholds were chosen to correspond with recognizable changes in species and communities, and follow those described in Anderson and Ferree (2010). These categories, particularly the geological classes, had been found to correspond closely with biodiversity patterns in the Eastern North America and have been further tested for correspondence to biodiversity patterns in the Southeastern US (Figure 4.1). We recognized and mapped five elevation zones and 12 geological classes for the region which resulted in 61 geophysical settings, slightly less than the potential 70 because some combinations of elevation and geology never occur.

Maps of each geophysical setting were created by compiling spatially explicit digital information on the physical characteristics of the regions from the following primary sources (for more information on settings see Anderson et al. 2016a; Chapter 2 Defining the Geophysical Settings):

- Bedrock geology: from state and national digital geology maps
- Soils: county-level USDA soil surveys from the Soil Survey Geographic database.
- Elevation: from a 30-m DEM
- Landforms: derived from the 30-m DEM

Figure 4.1. Actual species diversity plotted against predicted species diversity. This graph shows the model with the highest R^2 and lowest AICc (adj.R^2 = 0.94, P,0.0001), based on four factors: the number of geology classes, the area of calcareous bedrock, the degree latitude, and the elevation range. From Anderson & Ferree 2000.



Geology and elevation are not the only factors that drive species diversity patterns, at continental scales, for example, difference may be more driven by climate (Currie 1991, Currie & Paquin 1987). However, geophysical factors often take precedence over climate in explaining diversity patterns at local scales (Rosenzweig 1995, Willis & Whittaker 2002) and can overwhelm local biotic interactions (Benton 2009). Geology defines the available environments and shapes species diversity patterns through its influence on the chemical and physical properties of soil and water, and by creating topography that redistributes climatic effects to create predictable weather patterns and microclimates (Anderson et al. 2014, Dobrowski 2010). A dry, fire-prone, sand plain supports very different plants and animals than a karst-pocketed limestone valley, and a hot upper slope supports different species than a cool wet basin. The underlying physical differences in the land continue to influence the processes and composition of the habitats, even as species distributions change and novel communities form in response to a changing climate.

Secured Lands

We compiled over 100,000 tracts of permanently protected conservation land covering 44,000,000 acres in the Eastern US. The information is part of TNC's Eastern Conservation Science team's dataset of secured land defined as land that is permanently secured against conversion to development. This definition was developed by an international group of scientists to differentiate "secured land" from the International Union for Conservation of Nature (IUCN) term "protected areas" which refers to land with a formal designation of conservation value (Dudley 2008). The secured lands dataset includes many tracts of land with no formal designation but substantial conservation value, such as reserves held by The Nature Conservancy, forest management lands held by the Canadian Crown, or "forever wild" easements held by a conservation entity. In contrast, the dataset excludes some designated protected areas such as world biosphere preserves, as these areas are not formally protected from development.

To classify secured lands, we used a modified version of USFWS' GAP Status (Crist et al. 1998). Our version (TNC GAP) was similar in concept but used criteria that can be applied more easily than the USFWS criteria (Table 4.2). The three criteria for applying TNC GAP 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 (e.g., agency, owner, manager) 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 all considered to be potentially 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. 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 sufficient winter habitat. In this case, meeting the species conservation goal would require a network of secured lands each with the appropriate level of securement.

The Secured Lands dataset was compiled from over seventy sources and reflects land securement status through the end of the year 2013. Only parcels with permanent ownership duration were included in the mapped dataset. Non-permanent ownerships are very dynamic and it was beyond our capacity to track and maintain information on them. All parcels were assumed to meet the criterion of effective management potential because land-owning or easement-holding organizations in the US meet the standard for appropriate governance. Thus, TNC GAP status was usually determined by management intent alone. Intent can change over time and it is not uncommon for conservationists to have a goal of moving the GAP status of a key biodiversity parcel from GAP 3 (secured for multiple-uses) to GAP 1 (secured for nature).

The secured lands dataset was created using a combination of public land information typically maintained by state agencies, and private conservation land information compiled by TNC's state field offices. State-based Conservancy staff compiled the dataset for their state, and assigned TNC GAP status to both the public and private tracts. Standard fields on fee ownership, easements, interest holder, designation, and year of addition are completed as well. The state datasets are then compiled by TNC's Eastern Science office and quality checked for consistency and discrepancies. The final dataset shows all the permanently secured lands in the Eastern US by TNC GAP Status, designation, fee owner and interest holder (Figure 2.10). The dataset will be posted for public use and submitted to the Protected Areas Database US (PAD US) to become part of a national dataset of protected lands.

We combined the secured lands with geophysical settings and found that the settings are distributed unevenly across the ecoregion with the most common type being very low elevation acidic sedimentary (Tables 4.3 and 4.4).

Table 4.2. 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 are allowed to 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 so as 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 particular 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 the majority 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

Table 4.3. Geophysical settings: total amount, % converted, % secured, and the ratio of conversion to securement (C/S ratio) in coastal to low elevation. In the coastal zone, 1.8 acres are converted for every 1 acre secured.

Geology by Elevation Zone	% Agr.	% Dev.	% Nat.	Total Acres	% Secured	% Un-Secured	C/S ratio
Coastal	0.14	0.18	0.68	5,056,484	0.18	0.82	1.80
Acidic granitic	0.02	0.27	0.72	78,611	0.14	0.86	2.04
Acidic sedimentary	0.11	0.28	0.61	322,144	0.07	0.93	5.56
Calcareous	0.02	0.42	0.57	5,899	0.05	0.95	8.85
Loam	0.20	0.22	0.59	1,556,553	0.12	0.88	3.32
Mafic	0.02	0.20	0.79	72,238	0.13	0.87	1.65
Mod. calcareous	0.05	0.31	0.64	16,311	0.10	0.90	3.72
Sand	0.10	0.22	0.68	1,259,547	0.16	0.84	1.92
Silt/Clay	0.14	0.09	0.78	1,744,980	0.26	0.74	0.88
Ultramafic	0.00	0.63	0.37	202	0.00	1.00	573
Very Low	0.17	0.11	0.72	82,514,581	0.17	0.83	1.63
Acidic granitic	0.06	0.10	0.85	7,848,556	0.22	0.78	0.68
Acidic sedimentary	0.14	0.10	0.76	26,395,681	0.20	0.80	1.23
Acidic shale	0.32	0.10	0.58	119,018	0.14	0.86	3.01
Calcareous	0.43	0.13	0.44	5,499,291	0.05	0.95	11.32
Loam	0.18	0.16	0.66	12,087,723	0.15	0.85	2.24
Mafic	0.05	0.10	0.84	4,519,482	0.21	0.79	0.76
Mod. calcareous	0.20	0.09	0.71	7,766,786	0.13	0.87	2.27
Sand	0.09	0.11	0.80	9,828,757	0.24	0.76	0.85
Silt/Clay	0.31	0.11	0.58	8,356,599	0.11	0.89	3.70
Ultramafic	0.23	0.12	0.65	92,687	0.10	0.90	3.67
Low	0.11	0.02	0.87	49,717,516	0.32	0.68	0.40
Acidic granitic	0.02	0.01	0.97	6,052,305	0.44	0.56	0.07
Acidic sedimentary	0.09	0.01	0.90	25,309,953	0.34	0.66	0.29
Acidic shale	0.24	0.05	0.71	91,910	0.09	0.91	3.14
Calcareous	0.20	0.02	0.77	2,523,079	0.22	0.78	1.04
Loam	0.12	0.03	0.85	1,764,242	0.26	0.74	0.59
Mafic	0.02	0.01	0.97	3,288,983	0.43	0.57	0.07
Mod.calcareous	0.28	0.02	0.70	7,626,093	0.18	0.82	1.65
Sand	0.05	0.03	0.92	1,024,497	0.38	0.62	0.21
Silt/Clay	0.17	0.03	0.79	1,740,436	0.23	0.77	0.89
Ultramafic	0.14	0.02	0.84	296,018	0.08	0.92	2.15

Table 4.4. Geophysical settings: total amount, % converted, % secured, and the ratio of conversion to securement (C/S ratio) in Mid to Very High Elevation Zones. In the coastal zone, 1.8 acres are converted for every 1 acre secured, whereas in the high elevation zone more land is secured that is converted.

Geology by Elevation Zone	% Agr.	% Dev.	% Nat.	Total Acres	% Secured	% Un-Secured	C/S ratio
Mid	0.07	0.00	0.93	13,555,593	0.48	0.52	0.14
Acidic granitic	0.00	0.00	0.99	2,637,472	0.71	0.29	0.01
Acidic sedimentary	0.05	0.00	0.94	7,093,002	0.45	0.55	0.13
Calcareous	0.02	0.01	0.97	357,284	0.61	0.39	0.05
Loam	0.02	0.01	0.97	295,190	0.59	0.41	0.05
Mafic	0.00	0.00	0.99	877,609	0.73	0.27	0.01
Moderately calcareous	0.22	0.00	0.78	2,133,480	0.18	0.82	1.21
Sand	0.00	0.01	0.98	59,600	0.67	0.33	0.02
Silt/Clay	0.12	0.01	0.87	101,956	0.29	0.71	0.44
Mid, High, Very High	0.00	0.00	1.00	65,731	0.57	0.43	0.01
Ultramafic	0.00	0.00	1.00	65,731	0.57	0.43	0.01
High	0.00	0.00	1.00	1,283,341	0.82	0.18	0.00
Acidic granitic	0.00	0.00	1.00	491,709	0.84	0.16	0.00
Acidic sedimentary	0.00	0.00	1.00	460,881	0.72	0.28	0.01
Calcareous	0.00	0.00	1.00	12,322	0.95	0.05	0.00
Mafic	0.00	0.00	1.00	263,980	0.92	0.08	0.00
Moderately calcareous	0.00	0.00	1.00	48,859	0.86	0.14	0.00
Sand, Loam, Silt/Clay	0.00	0.00	1.00	5,591	0.87	0.13	0.00
Very High	0.00	0.00	1.00	86,596	0.96	0.04	0.00
Acidic granitic	0.00	0.00	1.00	29,489	0.96	0.04	0.00
Acidic sedimentary	0.00	0.01	0.99	29,342	0.96	0.04	0.01
Mafic	0.00	0.00	1.00	27,249	0.95	0.05	0.00
Moderately calcareous	0.00	0.00	1.00	161	1.00	0.00	0.00
Sand, Loam, Silt/Clay	0.00	0.00	1.00	354	0.96	0.04	0.00
Grand Total	0.14	0.07	0.79	152,279,842	0.25	0.75	0.83

Representation of Geophysical Settings

Analysis of the land secured for conservation in the Eastern US has revealed a systematic bias towards acidic soils, high elevations and steeply sloping land, and a bias against productive soils, low elevations, and flat or gently sloping land, even though the latter environments are often the most biodiverse (Anderson & Weaver 2014). As a result, many agencies, land trusts, and conservation organizations have started to focus their conservation efforts on geophysical settings that support high levels of diversity but are under-represented in the current network of secured lands such as low limestone valleys, fine silt floodplains, and Coastal Plain sand.

How well a geophysical setting is represented in the current system of conservation lands can be easily measured but is partially a function of the scale of investigation. For example, low elevation granite is well-represented across the region but under-represented in the Piedmont ecoregion where it occurs as unique outcrops within a relatively flat plateau, not at all like the vast mountains it underlies to the north. To assess the representativeness, we categorized each setting into three categories based on the degree of securement:

- **UR = Underrepresented** (0-15% Secured)
- **R = Represented** (15%-30% Secured)
- **WR = Well represented** (>30% secured)

This categorization was applied to the data across three scales: the geology, the setting (geology plus elevation), and the setting within an ecoregion (geology plus elevation plus ecoregion). Each setting was coded with its score for each scale (Tables 4.5 and 4.6). For example, Granite in the Piedmont scores R_R_UR indicating that it is represented (R= 25%) at the scale of the geology type, and represented (R = 27%) at the scale of the setting "low elevation granite" but underrepresented at the scale of the setting in the ecoregion (UR = 3%). This information was used when developing the resilient and connected networks to ensure sufficient representation of the underrepresented settings.

Table 4.5. Securement status of low elevation geophysical settings. ER=ecoregion.

Setting	% Secured Geology		% Secured Setting		# ER	Ecoregion Status			Ecoregion Statistics		
						UR	R	WR	Ave	Min	Max
Coastal: Acidic granitic	0.25	R	0.26	R	3		2	1	0.29	0.25	0.34
Coastal: Acidic sedimentary	0.22	R	0.12	UR	8	4	3	1	0.14	0.00	0.38
Coastal: Calcareous	0.07	UR	0.11	UR	3	2	1		0.10	0.00	0.19
Coastal: Loam/limestone	0.10	UR	0.68	WR	5	1	1	3	0.44	0.01	0.89
Coastal: Sand/limestone	0.25	R	0.48	WR	5	1	1	3	0.35	0.08	0.52
Coastal: Silt/limestone	0.15	UR	0.76	WR	5		2	3	0.45	0.17	0.78
Coastal: Loam	0.11	UR	0.28	R	13	6	3	4	0.26	0.00	0.86
Coastal: Mafic	0.28	R	0.25	R	3		3		0.23	0.17	0.28
Coastal: Mod. Calcareous	0.11	UR	0.17	R	3	1	2		0.18	0.08	0.25
Coastal: Sand	0.22	R	0.35	WR	12	2	5	5	0.27	0.00	0.65
Coastal: Silt or Clay	0.10	UR	0.35	WR	14	4	7	3	0.27	0.00	0.95
Coastal: Ultramafic	0.16	R	0.01	UR	2	2			0.00	0.00	0.01
Very Low: Acidic granitic	0.25	R	0.13	UR	9	4	4	1	0.16	0.00	0.36
Very Low: Acidic sediment.	0.22	R	0.14	UR	18	15	2	1	0.11	0.01	0.54
Very Low: Acidic shale	0.20	R	0.05	UR	3	2	1		0.14	0.04	0.28
Very Low: Calcareous	0.07	UR	0.04	UR	12	11	1		0.10	0.02	0.30
Very Low: Loam/limestone	0.10	UR	0.05	UR	7	5	1	1	0.15	0.00	0.64
Very Low: Sand/limestone	0.25	R	0.13	UR	6	4	2		0.12	0.01	0.24
Very Low: Silt/limestone	0.15	UR	0.06	UR	7	6	1		0.10	0.01	0.30
Very Low: Loam	0.11	UR	0.09	UR	20	14	3	3	0.14	0.00	0.54
Very Low: Mafic	0.28	R	0.15	UR	7	3	4		0.15	0.00	0.28
Very Low: Mod. Calcareous	0.11	UR	0.09	UR	12	9	3		0.10	0.02	0.29
Very Low: Sand	0.22	R	0.19	R	20	13	4	3	0.16	0.01	0.72
Very Low: Silt or Clay	0.10	UR	0.07	UR	19	16	3		0.09	0.03	0.26
Very Low: Ultramafic	0.16	R	0.10	UR	5	4	1		0.07	0.00	0.22
Low: Acidic granitic	0.25	R	0.27	R	8	2	4	2	0.30	0.03	0.80
Low: Acidic sedimentary	0.22	R	0.23	R	12	6	4	2	0.18	0.03	0.46
Low: Acidic shale	0.20	R	0.11	UR	5	4		1	0.11	0.00	0.32
Low: Calcareous	0.07	UR	0.07	UR	11	10		1	0.07	0.02	0.33
Low: Loam/limestone	0.10	UR	0.04	UR	1	1			0.04	0.04	0.04
Low: Silt/over limestone	0.15	UR	0.03	UR	1	1			0.03	0.03	0.03
Low: Loam	0.11	UR	0.16	R	13	10	2	1	0.12	0.00	0.47
Low: Mafic	0.28	R	0.36	WR	8	3	2	3	0.23	0.00	0.49
Low: Moderately calcareous	0.11	UR	0.11	UR	11	7	3	1	0.14	0.03	0.50
Low: Sand	0.22	R	0.44	WR	11	8	1	2	0.19	0.01	0.59
Low: Silt or Clay	0.10	UR	0.11	UR	12	10	1	1	0.10	0.01	0.45
Low: Ultramafic	0.16	R	0.08	UR	7	5		2	0.12	0.00	0.42

Table 4.6. Securement status of mid to high elevation geophysical settings.
ER=ecoregion. Sed. = sedimentary. Mod. calc. = moderately calcareous.

Setting	% Secured Geology		% Secured Setting		# ER	Ecoregion Status			Ecoregion Statistics		
						UR	R	WR	Ave	Min	Max
Mid to Very High: Ultramafic	0.16	R	0.50	WR	4	3		1	0.18	0.00	0.58
Mid: Acidic granitic	0.25	R	0.59	WR	8		2	6	0.56	0.28	0.96
Mid: Acidic sedimentary	0.22	R	0.35	WR	11	5		6	0.27	0.01	0.59
Mid: Acidic shale	0.20	R	0.37	WR	2		1	1	0.27	0.16	0.38
Mid: Calcareous	0.07	UR	0.22	R	9	4	3	2	0.21	0.00	0.67
Mid: Loam	0.11	UR	0.41	WR	10	4	2	4	0.27	0.01	0.74
Mid: Mafic	0.28	R	0.61	WR	7	2		5	0.52	0.03	1.00
Mid: Mod. Calcareous	0.11	UR	0.15	UR	9	6	1	2	0.19	0.01	0.59
Mid: Sand	0.22	R	0.74	WR	5	1	1	3	0.50	0.10	0.81
Mid: Silt or Clay	0.10	UR	0.16	R	9	5	2	2	0.20	0.00	0.54
High: Acidic granitic	0.25	R	0.43	WR	6	1		5	0.60	0.00	0.86
High: Acidic sedimentary	0.22	R	0.52	WR	7		1	6	0.63	0.21	0.92
High: Acidic shale	0.20	R	0.56	WR	2			2	0.55	0.53	0.56
High: Calcareous	0.07	UR	0.21	R	5	1	2	2	0.47	0.15	0.97
High: Mafic	0.28	R	0.51	WR	4		1	3	0.71	0.27	0.93
High: Mod. calcareous	0.11	UR	0.21	R	6		2	4	0.47	0.16	0.96
High: Sand, Loam, Silt	0.29	R	0.28	R	6		3	3	0.52	0.16	0.95
Very High: Acidic granitic	0.25	R	0.88	WR	3			3	0.89	0.85	0.96
Very High: Acidic sed.	0.22	R	0.75	WR	6			6	0.84	0.60	0.98
Very High: Acidic shale	0.20	R	0.89	WR	1			1	0.89	0.89	0.89
Very High: Calcareous	0.07	UR	0.32	WR	1			1	0.32	0.32	0.32
Very High: Mafic	0.28	R	0.84	WR	3			3	0.86	0.72	0.95
Very High: Mod. Calc.	0.11	UR	0.55	WR	3			3	0.78	0.55	1.00
Very High: Sediment	0.29	R	0.71	WR	3			3	0.82	0.62	0.99
All Geophysical Settings	0.17		0.26		451	228	98	125	0.25	0.00	1.00

RESILIENT AND CONNECTED CONSERVATION NETWORKS

CHAPTER 5

The goal of this section was to identify a network of resilient sites and linkages – a "braided through line" - that if adequately managed or conserved would sustain the diversity of the region under a dynamically changing climate. Our basic approach to mapping such a network was to prioritize a subset of resilient sites using criteria based on diversity, representation, and flow. Next, we identified the between-site linkages that both connected essential features and corresponded to areas of concentrated flow.

The resilient site analysis upon which this is based (Anderson et al. 2016a) highlights a fixed portion (approx. 33%) of each of the region's 61 geophysical settings based on its microclimates and degree of local connectedness. In that study, we used a statistical distribution to calculate the average resilience score for each geophysical setting, and then identified the places that scored above average (>0.5 SD) for each setting within an ecoregion. On top of this we added a regional override to bring in sites that scored only average in their setting and ecoregion but were nevertheless among the highest scoring sites for the whole region (>1 SD for the region). This increased the portion of the region identified as resilient to 39%. Our goal in this study was to prioritize among that 39% in order to identify the places most essential for conserving and sustaining diversity under a changing climate.

One way to prioritize the sites is to use a higher resilience score threshold. For example, if you select all sites that score >1 SD you will identify the top scoring areas 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. Reaching this goal required that we study how the natural flow patterns are arranged across the region, where the rare species 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 differs from similar studies in that we did not first identify sites and then try to connect them, instead we started with the natural flow patterns as the spatial template and then prioritized resilient and diverse sites that were aligned with the flow patterns. To facilitate adaptation, the goal is to have source areas representing the region's diverse species and environments situated in places that naturally intercept and transmit population movements.

We prioritized areas based on three themes – resilience, diversity, and flow. All sites had to meet the qualifying resilience criteria, so we were in effect prioritizing a subset of the resilient sites using diversity and flow. Diversity criteria were based on confirmed rare species and natural community occurrences, as well as large examples of geophysical settings. 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 and ample amounts of underrepresented geophysical settings. Flow criteria were based on permeable areas with high regional flow (>0.5 SD), expressed as riparian climate corridors, concentrated flow areas, or diffuse flow areas. The idea was to take advantage of the natural flow patterns in the region and select sites that enhanced or reinforced those patterns. After the resilient sites were prioritized, other between-site linkages were added to facilitate movement in areas with less resilience but high flow. We use the term "linkage" only for these "non-resilient" areas in order to separate them from connectors that occur within resilient sites and comprise the majority of the permeable landscape.

We did not set a numeric acreage goal for this prioritization but we aimed for about 20-25% of the region, which is roughly half of all the resilient areas. This forced us to study and prioritize the resilient sites, but it is not an estimate of how much conservation is needed to sustain diversity. The acreage increases to almost 40% of the region if the rest of the resilient sites, and the linkages between sites, are added to the prioritized area. This approaches EO Wilson's Half Earth goal 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 12% percent of the region is in some form of permanent conservation, so a prioritized network of 20-25% secured for conservation or sustainably managed is not unrealistic.

Site Prioritization: Resilience, Flow, and Diversity

Resilience

An above average resilience score (>0.5 SD) was the qualifying criterion that every cell had to meet, thus the diversity and flow characteristics features described below were applied only to areas that met this criterion. Linkages added separately in the next section did not have to score high for resilience.

Flow

The flow criteria had three parts: two types of concentrated flow areas (terrestrial pinch points and riparian climate corridors) and diffuse flow areas. "Flow" refers to the gradual movement of plant and animal populations across the landscape over time and was measured by the amount and concentration of "current" channeled through a given cell in the Circuitscape analysis (see section on Landscape Permeability).

1. Concentrated flow areas: This criterion identified any patch of concentrated flow that had a minimum size of 10,000 acres and was at least 75% within a resilient area (Figure 5.1).
2. Riparian Climate Corridors: This criterion identified any riparian unit with high flow, a minimum size of 1,000 acres, and that was at least 75% within a resilient area (Figure 5.1). *High flow in riparian areas is a complex variable based on the % of the unit with >0.5 SD flow, or the largest continuous patch of flow >0.5 SD, and these are scaled to river sizes – see riparian section*.
3. Diffuse flow areas: This criterion identified any cell of high or medium diffuse flow that also scored above average for resilience (Figure 5.2).

The goal of the permeability criteria was to identify resilient areas that also play an important role in maintaining regional flows because of how they are configured or where they are located. Prioritizing these areas essentially concentrates the resilient sites within the natural flow patterns of the region.

Diversity

Diversity criteria had several parts: confirmed species occurrences, high taxa diversity, confirmed natural communities, and large resilient examples of each geophysical setting weighted by the degree of representation (Figure 5.3).

1. Confirmed rare species: This criterion identified any hexagon that had a confirmed example of a G1-G4 species based on Natural Heritage Program information.
2. High taxa diversity: This criterion identified any hexagon that had more rare taxa (G1-G4) than expected for each type of geophysical settings. To measure this, we first calculated the average number of taxa per hexagon for each geophysical setting and then used rank-based z scores to identify hexagons with the number of taxa greater than 0.5 SD above the average.

Figure 5.1. Concentrated flow and riparian climate corridors. This map shows the areas that met the criteria for concentrated flow and riparian climate corridors. Orange indicates features that are mostly within resilient sites. Red indicates features that are mostly outside of resilient sites.

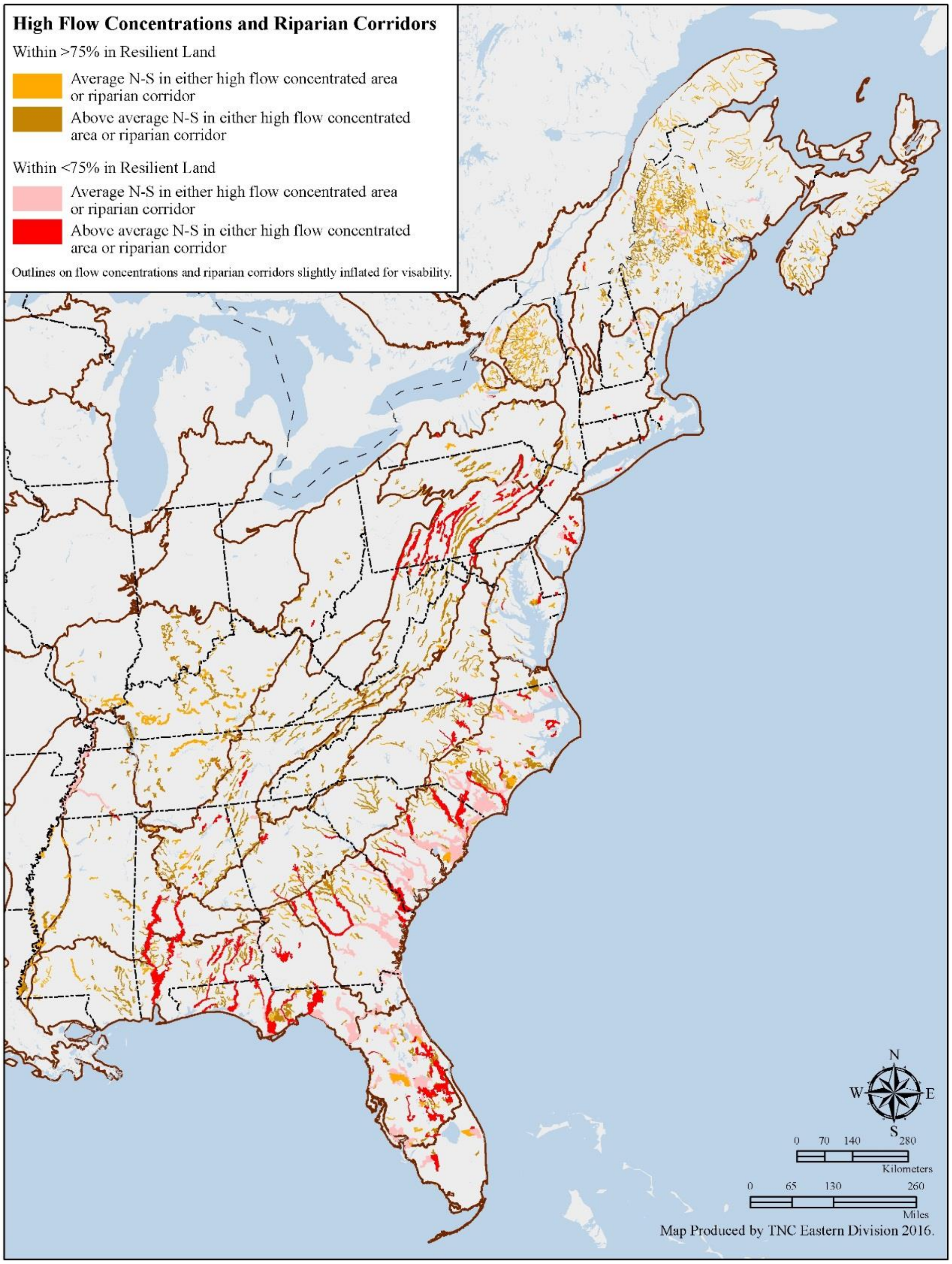


Figure 5.2. Diffuse flow areas. This map shows the areas that met the criteria for diffuse flow. Both high and moderate areas were included if they were within a resilient site.

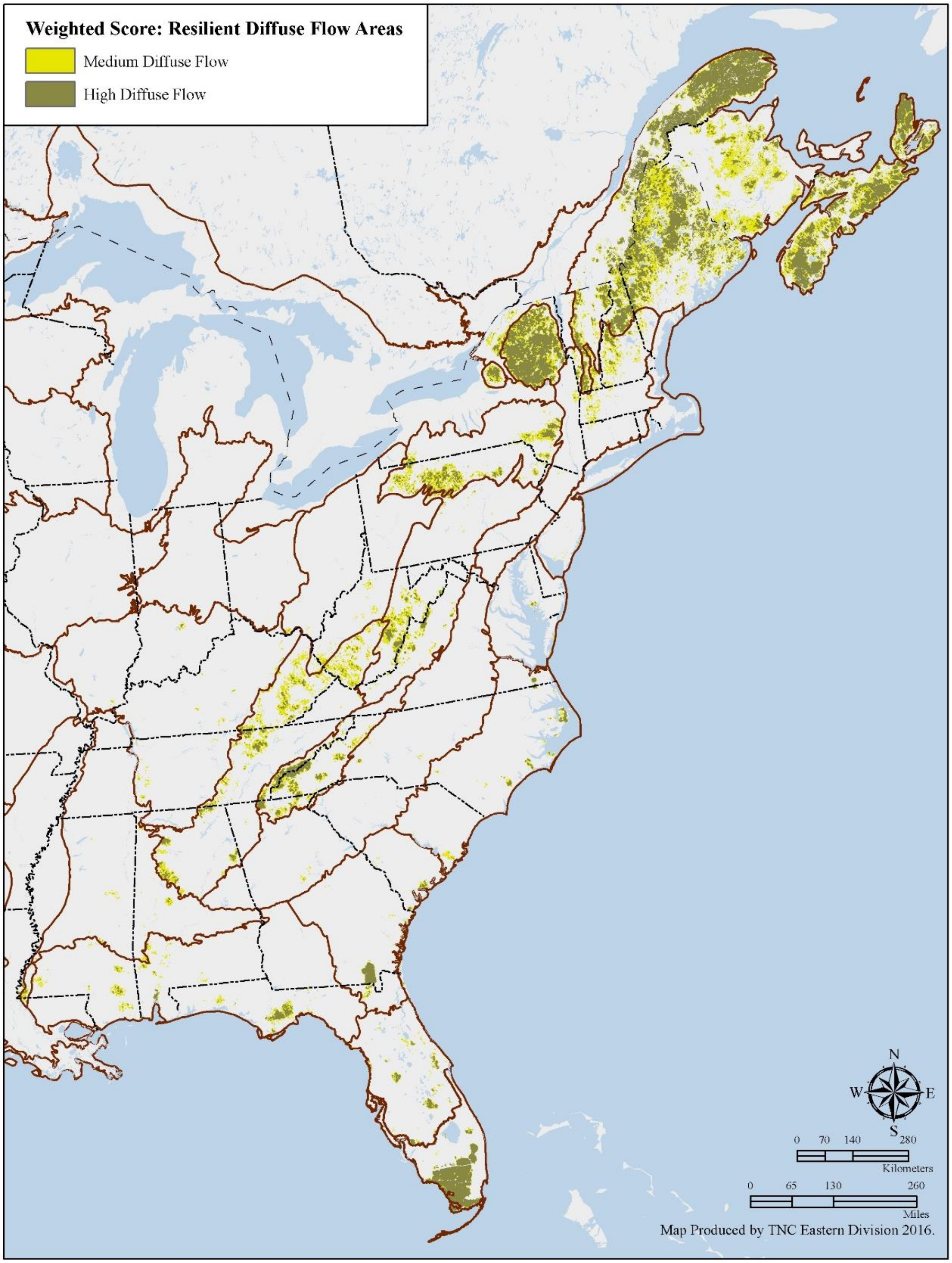
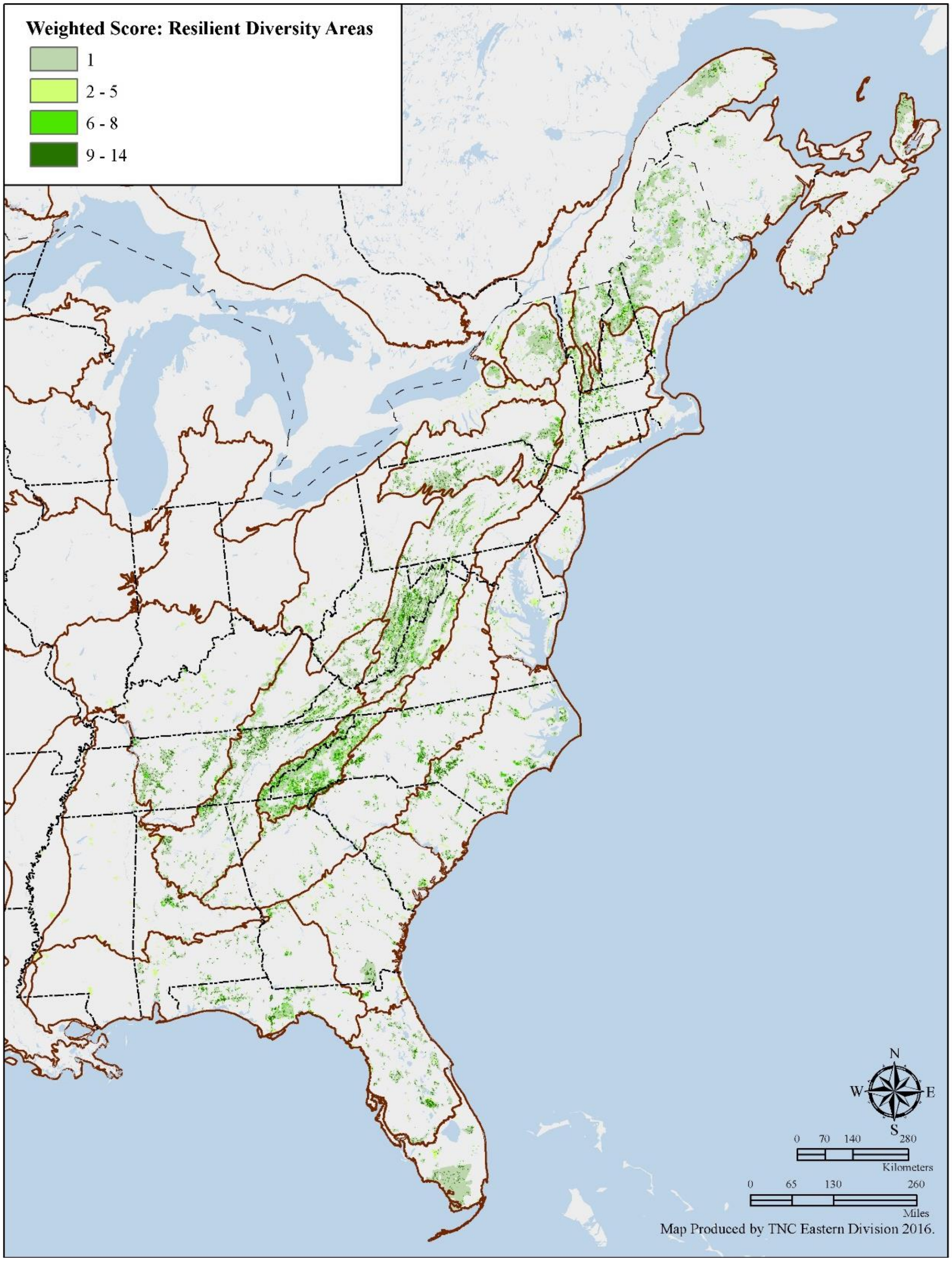


Figure 5.3. Diversity features. This map show the total number of diversity features present in each hexagon of resilient land. Features are either a confirmed occurrence of a rare species (G1-G4), a high quality occurrence of a natural community, or the largest continuous examples of a geophysical setting.



3. <u>Confirmed natural communities</u>: This criterion identified any hexagon that had a terrestrial, palustrine or subterranean natural community of A, B, C or Extant quality.
4. <u>Resilience patches:</u> These were large roadless patches of resilience that contained many EOs. The criteria were any large contiguous patch of resilient area (> 1000 acres) where the qualifying EOs described above made up more than 5% of the patch or amounted to over 25,000 acres.
5. <u>Large contiguous areas of each geophysical setting</u>: this criterion prioritized the largest contiguous patches of resilient area for each geophysical setting using a minimum size of 500 acres. The percent of the setting prioritized was determined by Criterion 6.
6. <u>Underrepresented geophysical settings</u>: Settings that were not well represented in the current secured lands were given a larger target for contiguous areas inclusion in Criterion 5 above. Settings that were underrepresented at all or most scales (i.e., region, geology, ecoregion) were given a minimum of 50,000 acres while settings that were well represented had a minimum of 25,000 acres.

The goal of the diversity criteria was to ensure that the prioritized resilient areas contained as many known and confirmed rare species sites 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.

A second goal was to increase the representation of unusual geophysical settings that support distinct diversity but were not well represented in the current set of secured lands. These are mostly low elevation rich soil areas on limestone, fine silt, or sand that are difficult to conserve due to their high value for agriculture or development. By including the largest contiguous patches of these settings with the highest level of connectivity and microclimates, these settings will continue to be available to future species. Often the plants and animals that thrive in the particular combinations of alkalinity and soil textures offered by these geophysical settings do not thrive on high acidic mountains or nutrient-poor bogs where much of our current conservation land occurs.

Including the higher quality natural community occurrences described by the Natural Heritage programs also ensured that the geophysical settings currently supporting recognizable community types would be included in the prioritization. Although we expect the communities to rearrange over time we know that the starting materials, the soils, and topography as well as the vegetation, are there now.

Linkage Prioritization

By definition, linkages occur outside of the resilient sites but link together diversity features.

Diversity and Flow

Criteria for the linkage areas had two parts. First, they had to have ample amounts of concentrated or riparian flow (diffuse flow was not included). Second, they had to connect areas of prioritized diversity.

1. Concentrated flow areas: This criterion identified any patch of concentrated flow that occurred largely outside of a resilient site (<75%), had a minimum size of 5000 acres, and touched at least three prioritized diversity features: rare species or community hexagons or one of the largest contiguous occurrences of a geophysical setting (Figure 5.2)
2. Riparian Climate Corridors: This criterion identified any riparian unit with high flow that occurred largely outside of a resilient site (<75%), had a minimum size of 5000 acres, and touched at least three prioritized diversity features: rare species or community hexagons or one of the largest contiguous occurrences of a geophysical setting (Figure RCL 5.2). *High flow for riparian areas is a complex variable based on the percentage of the unit with >0.5 SD flow, or the largest continuous patch of flow >0.5 SD, and these are scaled to river sizes – see riparian section.*

Integration: Resilient and Connected Landscapes

We combined the prioritized resilient sites and the prioritized linkages to create a network of resilient and connected sites that covers 23% (106 million acres) of the region. It also represents all geophysical settings, contains over 80,000 known rare species and community locations, includes over 23 million acres of riparian corridors and terrestrial pinch points, and encompasses 50 million acres of diffuse flow regions (Table 5.1, Figures 5.4, 5.5, 5.6 and inside front cover).

The prioritized network represents all the characteristic environments of eastern North America while maximizing the permeability and flow that connects them. By first identifying the natural flows and pathways that allow species populations to shift over time, and then identifying representative resilient sites situated within those pathways, the network is specifically designed to sustain biological diversity while allowing nature to adapt and change (see inside front cover.)

Table 5.1. Area and percentages of prioritized resilient areas.

Category	% of total	% of resilient	Acres	Sq Miles
Prioritized Diversity	5.9	15.6	27,884,321	43,569
Prioritized Diversity and Diffuse	4.9	12.9	23,108,823	36,108
Prioritized Diversity & Concentrated/Riparian	1.5	3.9	6,933,228	10,833
Prioritized and Concentrated/Riparian	1.4	3.6	6,421,134	10,033
Prioritized and Diffuse Flow	6.8	17.9	32,015,592	50,024
Linkage - Resilient	0.6	1.6	2,910,067	4,547
Linkage - Non-resilient	1.5		6,845,216	10,696
Resilient Other	17.0	44.5	79,754,738	124,617
Vulnerable or Average	60.4		283,595,527	443,118
TOTAL	100		469,468,645	733,545

Figure 5.4. Prioritized resilient and connected sites. This map shows the resilient areas that met criteria for diversity and permeability, and the linkages between sites that have high flow and connect three or more diversity features. This represents 21% of the region and 55% of all resilient sites.

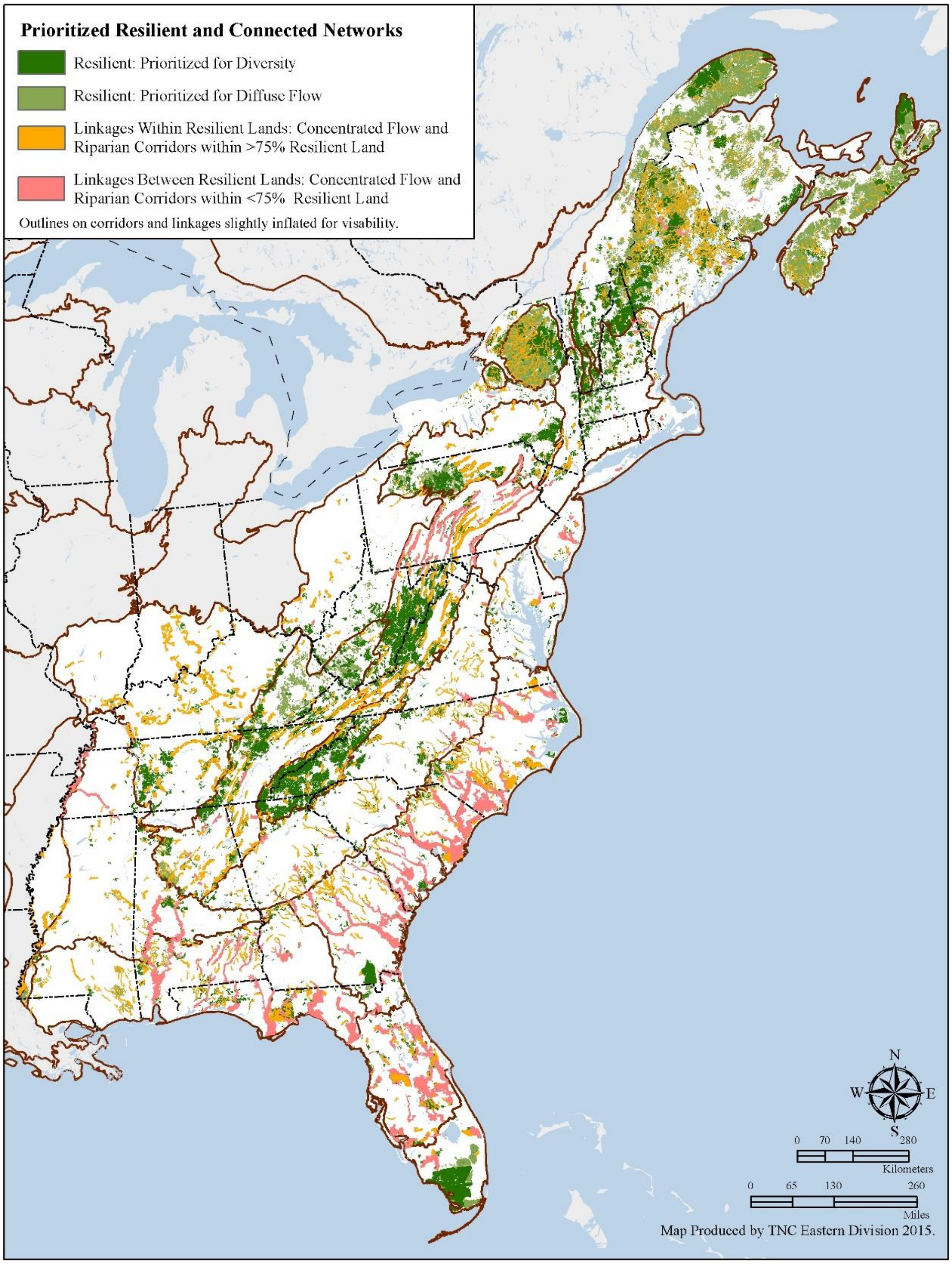


Figure 5.5. All resilient and connected sites. This map shows all the resilient areas overlaid with the sites that met criteria for diversity and permeability, and the linkages between sites that have high flow and connect three or more diversity features.

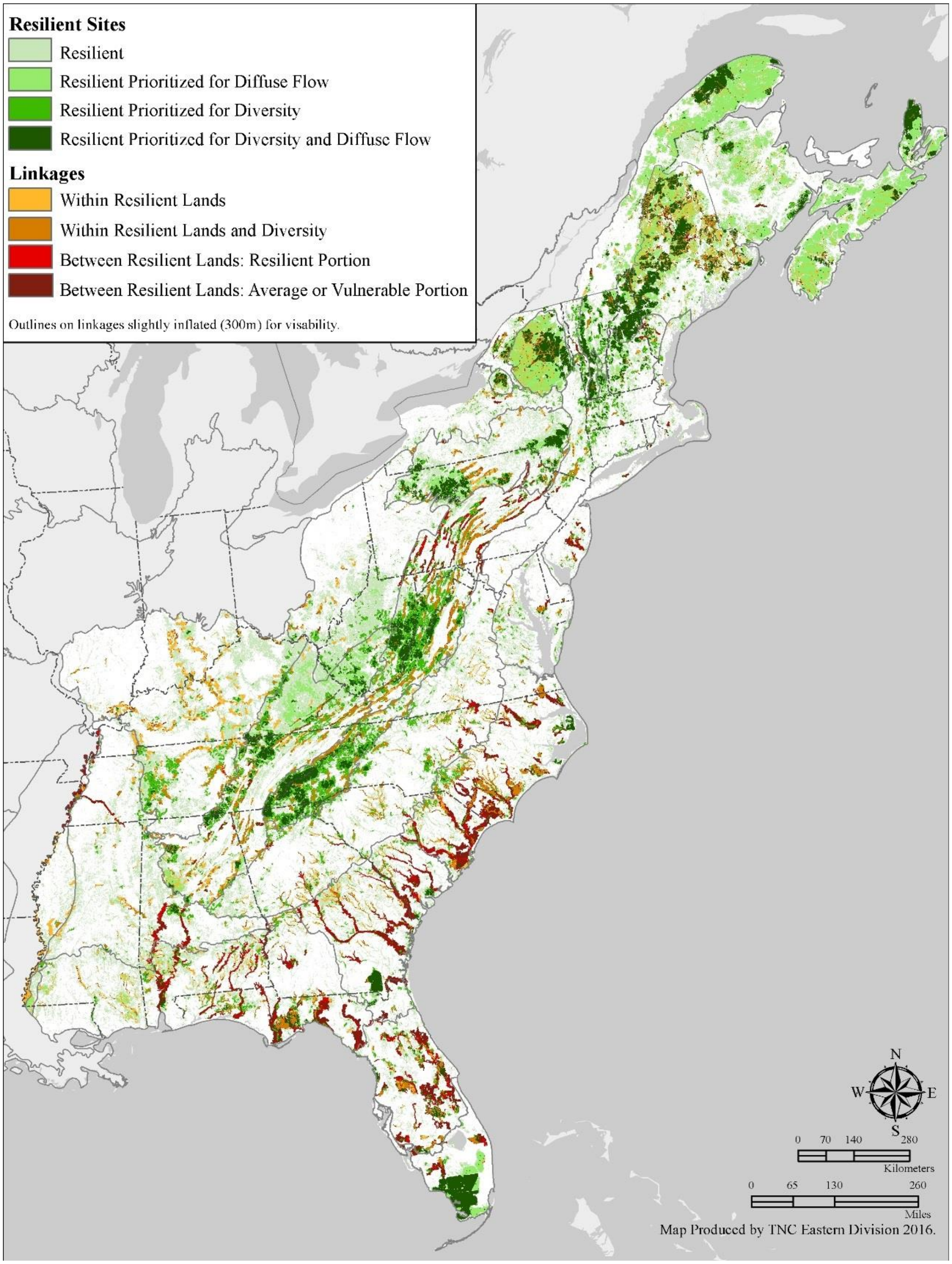


Figure 5.6. Continuous map of resilient and connected sites. This wall-to-wall map shows all the categories of resilience for sites and linkages, including the areas that score average or below average. This map is the counterpart to the estimated resilience map in Anderson et al. (2016a) which is based solely on score.

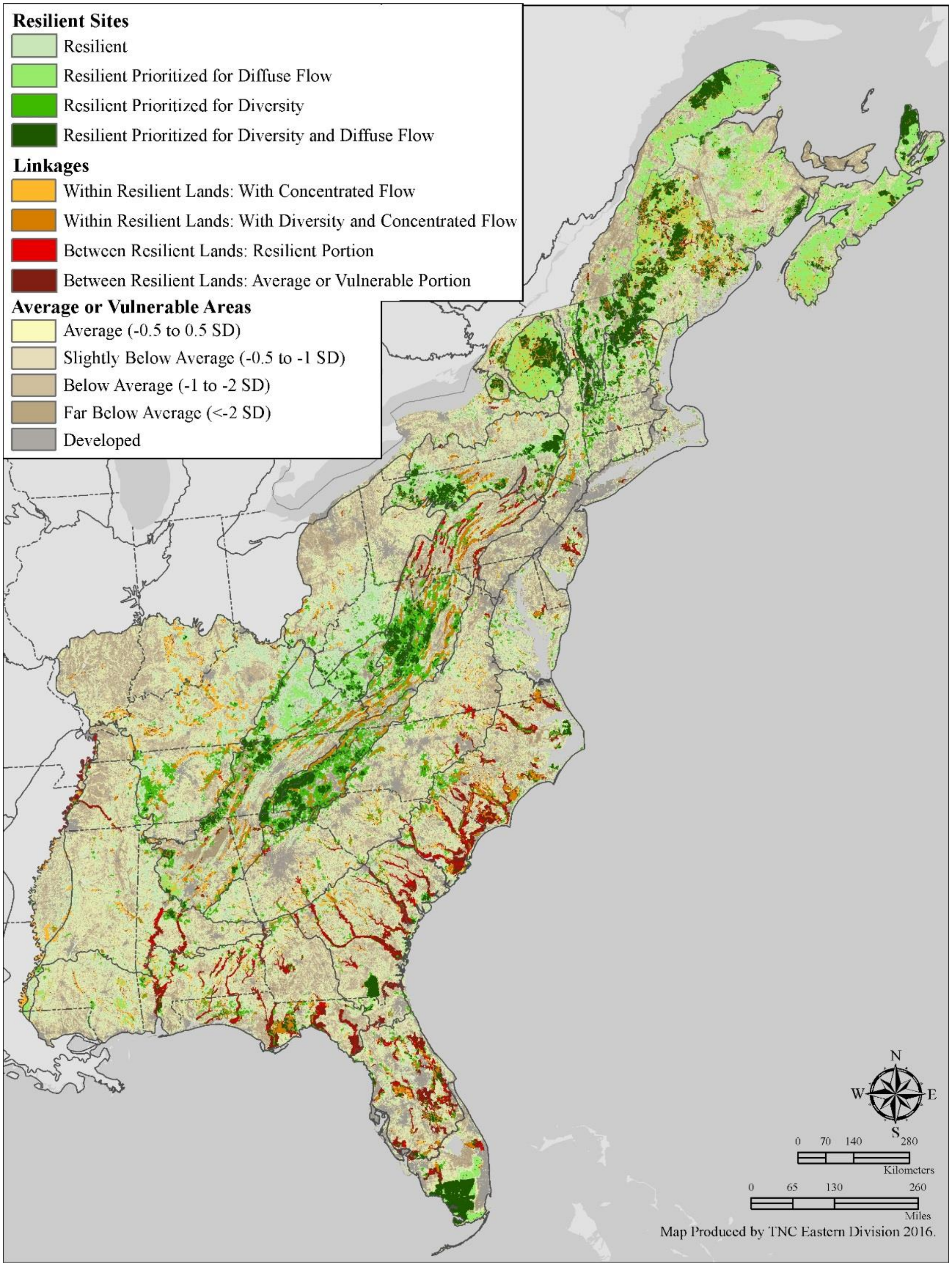
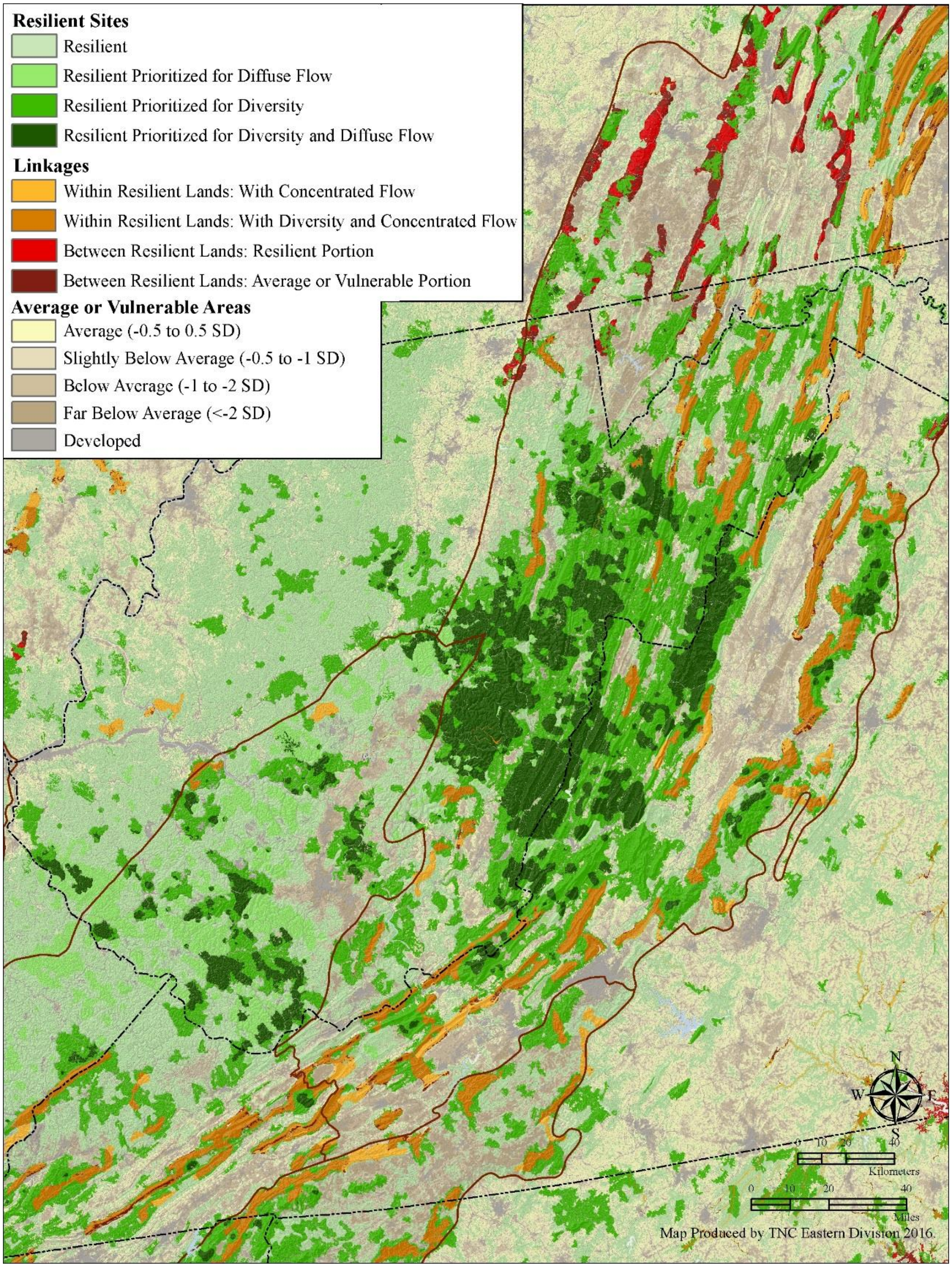


Figure 5.7. Zoom-in of West Virginia on the all resilient and connected sites map. This map shows all the resilient areas overlaid with the sites that met criteria for diversity and permeability, and the linkages between sites that have high flow and connect three or more diversity features.



Representation of Geophysical Settings

The prioritized network represents all geophysical settings in the region, but because we used connectivity values as prioritization criteria we were concerned that the network might be biased towards more acidic and high elevations settings that tend to be more intact. An assessment showed that 13 settings did decrease by more than five percent in the prioritized network compared to the non-prioritized resilient areas, and 12 of these were coastal or very low elevation settings (Table 5.2, Figure 5.7). Representation of coastal calcareous (5,613 total acres) and coastal ultramafic (148 total acres) were both less than 1%; however, this discrepancy may not be meaningful as so little actually exists.

Table 5.2. Geophysical settings with decreased representation in the prioritized network.

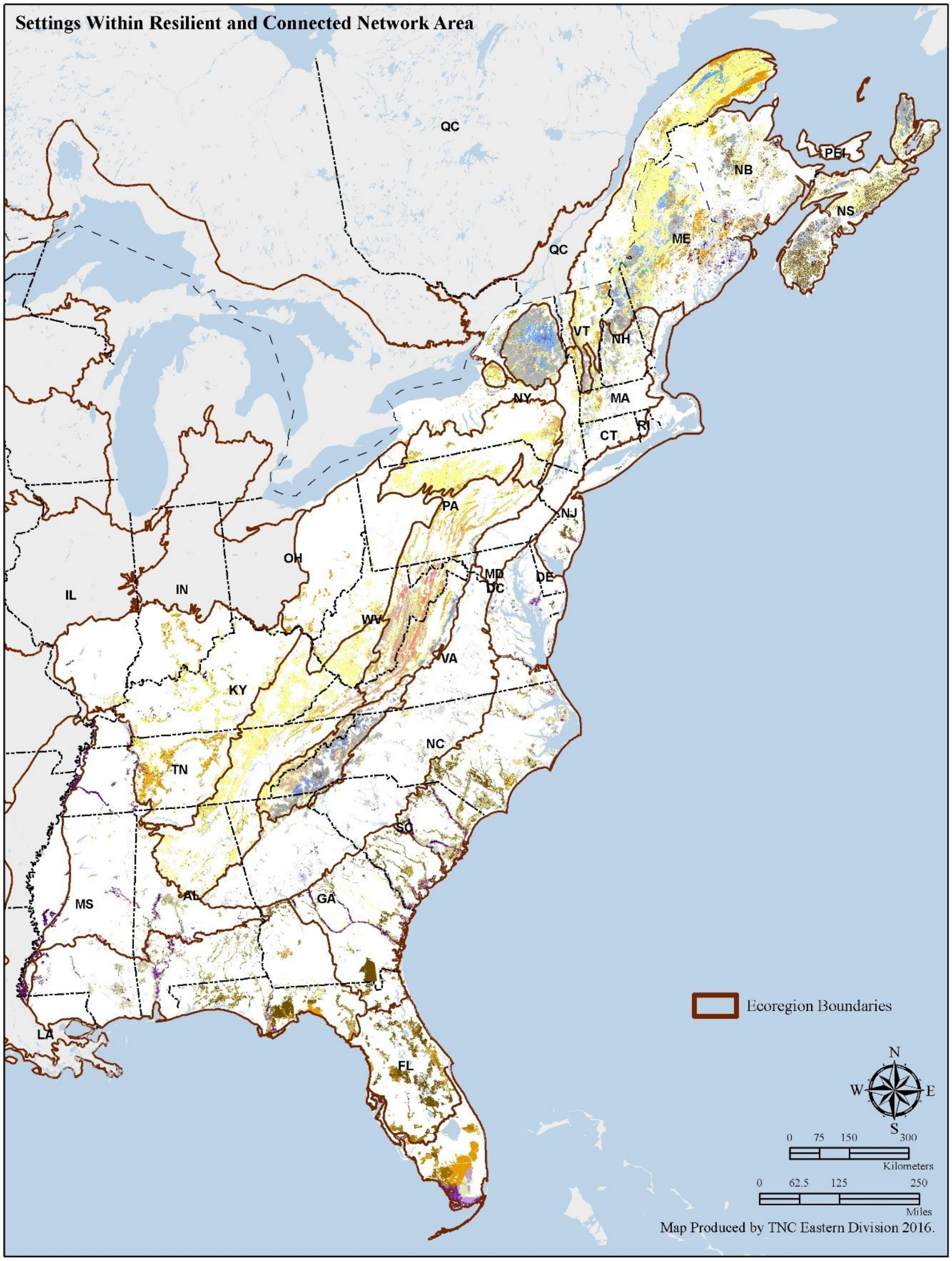
Geophysical Setting	Prioritized for Diversity	Prioritized for Diversity & Concentrated	Prioritized for Concentrated/Riparian	Prioritized for Diffuse Flow	Linkage: Resilient Portion	Linkage: Vulnerable Portion	Total Prioritized	Resilient: Not Prioritized	Total Resilient	Non-resilient
1. Coastal Acidic Granite	0.01	0.00	0.00	0.03	0.00	0.00	0.04	0.19	0.23	0.77
1. Coastal Acidic Sedimentary	0.01	0.00	0.00	0.02	0.00	0.02	0.05	0.17	0.23	0.77
1. Coastal Calcareous	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.17	0.83
1. Coastal Mafic	0.04	0.00	0.00	0.06	0.00	0.00	0.10	0.20	0.29	0.71
1. Coastal Moderately Calcareous	0.03	0.00	0.00	0.00	0.00	0.00	0.03	0.14	0.17	0.83
1. Coastal Ultramafic	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.10	0.90
2. Very Low Calcareous	0.05	0.01	0.02	0.01	0.00	0.00	0.09	0.17	0.26	0.74
2. Very Low Loam	0.04	0.01	0.02	0.02	0.01	0.02	0.12	0.18	0.30	0.70
2. Very Low Loam over Limestone	0.04	0.01	0.01	0.01	0.01	0.02	0.11	0.19	0.30	0.70
2. Very Low Silt	0.03	0.01	0.02	0.02	0.01	0.02	0.10	0.19	0.29	0.71
2. Very Low Silt over Limestone	0.03	0.00	0.02	0.01	0.00	0.01	0.07	0.21	0.28	0.72
2. Very Low Ultramafic	0.07	0.00	0.00	0.00	0.00	0.00	0.08	0.15	0.23	0.77
3. Low Moderately Calcareous	0.08	0.02	0.01	0.05	0.00	0.01	0.16	0.22	0.38	0.62

Examined individually by geology class or elevation zone, all geology classes except silt (-6%) and silt over limestone (-7%) are represented within 5% of their original amounts (Table 5.3). However, there are marked increases in acidic bedrocks (granite +18%, sedimentary +14%, and shale +24%), and mafic bedrocks (mafic +23%, ultramafic +21%). All elevation zones show an increase in representations except for the very low zone (20-800') which is the most common environment in the region accounting for 60% of the total area.

Table 5.3. Representation of geology and elevation in the prioritized network.

Geology Class or Elevation Zone	Prioritized for Diversity	Prioritized for Diversity & Corridors	Prioritized for Concentrated/Riparian	Prioritized for Diffuse Flow	Linkage: Resilient Portion	Linkage: Vulnerable Portion	total Prioritized Resilient	Resilient: Not Prioritized	Total Resilient	Non-resilient	Difference: Priority vs Non Priority
Acidic granite	0.19	0.01	0.01	0.11	0.00	0.00	0.33	0.14	0.47	0.53	0.18
Acidic sedimentary	0.15	0.02	0.01	0.12	0.00	0.01	0.32	0.18	0.50	0.50	0.14
Acidic shale	0.31	0.05	0.01	0.01	0.00	0.01	0.39	0.15	0.54	0.46	0.24
Calcareous	0.08	0.01	0.02	0.02	0.00	0.00	0.14	0.17	0.32	0.68	-0.03
Loam	0.05	0.01	0.02	0.03	0.01	0.03	0.14	0.17	0.32	0.68	-0.03
Loam over limestone	0.08	0.01	0.01	0.01	0.01	0.02	0.14	0.18	0.32	0.68	-0.03
Mafic	0.19	0.01	0.00	0.15	0.00	0.00	0.37	0.13	0.50	0.50	0.23
Mod. calcareous	0.09	0.02	0.02	0.04	0.00	0.01	0.18	0.20	0.37	0.63	-0.02
Sand	0.08	0.01	0.01	0.05	0.01	0.03	0.20	0.14	0.34	0.66	0.07
Sand over limestone	0.09	0.01	0.01	0.03	0.02	0.05	0.21	0.12	0.34	0.66	0.09
Sand/loam/silt/clay	0.39	0.03	0.00	0.01	0.00	0.01	0.44	0.12	0.56	0.44	0.33
Silt/Clay	0.04	0.01	0.02	0.03	0.01	0.02	0.12	0.18	0.31	0.69	-0.06
Silt over limestone	0.06	0.00	0.01	0.04	0.00	0.01	0.12	0.19	0.31	0.69	-0.07
Ultramafic	0.25	0.00	0.00	0.03	0.00	0.00	0.29	0.07	0.36	0.64	0.21
Grand Total	0.11	0.01	0.01	0.07	0.01	0.01	0.23	0.17	0.40	0.60	0.06
1. Coastal: 0-20'	0.14	0.01	0.00	0.04	0.02	0.07	0.28	0.10	0.38	0.62	0.18
2. Very Low: 20-800'	0.05	0.01	0.01	0.05	0.01	0.02	0.14	0.17	0.31	0.69	-0.02
3. Low: 800-1700'	0.13	0.02	0.01	0.11	0.00	0.00	0.28	0.19	0.48	0.52	0.09
4. Mid:1700-2500'	0.33	0.04	0.01	0.15	0.01	0.01	0.55	0.16	0.71	0.29	0.39
5. High: 2500-4000'	0.58	0.08	0.01	0.03	0.00	0.01	0.71	0.11	0.82	0.18	0.60
6. Very High:4000+	0.88	0.04	0.00	0.01	0.00	0.00	0.93	0.02	0.95	0.05	0.91
Grand Total	0.11	0.01	0.01	0.07	0.01	0.01	0.23	0.17	0.40	0.60	-0.17

Figure 5.8. Geophysical representation of the prioritized network. This map shows geophysical settings underlying the prioritized network. The intent is to show the diversity and comprehensiveness of 61 underlying settings. For legend see Anderson et al. 2016a.



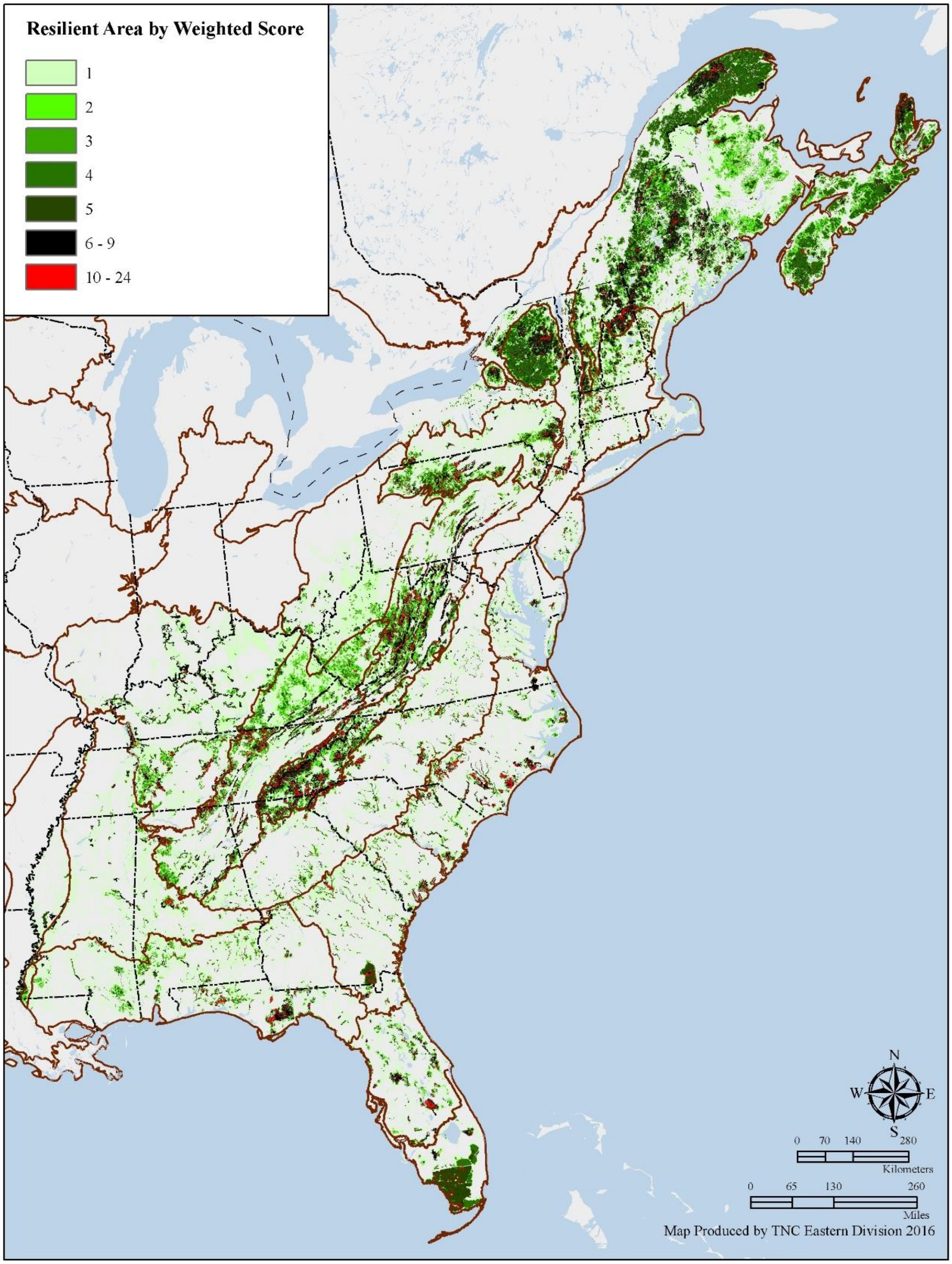
Weighted Summary Scores

To investigate the importance of areas within the prioritized network, each resilient grid cell (cells with >.5 SD resilience score) was given a weighted score based on the number of underlying priority features found in this location (Figure 5.8). All grid cells were given the following points:

Resilience Score
1 = any resilient area
Diversity Score
5 = overlap with 1000-acre hexagon containing a confirmed species or community
5 = geophysical setting block underrepresented at 3 scales (UR3)
5 = geophysical setting block underrepresented at 2 scales (UR2)
3 = geophysical setting block moderately well represented at some scales (R)
3 = overlap with 1000-acre hexagon containing above average taxa richness
1 = geophysical setting block well represented at all scales (WR)
1= roadless block of above average resilience >1000 acres containing confirmed biodiversity
Linkage Score
4 = resilient terrestrial concentrated flow (pinch point) area with above average N-S flow
4 = resilient (>75%) riparian corridor with above average N-S flow
3 = resilient terrestrial concentrated flow (pinch point) area with average N-S flow
3 = resilient (>75%) riparian corridor with average N-S flow
Diffuse Flow Score
3 = diffuse high flow area
1 = diffuse medium flow area
Upslope Score
1 = upslope flow areas falling on cells with a score > 1 (e.g., cells that had weighted scores more than just being resilient)

The total possible score was 15, and more weight was given to diversity. The highest scoring areas were often high elevation or coastal systems (Figure 5.8).

Figure 5.9. Weighted score. This map shows all the resilient areas weighted by the prioritization scheme described in the text. Red areas highlight the concentration of many diversity and connectedness values.



CHAPTER

6

CONSERVATION STRATEGIES

The prioritized network represents all the characteristic environments of eastern North America while maximizing the permeability and flow that connects them. By first identifying the natural flows and pathways that allow species populations to shift over time, and then identifying representative resilient sites situated within those pathways, the network was designed to sustain biological diversity while allowing nature to adapt and change. Of course, the network provides many other natural benefits. For example, the network contains 56% of the region's carbon, and 75% of the high value water supply lands.

In this section, we examine specific conservation strategies aimed at influencing decisions or maximizing the natural benefits and services provided by nature while simultaneously sustaining its diversity and resilience. This is a large topic. The results s presented here are intended as illustrative examples of the ways in which the resilience information can be used to make decisions, develop and map strategies, or be incorporated into existing efforts to ensure that regionally significant areas of diversity, resilience, and flow are recognized and maintained.

Multi-Objective Strategies

The following pages examine nine conservation strategies where the prioritized network of resilient and connected lands could be used, in conjunction with other spatial data, to strategically maximize benefits for multiple objectives. The strategies include:

1. Expanding Secured Lands
2. Increasing Carbon Storage
3. Identifying Shared Priorities with Partners
4. Protecting Water Supply
5. Siting Energy Infrastructure
6. Managing Forest Land
7. Mitigating Road Crossing
8. Influence Future Development
9. Identifying Vulnerable Species

1. Expanding Existing Secured Lands

Land and water permanently secured against conversion to development remains one of the most effective, long lasting, and essential tools for conserving the region's habitats and species. Terrestrial and aquatic habitats are increasingly understood as essential providers of ecosystem services and storehouses of the land's biological resources. Even though species will move and communities will change under a changing climate, by focusing acquisition on resilient examples of geophysical settings, or critical connectors for species movements, we can provide a template on which future diversity can adapt and thrive. The tools for securing land have greatly expanded in scope and versatility as conservation has grown in sophistication. Strict reserves still exist, but they are only part of a variety of restrictions, intents, designations, tenures, easements, interest holders, and ownerships found among conservation lands.

Datasets: TNC secured lands dataset.

The TNC secured lands data is compiled annually from over sixty sources, and it aims to include all permanently protected lands across 18 eastern US states and 4 Maritime provinces. It is a combination of public land information maintained by each state, and private conservation land information compiled by the Nature Conservancy's state field offices and Nature Conservancy Canada. In each state or province, Conservancy staff compile the information, assign the securement status to each tract, and fill out other standard fields such as designation, acres, ownership type, and management intent. The completed datasets are then compiled by the Eastern US regional science office and quality checked for consistency.

http://nature.ly/securedareas

Results and Strategy Map

The prioritized network identifies 21% of the region, of which 44% is already permanently secured (Table 6.1). One strategy for achieving more securement is to augment the current secured lands, increasing their size by conserving adjacent lands, and perhaps transferring the long-term ownership to the current owner. To determine where this would create the greatest impact we assessed the acreage surrounding each secured land (Figures 6.1 and 6.2).

Table 6.1. Land securement across the prioritized network.

	Unsecured		Secured		
Category	**Acres**	**%**	**Acres**	**%**	**Total Acres**
Prioritized for Diversity	28,394,755	56	22,598,389	44	50,993,144
Prioritized Diversity & Concentrated/Riparian	3,758,401	54	3,174,827	46	6,933,228
Prioritized and Concentrated/Riparian	4,951,526	77	1,469,608	23	6,421,134
Resilient: Prioritized for Diffuse Flow	14,773,817	46	17,241,775	54	32,015,592
Linkage: Resilient Portion	2,199,010	76	711,058	24	2,910,067
Linkage: Vulnerable Portion	5,375,776	79	1,469,440	21	6,845,216
Resilient: Not Prioritized	71,077,809	89	8,676,929	11	79,754,738
Non-resilient	266,049,066	94	17,533,118	6	283,582,185
Grand Total	396,580,160	84	72,875,143	16	469,455,303

Figure 6.1. Zoom-in: prioritized acquisition areas adjacent to secured lands. This zoom-in for central Florida shows where new acquisition within the prioritized network could add to the existing secured lands.

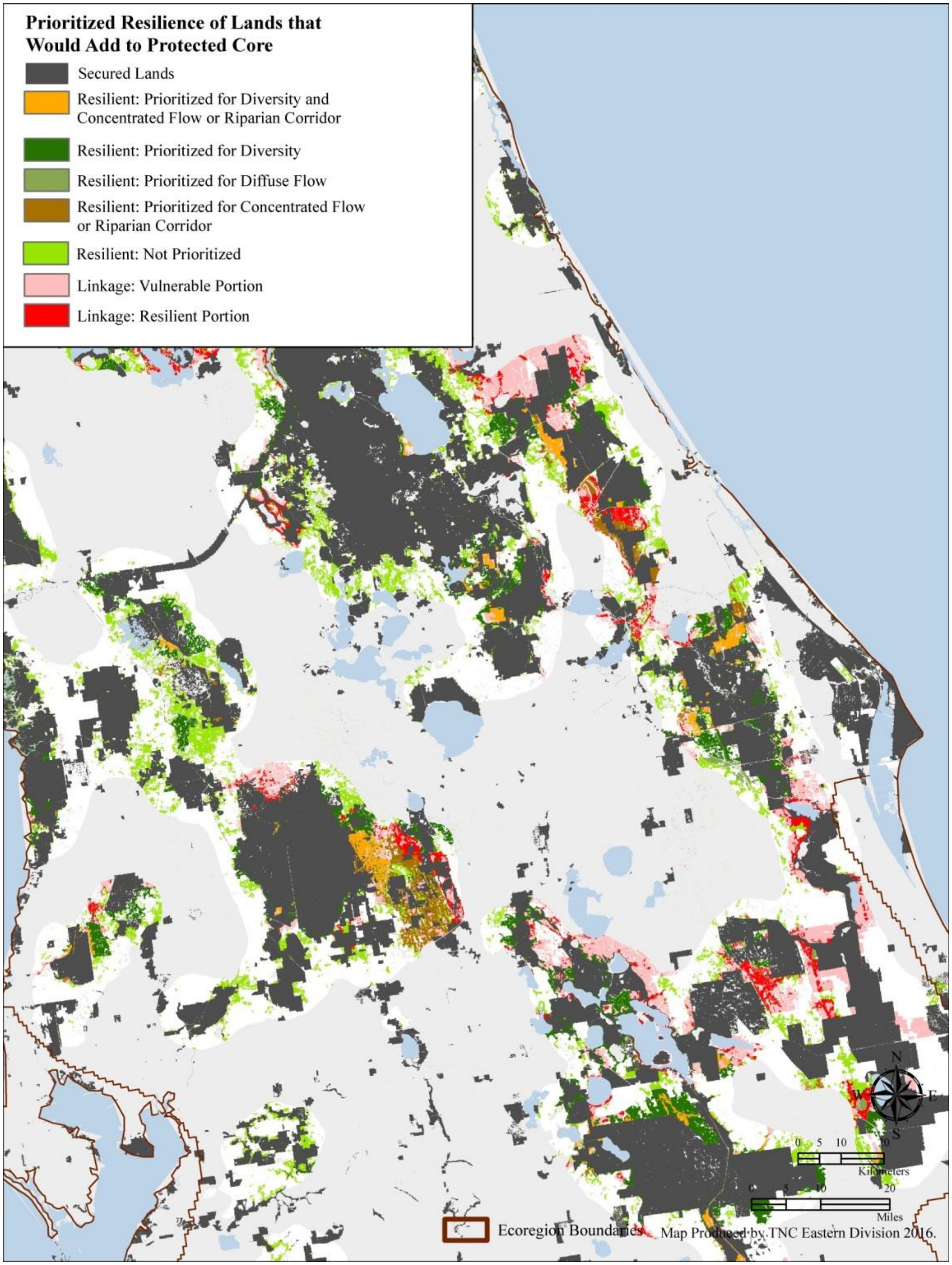
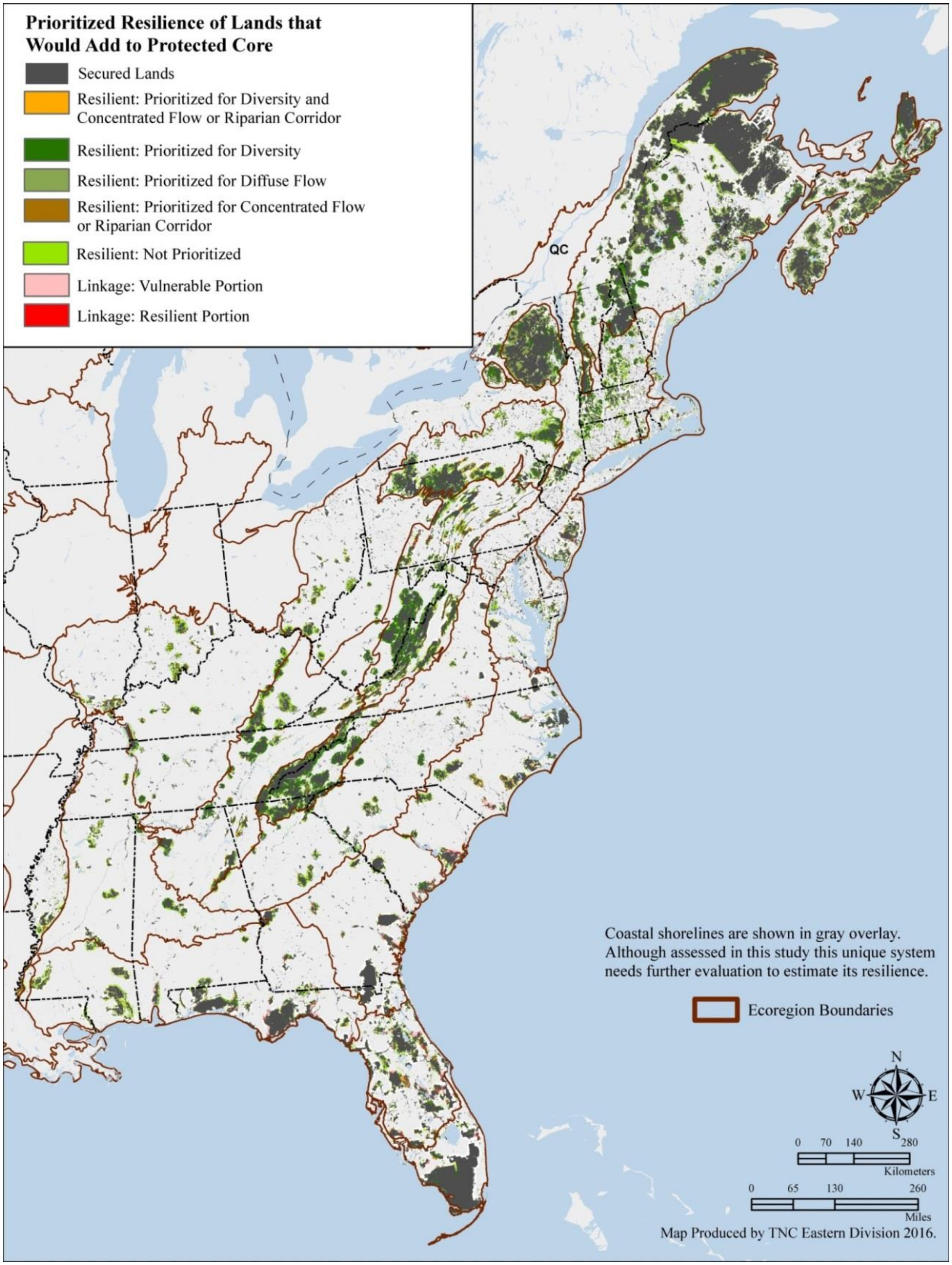


Figure 6.2. Prioritized resilient areas adjacent to secured lands. This maps shows where new acquisition focused on prioritized resilient land or climate linkages could be added to existing secured lands.



2. Increasing Carbon Storage

Eastern forests provide an essential ecosystem service in the form of carbon sequestration: the uptake and storage of carbon in forest soils, standing biomass, and wood products. This service is becoming more valuable as the impacts of greenhouse gas emissions are more fully understood. Because the conversion, degradation, or unsustainable management of forests leads to the release of carbon to the atmosphere, the management of ecosystems for carbon is now widely considered to be a key climate change mitigation strategy. The greater Appalachian region has some of the highest forest biomass in the United States. These forests can also be managed for reduced carbon emissions using techniques such as longer harvest intervals and reduced harvest levels.

Dataset: National Biomass and Carbon Dataset for the year 2000 (Kellnsdorfer 2012) and Forest Biomass (NBCD 2000).

This data is a 30-m grid that serves as a year 2000 baseline estimate of basal area-weighted canopy height, aboveground live biomass, and standing carbon stock for the conterminous United States. Development of the dataset is based on an empirical modeling approach that combines USDA Forest Service Forest Inventory and Analysis (FIA) data with high-resolution Interferometric Synthetic Aperture Radar (InSAR) data acquired from the 2000 Shuttle Radar Topography Mission (SRTM) and optical remote sensing data acquired from the Landsat ETM+ sensor.

Results and Strategy Map

Forests in the study area sequester an estimated 6,962,397,150 total tons of carbon, and 56% of that total carbon is on resilient lands (Figures 6.3 and 6.4). The prioritized network is dominated by carbon storage in the highest category (>150 tons/ha) although the linkages tend to be in the lower categories (Table 6.2).

Table 6.2. Tons of carbon storage by prioritization category.

	Tons of Above Ground Carbon Storage per Hectare					
Categories	**0-50**	**50-100**	**100-125**	**125-150**	**Over 150**	**Acres**
Resilient Prioritized Diversity and Diffuse	15%	14%	15%	21%	35%	47,389,194
Resilient Prioritized Diversity and Corridor	13%	19%	16%	21%	31%	6,893,544
Resilient Prioritized Corridor	15%	24%	21%	20%	20%	6,192,349
Resilient Prioritized Diffuse Flow	12%	16%	19%	24%	29%	15,650,566
Linkage Resilient Portion	23%	26%	16%	13%	21%	2,882,649
Linkage or Corridor Non-Resilient Portion	33%	26%	15%	11%	15%	6,788,128
Total Prioritized	16%	17%	16%	20%	31%	85,796,430
Other Resilient	23%	22%	16%	18%	21%	75,004,379
Total Resilient	19%	19%	16%	19%	26%	160,800,809

Figure 6.3. Distribution of carbon storage by prioritized network. Carbon storage is in tons per ha. Map is for the US only.

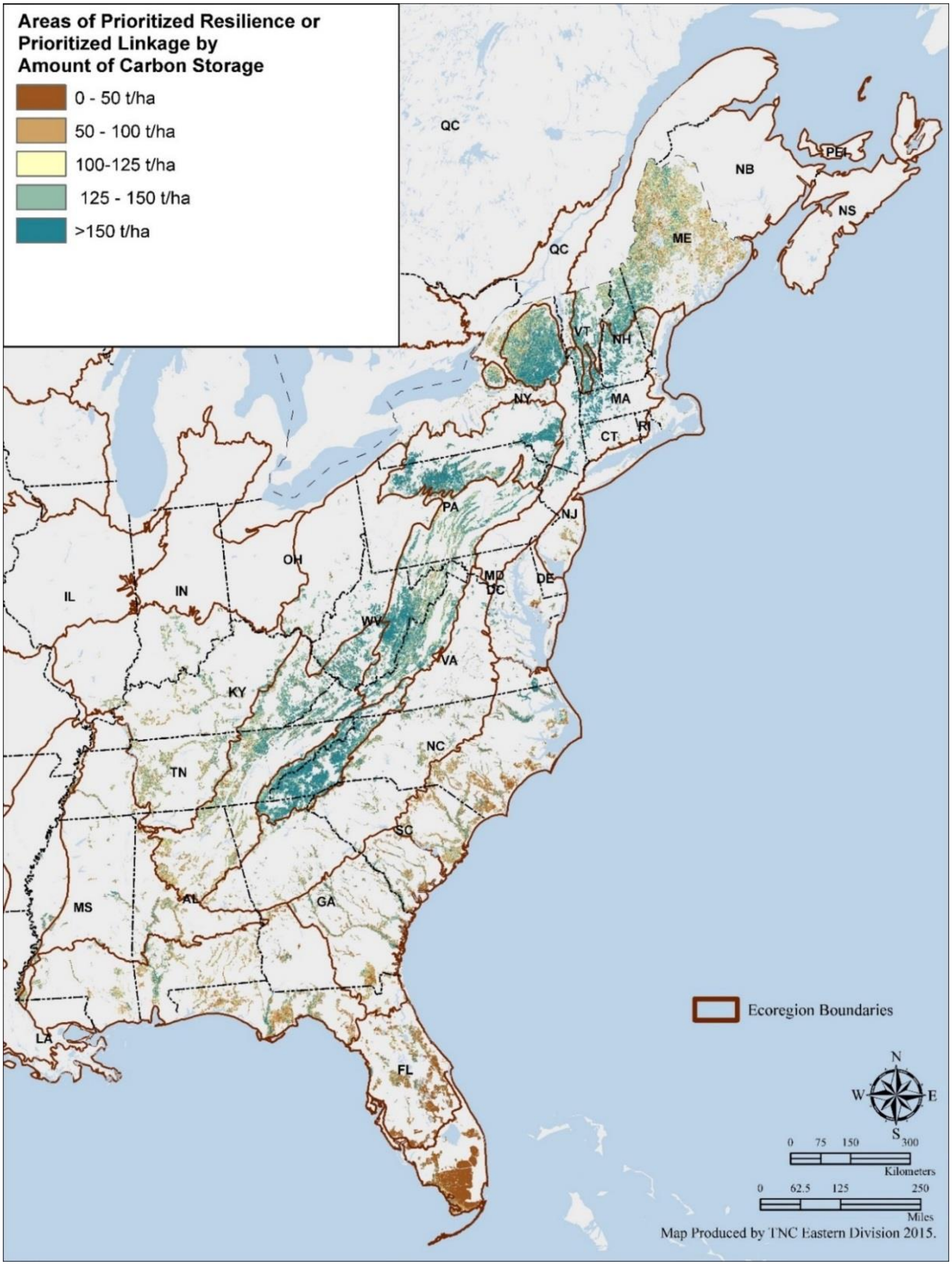
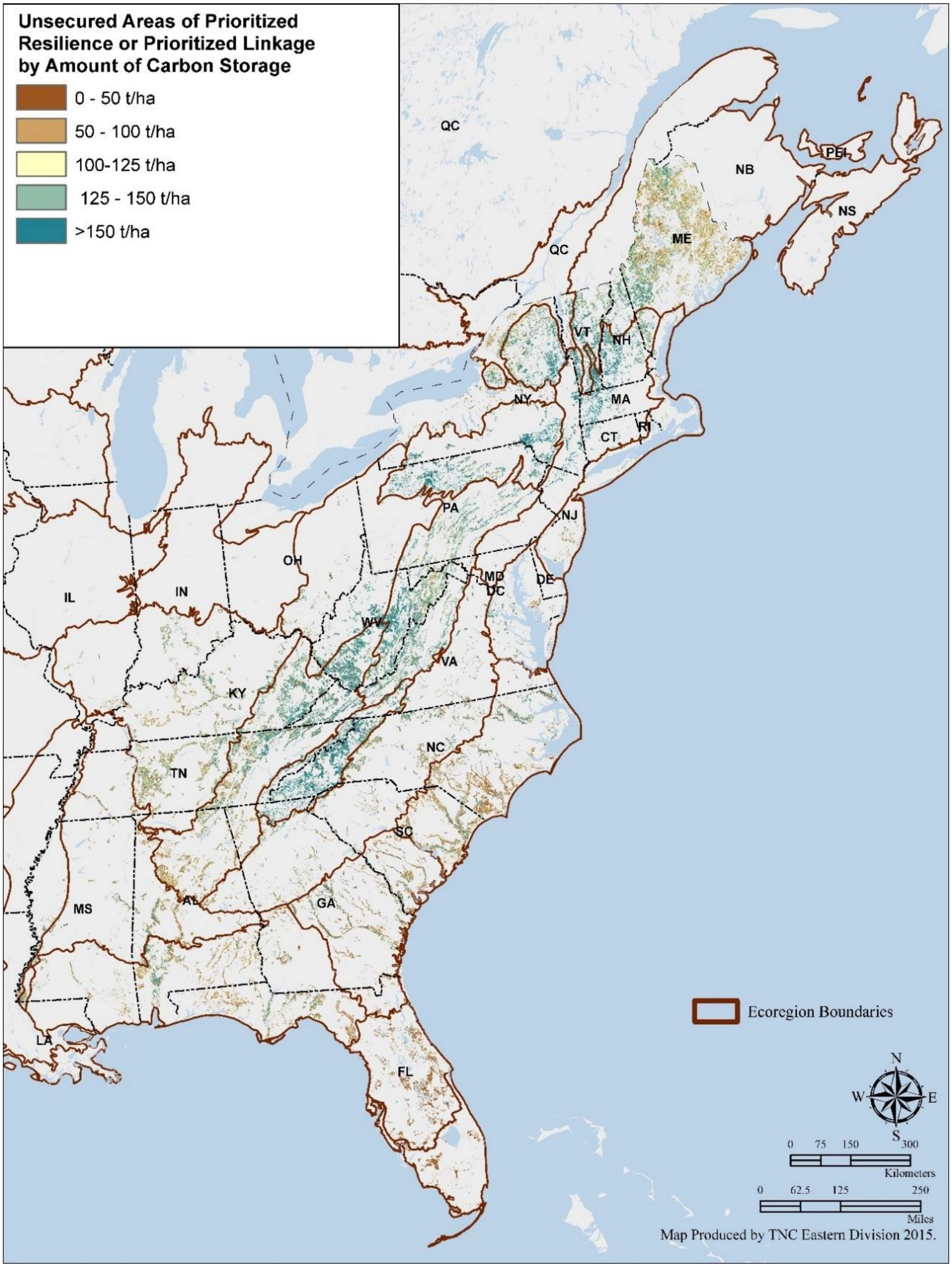


Figure 6.4. Distribution of carbon storage in the unsecured portion of the prioritized network. Carbon storage is in tons per ha. Map is for the US only.



3. *Identifying Shared Priorities with Partners*

Working with partners is fundamental to successful long-term conservation. In a world with a variety of competing needs for conservation activities and dollars, working with partners on shared priorities can lend additional resources and higher probability of success to conservation projects. The Nature Conservancy and an increasing number of its partner organizations are committed to using an open and transparent process to identify priorities, and to making all base datasets available to the public. Here we examine the intersection of shared priorities with our Fish and Wildlife Service partners to identify lands and waters where there is strong agreement and overlap among our priorities.

Datasets: USFWS Landscape Conservation Cooperative (LCC) – Conservation Designs

We evaluated the overlap of the prioritized network with the high priority areas from two multi-state land prioritizations: 1) the USFWS North Atlantic LCC's *Connect the Connecticut* watershed plan, and 2) the USFWS South Atlantic LCC's *Blueprint 2.1 for the South Atlantic Landscape Conservation Cooperative Area*. Both prioritizations incorporated earlier versions of the TNC resilient lands dataset (Anderson et al. 2012, 2014) so *the TNC and USFWS datasets are not truly independent.*

Connecticut River Watershed

The dataset we used is a component of a complete package of products from the *Connect the Connecticut* project. *Connect the Connecticut* is a collaborative effort to identify shared priorities for conserving the Connecticut River Watershed for future generations, considering the value of fish and wildlife species and the natural ecosystems they inhabit. The datasets we selected for overlay with the priority networks represent the terrestrial Tier 1 core areas and the connectors between them. The Tier 1 results represent a highly strategic scenario designed to target the very best, highest priority core areas encompassing 25% of the landscape area. Full data package, including all documentation is available at:
http://d25ripjvlq5c77.cloudfront.net/Final_download_package.zip

South Atlantic Landscape Conservation Cooperative

The South Atlantic Conservation Blueprint is a living spatial plan to conserve natural and cultural resources for future generations. It is a totally data-driven plan based on terrestrial, freshwater, marine, and cross-ecosystem indicators. It uses the current condition of those indicators to prioritize the most ecologically and culturally valuable areas in the South Atlantic geography. Through a connectivity analysis, the Blueprint also identifies corridors that link coastal and inland areas and span climate gradients.

The draft results for Blueprint 2.1 identify hubs and least-cost paths between them. To identify hubs, they selected patches that were at least 2000 hectares (~ 5000 acres) and either permanently protected or in the top 15% of Blueprint priorities. They then used software called Linkage Mapper to calculate least-cost paths between hubs. The Blueprint priority layer defines the cost for moving across each pixel. Moving across high priority areas is easier and moving across low priority areas is harder. Citation: http://www.southatlanticlcc.org/2016/04/01/update-on-blueprint-2-1-progress/

Results and Strategy Map

The results of overlaying partner priorities with the prioritized network identifies places of high ecological value where there is overlap with other partners regarding the value of these lands for conservation attention (Figures 6.5 and 6.6). A number of strategies can be used to maintain and improve natural conditions on these lands by working with partners.

Connecticut River Watershed

In the Connecticut River watershed, the two spatial priorities agreed on 36% = shared priority areas and on 32% = non-prioritized areas (68% total). Together the results identify 1.5 million acres of unsecured lands that both groups identify as being important for diversity and resilience (Table 6.3). Disagreement is most obvious in the White River watershed which is a high priority in the TNC assessment but not in the USFWs assessment (Figure 6.5).

Table 6.3. Overlap in spatial priorities: Connecticut River Watershed.

Category	Unsecured	Secured	Total Acres	%
NALCC and TNC Priority	1,502,775	1,052,898	2,555,673	36%
NALCC only Priority	635,279	174,086	809,365	11%
TNC only Priority	1,133,720	347,263	1,480,984	21%
Shared low priority	2,052,845	199,043	2,251,889	32%
Grand Total	**5,324,619**	**1,773,291**	**7,097,910**	**100%**

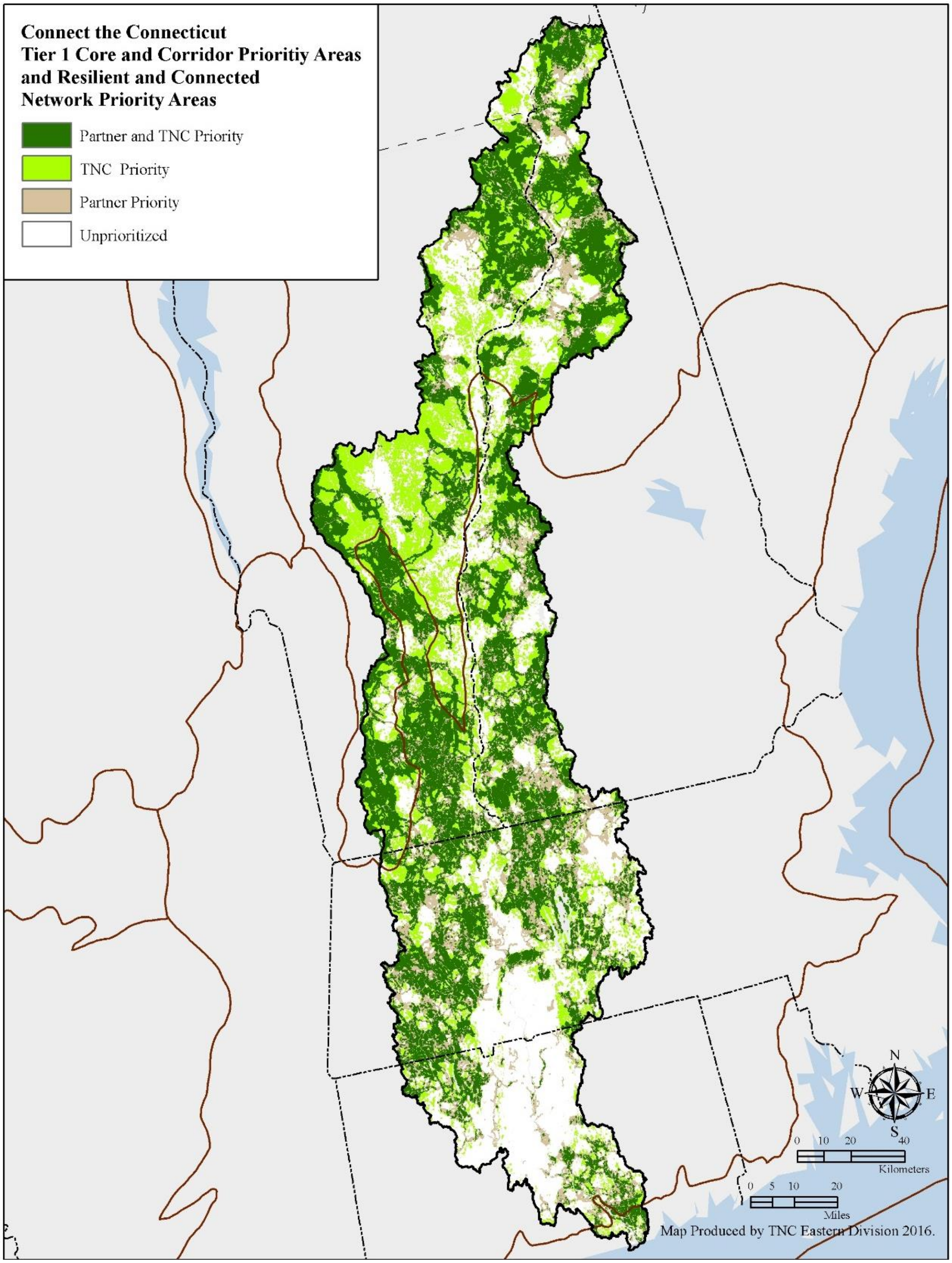
South Atlantic Landscape Conservation Cooperative

In the South Atlantic, the two spatial priorities agreed on 21% = shared priority areas, and 42% = non-prioritized areas (63%). The results identify 14.7 million acres of unsecured lands that both groups agree on as being important for diversity and resilience (Table 6.4, Figure 6.6).

Table 6.4. Overlap in spatial priorities: South Atlantic LCC Blueprint 2.1

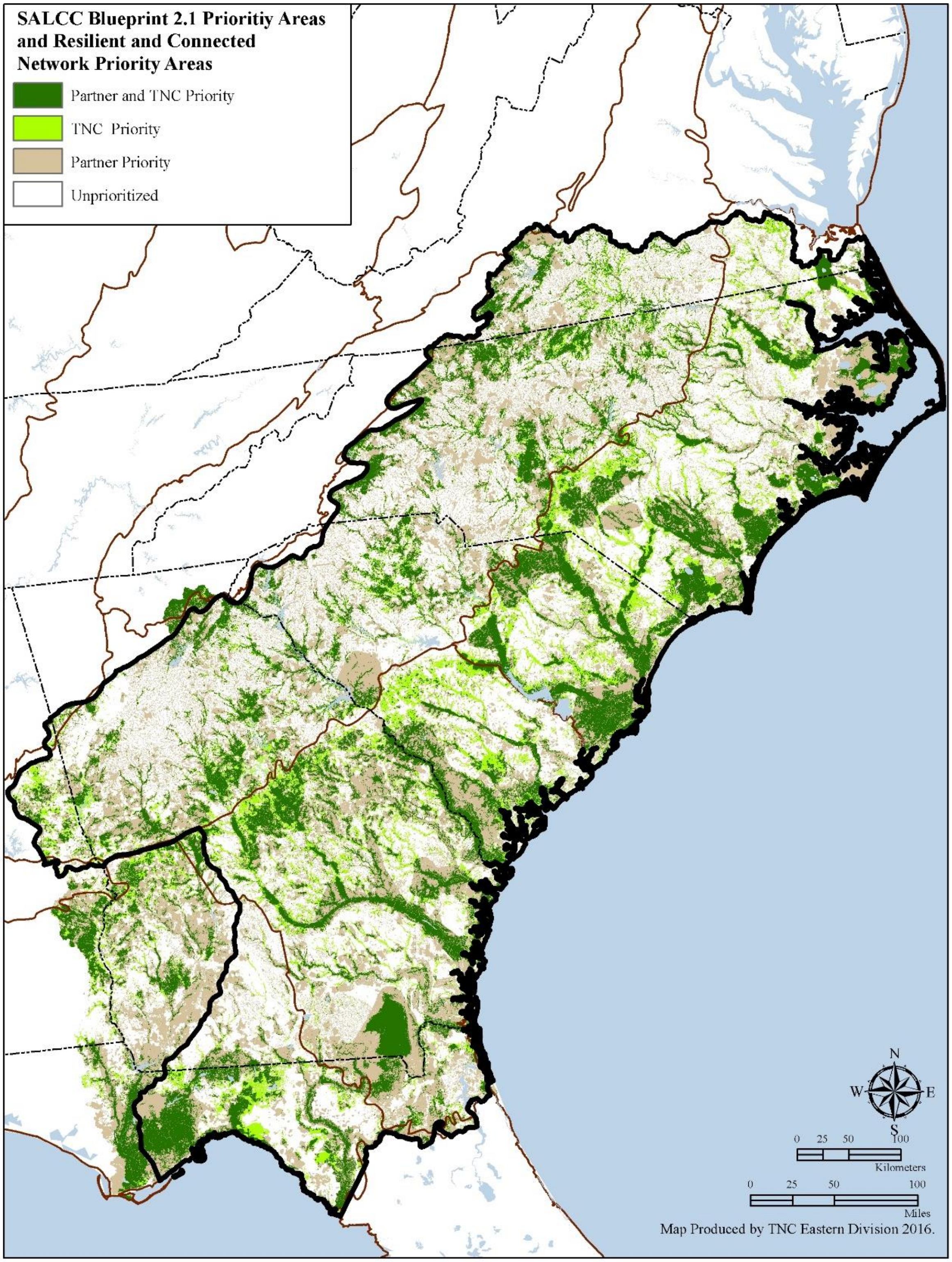
Category	Unsecured	Secured	Total	%
SALCC and TNC Priority	14,751,219	5,048,195	19,799,414	21%
SALCC only Priority	25,391,356	1,940,075	27,331,431	29%
TNC only Priority	7,842,217	529,727	8,371,944	9%
Shared low priority	39,746,582	542,665	40,289,247	42%
Grand Total	**87,731,373**	**8,060,662**	**95,792,035**	**100%**

Figure 6.5. Shared priorities between the NALCC and TNC. The map shows the North Atlantic LCC *Connect the Connecticut* Tier 1 Core and Connector Priority Areas and TNC Prioritized Network. Shared priorities = 36%, TNC only = 21%, USFWS only = 11%, Shared Un-prioritized = 32% of the watershed area.



Map Produced by TNC Eastern Division 2016.

Figure 6.6. Shared priorities between SALCC and TNC. The map shows the South Atlantic LCC Blueprint 2.1 and the TNC Prioritized Network. Shared priorities = 21%, TNC only = 9%, SALCC only = 29%, Shared Un-prioritized = 42%



Map Produced by TNC Eastern Division 2016.

4. Protecting Water Supply

Forests provide the essential benefit of filtering clean water for human consumption. This service is becoming more valuable as the cost of chemical or other water purification methods and the demand for clean water puts more pressure on municipal water suppliers.

Dataset: Forests to Faucets (USFS 2012)

The USDA Forest Service *Forests to Faucets* project (USFS 2012) used a GIS to model and map the land areas most important to surface drinking water across the continental United States at a small watershed scale (HUC12). The report highlights the role forests play in protecting these areas, and the extent to which these forests are threatened by development, insects, disease, and wildland fire. On a macro scale, the *Forests to Faucets* data identifies areas that supply surface drinking water, have consumer demand for this water, and are facing significant development threats.

Results and Strategy Map

We overlaid the prioritized network plus other resilient areas on the *Forests to Faucets* dataset to understand the potential for supplying clean water and to identify the areas of resilient land that provide the greatest clean water supply (Table 6.5, Figure 6.7). Approximately 97 million acres (62% of the resilient sites exclusive of Canada) ranked high to very high in importance to surface drinking water. Of that 77% (75 million acres) are on land that is not secured against future development and would thus be good targets for acquisition (Figure 6.8).

Table 6.5. Water supply importance areas and prioritized network.

Importance for Water Supply (Normalized Rank)	Total Prioritized Acres	% Prioritized	Unsecured Prioritized Areas	% Unsecured	Total Acres Evaluated
0 – 9	33,591,912	21	22,395,038	19	104,470,849
10 – 19 Low	159,831	0	120,883	0	765,416
20 – 29	1,358,155	1	1,101,178	1	3,742,486
30 – 39	2,632,453	2	1,876,703	2	6,727,830
40 – 49 Medium	3,928,396	2	3,444,678	3	13,094,567
50 – 59	5,865,948	4	4,612,846	4	17,539,306
60 – 69	12,102,887	8	9,579,560	8	33,513,064
70 – 79 High	23,025,341	15	17,899,729	15	53,903,685
80 – 89	34,876,347	22	27,176,950	23	74,896,226
90 – 100	39,608,645	25	30,369,935	26	102,181,841
Grand Total	157,149,916	100	118,577,502	100	410,835,269

Figure 6.7. Prioritised network by importance to surface drinking water.
This map shows the prioritized network by importance to water supply. Source: USFS Forests to Faucets HUC 12 Watershed Score Normalized on a 0-100 scale. US only.

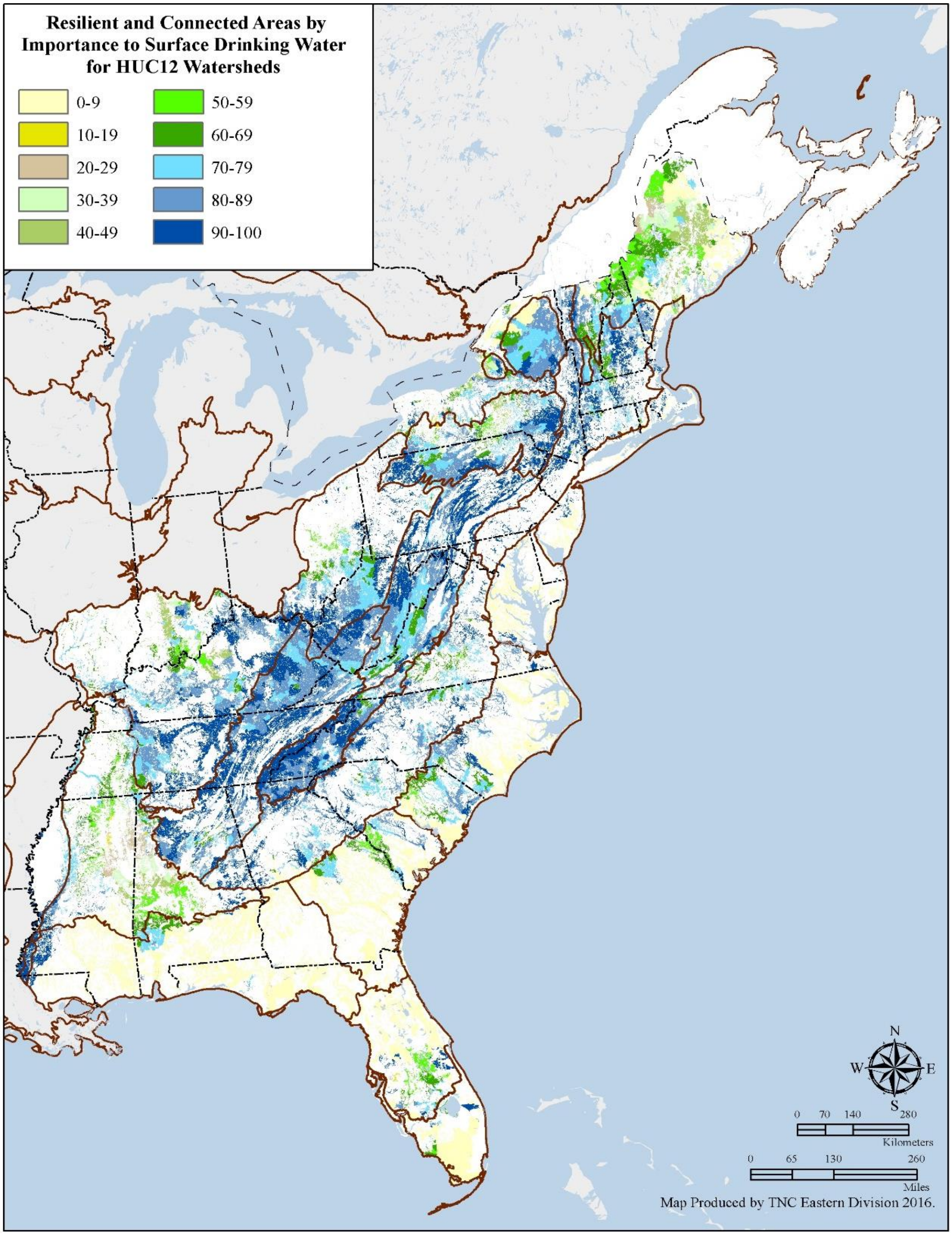
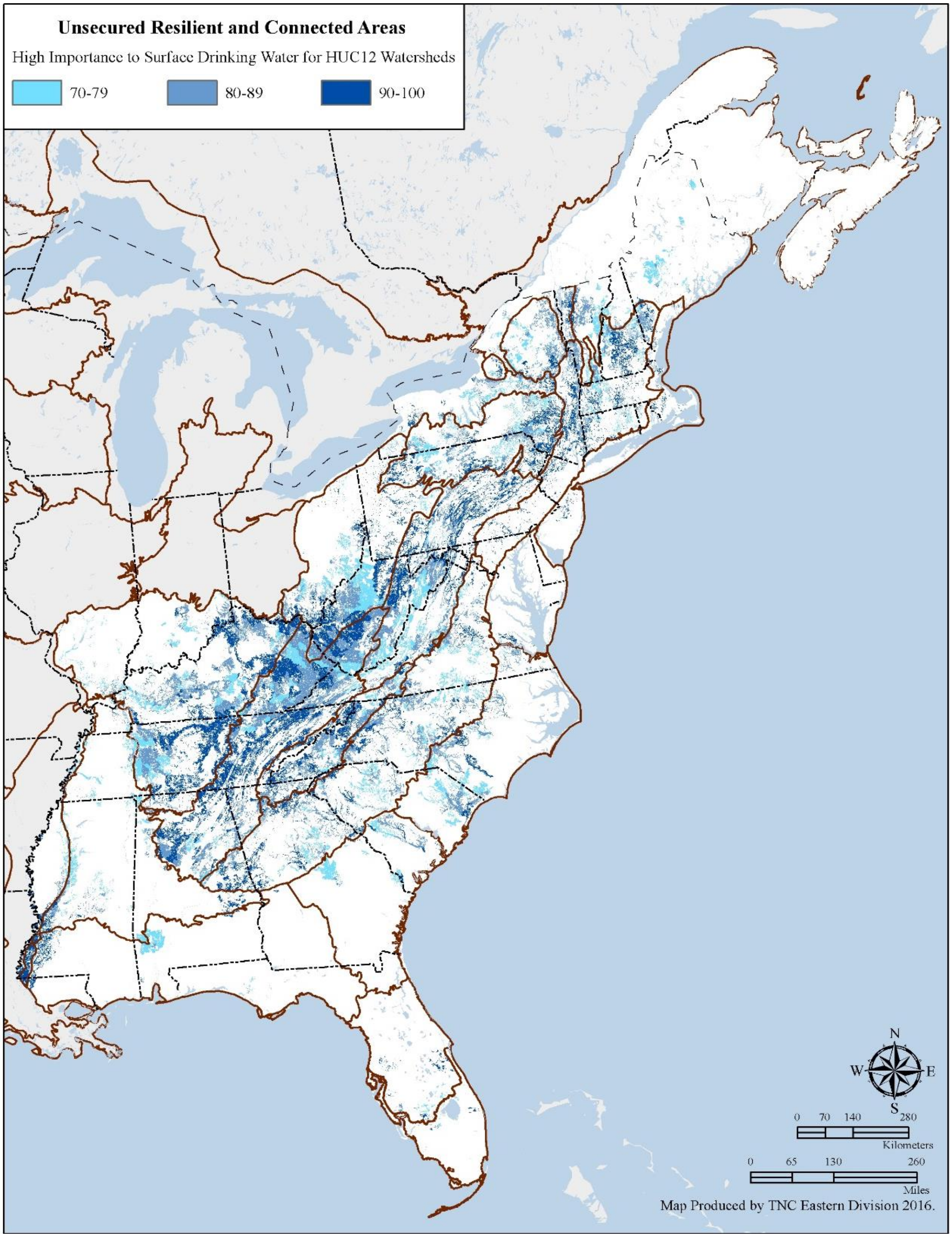


Figure 6.8. Unsecured areas of high importance to surface drinking water. This map shows the unsecured portions of the prioritized network with high to very high importance to water supply.



5. Siting Energy Infrastructure

The Central Appalachian region is an area of outstanding diversity and resilience, but it is also an area of high importance to energy development and energy security in the United States. This creates a challenge in determining how to balance energy needs with conservation values to meet multiple-objectives. Coal mining has historically been a major industry in the area, but the area is seeing a quick expansion of shale gas and wind energy. With each industry comes associated infrastructure and transmission needs that together with siting requirements result in a more fragmented landscape. Understanding the spatial structure of the energy resources as well as of the biological resources and ecological flows is key to developing a plan that balances energy and conservation.

Datasets: "Assessing Future Energy Development across the Appalachian LCC" (Dunscomb et al. 2014)

In this study funded by the USFWS Appalachian Landscape Conservation Cooperative (LCC), The Nature Conservancy assessed current and future energy development across the Appalachian area. The research identified areas in the Appalachian region most likely to undergo changes in land cover as a result of the development of wind, shale gas, and coal.

Results and Strategy map

Dunscomb et al. (2014) determined that nearly 7.6 million acres within the Appalachian LCC have a high probability of energy development from one or more sources. These areas are concentrated in the eastern portion of the Central Appalachians on the Allegheny and Cumberland plateaus. Pennsylvania alone supplies 44% of the total high energy development area, while West Virginia contributes 21%. This constitutes approximately 11% of the total land area in each of the two states. The report suggested a basic strategy of avoiding areas with important ecological values and where impacts cannot be avoided, mitigate and offset impacts of future energy development.

To understand how energy development areas corresponded spatially to the prioritized network, we intersected the two datasets using the prioritized network as a measure of ecological value. The overlap between the two was high (53%), but there were ample areas (47%) without prioritized features that could provide opportunities for avoidance (Table 6.6, Figure 6.9).

Table 6.6. Acres of prioritized network by energy type.

Category	Coal (ac)	%	Wind (ac)	%	Shale (ac)	%
Resilient Prioritized for Diversity	204,157	14	531,322	31	307,737	7
Resilient: Prioritized for Diversity and Corridors	8,672	1	106,375	06	59,612	1
Resilient: Prioritized for Corridors	10,787	1	28,478	02	105,117	2
Resilient Prioritized for Diffuse Flow	299,052	21	52,425	03	116,496	3
Linkage: Resilient Portion	161	0	51,187	03	5,541	0
Linkage: Vulnerable Portion	1,133	0	93,744	05	31,646	1
Resilient: Not Prioritized	600,358	42	298,047	17	1,153,183	26
Vulnerable or Average	300,722	21	567,942	33	2,704,751	60
Total	**1,220,886**		**1,198,198**		**4,176,346**	

Coal Energy

Almost all coal mining takes place on lands that score high for resilience (78%), because the coal region is rich with topographic complexity that is highly connected. The area also supports a diversity of rare species (14%) and has large patches of intact diffuse flow (21%, Table 6.6, Figure 6.9). Recently the coal industry has been on the decline due to broad scientific consensus that carbon emissions drive global warming. This has created regulatory bias against coal-fired power generation as governments in the US and around the world incentivize power generators to lower their emissions. Additionally, the rapid advances in natural gas extraction techniques have made the production of vast reserves of nearby shale gas economically viable, creating a cheap alternative to coal. As the region transitions to a new economic structure, there may be opportunities to increase conservation and find sustainable nature-based solutions to some of the inevitable economic and human well-being challenges that would be more compatible with the outstanding natural features of the region.

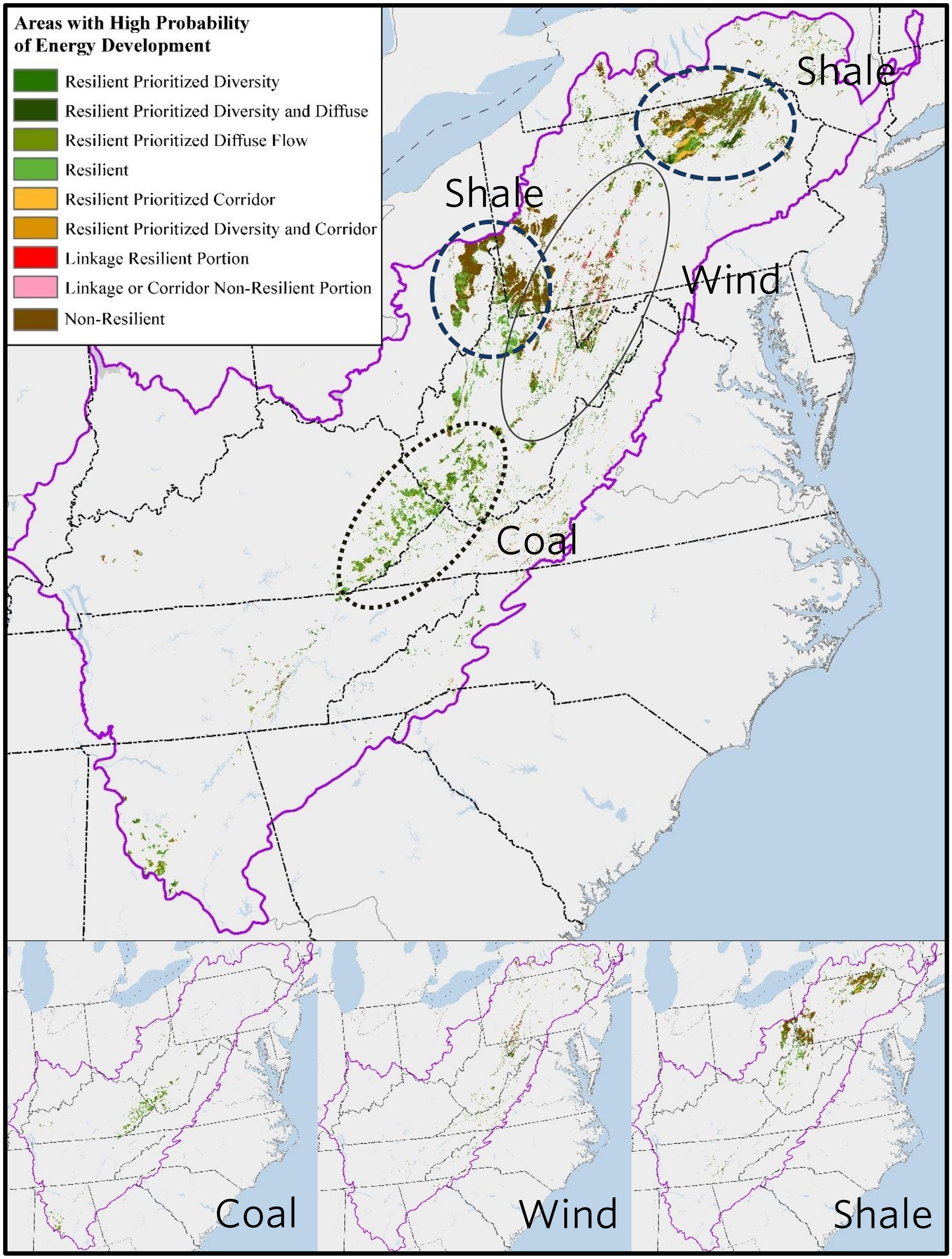
Wind Energy

The areas with the highest probability for wind energy development occur along high-elevation ridgetops, which tend to also be areas of concentrated flow and priority linkages. The series of sandstone ridges function as key connectors linking the Central and Southern Appalachians to the High Allegheny Plateau and Northern Appalachians, facilitating the movements and range shifts necessary for climate adaptation. Because the best areas for wind development are atop ridgelines, this affords wind developers less flexibility in siting turbines in ways that will mitigate potential impacts to forests (Northrup and Wittemyer 2013). A full 50% of the areas with a high probability for wind development overlap directly with the prioritized network, with 8% overlapping the resilient concentrated flow areas and another 8% occurring on the linkages between resilient sites (Figure 6.9). However, 33% of the projected areas for energy are in less critical places that score as non-resilient or vulnerable to climate change.

Shale Gas

On a landscape level, shale gas has the biggest geographic extent in the Central Appalachians, but the least spatial overlap with the prioritized network (14%). The non-prioritized sites make up another 26% of the area with the remaining area (60%) scoring average or vulnerable (Table 6.6). Additionally, shale gas development offers the most opportunities for conservation at the site level and the landscape level. Shale gas is typically extracted using multiple lateral wells sited on a single pad. The lateral reach of shale gas wells means there is more flexibility in where pads and infrastructure are placed (Johnson 2010, Rozell and Reaven 2012). This flexibility could be used to avoid or minimize impacts due to siting, though there are many other issues associated with hydraulic fracturing (i.e., fracking) such as the contamination of ground and surface water and the migration of fracking chemicals to the surface.

Figure 6.9. Projected energy development areas and the prioritized network. This map shows the resilient and connected network priority areas within the footprint of projected energy development (Dunscomb et al. 2014).



6. Influencing Forest Management

A range of management activities can contribute to maintaining or increasing the adaptive capacity of forests. They include actions oriented toward maintaining forest productivity by application of appropriate silvicultural treatments, managing pests and disease, sustaining biodiversity by effective management of forest conservation areas, and enhancing connectivity between forest areas. Many of these management actions also help conserve forest carbon and enhance forest carbon sinks.

Datasets: TNC Secured Lands

The TNC secured lands data is compiled annually from over sixty sources and aims to include all permanently protected lands across 18 eastern US states and Maritime Canada. It is a combination of public land information maintained by each state, and private conservation land information compiled by the Nature Conservancy's state field offices. Nature Conservancy staff compile the dataset in each state, assign the securement status to each tract, and fill out the other standard fields such as designation, acres, ownership type and management intent. The completed state datasets are then compiled by the Eastern US regional science office and quality checked for consistency and discrepancies. For private landowners, we used the ParcelPoint ownership data (see chapter on mapping landscape permeability). For the analysis, the secured lands dataset was intersected with the priority networks.

http://nature.ly/securedareas

Results and Strategy Map

Public agencies and private nonprofit organizations collectively own over 42 million acres of the prioritized network (Figure 6.10). Of those ownerships, state and provincial agencies own 88% of the diffuse flow area and 62% of the terrestrial pinch points and riparian corridors (Table 6.7). Ensuring that these lands are appropriately managed to promote movement and connectivity could play a large role in maintaining diversity under climate change.

Table 6.7. Forest ownership by priority network.

Category	Federal	State	Local	Nonprofit	Collective Ownership	Total Acres
Prioritized Diversity	45%	46%	2%	7%	20,795,908	50,993,144
Prioritized Diversity and Corridor	45%	45%	2%	8%	2,869,089	6,933,228
Prioritized Corridor	27%	62%	2%	9%	936,796	6,421,134
Prioritized Diffuse Flow	5%	88%	1%	6%	15,691,690	32,015,592
Linkage Resilient Portion	26%	65%	3%	5%	742,917	2,910,067
Linkage Non-resilient Portion	25%	64%	5%	6%	1,431,439	6,845,216
Other Resilient	21%	65%	7%	7%	7,094,613	79,754,738
Vulnerable or Average	21%	60%	10%	9%	16,796,804	283,582,185
TOTAL					66,359,256	469,455,303

Figure 6.10. Distribution of prioritized resilient areas by forest ownership type. Ownership of the 42,460,410 acres is divided among state and province (63%), federal (29%), non-profit (7%), and local agencies (2%). The majority of land is in areas with high diversity and/or diffuse flow. "Manager Organization" refers to the organization who has responsibility for managing the land.

7. Mitigating Road Crossings

Roads are essential to daily life but their presence and traffic volume have increased so rapidly over the last decades it is difficult to grasp their impact on nature. One century after the 1916 US Highway Act was developed to create a national road network, that network is now supporting over 3 trillion vehicle miles per year and the Northeast alone now has enough roads to circle the earth 29 times. Road networks carve up and fragment landscapes into small, isolated patches in which wildlife must live and move. Road mortality is documented as one of the major threats to the survival of 21 federally listed threatened or endangered species in North America (http://arc-solutions.org/new-thinking/). Wildlife movements often conflict with roads that cross important migration areas.

Datasets: US Census Bureau (2014). 2014 TIGER/Line Shapefiles roads dataset (machine-readable data files). http://www.census.gov/geo/maps-data/data/tiger.html

For this preliminary analysis we examined major road crossings in areas of concentrated flow from the regional flow concentration dataset. We used a 3-km neighborhood function to measure how much concentrated flow was within the local neighborhood of each road segment, and then we identified those roads with over 50% of their local neighborhood in concentrated regional flow. The results highlighted the roads that potentially block the greatest flow and thus form the greatest barriers to range shifts and species movements. To eliminate data noise, we restricted the results to larger areas over 1800 meters in size (e.g., 10 grid cells) but this may have eliminated some small high-flow crossings.

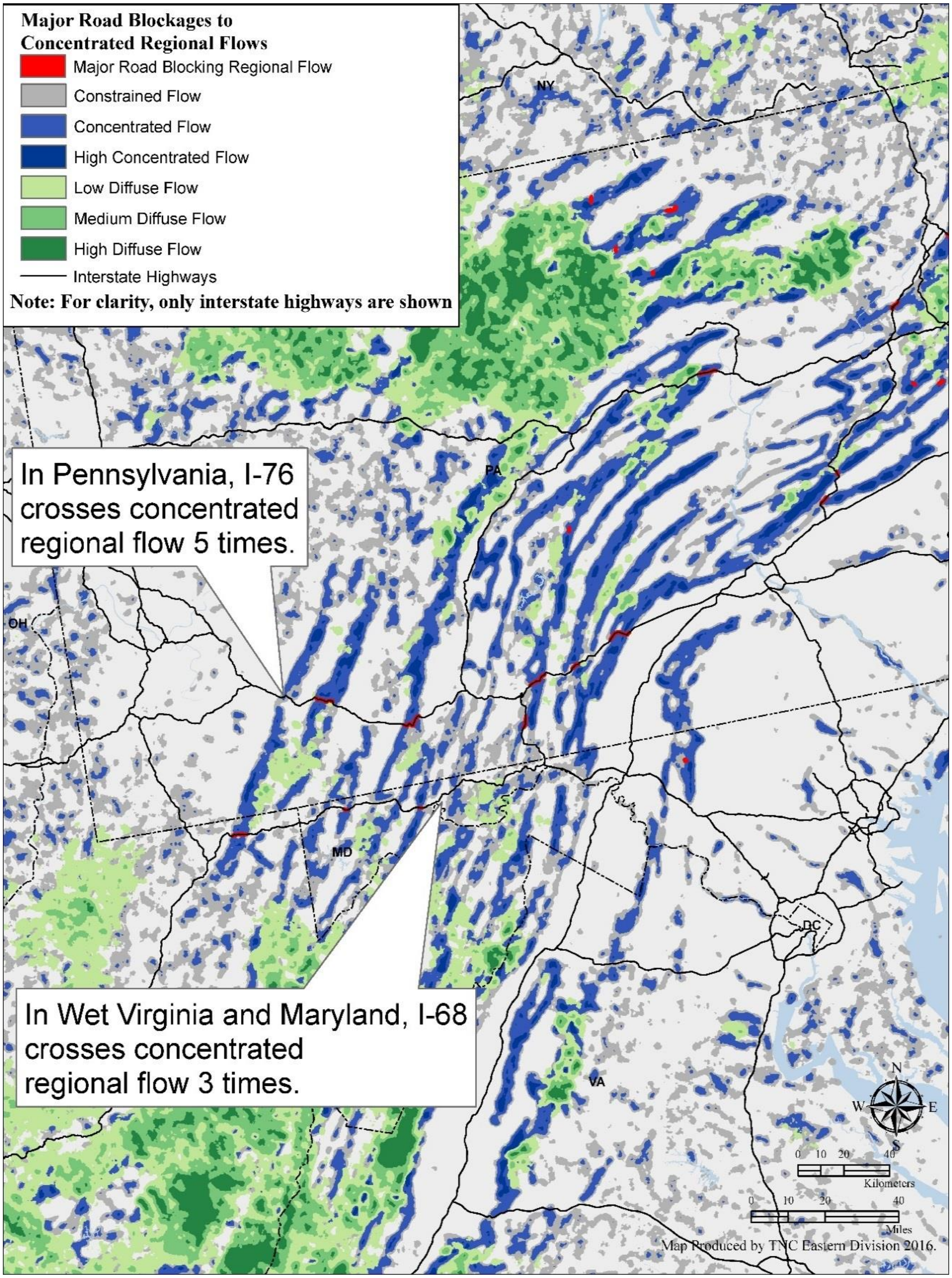
Results and Strategy Map

The results identified 201 areas where major roads intersected with areas of concentrated regional flow. Road/flow crossings were greatest in Pennsylvania (21) followed by Florida (12), Georgia (16), and Quebec (19) (Table 6.8). The Pennsylvania Turnpike (Interstate 76) has five road/flow crossings, the most of any single road (Figures 6.11 and 6.12).

Table 6.8. A list of states and the major roads that the concentrated regional flow crosses. The format is: road name (number of individual crossings)

Number of Road/Flow crossings	State	Road Name and Number of Crossings
21	PA	I- 76 (5), I- 81 (3), I- 380 (2), State Rte 287 (1), Roosevelt Hwy (1), Pennsylvania Tpke NE Exn (1), I- 80 (1), State Rte 26 (1), US Hwy 15 (1), E Catawissa St (1), Stock St (1), US Rte 6 (1), Bloss Mountain Rd (1), Mill Hill Rd (1)
19	QC	State Rte 105A (4), State Rte 37 (2), Daniel Webster Hwy (2), US Hwy 201 (2), State Rte 243 (2), State Rte 30 (2), I- 91 (1), Main St
16	GA	I- 95 (3), I- 16 (2), US Hwy 411 (2), I- 475(1), State Rte 1 (1), Kingston Hwy (1), State Rte 140 (1), State Rte 136 (1), Cartersville Hwy (1), Joe Frank Harris Pkwy NW (1) Canton Hwy (1), Joe Frank Harris Pkwy (1)
12	FL	State Hwy 9 (2), I- 75(2), State Hwy 93 (2), I- 10(2), I- 95(2), State Hwy 9336 (1), Beeline Expy (1)
9	KY	I- 65 (2), I- 71(1), Western Kentucky Pkwy (1), I- 75 (1), US Hwy 60 (1), I- 66 (1), I- 24 (1), I- -66 (1)
7	NY	I- 88(2), State Rte 27 (1), New York State Thruway (1), Long Island Expy (1), US Hwy 6 (1), New York State Throughway (1)
7	TN	I- 40 (3), I- 24 (2), US Hwy 411 (1), Genesis Rd (1)
6	AL	I- 59 (3), I- 65(2), I- 20 (1)
5	IL	I- 64 (1), I- 180 (1), State Rte 83(1), I- 24(1), I- 57(1)
5	MS	I- 10 (2), I- 55 (2), US Hwy 49 (1)
5	NC	State Hwy 80 (1), Haynes Lennon Hwy (1), US Hwy 70(1), I- 26 (1), State Hwy 211(1)
4	LA	I- 10(2), US Hwy 51(1), I- 59 (1)
4	MD	I- 68 (2), Rocky Ridge Rd (1), National Fwy (1)
4	NB	State Rte 6 (2), Water St (1) US Hwy 1 (1)
4	VA	US Hwy 460 (1), State Rte 8(1), I- 77 (1), I- 81 (1)
3	IN	I- 64 (2), Dwight D Eisenhower Hwy (1)
3	SC	I- 95 (2), US Hwy 21 (1)
2	MA	Massachusetts Tpke (1), I- 195(1)
2	NJ	I- 80(2)
1	OH	State Rte 650 (1)
1	PEI	State Rte 190 (1)
1	RI	I- 95(1)
1	WV	I- 68(1)

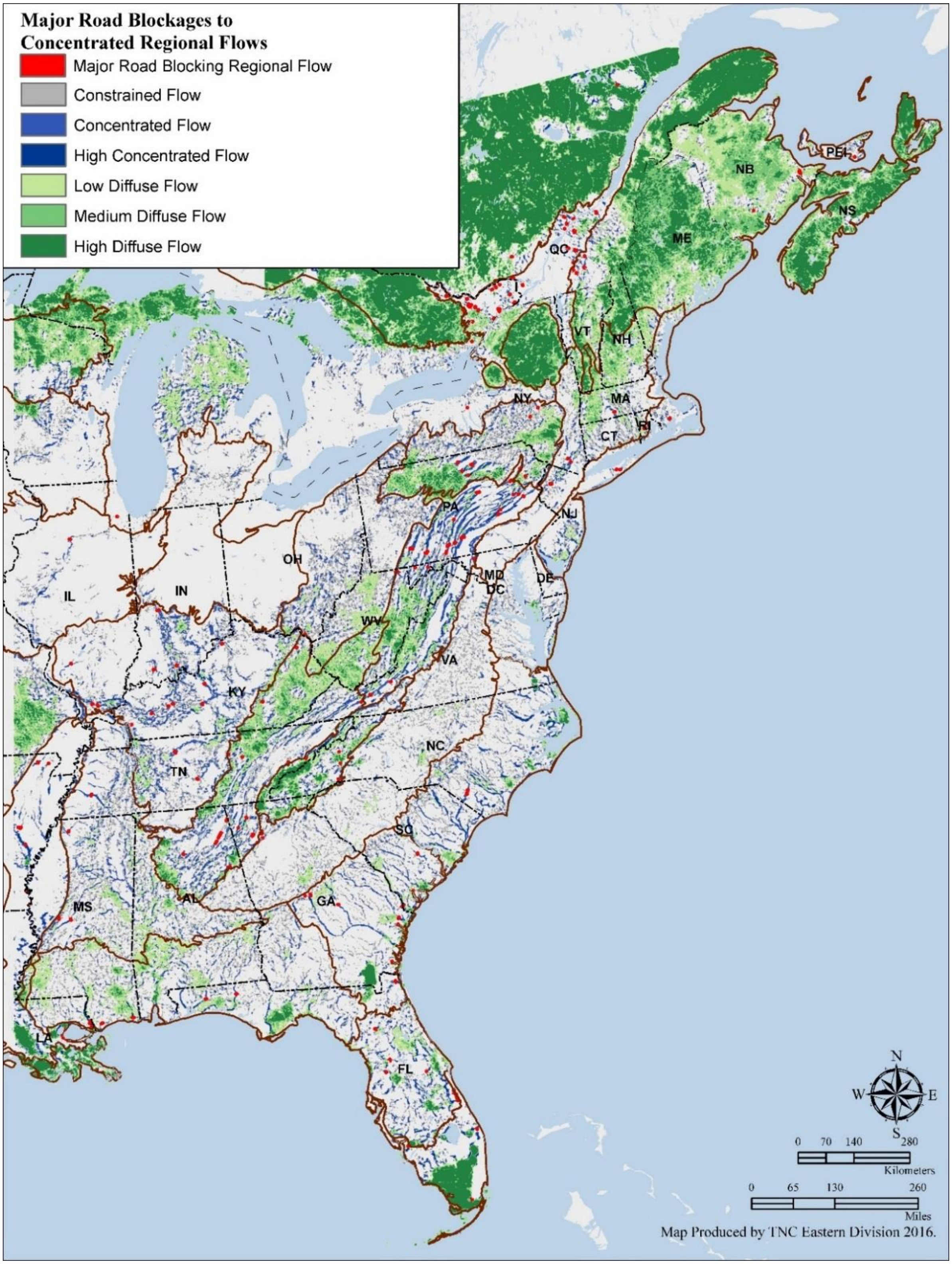
Figure 6.11. Major roads that cross concentrated regional flow. A zoomed in map showing areas where major roads cross concentrated flow in Pennsylvania.



In Pennsylvania, I-76 crosses concentrated regional flow 5 times.

In Wet Virginia and Maryland, I-68 crosses concentrated regional flow 3 times.

Figure 6.12. Major roads that cross areas of concentrated regional flow.



8. Influencing Future Development

Development is perhaps the greatest and most permanent threat to natural systems. In the US, more than 34 million acres of open space were lost to development between 1982 and 2001, about 6000 acres per day, 4 acres a minute. Of this loss, over 10 million acres were in forestland. Rapid development of forestland is expected to continue over the next couple of decades bringing not only direct destruction of habitat, but also people, roads, noise and pollution (http://www.fs.fed.us/projects/four-threats).

In addition to habitat destruction, high-density development of natural habitats can transform a landscape by changing local hydrology, increasing recreation pressure, and introducing invasive species either by design or by accident with the introduction of vehicles. Moreover, urbanization and fragmentation are inextricably linked since the dispersal and movement of forest plants and animals are disrupted by development and roads.

Dataset: Land Transformation Model (LTM) Version 3 developed by the Human-Environment Modeling and Analysis Laboratory at Purdue (Tayyebi et al. 2013)

We used future development predictions to represent the acres of a habitat predicted to be developed over the next 50 years. In this model the quantity of urban growth at county and city scales is simulated using population, urban density, and nearest neighbor dependent attributes. Future urban land cover is meant to serve as an example of one possible scenario of urban expansion. Future land use predictions were created for every 30-m pixel in the region in five-year increments from 2010 to 2060 and used NLCD 2001 version 2 as the basis for projections. We caution users that some interpretation of this metric and maps is needed. The predicted development data is modeled at a 30-m scale, and in some areas, results may not be as fine scaled as the ecological data and may reflect the larger surrounding landscape. Because the predicted development areas are so small and often on the periphery of larger resilient land chunks, more study is also needed to evaluate the impact of development.

Results and Strategy Map

Across the entire project area, 15.2 million acres of land were predicted to be developed, including 2.4 million acres of land prioritized for resilience and connectivity (Table 6.9). Although the results are difficult to see at a regional scale, maps at county scales show these small areas of predicted development along the fringe of existing development and roads (Figures 6.13, 6.14, and 6.15). The dataset does not factor in land securement, which by definition is a strategy to prevent development, so we grouped the results into secured or unsecured land assuming that the secured land will not be developed. This reduces the projected impact of development across the prioritized network by 8% (2.2 million acres, Table 6.9).

In addition to highlighting lands for securement, this dataset can be used to influence development patterns so that existing developed land is used more efficiently for additional housing. A variety of strategies such as smart growth, compact development, and redevelopment of existing brownfields and non-natural lands may allow certain areas to accommodate additional housing and development without converting remaining natural and resilient lands.

Table 6.9. Total acres of land in the prioritized network predicted to transform to urban land use by 2060. The 201,136 acres of secured land can be assumed to prevent conversion, leaving the unsecured land as the most likely estimate of conversion. The table is sorted by the amount of unsecured acres.

State	Unsecured	Secured	Total Acres
Kentucky	216,498	2,855	219,353
West Virginia	192,870	4,533	197,404
Alabama	188,934	4,428	193,361
Florida	187,550	62,184	249,734
Tennessee	184,709	6,674	191,384
New York	165,596	11,093	176,689
Pennsylvania	160,147	15,099	175,245
North Carolina	145,369	14,513	159,881
Georgia	143,410	10,603	154,013
Virginia	107,416	7,171	114,587
Mississippi	106,205	4,473	110,678
South Carolina	82,758	1,806	84,563
Ohio	58,847	4,169	63,017
Maine	50,827	3,428	54,255
Massachusetts	48,910	12,901	61,811
Vermont	42,647	3,533	46,180
Maryland	35,929	8,003	43,932
New Hampshire	31,839	4,957	36,796
Connecticut	28,520	4,099	32,620
Indiana	26,147	2,292	28,439
New Jersey	24,837	8,609	33,445
Illinois	14,041	1,907	15,947
Louisiana	5,347	134	5,481
Rhode Island	5,229	1,018	6,247
Delaware	1,330	645	1,975
District of Columbia	36	11	47
Grand Total	2,255,948	201,136	2,457,084

Figure 6.13. New Hampshire example: Land Transformation Model Future 2060 urban land projections by their correspondence within or outside the prioritized network.

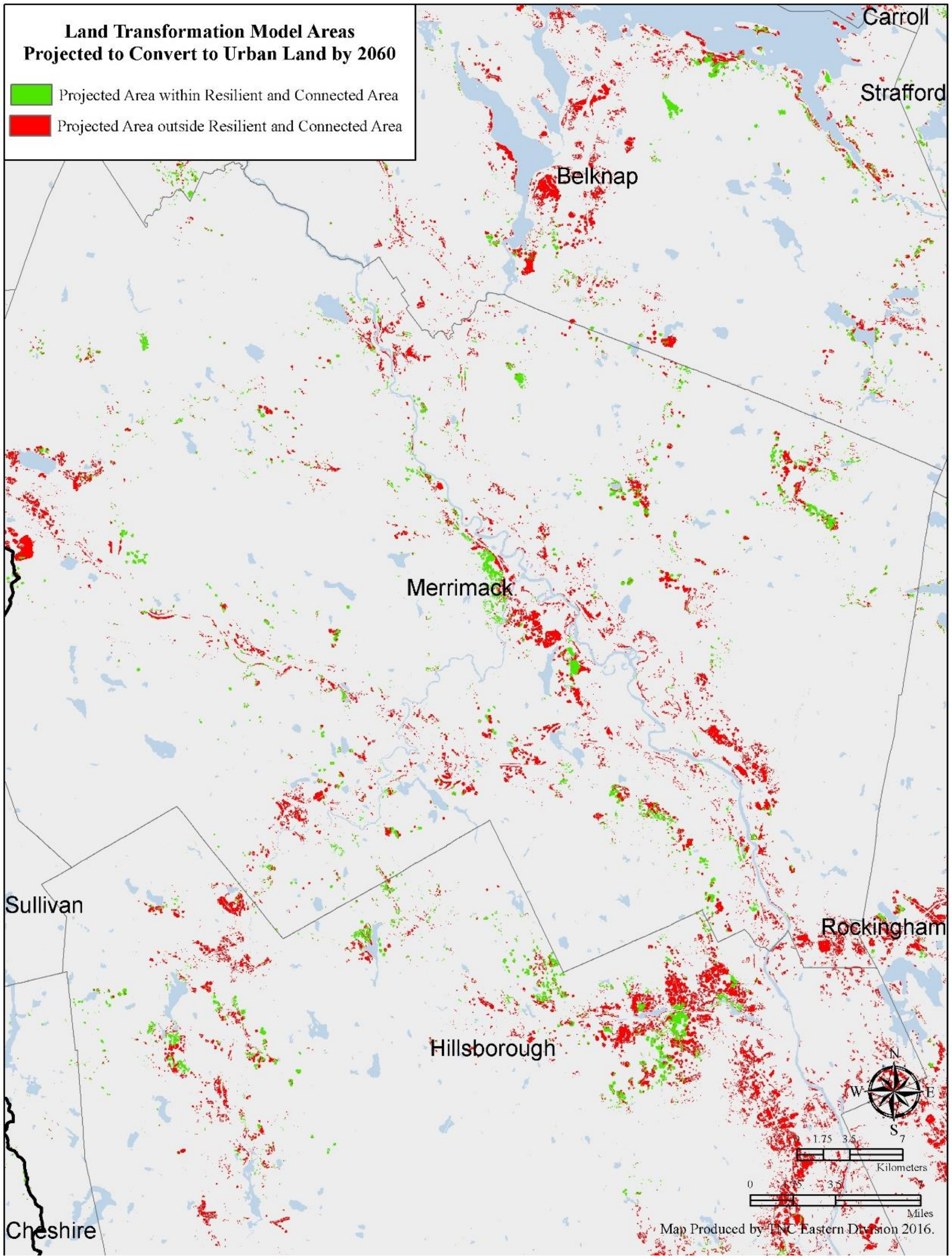


Figure 6.14. West Virginia example: Land Transformation Model Future 2060 urban land projections by their correspondence within or outside the prioritized network.

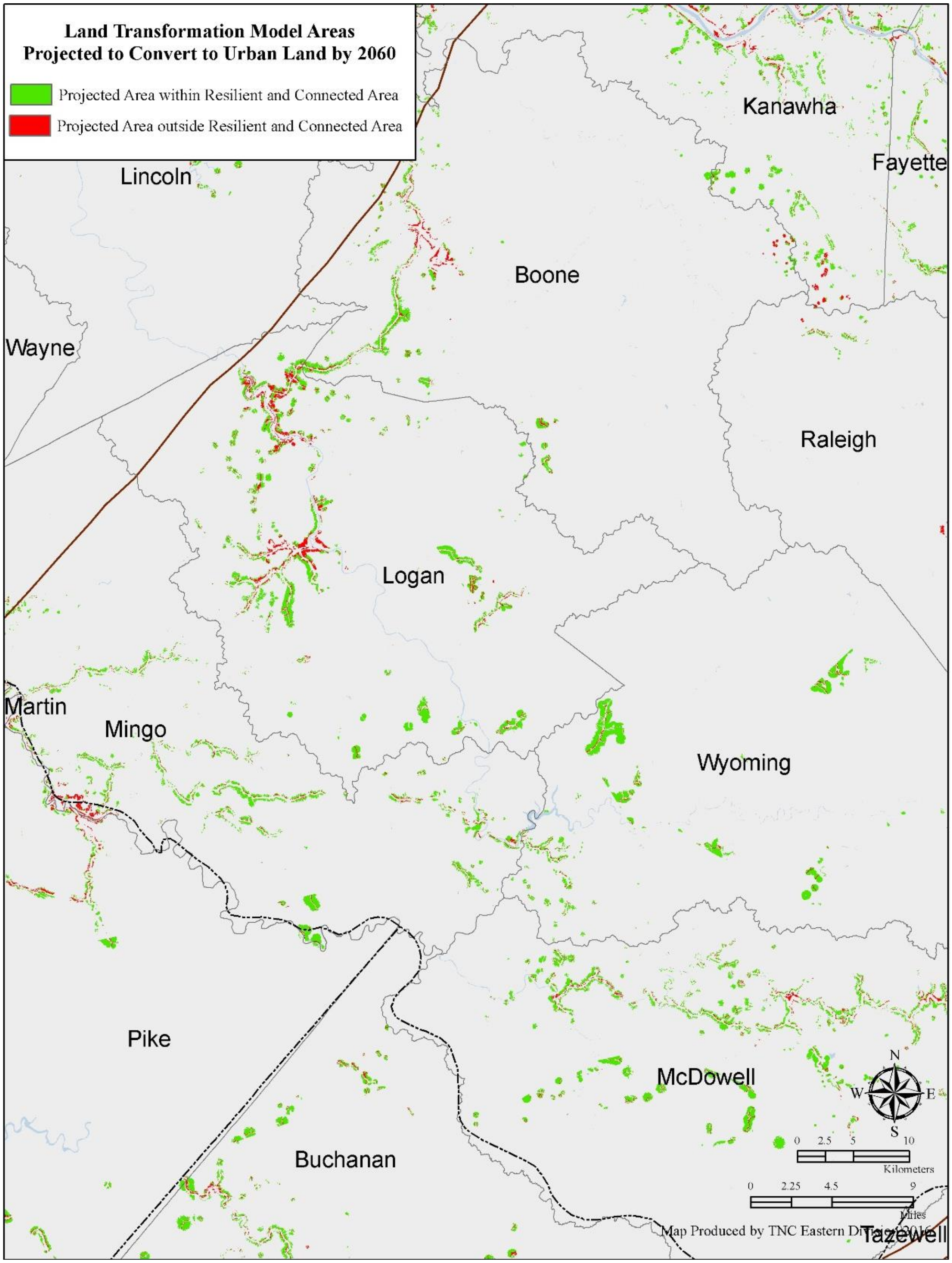
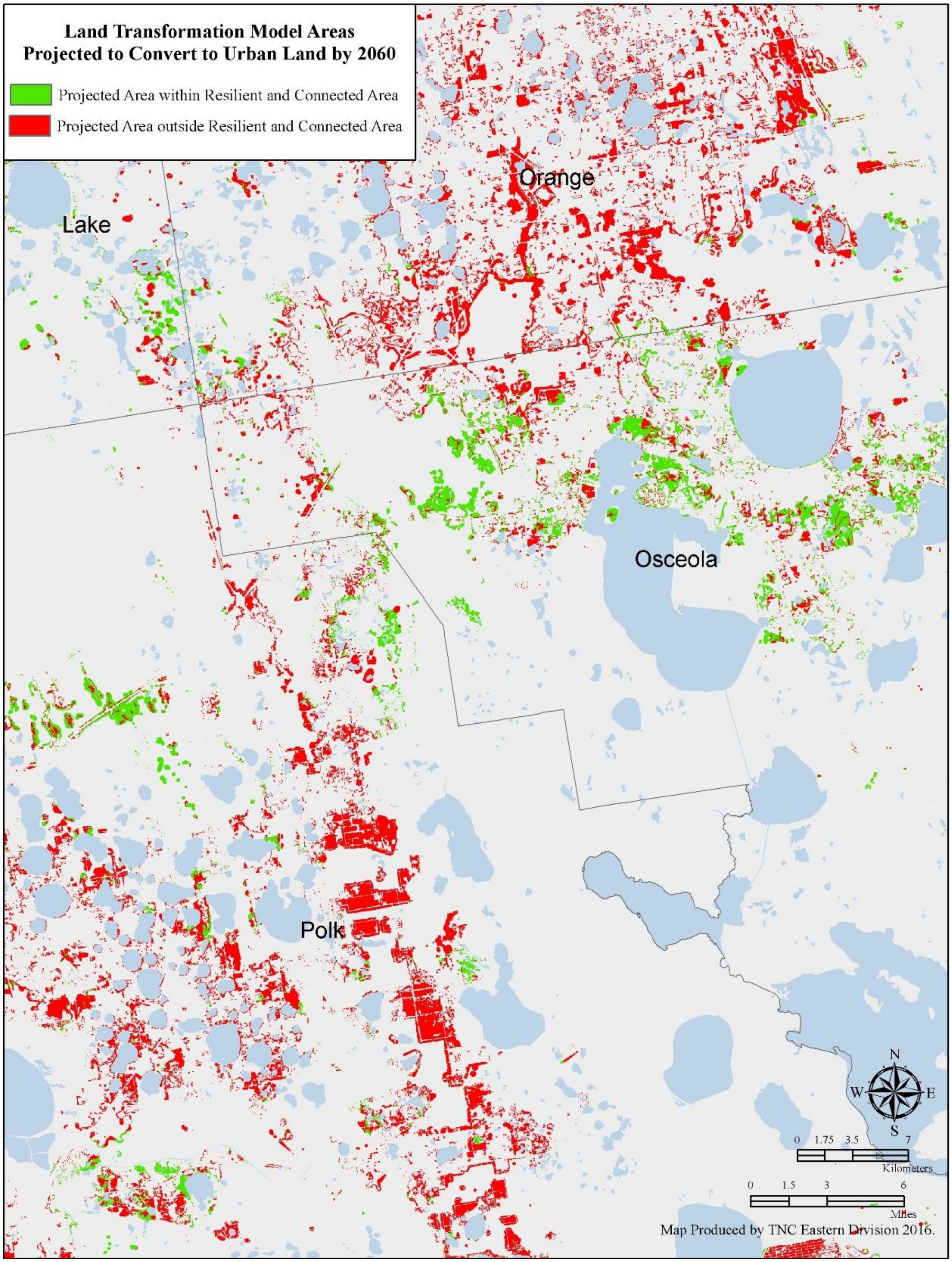


Figure 6.15. Florida example: Land Transformation Model Future 2060 urban land projections by their correspondence within or outside the prioritized network.



9. Identifying Vulnerable Species

Rare species are often the target of conservation efforts and over the last decade many of them have been assessed for their vulnerability to climate change based on their life history characteristics (Young et al. 2015). By definition, these species have very small and isolated populations and we wanted to explore what their locations and habitats revealed about their climate vulnerability. For example, a population in a highly fragmented and flat landscape may find little climate relief in their local neighborhood and will likely need to move some distance through a landscape of high resistance, whereas a population in a resilient topographically complex and highly connected landscape may be able to persist indefinitely by taking advantage of local microclimates that provide suitable habitat. Previous examination of TNC's biodiversity portfolios suggested the Coastal Plain was relatively vulnerable (Figure 6.16).

To measure a species climate-vulnerability based on landscape properties, we overlaid the known locations of 2861 G1-G4 species on the terrestrial resilience dataset. For each species, we calculated the percent of the known locations that were found in each of the seven statistical categories of the resilience data (Table 6.10). At least 427 species were found to have 75% or more of their known locations in low- scoring sites (average or below). These included a wide variety of Coastal Plain species and coastal breeding birds (Table 6.11). The full table is included in this report.

Table 6.10. Rare amphibians with 75% or more of their known locations in vulnerable sites.

Common Name	Rank	Total EO	3SD -	2SD -	1SD -	0.5SD -	Mean	0.5SD +	1SD +	2SD +	3SD +	% in A or V
Gulf Coast Waterdog	G4	9				0.67	0.33					1.00
Reticulated Flatwoods Salamander	G2	8				0.50	0.50					1.00
Southern Appalachian Salamander	G3	4					1.00					1.00
Mabee's Salamander	G4	35		0.04	0.08	0.58	0.25		0.04			0.96
Striped Newt	G2	40			0.19	0.61	0.08	0.03	0.08			0.89
Carpenter Frog	G4	40				0.44	0.43	0.05	0.05	0.03		0.87
Carolina Gopher Frog	G3	123		0.01	0.09	0.52	0.21	0.02	0.14	0.01		0.83
Flatwoods Salamander	G2	64			0.12	0.62	0.10	0.08	0.10			0.83
One-toed Amphiuma	G3	5			0.25	0.50			0.25			0.75

Table 6.11. Count of rare species (G1-G4) with 75% or more of their locations in vulnerable sites. Table is based on species with at least three occurrences, excluding fish, mussels, and crayfish.

TAXA	G1	G2	G3	G4	T2	T3	T4	TOTAL
Invertebrate	21	33	27	4				85
Nonvascular plant	1	1	8	1				11
Vascular plant	23	42	60	74	3	7	4	213
Vertebrate	10	11	33	17	1	3	2	77
Amphibian		3	3	3	1			10
Bird			6	5		1	1	13
Mammal	1		3					4
Reptile		1	8	2		2	1	14
Grand Total	56	91	148	106	5	13	8	427

Figure 6.16. The Nature Conservancy's portfolio of sites for the conservation of biodiversity compared with sites that scored above average for resilience.

REFERENCES

Ackerly, D. D., S. R. Loarie, W. K. Cornwall, S. B. Weiss, H. Hamilton, R. Branciforte, and N. J. B. Kraft. 2010. The geography of climate change: implications for conservation biogeography. Diversity and Distributions 16:476–487.

Anco, C. 2011. *Habitat suitability and reintroduction potential for Puma concolour in the state of Georgia.* (Master's Thesis). Duke University, Durham, North Carolina.

Anderson, M.G., A. Barnett, M. Clark, C. Ferree, and A. Olivero Sheldon, J. Prince. 2016a. Resilient Sites for Terrestrial Conservation in the Eastern North America Division. The Nature Conservancy, Eastern Conservation Science. 127 pp.

Anderson, M.G., A. Barnett, M. Clark, C. Ferree, A. Olivero Sheldon, and J. Prince. 2014. Resilient Sites for Terrestrial Conservation in the Southeast Region. The Nature Conservancy, Eastern Conservation Science. 127 pp

Anderson, M. G., and C. Ferree. 2010. Conserving the stage: climate change and the geophysical underpinnings of species diversity. PLoS ONE 5(7):E11554. DOI:10.1371/journal.pone.0011554

Anderson, M.G., Clark, M., and Sheldon, A. O. 2014. Estimating climate resilience for conservation across geophysical settings. *Conservation Biology*, *28*(4), 959-970.

Anderson, M.G. 1999. Viability and Spatial Assessment of Ecological Communities in the Northern Appalachian Ecoregion. PhD dissertation. Univ. of New Hampshire. 224 pp.

Anderson, M.G., Clark, M. and A. Olivero Sheldon. 2012. Resilient Sites for Terrestrial Conservation in the Northeast and Mid-Atlantic Region. The Nature Conservancy, Eastern Conservation Science. 168pp

Beier, P., and B. Brost. 2010. Use of land facets to plan for climate change: conserving the arenas, not the actors. Conservation Biology 24:701–710.

Beier, P., Spencer, W., Baldwin, R. F., & McRae, B.H. 2011. Toward best practices for developing regional connectivity maps. *Conservation Biology*, *25*(5), 879-892.

Beier, P., Spencer, W., Baldwin, R.F., and McRae, B.H. 2011. Towards best practices for developing regional connectivity maps. Conservation Biology. (get cite).

Botkin, D. B., Saxe, H., Araujo, M. B., Betts, R., Bradshaw, R. H., Cedhagen, T., and Stockwell, D. R. 2007). Forecasting the effects of global warming on biodiversity. *Bioscience*, *57*(3), 227-236.

Breckheimer, I. 2012. *Mapping habitat quality in conservation's neglected geography*. (Master's Thesis). University of North Carolina, Chapel Hill, North Carolina.

Brown, Cheeseman, Garrett, Dunham, Bryant. 2009. Adirondack-Tug Hill Connectivity Project Planning Phase Final Report, TNC Adirondacks. Novermber 30, 2009.

Carroll, C., Dunk, J. R., & Moilanen, A. 2010. Optimizing resiliency of reserve networks to climate change: multispecies conservation planning in the Pacific Northwest, USA. *Global Change Biology*, *16*(3), 891-904.

Chen, I. C., Hill, J. K., Ohlemüller, R., Roy, D. B., & Thomas, C. D. 2011. Rapid range shifts of species associated with high levels of climate warming. *Science*, *333*(6045), 1024-1026.

Colwell, R.R., Brehm, G., Cardelús, C.L., Gilman, A.C., Longino, J.T. 2008. Global Warming, Elevational Range Shifts, and Lowland Biotic Attrition in the Wet Tropics. *Science* 322, 258-261.

Cook, K.L. 2007. *Space use and predictive habitat models for American Black Bears (Ursus Americanus) in Central Georgia, USA.* (Master's Thesis). University of Georiga, Athens, Georgia.

Corlett, R.T. and Westcott, D.A. 2015. Will plant movements keep up with climate change? Trends in Ecology & Evolution (in press)

Davis, M. B., & Shaw, R. G. 2001. Range shifts and adaptive responses to Quaternary climate change. *Science*, *292*(5517), 673-679.

Dixon, J.D. 2004. *Conservation genetics of the Florida black bear*. (Master's Thesis). University of Florida, Gainesville, Florida.

Dobrowski, S. Z. 2010. A climatic basis for microrefugia: the influence of terrain on climate. Global Change Biology DOI:10.1111/j.1365-2486.2010.02263x

Duke Energy 2014. Transmission Rights of Way. http://www.duke-energy.com/safety/right-of-way-management/transmission.asp

Dunscomb JK, Evans JS, Strager JM, Strager MP, Kiesecker JM. 2014. Assessing Future Energy Development across the Appalachian Landscape Conservation Cooperative. Charlottesville (VA): The Nature Conservancy. 48 pp with appendices. Appalachian Landscape Conservation Cooperative Grant #2012-02.

Eastern Conservation Science. 2009. Active River Area Riparian Component Model Using 30m DEM. http://easterndivision.s3.amazonaws.com/Freshwater/Full%20Region%20Final%20Data,ARA_RIP_ALL_090810.zip

Faith, D. P., and P. A. Walker. 1996. Environmental diversity: on the best-possible use of surrogate data for assessing the relative biodiversity of sets of areas. Biodiversity and Conservation 5:399–415

Fischer, J., & Lindenmayer, D. B. 2007. Landscape modification and habitat fragmentation: a synthesis. *Global Ecology and Biogeography*, *16*(3), 265-280.

Fisette, T., Davidson, A., Daneshfar, B., Rollin, P., Aly, Z., Campbell, L. 2014. Annual space-based crop inventory for Canada: 2009–2014. Geoscience and Remote Sensing Symposium (IGARSS), 2014 IEEE International, Issue Date: 13-18 July 2014. http://open.canada.ca/data/en/dataset/ba2645d5-4458-414d-b196-6303ac06c1c9

Groves, C. 2003. Drafting a conservation blueprint: a practitioners guide to planning for biodiversity. Island Press, Washington, D.C.

Gruber, J. 2009. *Targeting potential conservation sites for swallow-tailed kites (Elanoides forficatus) in Levy County, Florida.* (Master's Thesis). Duke University, Durham, North Carolina.

Gunderson, L. H. 2000. Ecological resilience–in theory and application. Annual Review of Ecology and Systematics 31:425–439.

Guthrie, J.M. 2012. *Modeling movement behavior and road crossing in the black bear of south central Florida.* (Master's Thesis). University of Kentucky, Lexington, Kentucky.

Hannah, L. 2011. Climate change, connectivity, and conservation success. Conservation Biology 25:1139–1142.

Hansen, J., Ruedy, R., Sato, M., & Lo, K. 2010. Global surface temperature change. Reviews of Geophysics, 48(4).

Hawk, R., Miller, C., Reining, C., and Gratton, L. 2012. *Staying Connected in the Northern Green Mountains: Identifying Structural Pathways and other Areas of High Conservation Priority.* *http://216.92.98.160/assets/ngm_structural_pathways_and_parcels_29oct12_final.pdf*

Heller, N. E., & Zavaleta, E. S. 2009. Biodiversity management in the face of climate change: a review of 22 years of recommendations. *Biological conservation*, *142*(1), 14-32.

Hilty, J. A., & Merenlender, A. M. 2004. Use of riparian corridors and vineyards by mammalian predators in northern California. *Conservation Biology*, *18*(1), 126-135.

Hoctor,T, M. Volk, and M. Spontak. 2013. Updating the Florida Ecological Greenways Network. Final Report, Florida Fish and Wildlife Conservation Commission, Tallahassee, FL.

Hodgson, J.A., Thomas, C.D., Wintle, B.A. & Moilanen, A. 2009. Climate change, connectivity and conservation decision making: back to basics. Journal of Applied Ecology 2009, 46, 964–969 doi: 10.1111/j.1365-2664.2009.01695.x

Hunter, M. L., G. L. Jacobson, and T.Webb. 1988. Paleoecology and the coarse-filter approach to maintaining biological diversity. Conservation Biology 2:375–385.

Jin, S., Yang, L., Danielson, P., Homer, C., Fry, J., & Xian, G. 2013. A comprehensive change detection method for updating the National Land Cover Database to circa 2011. *Remote Sensing of Environment*, *132*, 159-175.

Johnson N. 2010. Pennsylvania Energy Impacts Assessment. Report 1: Marcellus Shale Natural Gas and Wind. The Nature Conservancy, Western Pennsylvania Conservancy and Audubon Pennsylvania. Harrisburg (PA): The Nature Conservancy. [Cited 2013 January 12]. Available from http://www.nature.org/ourinitiatives/regions/northamerica/unitedstates/pennsylvania/pa-energyexecutive-summary.pdf

Jones, E.R. 2008. *The effectiveness of wildlife crossing structures for black bears in Madison county, North Carolina.* (Master's Thesis). North Carolina State University, Raleigh, North Carolina.

Kellndorfer, J., Walker, W., LaPoint, E., Bishop, J., Cormier, T., Fiske, G., Hoppus, M., Kirsch, K., and Westfall, J. 2012. NACP Aboveground Biomass and Carbon Baseline Data (NBCD 2000), USA., 2000. Data set. Available on-line athttp://daac.ornl.gov from ORNL DAAC, Oak Ridge, Tennessee, USA. http://dx.doi.org/10.3334/ORNLDAAC/1081.

Kindall, J.L. and van Manen, FT. 2007. Identifying Habitat Linkages for American Black Bears in North Carolina, USA. *Journal of Wildlife Management*, 71(2):487-495.

Koen, E. L., Bowman, J., Sadowski, C., & Walpole, A. A. 2014. Landscape connectivity for wildlife: development and validation of multispecies linkage maps. *Methods in Ecology and Evolution*, *5*(7), 626-633.

Koen, E. L., Garroway, C. J., Wilson, P. J., & Bowman, J. 2010. The effect of map boundary on estimates of landscape resistance to animal movement. *PLoS One*, *5*(7), e11785.

Krosby, M, Breckheimer, I, Pierce, D.J, et al. 2015. Focal species and landscape "naturalness" corridor models offer complementary approaches for connectivity conservation planning. *Landscape Ecology* 30 (10): 2121-2132.

Krosby, M., J. Tewksbury, N. M. Haddad, and J. Hoekstra. 2010. Ecological connectivity for a changing climate. Conservation Biology 24(6):1686–1689.Hunter et al. 1988, Krosby, M., Norheim, R., Theobald, D. M., and B. H. McRae. 2014. Riparian climate-corridors: Identifying priority areas for conservation in a changing climate. Technical Report. Available at http://nplcc.databasin.org/datasets/46caec8762194138a8a6421322ea170d.

Krosby, M., Tewksbury, J., Haddad, N. M., & Hoekstra, J. 2010. Ecological connectivity for a changing climate. *Conservation Biology*, *24*(6), 1686-1689.

Lawler J.J, Ackerly, D.D., Albano, C.M., Anderson, M.G., Dobrowski, S.Z., Gill, J.L., Heller, N.E., Pressey, R.L., Sanderson, E.W., Weiss, S. B. 2015. The theory behind, and challenges of, conserving nature's stage in a time of rapid change. Conservation Biology 29:618–629

Lenoir, J., Gégout, J. C., Guisan, A., Vittoz, P., Wohlgemuth, T., Zimmermann, N. E.,& Svenning, J. C. 2010. Going against the flow: potential mechanisms for unexpected downslope range shifts in a warming climate. *Ecography*, *33*(2), 295-303.

Lenoir, J., Gégout, J. C., Marquet, P. A., De Ruffray, P., & Brisse, H. 2008. A significant upward shift in plant species optimum elevation during the 20th century. *Science*, *320*(5884), 1768-1771.

Lindenmayor, D. and Fischer, J. 2006. Habitat fragmentation and Landscape change. Island Press. 352 pp

Loarie, S. R., P. B. Duffy, H. Hamilton, G. P. Asner, C. B. Field, and D. D. Ackerly. 2009. The velocity of climate change. Nature 462:1052– 1055.

Luoto, M., and R. K. Heikkinen. 2008. Disregarding topographical heterogeneity biases species turnover assessments based on bioclimatic models. Global Change Biology 14(3):483–494.

Manci, Karen M. 1989. Riparian ecosystem creation and restoration: A literature summary. US Fish and Wildlife Service Biological Report 89(20):1-59.

Marangelo, P. 2013. Development of Spatial Priorities for Habitat Connectivity Conservation Between the Green Mountains and Adirondacks. The Nature Conservancy, Vermont Chapter.

McGuire, J.L., Lawler, J.J., McRae, B.H., Nuñez T.A. and D. M. Theobald. 2016. Achieving climate connectivity in a fragmented landscape. Proceedings of the National Academy of Science www.pnas.org/cgi/doi/10.1073/pnas.1602817113

McRae, B. H., & Beier, P. 2007. Circuit theory predicts gene flow in plant and animal populations. *Proceedings of the National Academy of Sciences*, *104*(50), 19885-19890.

McRae, B. H., & Shah, V. B. 2009. Circuitscape user guide. *ONLINE. The University of California, Santa Barbara. Available at: http://www. circuitscape.org*.

McRae, B. H., Dickson, B. G., Keitt, T. H., & Shah, V. B. 2008. Using circuit theory to model connectivity in ecology, evolution, and conservation. *Ecology*, *89*(10), 2712-2724.

McRae, B.H., V.B. Shah, and T.K. Mohapatra. 2013. Circuitscape 4 User Guide. The Nature Conservancy. http://www.circuitscape.org.

Meehl, G.A., T.F. Stocker, W.D. Collins, P. Friedlingstein, A.T. Gaye, J.M. Gregory, A. Kitoh, R. Knutti, J.M. Murphy, A. Noda, S.C.B. Raper, I.G. Watterson, A.J. Weaver and Z.-C. Zhao. 2007. Global Climate Projections. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Meiklejohn, K., Ament, R. and Tabor, G. 2010. Habitat Corridors & Landscape Connectivity: Clarifying the Terminology. Center For Large Landscape Conservation. www.climateconservation.org.

Naiman, R. J., Decamps, H., & Pollock, M. 1993. The role of riparian corridors in maintaining regional biodiversity. *Ecological applications*, *3*(2), 209-212.

Northrup JM, Wittemyer G. 2013. Characterizing the impacts of emerging energy development on wildlife, with an eye towards mitigation. Ecology Letters. 6: 112–125.

Noseworthy, J. 2014. *Prioritizing Private Land for Wildlife Connectivity across the Chignecto Isthmus, New Brunswick.* The Nature Conservancy of Canada.

National Research Countil (NRC). 2010. Advancing the Science of Climate Change. National Research Council. The National Academies Press, Washington, DC, USA.

Nuñez, T. A., Lawler, J. J., McRae, B. H., Pierce, D., Krosby, M. B., Kavanagh, D. M., and Tewksbury, J. J. 2013. Connectivity planning to address climate change. *Conservation Biology*, *27*(2), 407-416.

Olivero, A, and M.G. Anderson. 2008. The Northeast Aquatic Habitat Classification. The Nature Conservancy, Eastern Conservation Science. 90 pp. http://www.rcngrants.org/spatialData

Olson, D. H., Anderson, P. D., Frissell, C. A., Welsh, H. H., & Bradford, D. F. 2007. Biodiversity management approaches for stream–riparian areas: perspectives for Pacific Northwest headwater forests, microclimates, and amphibians. *Forest Ecology and management*, *246*(1), 81-107.

Open Street Map 2014. Open Street map. http://www.openstreetmap.org

Pachauri, R. K., and A. Reisinger. 2007. Contribution of WorkingGroups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Core Writing Team, R. K. Pachauri,and A. Reisinger, editors. IPCC, Geneva, Switzerland.

Pardi, M.I. and Smith, F.A. 2012 Paleoecology in an era of climate change: how the past can provide insights into the future. In Paleontology in Ecology and Conservation (Louys, J., ed.), pp. 93–115, Springer-Verlag

Parmesan, C., & Yohe, G. 2003. A globally coherent fingerprint of climate change impacts across natural systems. *Nature*, *421*(6918), 37-42.

Pelletier, D., Clark, M., Anderson, M. G., Rayfield, B., Wulder, M. A., & Cardille, J. A. 2014. Applying circuit theory for corridor expansion and management at regional scales: tiling, pinch points, and omnidirectional connectivity. *PloS one*, *9*(1), e84135.

Pressey, R. L., M. Cabeza, M. E. Watts, R. M. Cowling, and K. A. Wilson.2007. Conservation planning in a changing world. TRENDS in Ecology and Evolution 22(11):583–592.

PRISM Climate Group. 2013. Oregon State University, http://prism.oregonstate.edu.

Pusey, B. J., & Arthington, A. H. 2003. Importance of the riparian zone to the conservation and management of freshwater fish: a review. *Marine and Freshwater Research*, *54*(1), 1-16.

Randin, C. F., R. Engler, S. Normand, M. Zappa, N. Zimmermann, P.B. Pearman, P. Vittoz, W. Thuiller, and A. Guisani. 2008. Climate change and plant distribution: local models predict high-elevation persistence. Global Change Biology 15(6):1557–1569.

Richardson, J.R., Burns, N., and Polinsky, R. 2013. National Ecological Framework Guide. Methods: Carr, M.H., T. D. Hoctor, C. Goodison, P.D. Zwick, J, Green, P. Hernandez, C. McCain, J. Teisinger, K. Whitney. 2002. Final Report: Southeastern Ecological Framework. The GeoPlan Center, Department of Landscape Architecture, Department of Urban and Regional Planning, Department of Wildlife Ecology and Conservation, University of Florida, Gainesville, Florida. 306 pps. http://geoplatform1.epa.gov/nef/docs/NEF_Guide.pdf

Robidoux, C. 2010 - Identification et validation préliminaire des corridors naturels du territoire de Corridor Appalachien – 2009-2010. Phase I. ACA - Corridor Appalachien. *Report is in French.*

Rodrigues, A. S. L., and T. M. Brooks. 2007. Shortcuts for biodiversity conservation planning: the effectiveness of surrogates. Annual Review of Ecology, Evolution, and Systematics 38:713–737.

Rozell D, Reaven S. 2012. Water pollution risk associated with natural gas extraction from the Marcellus Shale. Risk Analysis. 32: 1382–1393.

Schloss, C. A., J. J. Lawler, E. R. Larsron, H. L. Paperndick, M. J. Case, D. M. Evanse, J. H. DeLap, J. G. R. Landgon, S. A. Hall, and B.H. McRae. 2011. Systematic conservation planning in the face of climate change: bet-hedging on the Columbia Plateau. PLoS One 6 DOI: 10.1371/journal.pone.0028788

Seavy, N. E., Gardali, T., Golet, G. H., Griggs, F. T., Howell, C. A., Kelsey, R., and Weigand, J. F. (2009). Why climate change makes riparian restoration more important than ever: recommendations for practice and research. *Ecological Restoration*, *27*(3), 330-338.

Shaffer, J. 2007. *Analyzing a prospective red wolf (Canis rufus) reintroduction site for suitable habitat*. (Master's Thesis). Duke University, Durham, North Carolina.

Shah, B.V. and McRae, B. 2008. Circuitscape: a tool for landscape ecology. In proceeding of the 7th Python in Science Conference.

Simon, M.C. 2009. *Evaluating conservation assessments in the Sandhills of North Carolina*. (Master's Thesis). University of North Carolina, Chapel Hill, North Carolina.

Smith, M. P., Schiff, R., Olivero, A., and MacBroom, J. G. 2008. The active river area: A conservation framework for protecting rivers and streams. The Nature Conservancy, Boston, MA. 59p.

Steckler, P. and Bechtel, D., 2013. Staying Connected in the Northern Appalachians, Northeast Kingdom to Northern New Hampshire Linkage: Implementation Plan to Maintain and Enhance Landscape Connectivity for Wildlife. New Hampshire Chapter of The Nature Conservancy. Concord, NH.

Sutherland, R.W., Leonard, P., Carnes, R., Fedak, D., and Baldwin, R. Terrestrial habitat connectivity models for the South Atlantic Landscape Conservation Cooperative. 2014. Wildlands Network.

Tayyebi, Amin, Burak K. Pekin, Bryan C. Pijanowski, James D. Plourde, Jarrod S. Doucette, and David Braun. 2012. Hierarchical modeling of urban growth across the conterminous USA: developing meso-scale quantity drivers for the Land Transformation Model, Journal of Land Use Science.

Tele Atlas North America, Inc. 2009. US and Canada Railroads. 1:100,000. ESRI® Data & Maps: StreetMap. 2009 Data Update: North America. Redlands, California, USA. US and Canada Railroads represent the railroads of the United States and Canada.

Thatcher, C.A., van Manen, F.T., and Clark, J.D. 2009. A habitat assessment for Florida Panther population expansion into Central Florida. *Journal of Mammalogy* 90(4):918-925.

Trainor, A.M. 2011. *DISPERSAL behavior and connectivity of red-cockaded woodpeckers in the North Carolina sandhills.* (Doctoral dissertation). University of North Carolina, Chapel Hill, North Carolina.

US Census Bureau (2014). 2014 TIGER/Line Shapefiles (machine-readable data files). http://www.census.gov/geo/maps-data/data/tiger.html

Ventyx Corporation (2014) Velocity Suite: Transmission lines constrained or congested, transmission lines (In service by voltage class), and Natural Gas Pipelines (In service). http://www.ventyx. Accessed October 2014. com/en/enterprise/business-operations/business-products/velocitysuite.

Vermont Fish & Wildlife Department. 2009. VERMONT NATURAL COMMUNITY SURVEY FORM, Nongame and Natural Heritage Program. http://fpr.vermont.gov/sites/fpr/files/Forest_and_Forestry/Your_Woods/Library/VTNNHP%20NatComm%20PC%20form.pdf

Wang, T., Hamann, A., Spittlehouse, D. L., & Aitken, S. N. 2006. Development of scale-free climate data for Western Canada for use in resource management. *International Journal of Climatology*, *26*(3), 383-397.

Wang, T., Hamann, A., Spittlehouse, D. L., & Murdock, T. Q. 2012. ClimateWNA-high-resolution spatial climate data for western North America. *Journal of Applied Meteorology and Climatology*, *51*(1), 16-29.

Weidner, E. and Todd, A. 2011. From the Forest to the Faucet: Drinking Water and Forests in the US. - Methods Paper. USDA Forest Service. 34p. http://www.fs.fed.us/ecosystemservices/FS_Efforts/forests2faucets.shtml

Weiss, S. B., D. D. Murphy, and R. R. White. 1988. Sun, slope, and butterflies: topographic determinants of habitat quality for *Euphydryas editha bayensis*. Ecology 69:1486–1496.

Willis, K. J., and S. A. Bhagwat. 2009. Biodiversity and climate change. Science 326:806–807.

Young BE, Byers E, Hammerson G, Frances A, Oliver L, and Treher A. 2015. Guidelines for using the NatureServe Climate Change Vulnerability Index Release 3.0. Arlington, VA: NatureServe.