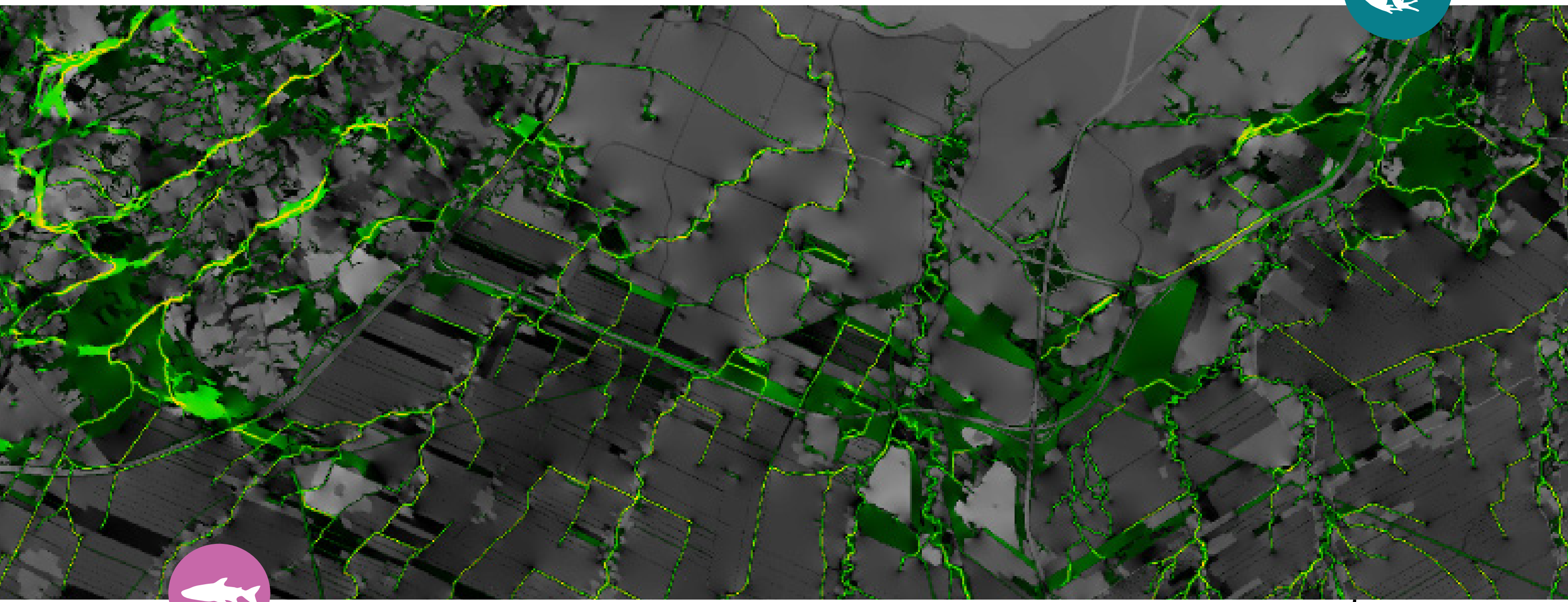
A review of ecological connectivity science in the Region of Resolution 40-3

An Assessment of the Science and Projects Describing the Ecologically Connected Landscape of the Northeast Region of North America



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1 Summary

This report reviews the science of connectivity and the ensemble of plans and projects focused on evaluating and protecting the ecological connectivity of the region addressed by the Resolution 40-3 (referred to as the Region). These projects are now inventoried on the Ecological Connectivity web portal (**https://ecologicalconnectivity.com**). We compare the objectives and geographic scope of these projects, while contrasting the scientific methods and measures used to define the networks of habitat and corridors they identify. We compare these methods to current approaches in the connectivity science literature and identify opportunities for integrating information and conservation goals across plans. To aid interpretation, we provide a brief review of key concepts in connectivity research. Through comparison of the methodologies, scales, and coverage of these projects, we identify current gaps in analyses but also the opportunities for harnessing connectivity science for conservation in the Region.

Main findings

The Region retains large areas of contiguous habitat vital to the persistence and resilience of the Region's biodiversity and ecosystems. However, land use change and climate change threaten the ecological connectivity and integrity of these natural spaces. Spurred by these observations, many organizations and research groups have generated a rich body of research and projects that have delivered state-of-the-art assessments for connectivity planning. A number of past and ongoing initiatives in the Region have achieved a comprehensive and scientifically thorough evaluation of terrestrial and, to a lesser extent, aquatic connectivity.

While most projects agree on the large core natural areas and connectors to protect within the Region, we identified several gaps centered around methodology, ecosystem coverage and regional coverage. Only a few projects have covered a large fraction of the Region and large areas remain under-represented especially at fine spatial scales. Further, an integration of structural and functional connectivity is needed if we are to account for near and long term changes in species distributions and ecosystem processes. Finally, there are clear methodological opportunities to improve assessments and connectivity planning: among them we cite the adoption of scenario planning for future climate and land use impacts on the Region's connectivity, spatial biodiversity modeling to anticipate range shifts and assemblage turnover, and the initiation of adaptive monitoring of functional connectivity and biodiversity to validate current network models and plans.

Conclusions

Our review of the literature associated with the Region's connectivity conservation plans led us to four conclusions and a set of five related recommendations. Increasing threats to connectivity will require the establishment of a connectivity monitoring network to support adaptive management of the landscape as well as scenario-based planning which incorporates uncertainties relating to climate change and land use change in the future (rec 4 & 5). This connectivity monitoring network, built off of existing initiatives, should include regular assessments to evaluate the changing state of connectivity at the scale of the Region (Rec 1). We also found a large percentage of areas identified as priorities for connectivity conservation are not protected and many of these areas cover multiple states and provinces creating challenges for collaborative action. However, through the support of Resolution 40-3, there is an opportunity to foster the open sharing of methods and data for collaboration at the scale of the Region (Rec 2). This collaboration should lead to an integration of analytical methods and a multi-scale approach throughout the Region supporting the establishment of an ecological network for conservation across jurisdictions and scales (Rec 3).

2

Context

2.1 Resolution 40-3

At the 40th Conference of New England Governors and Eastern Canadian Premiers held on August 28 and 29, 2016, the Governors and Premiers adopted Resolution 40-3, titled **"Resolution on ecological connectivity, adaptation to climate change, and biodiversity conservation"**. The states and provinces in the NEG/ECP region include Quebec, New Brunswick, Prince Edward Island, Nova Scotia, Newfoundland and Labrador, Maine, Vermont, New Hampshire, Massachusetts, Rhode Island, and Connecticut. The ensemble of these states and provinces we will hereafter call "the Region" (Figure 1).

▲ **Figure 1.** Region of Resolution 40-3 shown by the blue shading.

This resolution highlights, among other things, the "importance of ecological connectivity for the adaptability and resilience of our region's ecosystems, biodiversity, and human communities in the face of climate change", "the need to work across landscapes and borders to advance efforts to restore and maintain ecological connectivity", and the need for "agencies within their jurisdictions to elevate ecological connectivity, conservation, and restoration in their activities. These agencies are further instructed to encourage regional collaboration, as appropriate, in order to identify priority connectivity zones that connect and expand existing protected areas and to mobilize and apply resources most effectively."

The call for action that arose from this resolution highlighted the need 1) for coordination among agencies, governments and land managers, 2) for the consolidation of information and data from projects on connectivity in the Region, and 3) for the evaluation of practices and methodologies used in connectivity assessments within the Region.

In this report, we first give an overview of the Region and the threats to biodiversity, we summarize key concepts in connectivity science. Further, we evaluate the science of connectivity assessments conducted in the Region. We also review conservation projects currently active in the Region, with a particular emphasis on major projects that cover large areas or cross borders. We finish by identifying opportunities for connectivity science in the Region and offer some recommendations for future actions.

2.2 Biodiversity change and the link to ecological connectivity

We are not winning the battle to protect the planet's biological diversity. Despite public support for biodiversity conservation, pervasive impacts of humans on nature mean that over 1 million species now face extinction, with declines in species abundances occurring in almost every known habitat (IPBES 2019, WWF 2018). Habitat transformations caused by human land-use change are considered major contributors to biodiversity loss and will likely remain so over the coming century (Marques et al. 2019, Powers and Jetz 2019). Ongoing climate change this century will also contribute to biodiversity loss as species experience climate extremes and their niches shift geographically over time (Urban 2015, Urban et al. 2016, Lovejoy and Wilson 2019). In order to keep pace with their habitat needs and climate preferences, species must shift their distribution (Burrows et al. 2011, Scheffers et al. 2016). For example, in Eastern North America, trees are shifting their distribution on average 10 km northward and 11 km westard per decade (Fei et al. 2017). Globally, species distributions across all major taxa groups have shifted an average of 19.7 km north per decade and 36 ft upslope per decade (Chen et al. 2011, Scheffers et al. 2016).

Geographic range shifts will change the composition of ecological communities (Berteaux et al. 2015, Lovejoy and Hannah 2019) which will alter the structure and function of ecosystems from the smallest to the largest spatial scales (Gonzalez et al. 2020). The spatial redistribution of species and ecosystems will also affect the supply of ecosystem services that human society relies upon (Diaz et al. 2020).

The extinction of many species and movement of many others will result in the reorganization of ecological communities this century; this highly dynamic situation creates many challenges for conservation. In the geological past, species appear to have moved to track climatic change resulting in few extinctions (Botkin et al. 2007), but today the landscape is fragmented by roads, powerlines, urban development, industrial agriculture and thousands of other barriers that create resistance to movement (McGuire et al. 2016, Tucker et al. 2018).

Pressed by the severity and scale of the problem of eroding ecological connectivity, conservation science has developed the science and policy support (i.e. a IUCN connectivity conservation specialist group) for implementing spatial ecological networks as an integrated conservation strategy. The science of ecological connectivity assesses the magnitude and scale of these human impacts on the movement of animals and plants, while accounting for their natural patterns of movement and habitat needs. The science indicates that the protection and restoration of ecological connectivity can mitigate some of the effects of anthropogenic landscape change on biodiversity and ecosystems. In the next section we address the status of biodiversity and connectivity in the Region.

2.2.1 Land use and threats to connectivity in the Region

The Resolution states that "the Region's economy, culture, and identity are closely tied to and dependent upon its forests and water resources". Indeed, the Region comprises a complex matrix of natural habitats, areas with intense human pressures, an elaborate network of streams and roads, and a long, intricate, coastline. The Region includes some populated city centers like Boston and Montreal, large extents of suburban areas, some of the largest contiguous areas of forest in the White and Green Mountains and the Appalachians of the U.S. and in the Canadian provinces of Quebec, Newfoundland, New Brunswick, and Nova Scotia. The Region also includes important agricultural land in the valley of the Saint Lawrence River, in the central valley of Nova Scotia, and throughout New England.

Land use change is currently one of the major threats to ecosystems and biodiversity worldwide and in the Region (Theobald 2005, Liu et al. 2020). The Region harbours a large biological diversity and represents an important migratory pathway for many bird and butterfly species. Many species inhabiting the Region are also at the northern limit of their range and are expected to shift their range under climate change (Berteaux and et al. 2015). Land use change and land degradation encompasses pervasive trends such as deforestation, urban sprawl, the expansion of transport infrastructure, and the conversion of wetlands and grasslands into agricultural lands. Furthermore, land use change can exacerbate the effects of other threats including pollutants, invasive species, and emergent pathogens (Trombulak et al. 2008).

The impacts of land use change can be explored in at least two ways that are relevant to the region of Resolution 40-3: the ecological integrity of the land and its interaction with climate change. Although a systematic assessment of land use change in the Region has not yet been produced, it is possible to look at trends in each state and province. For instance, the National Climate Assessment shows that since the 1970s, the northeast of the United States has been showing consistent trends in forest and agricultural land loss (net loss of 300 squares miles of forest 2006-2011), a large increase in developed land (net gain of 200 squares miles) and a rather substantial increase in grassland and shrubland (Reidmiller et al. 2018).

One of the most important drivers of habitat change is the development of transportation networks. For example, in the US, the total length of roads has increased 8% from 1980-2017 (U.S. Department of Transportation 2018). Roads fragment landscapes and trigger human colonization and degradation of ecosystems, to the detriment of biodiversity and ecosystem functions. Recent global projections indicate that roads are expected to increase by >60% globally from 2010 to 2050 (Dulac 2013). Moreover, analysis has shown that much of the world's roadless wilderness is threatened by expansion of the network (Ibisch et al. 2016), and this is true for many parts of the Region. In addition to stimulating human development, roads are major obstacles to animal movements and the associated edge effects result in the loss of interior forest habitat required by many species (Haddad et al. 2015). For example, in Maine, over 2,000 new kilometers of road were built over a 17-year period between 1994 and 2003. This shows that even in long-settled landscapes, like the Northern Appalachians of the U.S. and Canada, road building is an on-going form of land use change (Baldwin et al. 2007, Ibisch et al. 2016). Although research has demonstrated the efficiency of well-designed crossing structures (Jaeger et al. 2019), the price associated with their construction is an obstacle to connectivity conservation.

Land use change for agriculture, urban expansion and transport networks modifies connectivity by dissecting and perforating habitat (Haddad et al. 2015). Probably the most studied effect of these transformations is the increase in the length of habitat edge and the effects of opening edges on biodiversity. These are diverse physical and biotic alterations associated with the artificial boundaries of fragments (Laurance et al. 2007). Those edge effects modify microclimate and habitat quality and can reduce the fitness of small populations and accelerate their extirpation (Ewers and Didham 2007).

A recent study on the impacts of land use change on connectivity in North America (Parks et al. 2020) shows that land use change poses additional risks in the context of climate warming (see next section for further discussion of climate change risks). In Canada, the climate is warming at twice the global rate (Bush and Lemmen 2019). For instance, it is predicted that regions like Saguenay in Quebec will see between 3 and 6 °C of warming by 2100 (Ouranos n.d.). The effects of climate change will be numerous, and include less distinct seasons with milder winters and earlier springs, ocean acidification, coastal erosion and flooding, and more intense precipitation (Reidmiller et al. 2018). These changes will have direct effects on biodiversity in the Region, including the expected geographic shift in species' distributions and ranges as their climate niche requirements move northward.

Of particular importance is the speed at which species' ranges must shift to track their climate requirements. The speed at which these requirements will change over the next century will be a major determinant of biodiversity change in the Region. Much research has been done to estimate and predict climate velocities (Anderson et al. 2016). Connectivity conservation must address the need for contiguous land and river networks that can support the short and long-range movements required for range shifts (Parks et al. 2020).

2.3 Importance of connectivity conservation in the Region

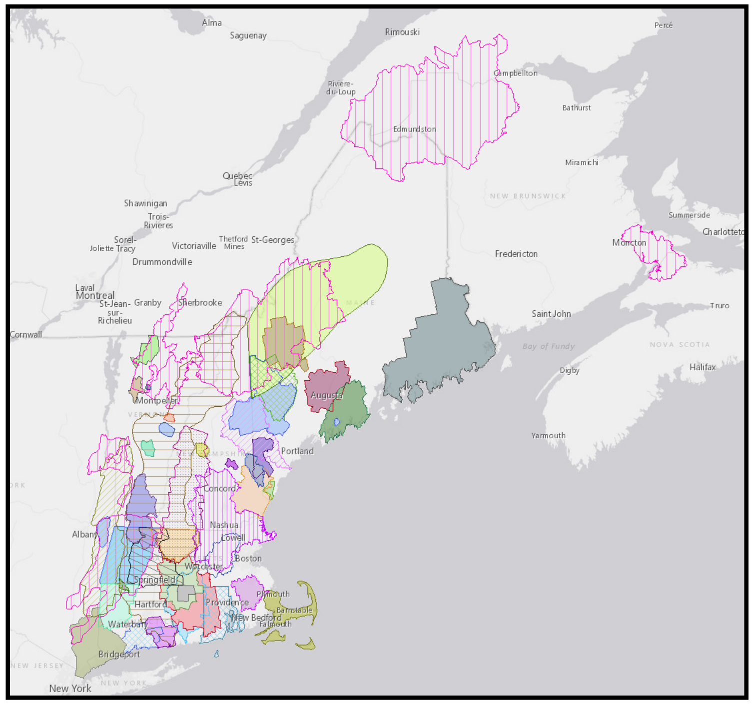
The conservation and restoration of ecological connectivity is an important measure to mitigate the impacts of land use change and climate change on biodiversity and ecosystems. But, connectivity planning is now increasingly seen as a means to support the adaptation of a region's flora and fauna to the impacts of these drivers (Reside et al. 2018). Protecting and restoring connectivity can also address multiple ecological and societal objectives such as the protection of species, ecosystems, geophysical diversity and the ecological processes that support ecosystem services such as climate regulation, natural resource provisioning, and important cultural services in human modified landscapes (Perino et al. 2019).

The geography of the Region, with the Great Lakes to the west and the Atlantic Ocean to the east, forms a large natural corridor for animal migration. The connectivity of the Region will therefore be vital to the persistence and adaptive response of species as they undergo northward range shifts. The resolution acknowledges this key role of the Region: "the Northeastern coastal forest, including the coastal plain, and the Gulf of Saint Lawrence lowland forest provide a vital link for neotropical migrants of global significance. Boreal forests are globally important for millions of resident and migratory species, including songbirds which depend on Boreal forests during different stages of their life cycles."

The diversity in the geophysical, socio-cultural and biological landscapes that covers the Region has stimulated a vibrant and active community focused on connectivity conservation. This diversity makes the implementation of an integrated spatial ecological network across such a wide region challenging. This challenge has long been identified, and analyses have been produced to determine how to best link the Region with other important adjacent ecoregions (Trombulak et al., 2008).

An example of the diversity in connectivity profiles in the region, is the contrast between the Northern Appalachian-Acadian (NAPA) section of the region and the Great Lakes Lowlands section (GLL). The Northern Appalachian-Acadian forest is a globally significant temperate broadleaf forest. The NAPA is still one of the most forested ecoregions in eastern North America, while the GLL, especially the Saint Lawrence lowlands, is largely fragmented and dominated by agriculture, and represents an obstacle at the regional level for linking the south of the region to the more forested areas north of the lowlands in the Laurentian Mountains, and to the rest of Quebec.

Regions that are still forested are also vulnerable because of the large amount of undeveloped land in the vicinity of populated areas. Trombulak et al. (2008) conducted an analysis of vulnerable areas in NAPA and concluded that although they were concentrated in settled landscapes, these could expand given enough social-environmental incentives (changes in climate, location of large industries, etc.). In an attempt to protect those important areas for ecological connectivity, multiple strategies have been put forward and are described in this report, but there remains a lot of uncertainty in deciding which strategies should be applied and where.



▲ **Figure 2.**
Map showing the areas covered by 43 Regional Conservation Partnerships in New England. (https://www.wildlandsandwoodlands.org/rcpnetwork).

In summary, the conservation of aquatic and terrestrial connectivity in the Region needs to address the encroaching urban development and climate change. Human threats to habitat and connectivity are highly heterogeneous and differ greatly across the Region, but connectivity science provides a number of tools and strategies for protecting ecological integrity now and into the future. We summarize key concepts in the following section.

2.4 The conservation community in the Region

The conservation community is extremely active in each state and province of the Region. A large number of initiatives, led by groups of citizens, non-profit organizations, universities and colleges or governments at all levels are in place in the Region to improve land protection and management of specific natural areas. For example, the Wildlands and Woodlands initiative (wildlandsandwoodlands.org), in partnership with Harvard Forest, established an inventory of Regional Conservation Partnerships (RCPs) in New England, which are networks of people representing private and public organizations and agencies who work together to develop and implement a shared, long-term conservation vision across town and sometimes state and international boundaries. They have currently listed 43 RCPs covering about 60 percent of the New England regional landscape (Figure 2). A number of other similar partnerships exist in Quebec and the maritime provinces (New Brunswick, Nova Scotia, and Prince Edward Island). This number and diversity of projects highlights the great level of activity and desire for conservation action and also the multitude of stakeholders involved in connectivity conservation in the Region.

3
Ecological connectivity science

3.1 What is connectivity?

Ecological connectivity defines the extent to which the landscape facilitates or impedes the movement of animals and plants (Crooks and Sanjayan 2006). Movement can be active or passive; the former involves directed movement behaviour, while the latter involves diffusion by physical processes (e.g. wind and water currents) that displace organisms and their propagules such as seeds or eggs. Animals move over a great range of scales, from daily foraging movements to long-distance migrations. Well known examples of long-range animal movement include the migration of caribou, geese, or salmon, while other shorter range movements within species' home ranges, include coyotes and their nightly hunting routine, frogs aggregating to mate and white-tailed deer moving across agricultural fields to forage. Populations of plants 'move' via seed dispersal. Examples of plant dispersal include seeds dispersed through wind or water currents or via zoochory, where animals move seeds to other areas. The ease with which these movements are made defines the permeability of the landscape to plant and animal species (Theobald et al. 2012). Barriers to movement reduce landscape permeability, these include natural features that can fragment the landscape (e.g. mountains, rivers), but human infrastructure and activities are now seen to be the primary cause of declining ecological permeability and connectivity (Tucker et al. 2018).

Connectivity is an emergent property of species-landscape interactions (Taylor et al. 2006) and is inherently a multiscale phenomenon. At smaller spatial and temporal scales, the conservation of connectivity is concerned with enabling animals to establish a territory or home range. Defining and measuring connectivity at small scales is complicated by the fact that individuals within a given population differ in their needs and in their behaviors resulting in different habitat preferences and movement patterns (Finnegan et al. 2012, Baguette et al. 2013). At these smaller scales, landscape management and conservation are focused on interventions such corridors, crossings, and culverts that allow natural home range behaviour.

At larger spatial scales, and in the longer-term, connectivity science focuses on the persistence of interconnected networks of populations (metapopulations) and communities (metacommunities) across a region, and on maintaining long distance migrations that connect distant ecosystems (metaecosystems; Keeley et al. 2018). Connectivity is a fundamental ecological phenomenon that can restore a declining population, re-establish a population after local extinction, maintain genetic diversity by gene flow, and support the flows of nutrients and energy. However, connectivity is not sufficient on its own to ensure persistence of these elements of biodiversity; the amount and distribution of habitat is also a crucial co-determinant of persistence. The long term status of populations and communities depends on the joint contribution of connectivity and habitat quantity and quality that form an integrated network (Gonzalez et al. 2018). Together they define the capacity of the network to support biodiversity in the long-term (Saura et al. 2011).

Climate change is altering the capacity of ecological networks to support biodiversity. Species' movements are now shifting their ranges, and thus the science of ecological connectivity is concerned with determining how species will adapt their dispersal and migratory behaviour in the long term. At these larger scales connectivity science is concerned with quantifying movement, predicting how it will change (and evolve) and identifying opportunities to protect large continuous areas of habitat to support populations as they shift their ranges over the coming century.

3.2 Connectivity conservation

Connectivity conservation is the science and practice of intervening to protect or restore ecological connectivity in human transformed landscapes (Crooks and Sanjayan 2006, Worboys et al. 2010). Human transformation of land and waterways has increased fragmentation (Haddad et al. 2015) and as a consequence altered connectivity to the point where it may no longer be sufficient to support viable populations, offset extinction rates and maintain long-distance migrations and range shifts under climate change (Tucker et al. 2018).

These consequences of altered connectivity are now understood to extend to the ecosystem services and benefits we derive from connected ecosystems (Kremen and Merenlender 2018). Ecosystem services are the many and varied benefits that flow from nature to people (Reid et al. 2005, Díaz et al. 2018). This framework has emphasized four general categories : provisioning services, such as the production of food and water; regulating services, such as the control of climate and disease; supporting services, such as nutrient cycles and oxygen production; and cultural and relational services, such as spiritual and recreational benefits. Recent discussion has called for a more inclusive definition that reflects not only the many benefits people receive from nature, but also the role people play in reshaping landscapes, and the knowledge systems and actors who connect and disconnect people and nature. This broadening of the term is particularly relevant in the context of ecological networks and connectivity conservation (Gonzalez et al. 2018).

The field of connectivity conservation has rapidly responded to the research challenge of providing integrated assessments of connectivity, including the causes of and consequences of connectivity change for biodiversity and ecosystems. These developments include the collection of new data (e.g. on animal movement) and developing computational methods and graph models to support a shift from protecting habitat as islands, to protecting networks of core habitats and corridors (e.g. Urban et al. 2009, Saura and Rubio 2010, Rayfield et al. 2011). Most recently, the focus has been on identifying and protecting ecological networks of mixed ecosystems (and associated services) and their spatial relationships to quantify landscape resilience and connectivity for many species.

A growing emphasis on ecosystem processes and restoration via rewilding (Perino et al. 2019) has reinforced the importance of connectivity for large carnivores and the persistence of food webs of interacting species as they occur over a landscape (Gonzalez et al. 2011). This perspective is minimizing the binary distinction between habitat and nonhabitat and allows an emphasis of the permeability of terrestrial and aquatic ecosystems in the landscape.

To address these challenges, governments and conservation NGOs are proposing to protect **ecological networks for conservation (ENC):** defined *as a system of natural and/or semi natural ecosystem elements, or patches, that are configured and managed with the objective of maintaining, or restoring, ecological function as a means of conserving biodiversity and ecosystem functioning and services, while also providing appropriate opportunities for sustainable use of natural resources from the network* (modified after Bennett 2004, Hilty et al., 2019). Ecological networks are therefore integrated land planning solutions for connectivity designed to achieve multiple ecological and societal objectives (Figure 3).

The emphasis on "connected" stresses the importance of the permeability and traversability of the landscape. As climate and landscapes change, attention is given to addressing the changing patterns of functional connectivity of a region; species are expected to travel through and use the landscape differently as people change land cover and climate makes some areas more habitable than others.

It is now clear that to meet long-term policy objectives for connectivity in a region we must adapt land planning for climate change and land use change. Adaptive ENCs require a combination of permanent and temporary conservation areas as well as a focus on protecting vulnerable habitat and connections in the network to support shifting populations and processes in the long-term (D'Aloia et al. 2019).

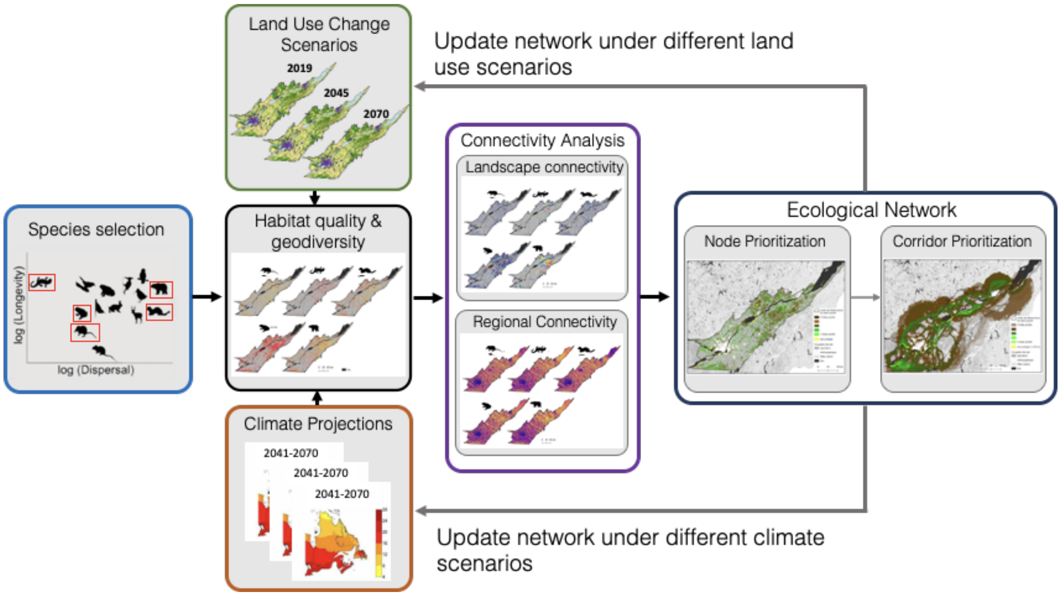


Figure 3. An example workflow required to design an ecological network for conservation (ENC); it is a multi-step process with information passing through the steps from left to right. The end point of this strategy is an ENC in which cores and corridors have been prioritized for multiple species and habitat types (ie. geodiversity). An iterative passage through multiple future scenarios of land use and climate change progressively adjusts the ENC so that it is robust to expected changes (after Albert et al. 2017, Gonzalez et al. 2017). This workflow requires the best possible science, including the integration of data, models and scenarios to achieve a robust ENC.

ENCs combine terrestrial and aquatic species and ecosystems, and while the focus is often on biodiversity, the restoration and protection of these ecosystems means that they can be considered as distributed nature-based solutions for a broader set of ecological benefits (i.e. ecosystem services) to society, including flood control, soil stability, and carbon sequestration to name a few (Gonzalez et al. 2017, Kremen and Merenlender 2018, Morecroft et al. 2019). The measures we use to quantify connectivity, the solutions we propose to manage it, and the criteria for success we adopt, depend on the taxa and ecosystem processes of interest and on the spatial and temporal scales over which they are changing. Methods exist for making rapid progress with the identification of ENCs for a broad and representative set of species across a range of spatial scales (Anderson et al. 2016, Albert et al. 2017, Meurant et al. 2018).

Resolution 40-3 articulates this integrated vision for ecological connectivity and many of the projects we review in this report are contributing plans for achieving ENCs or a partially nested set of ENCs for the Region. There are challenges with transboundary projects that must be overcome as we move from regional to national and continental scales (Santini et al. 2016). The conservation projects and assessments conducted in the Region all share a common goal of protecting and restoring connectivity at the largest spatial scale, but each has adopted different measures of connectivity and research workflows. We now review some of the key concepts from connectivity literature to facilitate an understanding of the proposals made by the projects in section 3.

3.3 The difference between structural and functional connectivity

Structural connectivity is a measure of the configuration and physical relation among patches of habitat on a landscape. It does not take into account the behavioural response of organisms to features of the landscape (Fagan and Calabrese 2006). Functional connectivity, on the other hand, explicitly takes into consideration species' perceptions of the landscape and the ways in which the configuration of landscape elements can change movement behaviour (Crooks and Sanjayan 2006, Baguette et al. 2013). Potential functional connectivity is assessed by modeling the needs and habitats of the species without any field validation, while direct functional connectivity assessments are carried out by observing (via satellite tracking, remote sensing, camera traps) or indirectly inferring the movement of organisms in the field (e.g. with genetic methods, Marrotte et al. 2014).

Structural connectivity and potential functional connectivity assessments are much more prevalent in connectivity studies because they are easier to conduct. Performing functional connectivity assessments requires information on movement in response to landscape elements which can be difficult and expensive to acquire. However, recent technological advancements have made these measurements more accessible through the use of less expensive genetic analyses (Spear et al. 2010) and satellite-based tracking devices.

3.4 Analytical methods for connectivity science

In this section we cover the main methodological steps that are usually undertaken by connectivity scientists, in order to provide context for the project descriptions that follow in section 3. To identify major methods and workflows, we reviewed 63 scientific studies spanning 13 different journals in ecology and conservation science (See Appendix 1 for more details). These studies considered a wide range of taxonomic groups (Fig. S2), geographic regions (Fig. S3), spatial extents (Fig. S4), and spatial resolutions (Fig. S5).

All connectivity assessments involve a multi-step process that begins by identifying the area of interest, followed by the selection of species, core habitats, links or movement paths between habitats, and then the application of connectivity analyses and models that support the prioritization of locations for protection or restoration across the region of interest (Fig. S1).

3.4.1 Species selection

The choice of species to select for a connectivity assessment is motivated by several factors such as data availability, conservation importance, economic importance, cultural value, or extinction risk. The choice of species should motivate the spatial extent and resolution of a connectivity study as different species perceive and occupy the landscape at different scales (Suárez-Seoane and Baudry 2002).

Assessments may involve single-species under an umbrella species approach to connectivity conservation, but recent emphasis has been given to multispecies assessments. These latter assessments are most often performed to include "surrogate species" (see Box 1) with a wide range of different life histories in an effort to create a conservation plan that preserves a large part of the region's biodiversity (Albert et al. 2017). In other cases, this is done to represent a single group more appropriately than with a single species (Arntzen et al. 2017), to take advantage of easily available data (Pereira et al. 2017, Dhanjal-Adams et al. 2017, Schoville et al. 2018, Xu et al. 2019), or to represent a single species crucial to the existence of others (Wang et al. 2018, Freeman et al. 2019). Another method which has gained interest is a generic species approach which groups species based on shared characteristics such as dispersal ability (Villemey et al. 2015, Lechner et al. 2017) or ecological needs (Villemey et al. 2015) (Fig. S6).

Box 1 | Surrogate species

Single species assessments may fall short of protecting a broad range of species in a region. The surrogate species approach uses a portfolio of species carefully chosen to represent the range of movement abilities and life-history characteristics in the region (e.g. Albert et al. 2017, Meurant et al. 2018). This approach assumes that other species which lie within the range of this movement and life-history space will also have their connectivity needs met and will thus be protected by the same ENC.

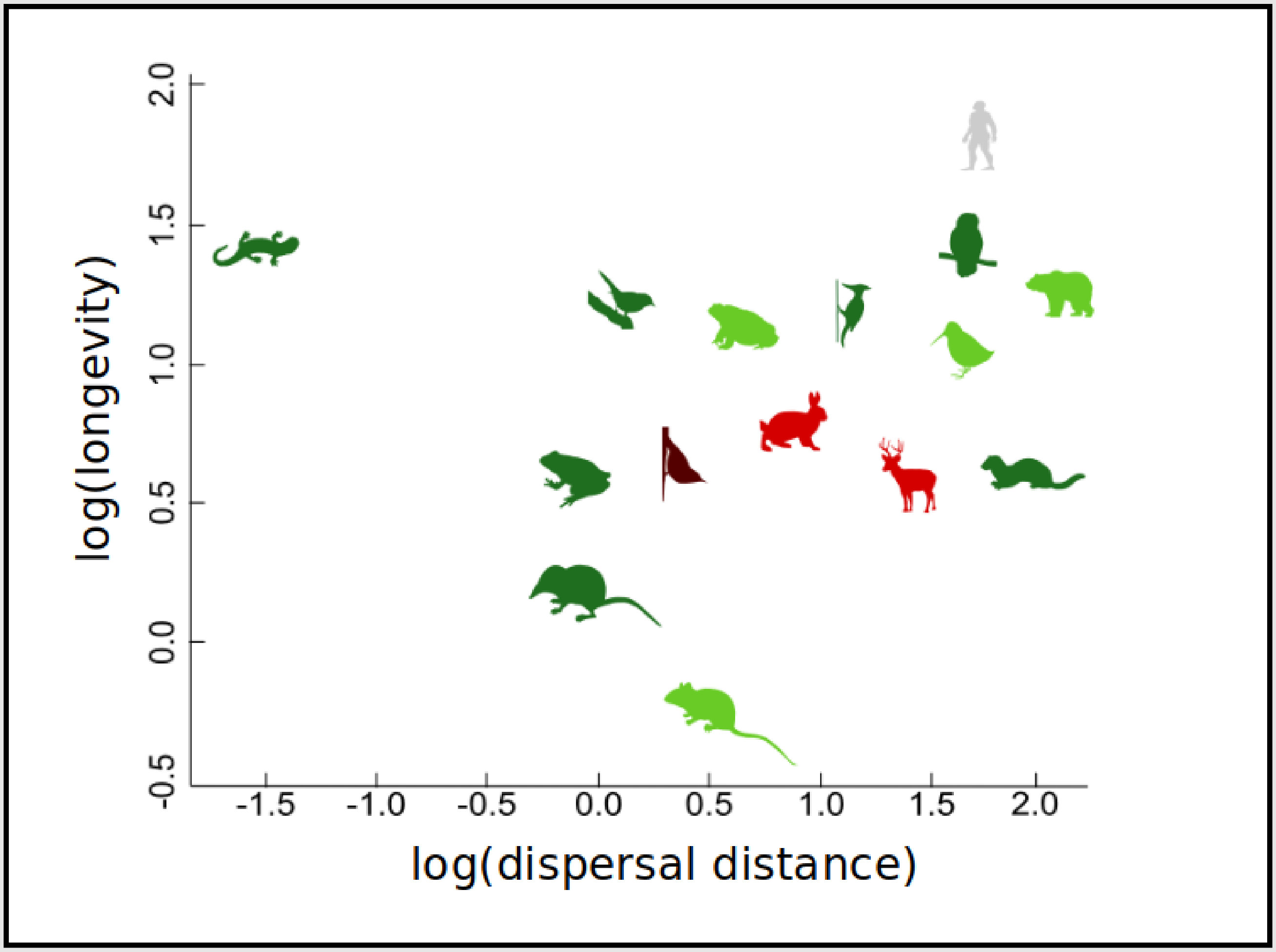


Figure 4. From Albert et al. (2017), graph showing the relationship between dispersal distance and longevity for 14 target species. These 14 species capture the regional diversity in vertebrate fauna around Montreal.

3.4.2 Habitat identification

Habitat is defined as "the resources and conditions present in an area that produce occupancy – including survival and reproduction – by a given species, or group of species. Habitat is species-specific; it relates the presence of a species, population, or individual to an area's physical and biological characteristics. Habitat implies more than vegetation or vegetation structure; it is the sum of the specific resources that are needed by organisms." (Hall et al. 1997). However, in many scientific studies and in some conservation projects, habitat is defined in a much broader sense to signify natural areas of certain ecosystem types (e.g. deciduous forest).

Connectivity studies often delineate between core and non-core habitat. Core habitats are often zones in the landscape expected, or known, to have high ecological value for many species in the region. Non-core habitats are areas which do not offer the full range of ecological needs that allow species to establish and reproduce, but it may be suitably permeable to allow movement and foraging. An ecological network for conservation will usually include core and non-core areas, especially if core habitat is scarce or poorly connected.

The approach of landscape geodiversity (Anderson et al, 2016; Box 2), defines potential habitats based on the geological, climatic and topographical structure of the landscape. A number of reviews suggest a good concordance between geodiversity and biodiversity because high geodiversity tends to signify environmental conditions that support rare species and high species richness (Beier et al. 2015, Hjort et al. 2015).

The three most commonly used methods for defining species' habitats were 1) distribution models, 2) remote sensing/pattern analysis, and 3) methods for quantifying how individuals use their habitat using telemetry. Distribution models were the most common of these three (Fig. S6). These models make use of sampled species presence or abundance data in one part of the considered region and make predictions from these data on the presence of this species across the region. Remote sensing methods consider patches as contiguous habitat for their species of interest. Finally, methods focused on individuals mostly relied on GPS telemetry data to determine how species used their habitat patches. However, some studies use genetic data in conjunction with GPS telemetry data to validate habitat models and species' habitat use and occupancy (Box 3, Marrotte et al 2014, Aylward et al. 2018, Zeller et al. 2018).

Box 2 Geodiversity

Many connectivity studies define habitat patches based on occurrence data or on the ecological needs of the focal organism. However, in a rapidly changing world faced with large scale land use change and climate change there is a need to create robust conservation plans that take the dynamics of our landscapes into account. One approach is to consider the geodiversity—the variability of Earth's surface materials, forms, and physical processes—of a landscape because it supports the dynamic physical processes that generate habitat (Hjort et al. 2015). Geodiversity can be seen as an abiotic surrogate for species representation (Beier et al. 2015, Anderson et al. 2016). Researchers argue that sites that offer a wide range of geophysical variation and micro-climates within a highly connected area will capture the needs of a large number of species and will be more resilient in the face of climate change.

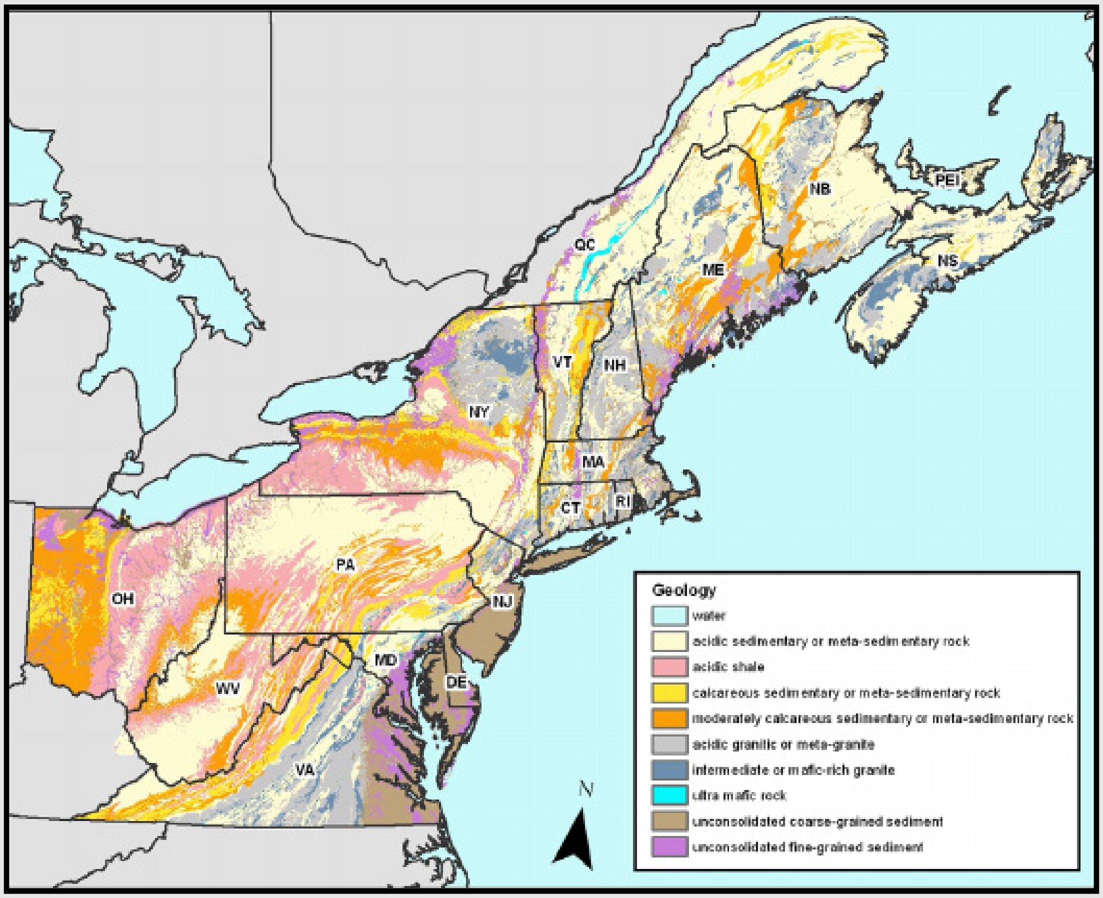


Figure 5. Map of diversity of geological land classes in Northeast US and Eastern Canada (Anderson and Ferree 2010)

Box 3 | Landscape genetics

Genetic analyses can be used in connectivity analyses to measure the genetic footprint of movement on a landscape. By comparing the genetic signature of multiple individuals of the same species researchers can determine which paths related individuals, such as parents and their offspring, have used on the landscape (Marrotte et al. 2014).

However, genetic analysis remains a costly approach especially in large landscapes. For this reason, many researchers choose to combine landscape genetics with more traditional GPS collars or species abundance data to validate their models of movement paths. Further, the combination of genetic data and telemetry can be used to combine both fine-scale movement captured by GPS to broader scale movement which has a genetic footprint (Zeller et al. 2017).

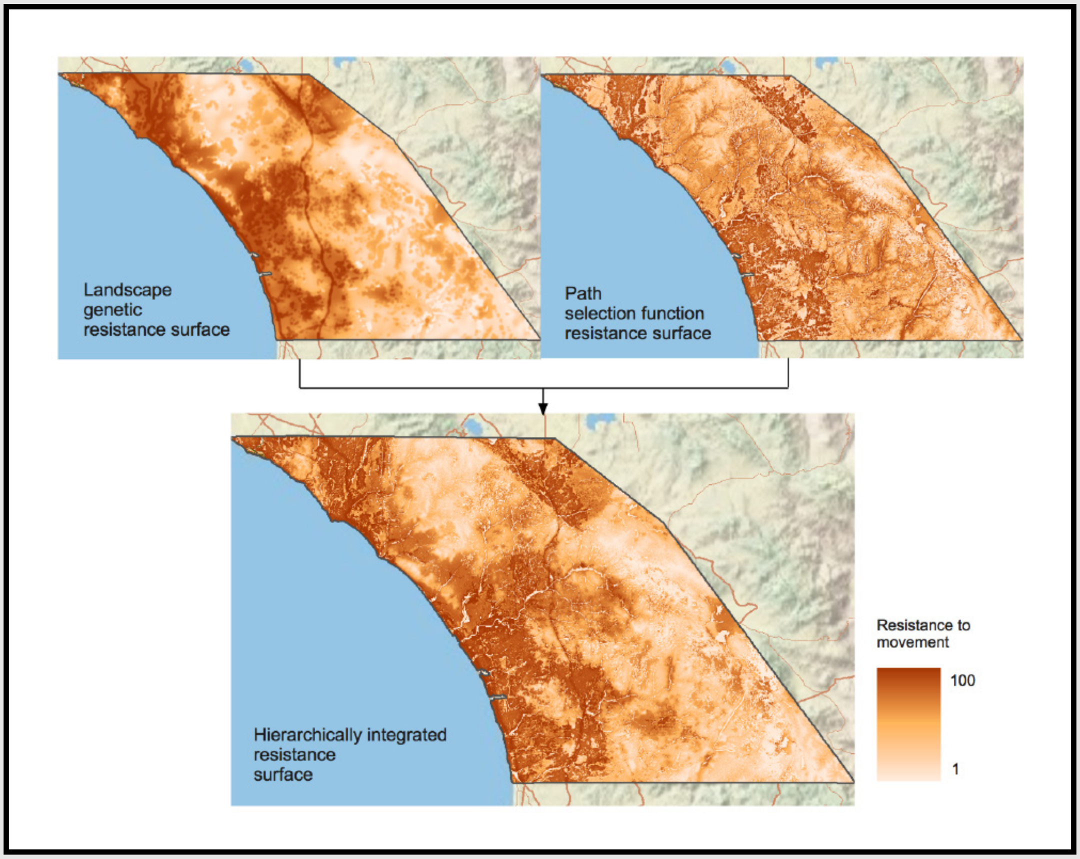


Figure 6. An illustration of the combination (bottom) of a resistance surface derived from landscape genetics (top left) and one derived from a path selection function from GPS telemetry (top right) (Zeller 2017).

3.4.3 Link identification

This step serves to identify the linkages that allow movement (dispersal and migration) that connect focal areas such as large blocks or smaller patches of natural habitat. In some cases, such as in the study of range shifts where a longer temporal scale is considered, these pathways might not represent contemporary linkages but rather potential paths through which species may expand their ranges in the future (e.g. Dilts et al. 2016).

Link identification establishes whether functional or structural connectivity is assessed. While some of these methods measure actual species movements, others use resistance surface models to identify potential functional links, while others use predefined movement rules to simplify the task. In the case of aquatic connectivity, links between habitats are defined by the topography of the river network since rivers are linear features with directional flow. Link weights are typically truncated relative to a maximum dispersal distance for the focal species, which requires knowledge of the species' dispersal capacity, or a more complete function describing how the probability of a movement event declines with distance.

A majority of recent studies tend to favour the use of resistance-based methods when determining the links between habitat patches (Dilts et al. 2016, Albert et al. 2017) (Fig. S6). These methods rely on an intermediate step to determine the resistance across the studied landscape often interpreted as the inverse of habitat suitability. The most common methods estimate least-cost paths through the landscape or derive resistance surfaces with circuit theory (Box 4) often with Circuitscape software (McRae et al. 2008, 2016).

Least cost path analysis defines links by assigning a cost to moving through a particular land type. Movement costs are tailored to each species based on a literature review of their movement success, or likelihood, through the different land cover types. Sometimes, direct movement data are available to validate resistance surfaces. Species-specific maps of movement resistance are derived by collating all the least cost paths for nonhabitat. The maps quantify the degree to which the matrix limits inter-patch movement relative to habitat (Etherington and Penelope Holland 2013). Resistance values are typically assigned based on land-cover type (e.g. intermediate in cropland, high on highways) and on the presence of linear elements of low resistance (e.g. hedges or riparian strips). A measure of increasing (cumulative) resistance is assigned as the path crosses different land cover classes.

Least-cost paths are rarely validated with data on observed species movements (Sawyer et al. 2011), but telemetry, isotopic analysis and genetic methods can be used to identify whether least-cost paths are being used between habitat blocks and patches.

Box 4 | Circuit theory

The assessment of connectivity for a landscape often requires the computation of a resistance surface to quantify the parts of the landscape which are unfavourable to species movement. The field of electronics also makes use of resistance when designing circuit networks. Ecologists have borrowed from circuit theory to represent landscape networks as circuits. By passing a voltage from one end of the landscape to the other, scientists can understand where the path of least resistance is for species following this dispersal direction and understand how easily permeable the entire landscape is.

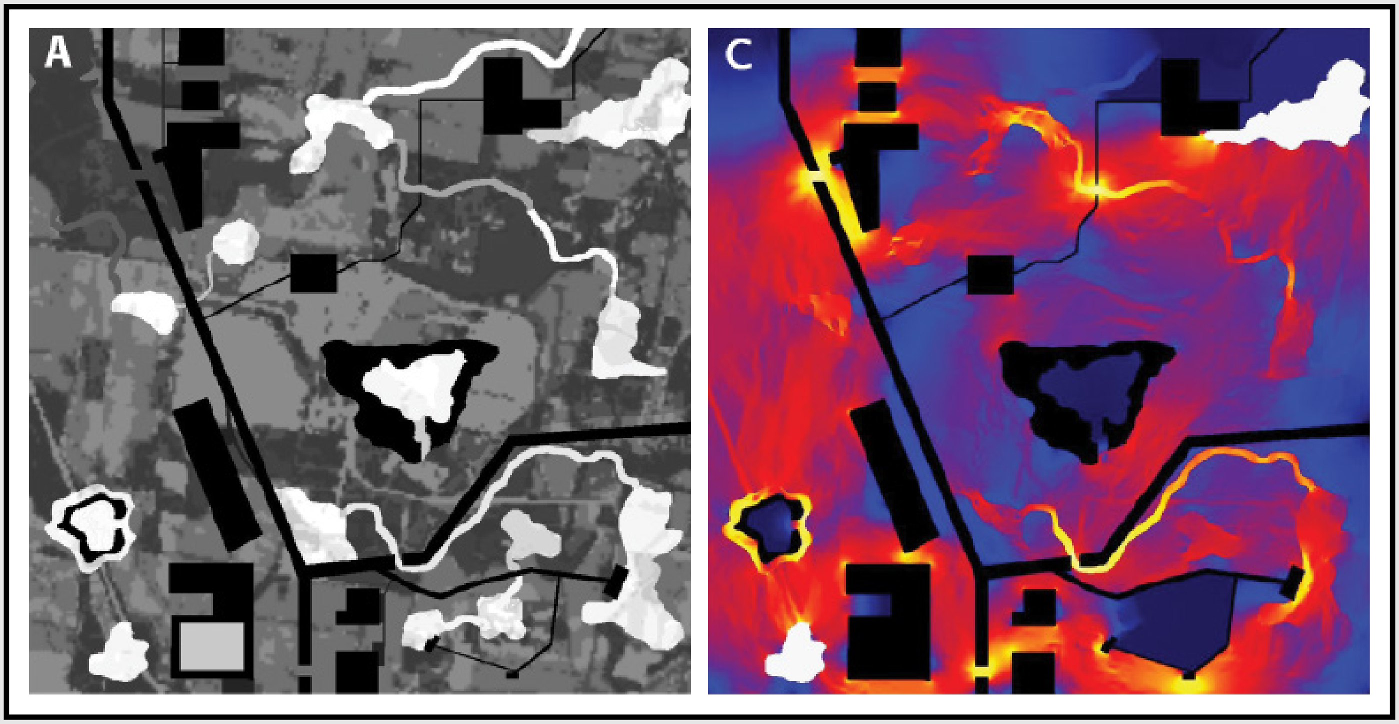


Figure 7. Landscape map of current connectivity (right) measured with circuit theory from a resistance map (left, light grey is 0 resistance and black is 100 percent resistance) between a patch in the bottom left and the top right (McRae 2008). Flows shown in yellow indicate areas of high and concentrated flow.

3.4.4 Modeling ecological networks as graphs

The final step in a connectivity project is to quantify and present the effective connectivity of the network of habitats and links across the landscape (Saura et al. 2011, Dilts et al. 2016, Albert et al. 2017). Two of the most prevalent ways scientists identify the network are through the use of graph theory (Box 5, Urban et al. 2009), and specific derivations of it, such as circuit theory (Box 4, McRae et al. 2008).

Graphs are models of landscapes; simplifications of a complex ecological context to aid our understanding and decisions. A graph defines a spatial network composed of nodes (or vertices) and edges, where the nodes represent individual spatial units (e.g. a block or patch of habitat) and the edges represent connections or flows of movement between the nodes. The edges can be weighted and directional to describe patterns of movement on the network. Methods for network identification are now built on a powerful array of tools for identifying the nodes and links, and for ranking the importance of these nodes and links to the network's structure, such as its traversability (Dale and Fortin 2010). In many cases, the identification of the network's nodes and links requires the application of binary thresholds where habitats and links are viewed as 'islands' in a sea of non-habitat. This simplification can preclude the application of this simple description to situations where habitat is more continuously distributed (Moilanen 2011).

Circuit theory makes the analogy between ecological connectivity and electrical circuits (Dickson et al. 2019). Circuits are a form of graph (Box 4 and 5), defined by the resistance to movement between nodes. McRae (2006) posited that concepts and metrics from electrical circuit theory are a robust way to quantify movement across multiple possible paths in a landscape. By passing a voltage from one end of the landscape to the other, researchers can quantify where the paths of least resistance occur. This model allows a direct assessment of the permeability of the entire landscape. Maps summarizing the findings of these analyses will depict either the conductance of the landscape, which shows the cost of movement through the landscape (a visualization of the resistance), or the potential corridors that can be generated from this surface using software such as Linkage Mapper.

Recently, stochastic movement simulators (SMS, Palmer et al. 2011) have been added to the toolbox. The SMS integrate features of least cost path analysis with models of the stochastic movement of individuals. It relaxes assumptions that are implicit in the least cost path algorithm (e.g. that an individual has a planned destination when it leaves a habitat patch, or has full knowledge of the path's cost). The SMS algorithm incorporates the perceptual range of individuals and the degree of correlation in movement paths among individuals. By simulating movements of many individuals emigrating from habitat patches, relative connectivities between habitat patches are estimated. Some evidence suggests that SMS models can better job modeling connectivity than circuit and graph models (Coulon et al. 2015).

What do we get from the graph model?

Once built, graph models allow the analysis of the features that define how much habitat is effectively connected, how easy it is for species to move through the network, and the contribution of particular nodes (blocks of habitat) to the capacity of the network to maintain species in the long term. These properties are easy to calculate and compare across different scenarios, allowing the researcher to evaluate how effective the network will be in maintaining biodiversity and ecosystems in the future. These emergent properties are impossible to derive without assembling the graph. Graph models are often easy to analyse and low in parameters which makes them easy to validate with independent data.

Validation of the network model

Validation of the graph models is an important step in the application of connectivity science for conservation. Validation proceeds by seeing how well the model explains independent data on the distribution and movements of species (Minor and Lookingbill 2010). Can a graph model adequately represent habitat patches and dispersal paths and rates with the right assignments of nodes and links? If ecological networks are monitored over time (e.g. with telemetry data) then a good graph model should explain observations, and guide future monitoring and sample via predictions of unobserved movements. Research shows that graph models can do this well (McRae and Beier 2007, Minor and Urban 2008, Bergerot et al. 2013, Bishop-Taylor et al. 2018).

Optimization

Spatial prioritization methods can be used to identify the nodes and links in the network that most efficiently maximize connectivity, and other conservation criteria such as effective connected area. Methods of analysis and tools (e.g. Zonation) are now widely available and have been combined with graph models to define effective ecological networks (Phillips and Dudík 2008, Albert et al. 2017, Meurant et al. 2018, Jalkanen et al. 2020) across large regions. The patch and link prioritization can involve multiple weighted conservation criteria, including different measures of connectivity, species and ecosystem services (Gonzalez et al. 2018). The end result is a map showing which nodes and links of the network to prioritize spatial conservation targets (e.g. 17% of land area to be protected).

Box 5 | Graph theory

Graph theory is a branch of mathematics which deals with the graph structure: a set of nodes (or vertices) with connections between them called links (or edges). Since landscape networks of habitat patches with migration links (e.g. least cost paths) between them can be easily represented as graphs, ecologists can make use of the rich analytical theory to evaluate the connectivity of a landscape (Minor and Urban 2008, Urban et al. 2009). The equations and mathematics from graph theory give scientists an insight into the structure of the landscape at the node and network scale. For example, network statistics can be applied at the node and network level. For example, in figure 8, below, patch 6 is of high betweenness centrality because all paths between the two modules of patches to the left and right must pass through it. The probability of connectivity (PC) quantifies functional connectivity of the entire network. It is defined as the probability that two points randomly placed within the landscape fall into habitat areas that are reachable from each other given a set of habitat patches and traversable links among them (e.g. Saura and Pascual-Hortal 2007, Saura and Rubio 2010).

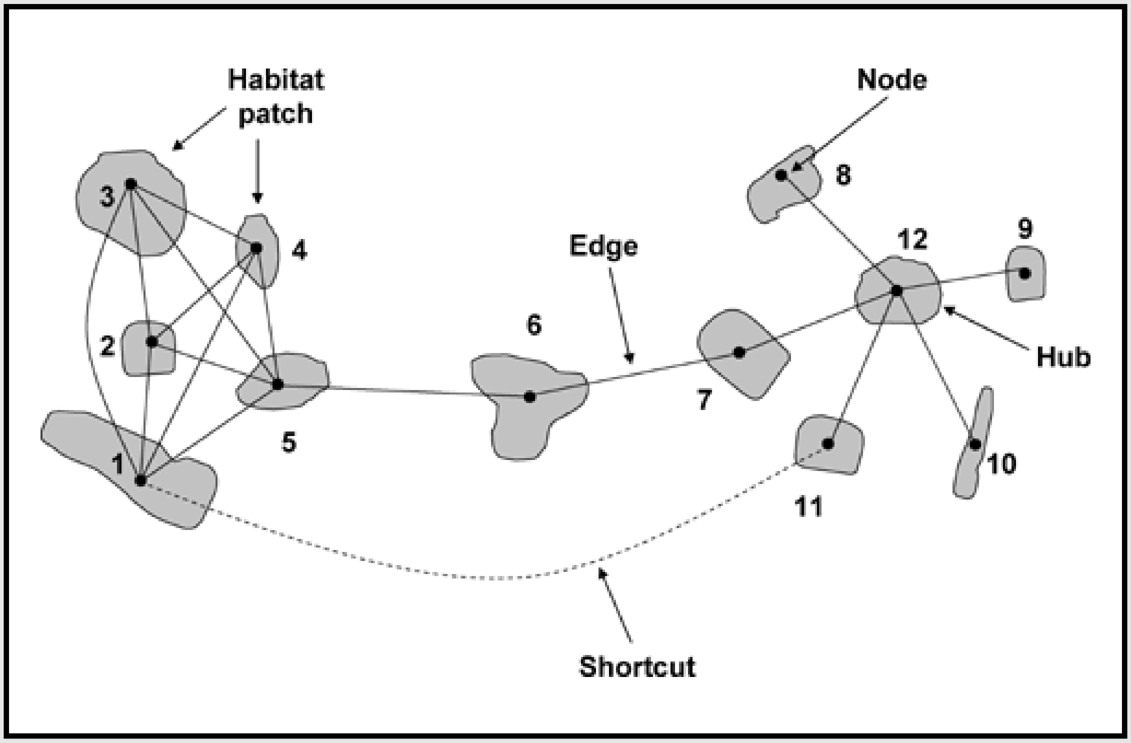


Figure 8. Example of a landscape of habitat patches represented as a graph with habitat 'nodes' indicated by numbers and links, or edges, connecting them (Minor and Urban 2008).

4

Connectivity assessments and projects in the region of resolution 40-3

4.1 Connectivity conservation in the Region

The Ecological Connectivity web portal (**https://ecologicalconnectivity.com**) was developed to inventory and allow a rapid exploration of all past and ongoing connectivity projects in the Region. The portal contains a form system to enter summary information about each project in the region, and detailed reports can be uploaded to the website as a complement. Once projects are entered, they can be searched through a mapping platform that allows the user to filter by region, taxa, connectivity action, or other broad category.

In the summer of 2019, a thorough inventory of existing connectivity projects in the region was conducted with participation from all NEG/ECP jurisdictions through a number of channels. The Conservation Corridor webpage offers a library of literature (**https://conservationcorridor.org/library/**) related to conservation planning which includes a consideration for connectivity. We queried this database for projects in the region and extracted the associated technical and methodological reports. We also researched various other online resources. All projects that were considered relevant were then entered on the Ecological Connectivity portal through the online form system. In addition, through expert recommendations, we contacted individuals leading current projects related to connectivity conservation to ask them to complete the online form and to provide technical reports.

As of May 2020, 58 connectivity projects have been entered on the Ecological Connectivity portal. These projects cover all states and provinces included in the region of Resolution 40-3, with Maine, Massachusetts, Vermont, and Quebec being the most represented regions (Figure 9). At the time of writing, the vast majority of projects entered on the portal were led by conservation organizations, with only a few university or government led projects. The academic literature is largely absent because the portal mostly focuses on applied connectivity projects, which are not usually the primary focus of university-led projects. Many projects led by government agencies are missing at the time of writing because they haven't been entered by the relevant organizations, or because the associated documentation is not readily available online. It is expected that additional projects will be added to the portal.

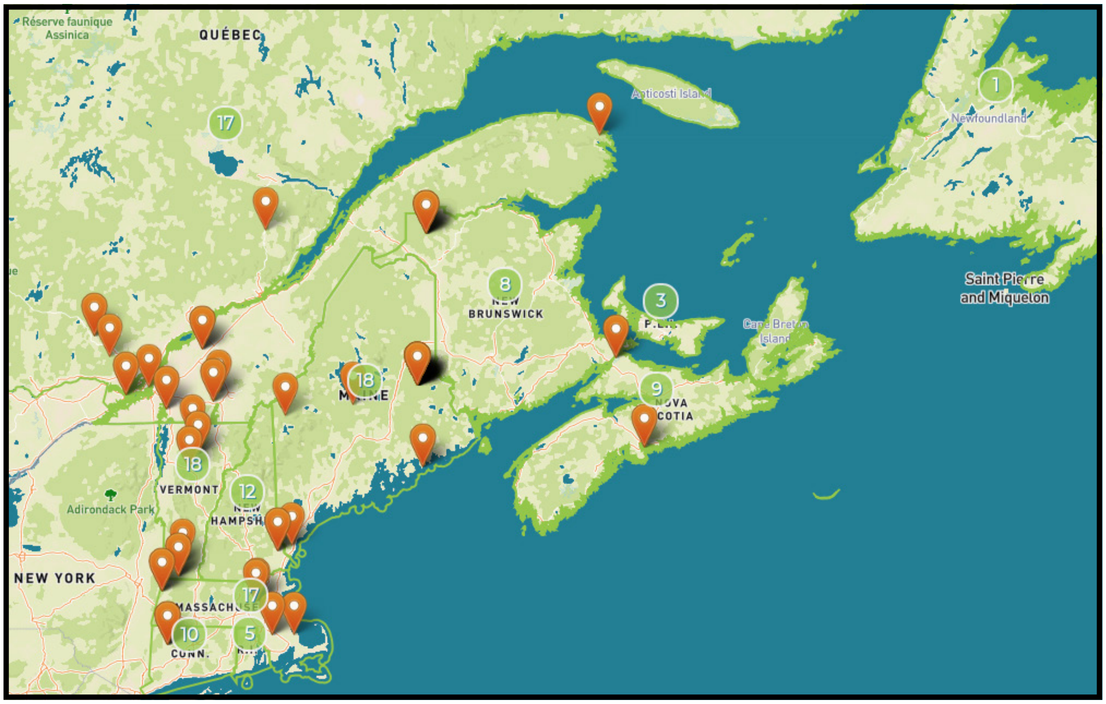


Figure 9.
Map showing coverage of conservation science projects in the Region (https://ecological connectivity.com/explore). Green circles indicate the number of projects in each state or province, including projects that cover entire states or provinces and cross-boundary projects. Orange markers indicate more localized connectivity conservation efforts.

4.2 Region-wide projects

A number of past or ongoing initiatives in the Region have conducted comprehensive and thorough evaluations of terrestrial and aquatic connectivity, often using state-of-the-art data sources and methods. A few of those initiatives have covered a large portion of the region of Resolution 40-3 and are described below. The main characteristics of each project are also summarized in Tables 1 and 2.

4.2.1 Staying Connected Initiative: Priority Linkage Areas in the Northern Appalachian-Acadian Ecoregion

The Staying Connected Initiative (SCI, **http://stayingconnectedinitiative.org/**) is an international collaboration with 65 partner organizations including representation from 6 states (CT, MA, ME, NH, NY, and VT) and 4 provinces (QC, NB, NS, and ON) as well as multiple nonprofit and public agencies. Encompassing 10 critical linkage areas within and extending beyond the Northern Appalachian-Acadian ecoregion (Figure 10), this partnership covers a region of approximately 50,000 square kilometers. The connectivity of each linkage area has been assessed in terms of habitat composition, habitat distribution, land protection status, and road-barrier effects. However, due to data limitations, not all of these are assessed equally for each linkage area at this time.

Table 1. Summary of key components of projects on ecological connectivity at the scale of the Region (blue) or at the national or continental scale (grey).

	Region Covered	Focal Ecosystem(s)	Species Approach	Connectivity Tools Used	Main Outcome
Staying Connected Initiative	Appalachian-Acadian Ecoregion and beyond	Mainly forests	Multispecies/ guild profiles	Least cost paths, corridor optimization	Identification of 10 critical linkage areas
Wildlands Network's Eastern Wildway	Greater Northern Appalachian region	Terrestrial and aquatic	Focal species selection	Cost surface modeling	A large web of important areas for connectivity
TNC Resilient and Connected Landscape	Entire Region, except northern Quebec, Newfoundland and Labrador	Terrestrial and aquatic	No target species	Local connectedness and circuit theory at regional scale	Maps of proposed priority networks
Northeast Aquatic Connectivity project	North Eastern U.S. including all of New England	Aquatic	No target species and generic species	Barriers to connectivity were assessed based on a suite of 38 metrics	Interactive map for exploration and prioritization of barriers
Nature's Network and Designing Sustainable Landscapes	North Eastern U.S. including all of New England	Terrestrial and aquatic	Multispecies	Least cost paths, buffer analysis.	Establish terrestrial core areas
Connectivity of core habitat in the Northeastern United States	North Eastern U.S. including all of New England	Terrestrial	Generic species	Graph theory	Maps showing the relative importance of core habitat areas for potentially connecting existing protected areas
Human land uses reduce climate connectivity across North America	North America	Terrestrial	No target species	Least cost paths	Delineation of potential movement routes under climate change
Identifying corridors among large protected areas in the United States	USA	Terrestrial	None	Circuit theory, corridor mapping	Map of regional connectivity between protected areas
Forest connectivity regions of Canada using circuit theory and image analysis	Canada	Forests	None	Circuit theory	A map of regional connectivity for most of Canada

Table 2. Summary of key components of projects on ecological connectivity at the provincial or state level.

	Region Covered	Focal Ecosystem(s)	Species Approach	Connectivity Tools Used	Main Outcome
Nova-Scotia - Dalhousie University	Nova-Scotia	Terrestrial and marine	None, and focal species	Cost-distance analysis, consensus mapping	Identification of existing protected areas,areas suitable for representation of natural landscape types, and other areas of significant ecological value
Vermont Conservation Design	Vermont	Terrestrial and aquatic	None	Least-cost paths, circuit theory	Connected network of unfragmented forest blocks, surface waters, and riparian areas
Massachusetts & Connecticut - Critical Linkages	Massachusetts and Connecticut	Terrestrial and aquatic	None	Least-cost paths	A series of maps that can be used by decision makers and land managers to see impacts of mitigation projects on connectivity
Massachusetts - BioMap 2	Massachusetts	Terrestrial and aquatic	None in connectivity assessment	Local connectedness	Map with several core components defined from an index of integrity that considers connectivity
Maine - Beginning with Habitat	Maine	Terrestrial and aquatic	Multispecies	Undefined	A series of maps that can be used by decision makers at the local level to incorporate connectivity results into decision making
Rhode Island - Conservation Opportunity Areas	Rhode Island	Terrestrial and aquatic	None	Undefined at local scale, regional scale with circuit theory	Map defining corridors of major or minor importance
New Hampshire Wildlife Corridors & Wildlife Connectivity Model	New Hampshire	Terrestrial and aquatic	Multispecies	Landscape permeability model, resistance surfaces	Identification of key areas for land protection efforts and strategic locations for restoring connectivity
Quebec - Connectivity in the Ste. Lawrence Lowlands	Ste. Lawrence Lowlands	Terrestrial	Multispecies	Graph theory and circuit theory	Maps of local and regional connectivity and prioritization of natural areas for habitat and connectivity conservation
Quebec - Ecological corridors: A climate change adaptation strategy	Southern Quebec	Mostly Terrestrial	Umbrella Species	Multiple frameworks	Network of collaborations and online story map on ecological corridors

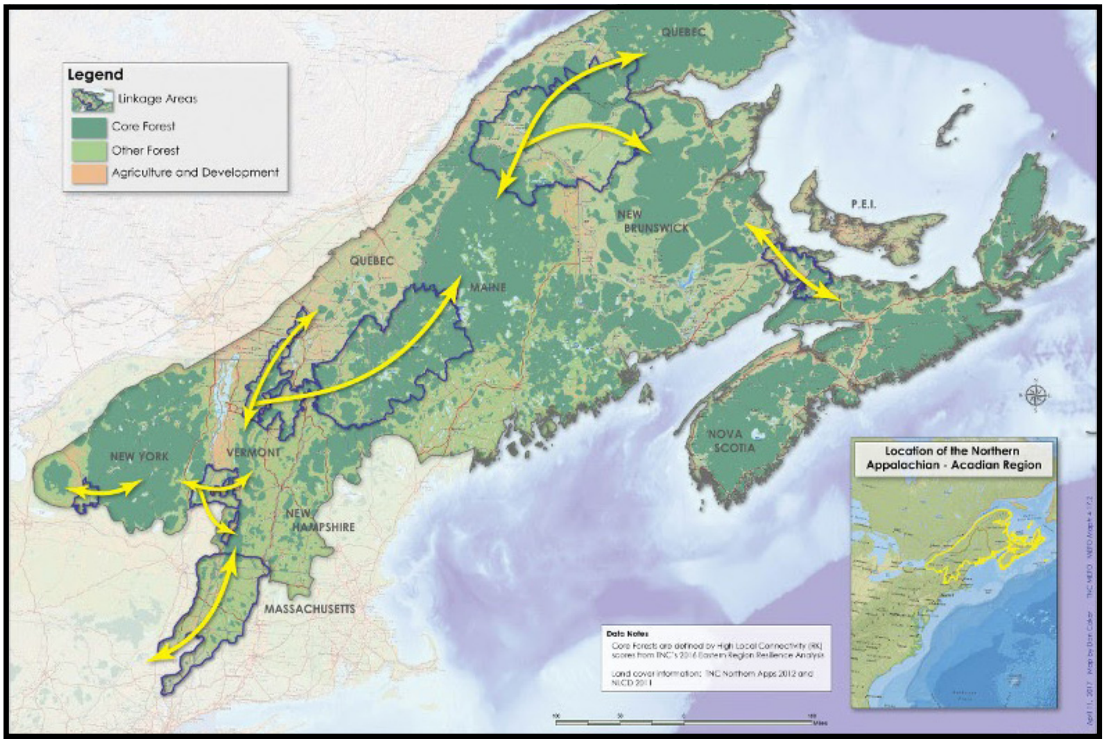


Figure 10. Nine priority linkage areas defined by the Staying Connected Initiative in the region of the Northern Appalachian-Acadian ecoregion

CONNECTIVITY APPROACH: The major objective of SCI is the protection of wide-ranging, forest-dwelling wildlife. Connectivity was assessed with up to four sets of measures. Two related to habitat composition and distribution derived from land-use data, one was related to the degree of land protection, and a final one was related to road barrier effects.

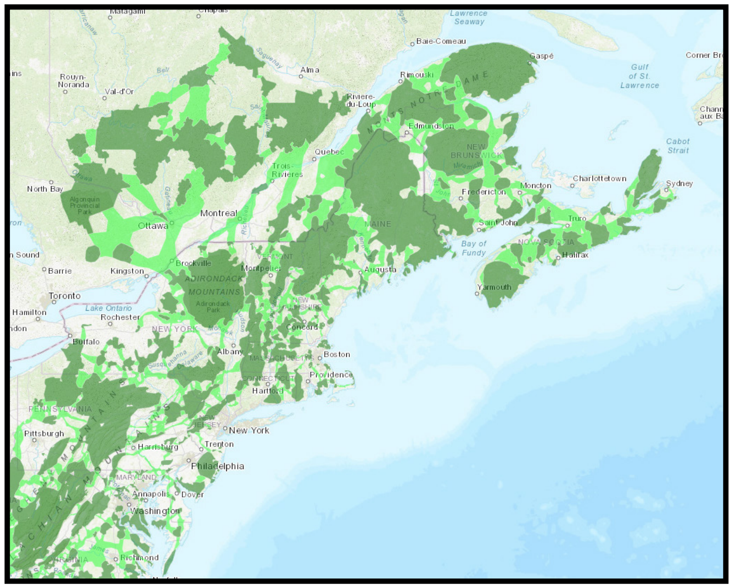
METHODS USED: Least cost path, pattern analysis habitat definition, rule-based habitat definition, corridor optimization.

MAJOR CONCLUSIONS OR OUTCOMES:

- The nine linkages encompass approximately 50,000 square kilometers of the assessed ecoregion: 92% of this region is in areas of natural cover.
- Based on a resistance kernel indicator half of the linkage areas are generally unfragmented while the other half face considerable fragmentation.
- The level of protection in each linkage area varies from 14% in the Tug Hill - Adirondacks linkage to 50% for the three Borders region.

4.2.2 Wildlands Network's Eastern Wildway

The Eastern Wildway project builds on existing protected areas and conserved private lands defined as core areas (Figure 11). The Wildlands Network identifies those reserve lands and other wild places that need to be protected and/or expanded to ensure biodiversity conservation in the Greater Northern Appalachian region. Given these identified core areas the Eastern Wildway project has identified 16 locations requiring protection to maintain habitat connectivity within the region. This project is an extension of the Adirondacks to Acadia (Reining et al. 2006) and Maine's Wildlands Vision (Long et al. 2002) initiatives.



CONNECTIVITY APPROACH: The Network uses a cores and links approach to connectivity, identifying potential core areas for protection, and identifying potential trajectories for ecological corridors that would best connect those priority areas. The Network integrates a wide range of existing data sets and expert knowledge from a diversity of actors, including federal agencies. The Network has grown from the Maine Wildland Network Vision and the Adirondacks to Acadia Wildlands Network Design, which use a "Three-track Approach" to prioritization ; selecting conservation sites based on focal species habitat preferences, relevant landscape features, and general land use and land cover data, via an optimization software (MARXAN or SITES).

▲ **Figure 11.** Section of the Map of the Eastern Wildway covering the Region with core areas in dark green and corridors in light green (see https://wildlandsnetwork.org/wildways/eastern/ for interactive map).

METHODS USED: Focal species selection (rule based and expert knowledge), cost surface modeling, habitat selection by optimization leading to potential functional connectivity assessment.

MAJOR CONCLUSIONS OR OUTCOMES:

▶ The Wildlands Network identifies a large web of important areas for connectivity among which we can count national parks, preserves and scenic rivers.

▶ It highlights the efforts required for continued collaboration across the entire region and for large scale planning.

▶ The Wildlands Network notes that eastern mountain ranges are located close to large population centers. Places that were once remote are now threatened by development.

▶ Rural economies continue to stagnate in the region, which pushes rural landowners to sell off large land parcels for development, logging, and resource extraction. A growing population is building first or second homes in relatively wild places, potentially destroying the natural environments they seek.

4.2.3 TNC Resilient and Connected Landscapes

The Nature Conservancy Resilient and Connected Landscapes project is aimed at assessing resilient sites in Eastern North America and the climate corridors between them which will allow organisms to migrate in response to climate change. In the first part, TNC mapped the resilient sites in the landscape which are expected to maintain suitable habitat through a changing climate. A site's resilience includes measures of landscape geodiversity and local connectedness. In a second part, corridors are mapped between these resilient sites based on expected species flow through the landscape in a climate change migration scenario. The final prioritization identifies a network which would ensure protection of the biodiversity in the region. In 2016, the map was revised and expanded to cover 20 ecoregions encompassing the entire Region except Northern Quebec and Newfoundland and Labrador. New mapping approaches have been used to improve the accuracy and utility of the data (Anderson et al. 2016a). Data updated in late 2019 will be soon made public and an updated report is forthcoming.

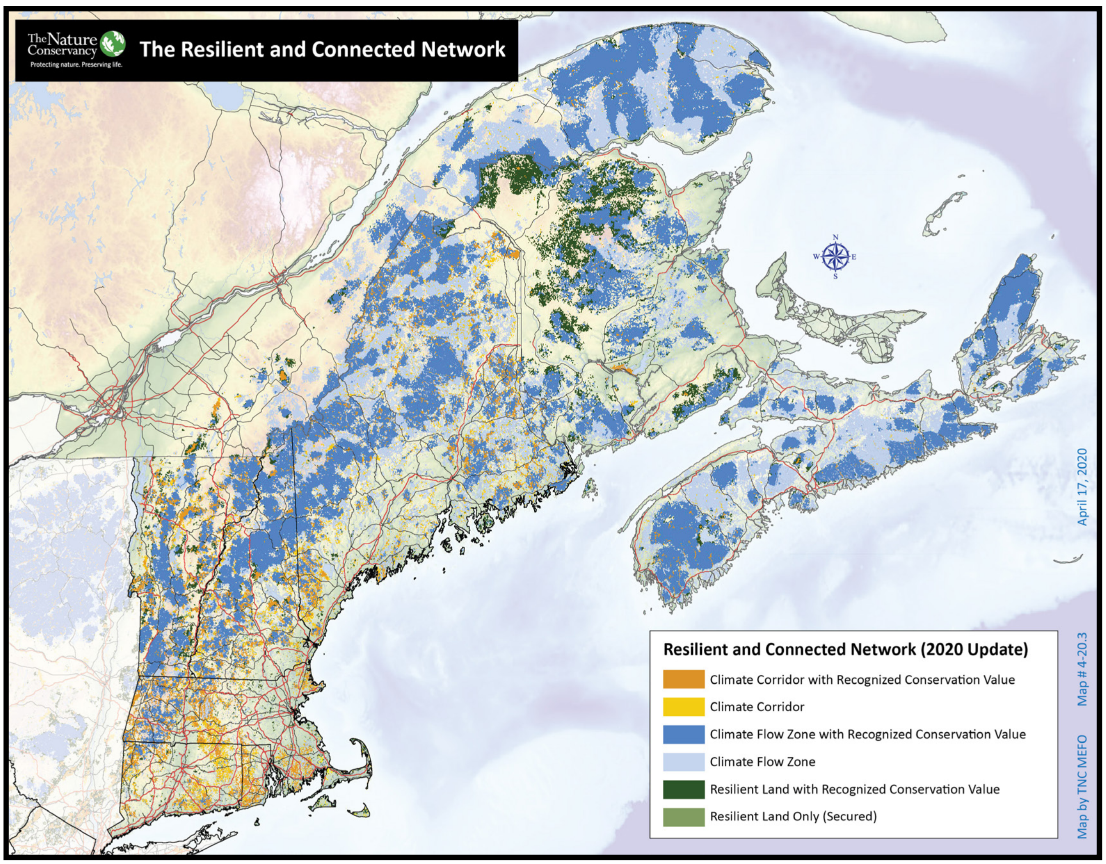


Figure 12. Map showing categories of zones defined as important for resilience and connectivity (From: http://maps.tnc.org/resilientland/).

CONNECTIVITY APPROACH: A connected network of resilient sites is developed taking into account the resilience of sites to future climate conditions and the permeability of the landscape for range shifts based on intensity of land modification.

METHODS USED: Circuit theory, rule-based habitat definition, network optimization.

MAJOR CONCLUSIONS OR OUTCOMES:

▶ 44% of the proposed priority network encompassing 21% of the region is already permanently secured.
▶ Protecting the resilient habitats in the network would ensure the sequestration of 56% of the total above ground carbon in forests of the region.
▶ There is a 36% consensus on protected areas with Connect the Connecticut priorities.
▶ 77% of lands of high importance for water supply are within the network of resilient sites and provide good targets for acquisition and protection.
▶ 47% of areas with high probability for energy development do not overlap with the network of resilient sites and represent opportunities for avoidance.
▶ State and provincial agencies own 88% of flow areas and 62% of riparian corridors and pinch points. These lands should be properly managed to promote high connectivity in the region.
▶ There are 201 areas where major roads interfere with areas of high regional flow.
▶ It is projected that future land development will interfere with 8% of the network of resilient sites.
▶ By analyzing the known locations of 2861 rare terrestrial species, it was found that 427 had 75% of their locations in low-scoring sites.

▲ **Figure 13.** Results of the Circuitscape connectivity model applied to an anthropogenic resistance grid (Anderson et al. 2016a).

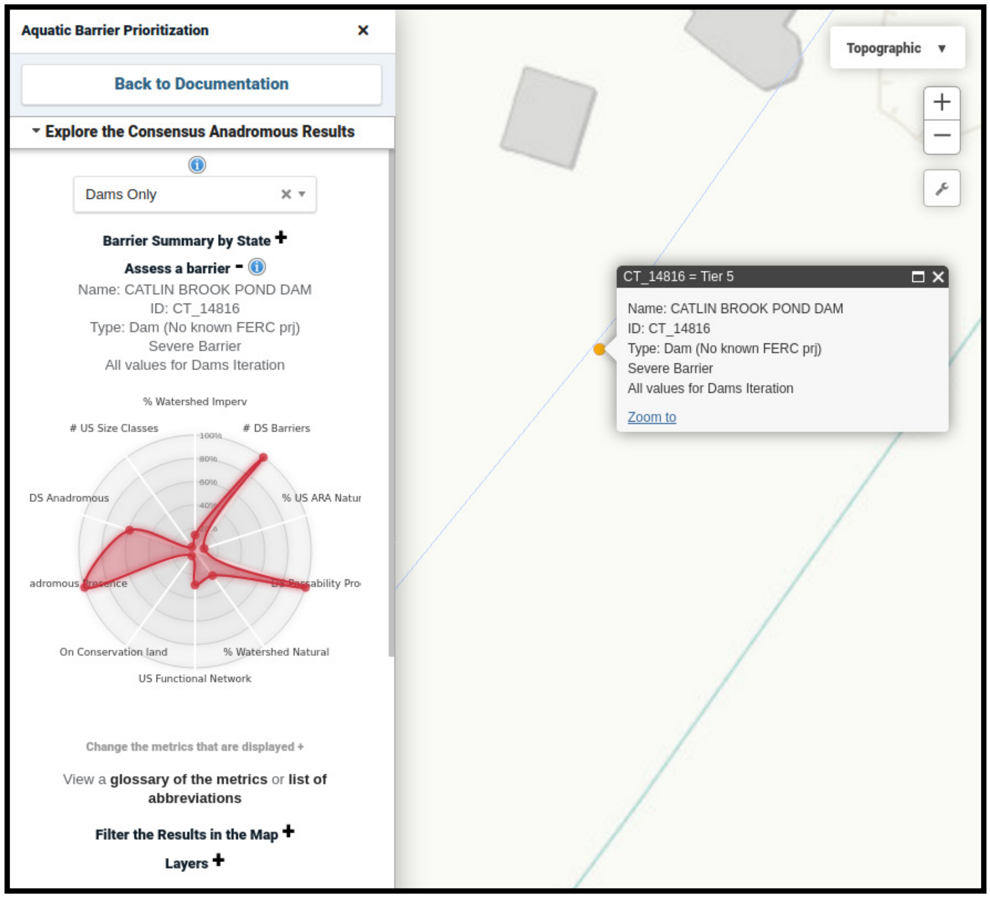
4.2.4 Northeast Aquatic Connectivity project

The Northeast Aquatic Connectivity Project (Martin and Levine 2017) is a collaboration which assesses barriers to aquatic connectivity in thirteen northeastern states in the United States. Revised in 2017, this project has assessed a total of 200,000 barriers to the connectivity of anadromous fish through the use of 38 ecologically relevant metrics such as amount of upstream habitat and number of rare species in upstream habitat. This project has led to the development of the Northeast Aquatic Connectivity project tool: an interactive map allowing the exploration and prioritization of the barrier database across the northeastern US (Figure 14).

CONNECTIVITY APPROACH: Barriers to connectivity were assessed based on a suite of 38 metrics. They were subsequently prioritized in terms of expected restoration benefit to the connectivity of the aquatic network.

METHODS USED: Rule-based link definition, optimization, observational habitat definition.

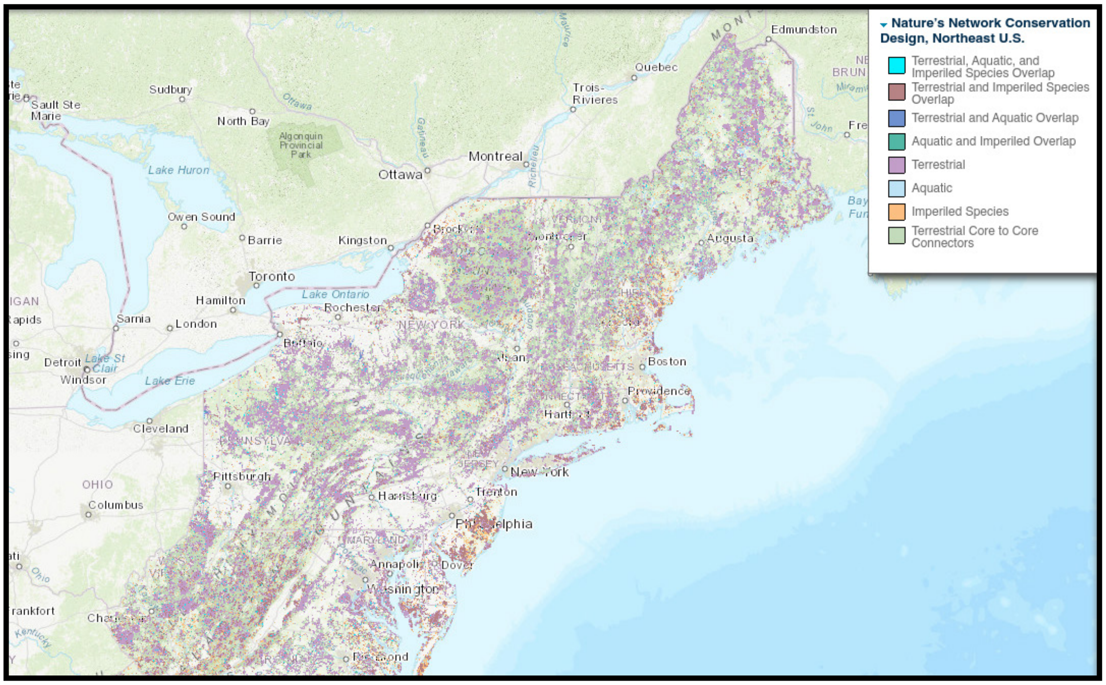
MAJOR CONCLUSIONS OR OUTCOMES: A web portal was created allowing users to visualize the results of the barrier prioritizations. The qualities of each barrier can be quickly assessed using a radar plot visualization. Further, users can run custom analyses by modifying the weighting associated to the 38 barrier attributes and modeling a specified geographic extent with the removal of barriers.



▲ **Figure 14.** Screenshot of the Northeast Aquatic Connectivity tool (https://maps.freshwaternetwork.org/northeast/) showing the radar plot profile of a severe barrier in Connecticut on the left.

4.2.5 Nature's Network and Designing Sustainable Landscapes

The Designing Sustainable Landscapes project (McGarigal et al. 2018a, 2018b), a project of the Landscape Ecology Lab at the University of Massachusetts, aims to provide guidance for strategic habitat conservation by assessing ecological integrity and landscape capability for a suite of representative species across the landscape for both the current landscape and potential future landscapes, as modified by an urban growth model and models of climate change and sea level rise. This project provides much of the basis of the conservation planning tools used in Nature's Network (**http://www.naturesnetwork.org/**, which is an extension of the Connect the Connecticut, effort, **http://connecttheconnecticut.org/**). The North Atlantic Landscape Conservation Cooperative (U.S. Fish and Wildlife Service) and the Northeast Association of Fish and Wildlife Agencies together with multiple partners developed Nature's Network to provide conservation priorities from Maine to Virginia. The Conservation Design depicts lands and waters that should be prioritized for conservation. These priorities were based on 3 earlier core area prioritizations: a terrestrial core connector network, a set of aquatic core areas, and a set of core habitats for imperilled species. This network design led to the development of a web tool to explore restoration scenarios in the Northeast (Figure 15).



◀ Figure 15. Overview map for Nature's Network Conservation Design http://www.naturesnetwork.org/).

CONNECTIVITY APPROACH: Potential functional connectivity based on a combination of ecosystem-based cores and core areas to meet the habitat needs of 28 representative terrestrial wildlife species. Aquatic connectivity is assessed by defining aquatic cores for rivers, streams, lakes and ponds, and aquatic buffers that represent the areas estimated to have a strong influence on the integrity of the aquatic cores based on watershed processes.

METHODS USED: Least cost path. Multiple species assessment. Hydrological analysis. Buffer analysis.

MAJOR CONCLUSIONS OR OUTCOMES:

▶ Terrestrial core areas identified in this product encompass ~25% of the Northeast including a total of 20,358 disjunct core areas encompassing a total of 16,160,371 ha and ranging in size from 3.6 to 107,996 ha, with an average size of 794 ha.

▶ Connectors encompass an additional ~17% of the Northeast.

▶ The river and stream cores encompass about 30% of the stream miles of the Northeast and Mid-Atlantic region.

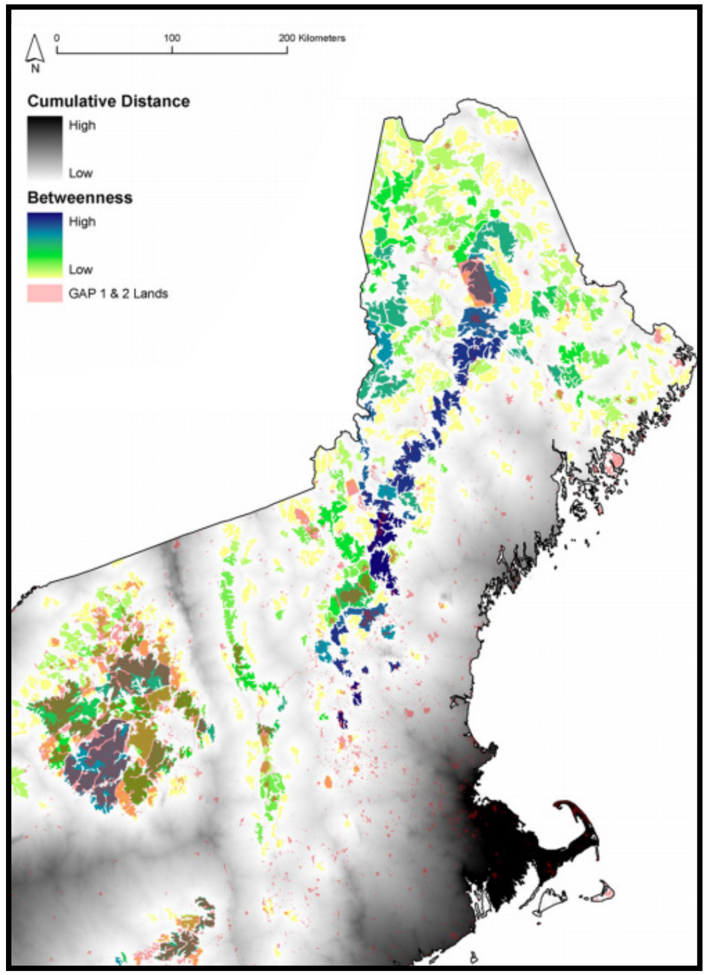
▶ The lake and pond cores encompass about 30% of the lake and pond area of the region, not including the 14 lakes larger than 8,000 ha in the region.

4.2.6 Connectivity of core habitat in the Northeastern United States: Parks and protected areas in a landscape context

Work done by Goetz and colleagues identified core habitat for the entire US part of the Region and extending south to North Carolina and Tennessee (Figure 16, Goetz et al. 2009). The area was stratified in terms of land ownership and management and then analyzed in a landscape context using connectivity metrics derived from graph theory. The connectivity analysis made use of a suitability surface derived from land cover information, which approximated the costs incurred by hypothetical animals traversing the landscape. They conducted a quantitative analysis of protection status in relation to connectivity and provided maps showing the relative importance of core habitat areas for potentially connecting existing protected areas.

CONNECTIVITY APPROACH: Structural connectivity analysis based on road density, impervious cover and tree cover.

METHODS USED: Graph theory.



▲ **Figure 16.** The 'betweenness' connectivity metric for the northeastern portion of the study region. The high values running through the center of the region indicate a high density of least cost paths traversing those core habitat areas.

MAJOR CONCLUSIONS OR OUTCOMES:

- Protected areas are frequently identified as core habitat but are typically isolated, albeit sometimes buffered by adjacent multi-use lands (such as state or national forests).
- Over one third of the core habitat identified has no protection, and another 42% is subject to motorized recreation or timber extraction. Roughly 20% of the core area identified is currently protected from development and has strong land use controls.
- Conversely, almost 80% of core areas are subject either to development or management activities that could modify habitat quality.
- Large numbers of core areas were identified in northern and western Maine, and these expanded south into New Hampshire where large core areas were contained within the White Mountain National Forest. A linear strip of core areas also extended along the north–south axis of Vermont within the Green Mountain National Forest. The Adirondack and Catskill State Parks in New York contained relatively isolated but large clusters of core areas, including the single largest, as did mountainous areas of the ridge and valley physiographic province. The remaining areas were sparsely distributed across the study area, mostly along the ridges of the Appalachian Mountains.

4.3 Nation-wide and continental projects

4.3.1 North America

Human land uses reduce climate connectivity across North America

Parks et al. (2020) evaluated the influence of human land uses on climate connectivity across North America by comparing one connectivity scenario considering climate in isolation and the other considering climate change and human land uses. They delineated potential movement routes and evaluated whether the protected area network supports movement corridors better than non-protected lands.

CONNECTIVITY APPROACH: Structural connectivity based on climate and an index of human modification to terrestrial land.

METHODS USED: Least cost paths.

MAJOR CONCLUSIONS OR OUTCOMES:

- When incorporating human land uses, climate connectivity decreased; climate velocity increased on average by 0.3 km/yr and cumulative climatic resistance increased for ~83% of the continent.
- ~96% of movement routes in North America must contend with human land uses to some degree.
- Protected areas do not support climate corridors at a higher rate than non-protected lands; however, variability across North America is evident, as many ecoregions contain protected areas that exhibit both more and less representation of climate corridors compared to non-protected lands.

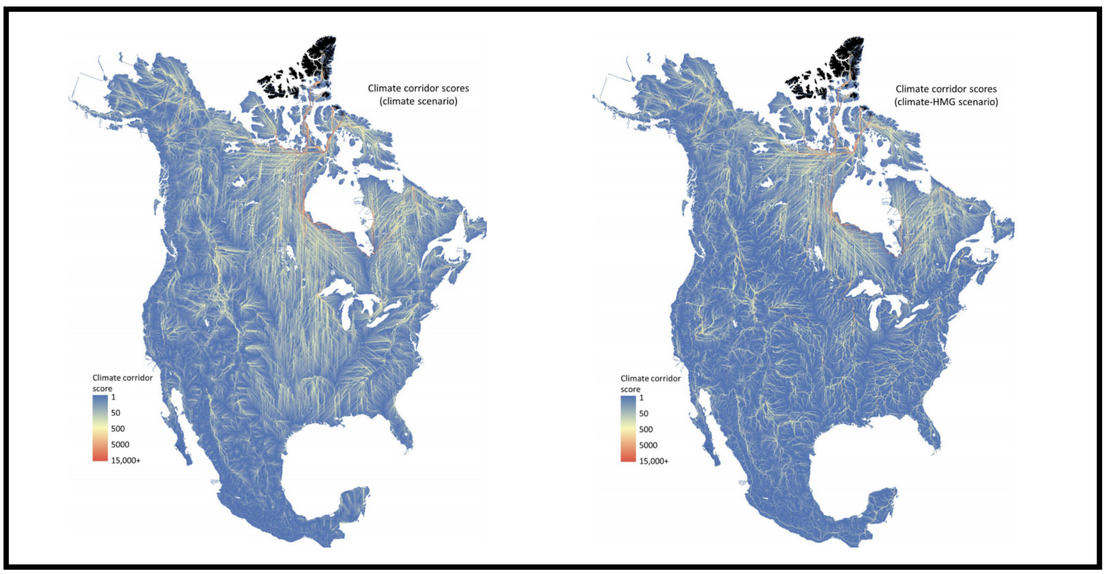
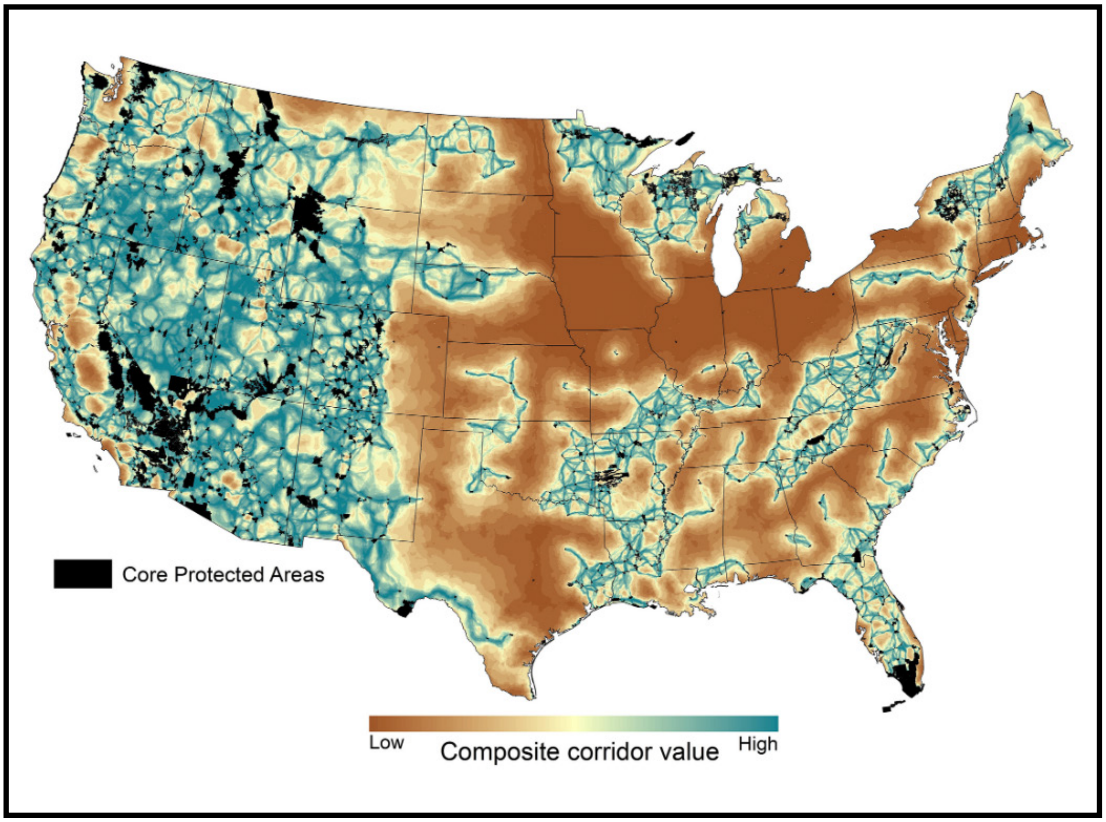


Figure 17. Map depicts the climate corridor scores for the climate scenario (no land use effects, left) and with climate and the influence of human land uses (right). The climate score indicates the ability of a landscape to promote or hinder the movement of organisms in response to a changing climate. Black indicates disappearing climates (Parks et al. 2020).

4.3.2 USA

Identifying corridors among large protected areas in the United States

Belote et al. (2016) identified potential connections between protected areas in the conterminous United States by applying a modeling approach that maps "natural" (i.e., least human-modified) corridors between large protected areas (Figure 18).



◀ **Figure 18.** Composite corridor value between large protected areas of the USA (Belote et al. 2016)

CONNECTIVITY APPROACH: Structural connectivity between core protected areas and resistance surfaces based on indices of map anthropogenic alterations to ecosystems.

METHODS USED: Circuit theory, Linkage Mapper.

MAJOR CONCLUSIONS OR OUTCOMES:

▶ Western regions tended to have lower resistance values leading to higher corridor values, but many eastern regions also host relatively well-connected networks of protected areas, including the southern Appalachians and northern New England.

4.3.3 Canada

Forest connectivity regions of Canada using circuit theory and image analysis

Pelletier et al. (2017) used circuit theory to derive a map of the connectivity of forests regions for the entire geographic extent of Canada (Figure 19).

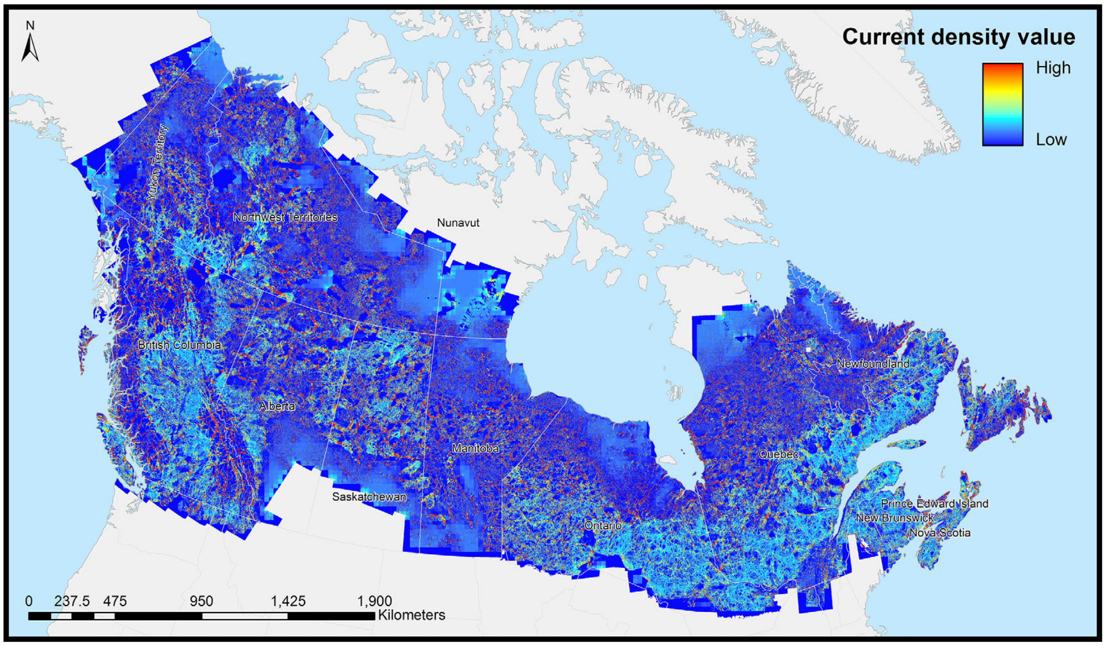


Figure 19. Map of current density (regional flow) using a resistance layer based on forested areas in Canada (Pelletier et al. 2017).

CONNECTIVITY APPROACH: Structural connectivity based on presence of forest.

METHODS USED: Circuit theory.

MAJOR CONCLUSIONS OR OUTCOMES:

- A map of forest connectivity (conductivity) was obtained at the scale of Canada.

4.4 State- or province-level projects

A number of projects have been initiated at the state or province level.
We summarize these for the Region.

Vermont Conservation Design

Vermont Conservation Design identifies features at the landscape and natural community scales that are necessary for maintaining an ecologically functional landscape (Sorenson and Zaino 2018). At all scales, Vermont Conservation Design identifies locations of ecological priority. These are divided into priority or highest priority areas, to allow users to make informed decisions about the locations most suitable for development and those on which to focus conservation efforts.

CONNECTIVITY APPROACH: Structural connectivity using core areas defined from a multi-criteria identification of habitat blocks.

METHODS USED: Primarily least-cost path analysis between habitat blocks; also incorporation of circuit theory based on Anderson et al. 2016.

MAJOR CONCLUSIONS OR OUTCOMES:

- Maps that highlight priority connectivity blocks, regionally significant wildlife corridors, and wildlife road crossings.
- Highest priority habitat blocks (supporting interior forests, physical landscapes, and connectivity) and highest priority surface waters and riparian areas occupy about 68% of Vermont, one-third of which is already protected (Loeb and D'Amato 2020).

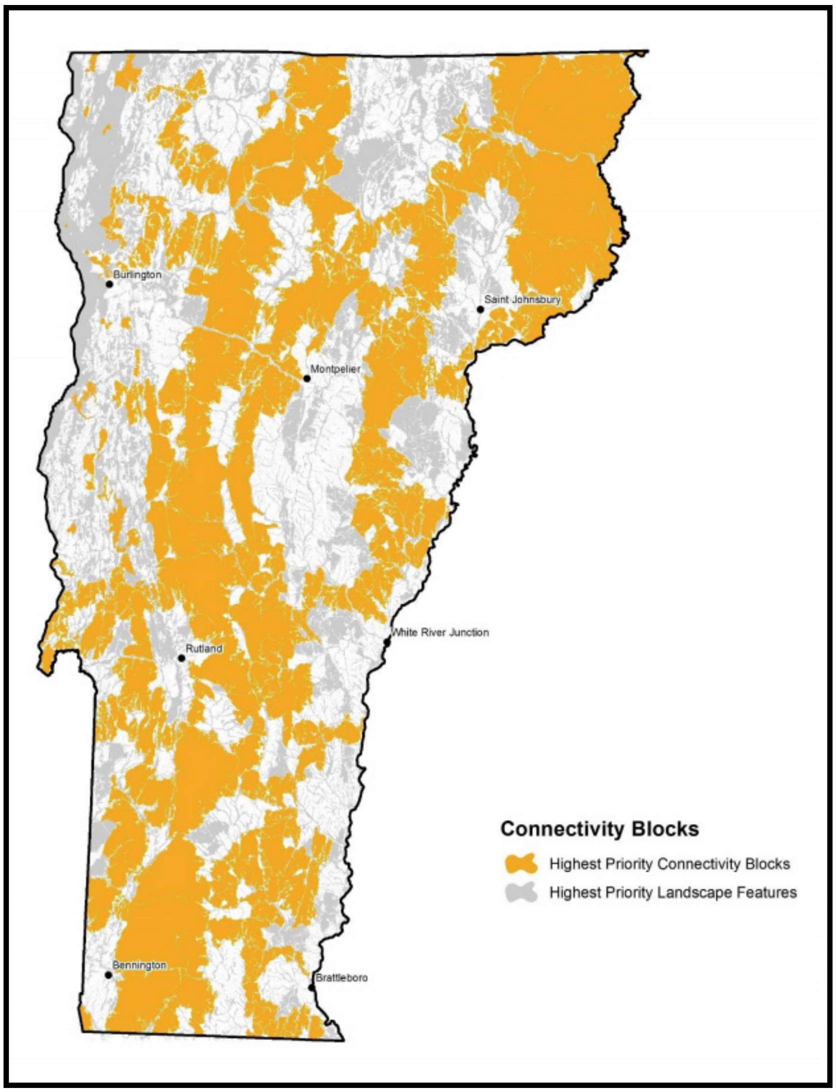


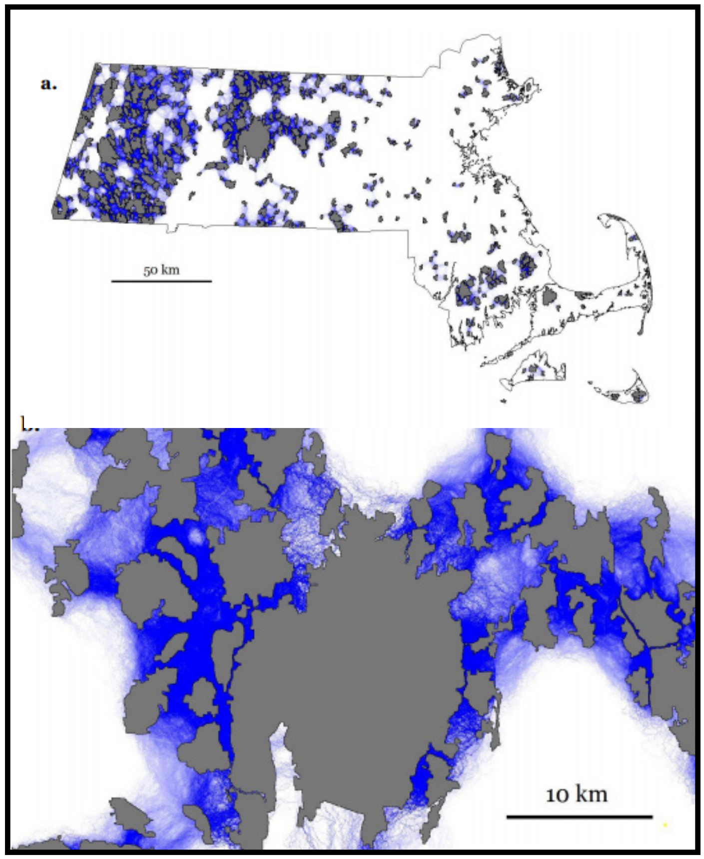
Figure 20. Highest priority connectivity blocks in Vermont Conservation Design (Sorenson and Zaino, 2018).

Massachusetts & Connecticut - Critical Linkages

The University of Massachusetts Amherst is working in partnership with The Nature Conservancy and state agencies to complete a comprehensive analysis of areas in Massachusetts and Connecticut where connections must be protected and restored to support the wildlife and biodiversity resources. The Critical Linkages project (McGarigal, K et al. 2013) has produced maps showing the change in connectedness that would be achieved by the construction of a wildlife passage structure on major roads, as well as maps depicting the effect that the improvement of crossing structures would have on changes in aquatic network connectedness.

CONNECTIVITY APPROACH: Local scale structural connectivity for both aquatic and terrestrial areas, used to assess potential of culverts and road passages to improve connectivity.

METHODS USED: Least cost path analysis.



MAJOR CONCLUSIONS OR OUTCOMES:

- A series of maps that can be used by decision makers and land managers to see impacts of mitigation projects on connectivity.

Massachusetts - BioMap 2

BioMap 2 is a comprehensive biodiversity conservation plan for Massachusetts built on conservation biology principles, rigorous data collection, and GIS analyses that also incorporates climate change adaptation strategies (Woolsey et al. 2010).
It combines 30 years of rigorously documented rare species and natural community data with spatial data identifying wildlife species and habitats. BioMap2 also integrates The Nature Conservancy's assessment of large, well-connected, and intact ecosystems and landscapes, incorporating concepts of ecosystem resilience to address anticipated climate change impacts. Some of the components of BioMap2 were derived using a data set representing a "local connectivity", or connectedness, metric adapted from The Nature Conservancy's Terrestrial Resilience analysis, but at a finer-scale. It identifies areas that support local movements of individual organisms and populations through their life cycle. The connectedness metric is part of an "Index of Ecological Integrity" used to define the Landscape Block, Forest Core, Wetland Core, and Vernal Pool Cluster components of BioMap2.

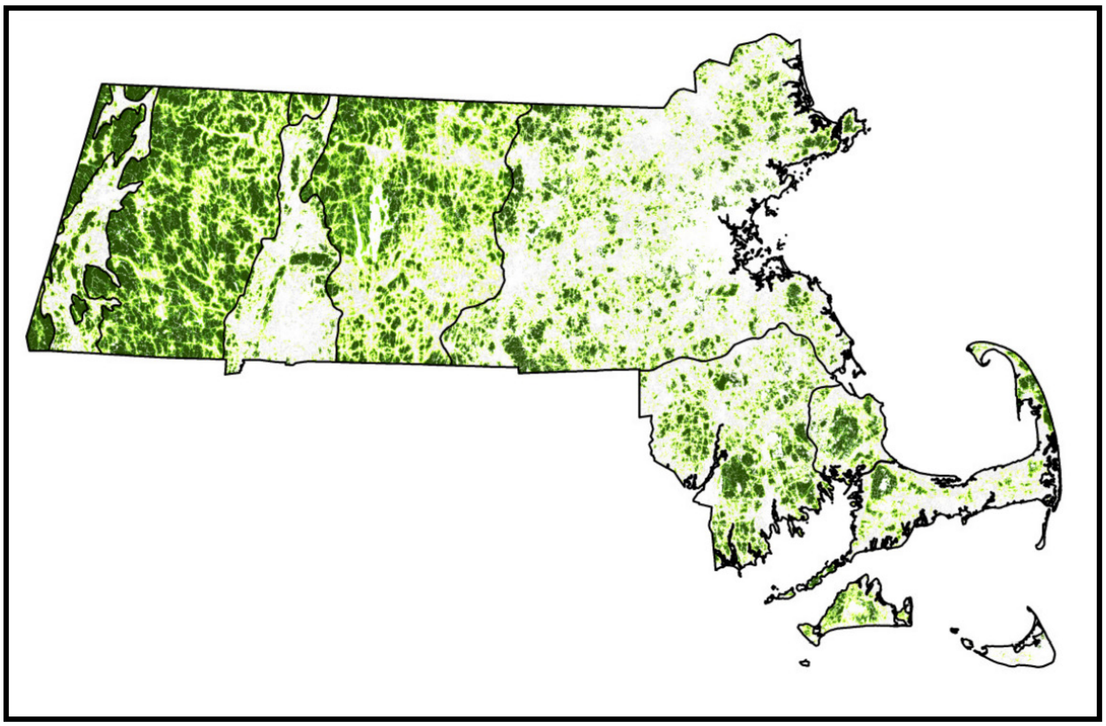
▲ **Figure 21.** Conductance at 10 km bandwidth (blue) and conservation core areas (gray) in the Massachusetts Critical Linkages Phase II analysis (McGarigal, 2013). (a) statewide, and (b) focal area. Conductance indicates the paths between core areas at a fine scale.

CONNECTIVITY APPROACH: Structural connectivity

METHODS USED: Local connectedness.

MAJOR CONCLUSIONS OR OUTCOMES:

▸ The areas identified by BioMap2 comprises 40% of the state's area, divided into Core Habitat areas (24% of the state) and Critical natural landscape areas (34%, with overlap) that collectively represent important habitats for rare species, and for terrestrial and aquatic biodiversity conservation and ecological resilience.



◂ **Figure 22.** Map of forests scored by the Index of Ecological Integrity that incorporates local connectedness as one of its defining metrics in the BioMap2 plan (Woolsey et al. 2010). Darker green areas have a higher ecological integrity score.

Maine - Beginning with Habitat

A collaborative program of federal, state and local agencies and non-governmental organizations, is a habitat-based approach to conserving wildlife and plant habitat on a landscape scale. Beginning with Habitat (**https://www.beginningwithhabitat.org/**) compiles habitat information from multiple sources, integrates it into one package, and makes it accessible to towns, land trusts, conservation organizations and others to use proactively. Each Maine town is provided with a collection of maps, accompanying information depicting and describing various habitats of statewide and national significance found in the town, and tools to implement habitat conservation in local land use planning efforts. BwH is designed to help local decision makers create a vision for their community, to design a landscape, and to develop a plan that provides habitat for all species and balances future development with conservation.

CONNECTIVITY APPROACH: The habitat connections highlight specific lands needed to maintain or restore functional wildlife travel corridors, between undeveloped habitat blocks greater than 100-acres, and between higher value wetlands.

METHODS USED: Unknown.

MAJOR CONCLUSIONS OR OUTCOMES:

- A series of maps that can be used by decision makers at the local level to incorporate results into decision making.
- Many towns in Maine still have continuous tracts of undeveloped land larger than 2,000 acres that support working forests and agriculture, and protect water supplies. However, in rural and remote areas of Maine, a substantial increase of new and newly upgraded (widened and/or paved) roads is fragmenting formerly unbroken forests.
- Along these roads, poorly sized or maintained culverts sometimes isolate aquatic species populations from one another, blocking them from moving through streams.
- Construction of new homes is also fragmenting wildlife habitat, both in subdivisions and on single lots with long, dead-end roads.

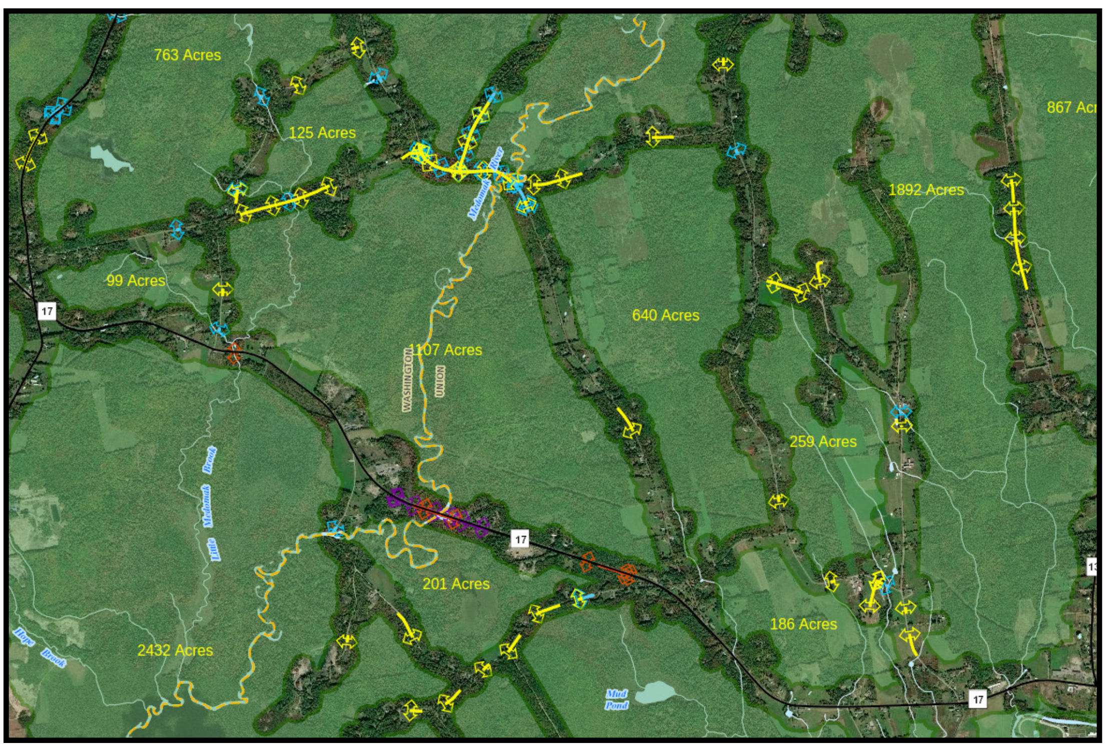


Figure 23. Section of the map viewer showing blocks larger than 100 acres (green), Block connectors (yellow and orange arrows), and Riparian connectors (blue and purple arrows).

Rhode Island - Conservation Opportunity Areas

The connectivity element of Rhode Island's Conservation Opportunity Areas (COA) mapping, referred to as Corridors, is two-fold. First, stream corridors and linear strips of undeveloped land that provide linkages between the state's largest unfragmented forests and other unique, high-value habitats (e.g., important wetland systems and diverse Ecological Land Units) were identified. Once those interstate corridors were delineated, the Rhode Island Chapter of The Nature Conservancy reviewed the map and added corridors previously identified in their regional connectivity, or "flow" analysis. Corridors were delineated as major or minor depending on the estimated amount and concentration of movement based on factors such as the amount and configuration of undeveloped habitat nearby.

CONNECTIVITY APPROACH: Local scale structural connectivity for both aquatic and terrestrial areas.

METHODS USED: Undefined at local scale, circuit theory at regional scale

MAJOR CONCLUSIONS OR OUTCOMES:

- In a state as developed as Rhode Island, the identified corridors tend to cross multiple roads already and remain at risk of further development and degradation. Thus, despite the simplicity of the Corridors element, it's an important tool to help planners and other decision-makers visualize both how and why these linkages must be protected.

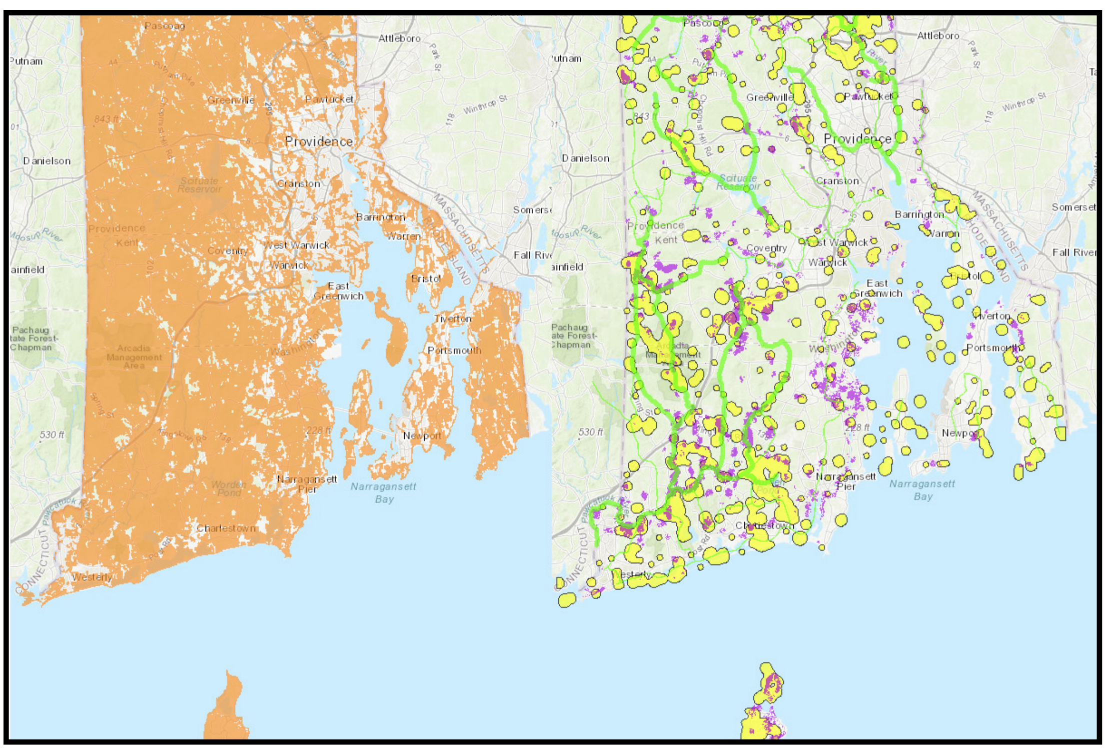


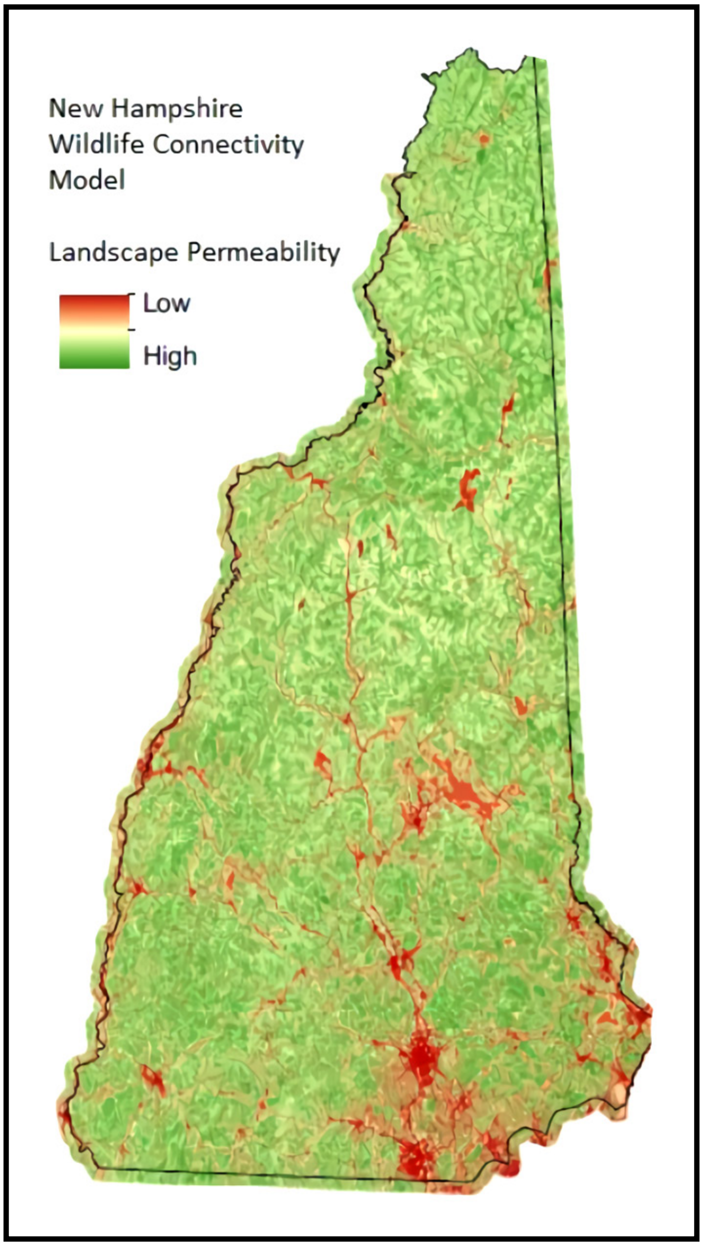
Figure 24. Maps from Rhode Island Conservation Opportunities mapping tool (https://ridemgis.maps.arcgis.com/apps/webappviewer/index.html?id=63f3ef956b3e4711ab3f8dd8349f346e), showing composite Conservation opportunities areas (left, orange), Natural Heritage areas (right, yellow), Ecological Land Units (right, purple) and Corridors (right, light green).

New Hampshire Wildlife Corridors & Wildlife Connectivity Model

The NH Wildlife Connectivity Model predicts wildlife connectivity zones and identifies both key areas for land protection efforts and strategic locations for restoring connectivity (New Hampshire Fish and Game 2018). The NH Wildlife Connectivity Model is a GIS-based, landscape permeability model that predicts broad-scale wildlife connectivity zones across the state. Resistance curves were used to model intense, moderate, and mild effects of distance from 41 roads (based on traffic volumes), land cover, slope, distance from riparian areas, and ridgelines. Sixteen species were chosen to represent a range of species based on the variation in their dispersal behaviors. Both common and rare species, including bobcat, fisher, mink, Blanding's turtle, and New England cottontail, were included. The relative influence of the landscape factors was determined based on literature review; and final scoring was peer-reviewed by biologists familiar with the species. The model has been updated (2006, 2010, 2016) to reflect updates to base data, primarily roads and recent land cover.

CONNECTIVITY APPROACH: NH Wildlife Connectivity Model identifies both key areas for land protection efforts and strategic locations for restoring connectivity in currently fragmented landscapes.

METHODS USED: Resistance surfaces, multispecies approach, potential functional connectivity.



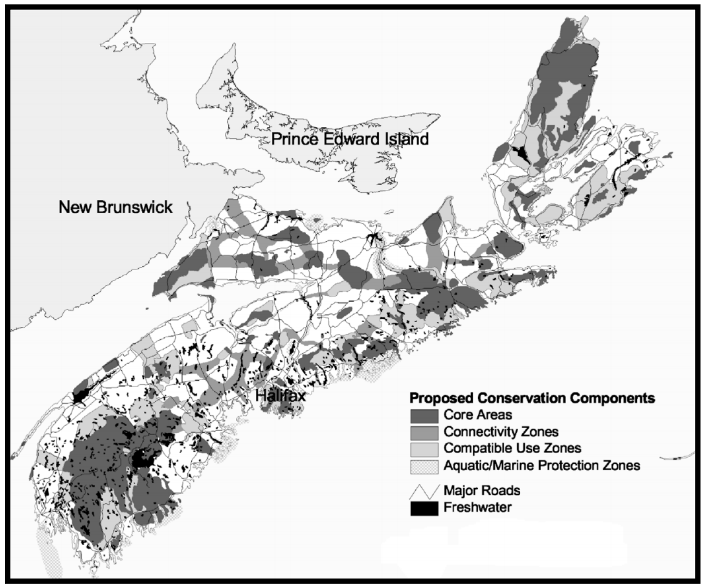
MAJOR CONCLUSIONS OR OUTCOMES:

- The NH Wildlife Connectivity Model was one of several datasets used in the NH Wildlife Action Plan to assess relative habitat condition.
- Wildlife Action Plan maps are provided to municipalities and conservation organizations to guide priorities.

▲ **Figure 25.** Landscape permeability from New Hampshire Wildlife Connectivity Model (New Hampshire Fish and Game. 2018).

Nova-Scotia - Dalhousie University

A workshop was held in 1999 to develop a conservation plan to maintain and restore terrestrial and marine biodiversity in Nova Scotia (Beazley et al. 2004). This effort produced vision maps and recommendations for biodiversity conservation. The wildlands conservation vision identified existing protected areas, areas suitable for filling gaps in the representation of natural landscape types, and other areas of significant ecological value. Four types of conservation areas were proposed: 1) core areas, to be managed primarily for ecological processes; 2) connectivity zones between core areas; 3) aquatic/marine zones around islands, headlands, bays, lakes and rivers; and, 4) compatible use zones, which provide a buffer function while allowing for human uses. In another study (Beazley et al. 2005), key areas of habitat connectivity were delineated by selecting the least-cost paths for three focal species between relevant core areas of high habitat suitability..



▲ **Figure 26.** Proposed conservation components obtained from a consensus building exercise at a workshop held in Nova Scotia (Beazley 2004).

CONNECTIVITY APPROACH: Priority core areas were identified taking into account representation of natural landscapes, focal species habitats, and special elements such as wetlands, biodiversity hotspots, and critical habitats for species at risk. Linkages were identified between these using least cost paths based on habitat suitability, road density, and minimum corridor width (Beazley 2005). Consensus mapping (Beazley 2004).

METHODS USED: Core areas, least-cost paths, multiple species assessment.

MAJOR CONCLUSIONS OR OUTCOMES:

▸ 60% of Nova Scotia with 32% core areas should be managed for conservation to ensure the maintenance of biodiversity in the region.

Quebec - Connectivity in the Ste. Lawrence Lowlands

The Ste. Lawrence Lowlands is an ecoregion of Southern Quebec that is dominated by agricultural activities and urban and suburban areas, with few remaining large patches of natural areas. The area separates the important forested regions of the Laurentians to the North-West to the Appalachian mountains in the South East and the remaining natural habitat fragments in the region might represent very important pieces for regional connectivity. In this context, analyses by Rayfield et al. (2018) and Albert et al. (2017) have adopted a multispecies approach and combined graph-based measures of connectivity and circuit theory and multicriteria spatial prioritization to identify areas of high priority for habitat connectivity in the region. These results have been added to the "Atlas des basses-terres du Saint-Laurent" and ongoing analyses (Rayfield et al. 2018) include land use and climate change scenarios to assess future risks to connectivity in the ecoregion.

CONNECTIVITY APPROACH: Structural connectivity based on habitat suitability maps derived from land cover for a selection of species.

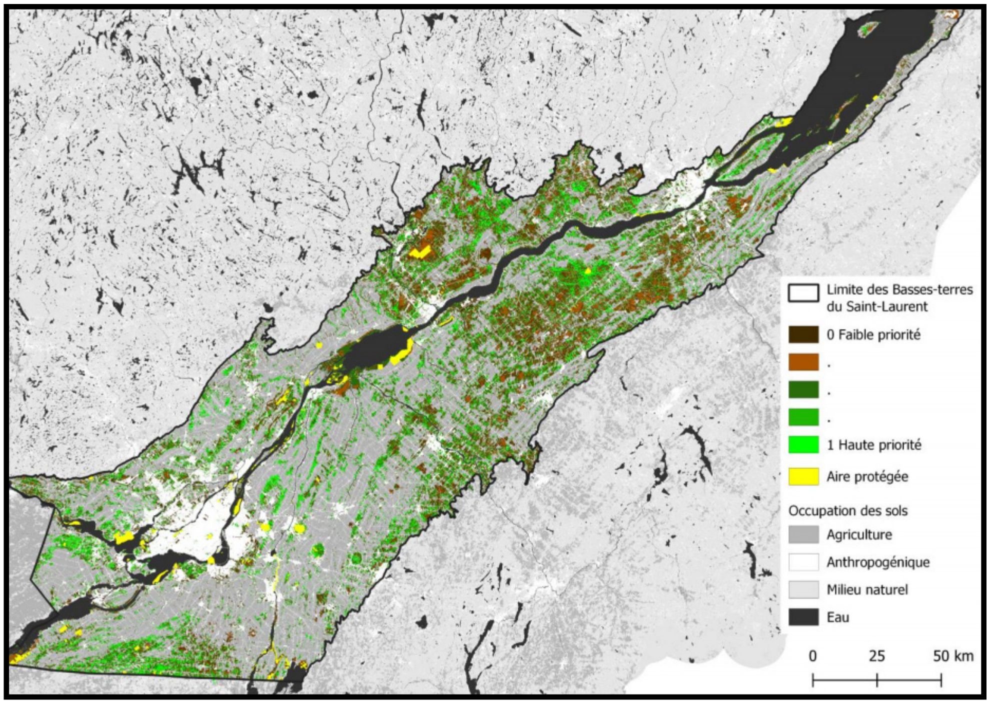
METHODS USED: Graph theory, circuit theory, least cost path, multiple species assessment, spatial prioritization, and scenarios from land use change models and forecasts from regional climate models.

MAJOR CONCLUSIONS OR OUTCOMES:

▶ Connectivity in the Ste. Lawrence Lowlands is relatively low compared with surrounding areas, but there are important zones of connectivity between Montreal and Quebec city that foster the traversability of the lowlands from south to north.

▶ A multicriteria and multispecies approach can combine the needs of species needing different habitat types (e.g. wetland dwelling species, and deciduous vs evergreen forest dwelling species).

▶ A spatial prioritization approach that combines multispecies habitat suitability and connectivity with future projections of land use change and climate change is recommended. Conservation priorities are expected to change over time as the landscape and climate changes so an adaptive management of connectivity is needed.



▲ **Figure 27.** Conservation priorities for natural areas in the Ste. Lawrence Lowlands, based on habitat suitability and connectivity for five target species (from Rayfield et al. 2018).

Quebec - Ecological corridors: A climate change adaptation strategy

In collaboration with several organizations, the Nature Conservancy of Canada is coordinating and implementing a project to conserve important ecological corridors in southern Quebec. This project makes the link with other projects mentioned above, including the Staying Connected Initiative, and Two Countries One Forest. The project, funded by the Quebec Green Fund, is ongoing.

CONNECTIVITY APPROACH: Similarly to the Wildland Network project, this project draws on multiple frameworks, and takes a core and linkage approach to conservation. This work is being carried out in collaboration with multiple organisations to identify corridors that would best connect pre-identified core areas.

Figure 28. Overview map from the Ecological Corridor web platform (http://www.natureconservancy.ca/en/where-we-work/quebec/our-work/ecological-corridors-story-map.html).

METHODS USED: They vary depending on the local partners, from structural to potential functional connectivity (using circuit theory modeling), and in some cases, functional connectivity with field-based habitat definition (relies on animal movement data to identify crucial crossing points, in collaboration with Prof Jochen Jaeger at Concordia University in Montreal, QC).

MAJOR CONCLUSIONS OR OUTCOMES:

- The main outcome of the project is a network of collaborations which extends to a multitude of actors at different scales (national, regional and even municipal).
- The online Ecological corridors - story map (**http://www.natureconservancy.ca/en/where-we-work/quebec/our-work/ecological-corridors-story-map.html**) frames the network produced by the project in an easily accessible way.

4.5 Overview of objectives and methods adopted by connectivity conservation projects in the Region

In this section we summarize the information we gathered from our review of the projects dedicated to connectivity conservation planning in the Region.

4.5.1 Objectives, target ecosystems and taxa

The most common objectives cited by the projects inventoried on the Ecological Connectivity portal are land protection, connected corridor network design and core priority area designation (Figure 29). While projects cover all types of terrestrial and aquatic ecosystems, forested and agricultural systems are the most well represented (Figure 30). When specific species are targeted or studied, mammals, birds, fish and plants are most frequently cited (Figure 31). Insects, other invertebrates, and fungi, molds and yeasts are very rarely directly considered a focal priority in these projects.

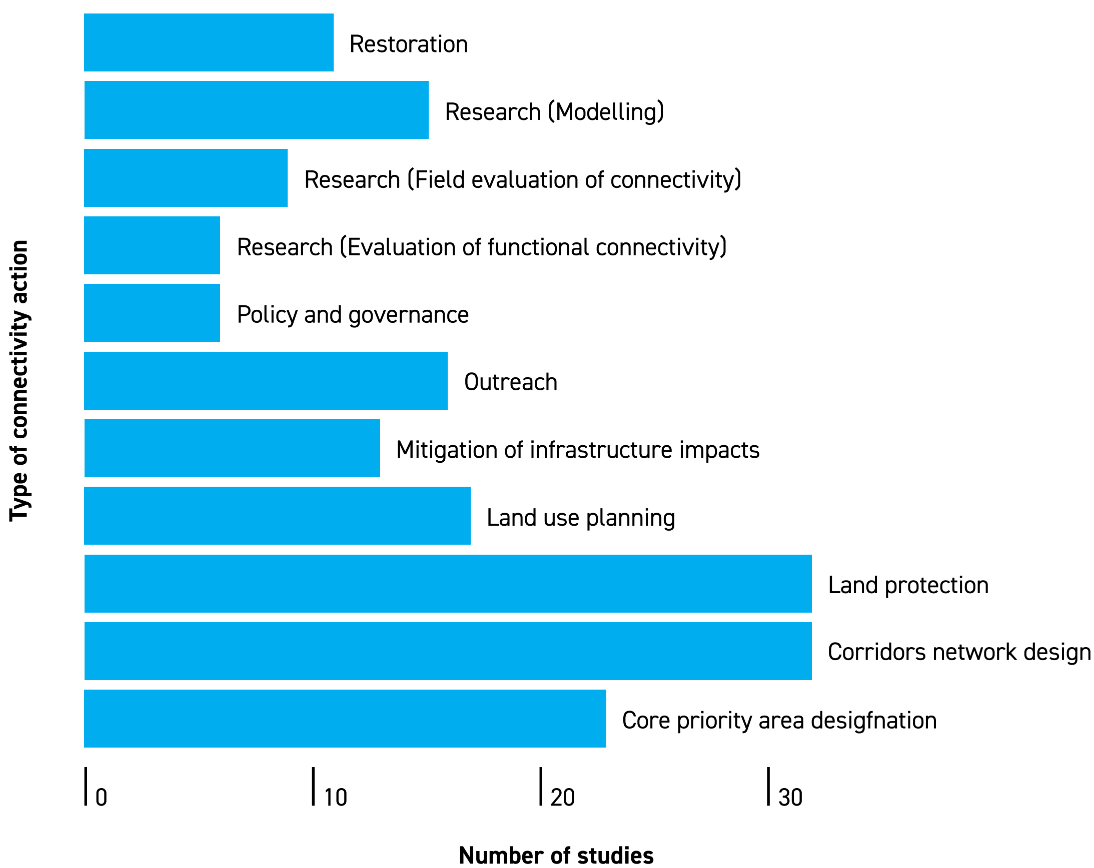


Figure 29. Number of connectivity projects in the Region by type of connectivity action.

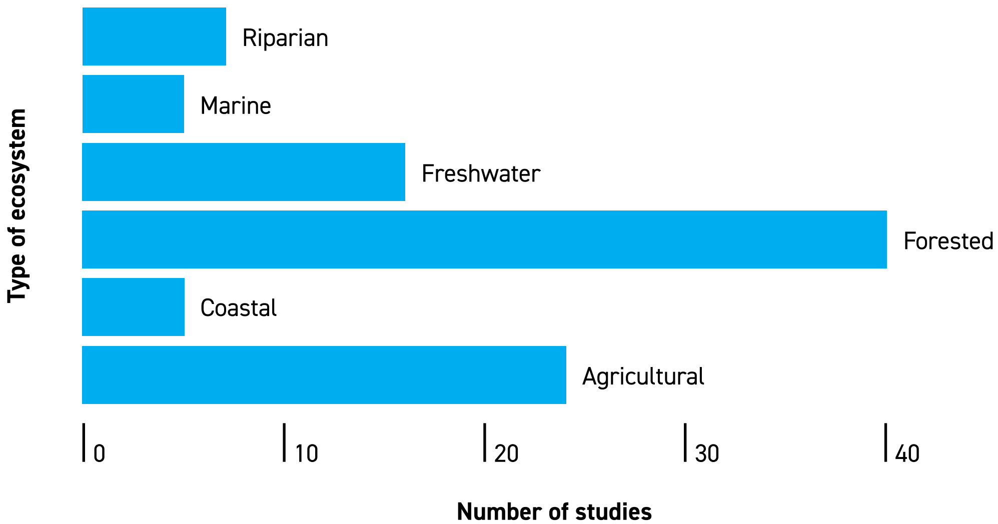


Figure 30. Number of connectivity projects in the Region by ecosystem type.

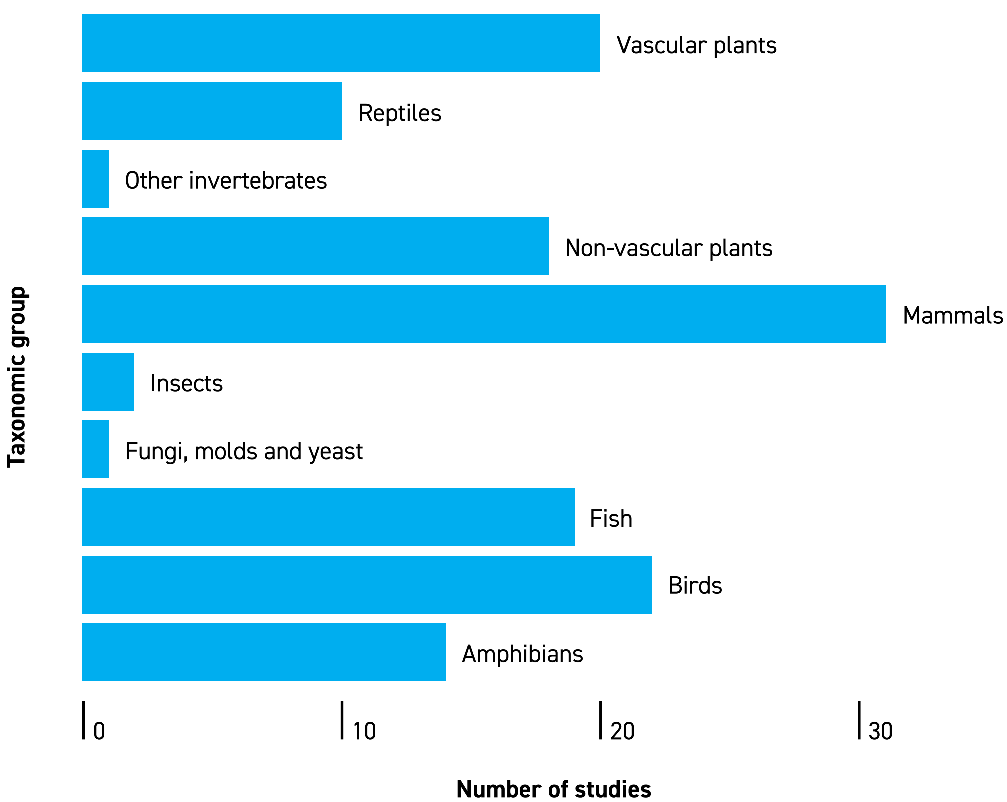


Figure 31. Number of conservation science projects in the Region by taxonomic group.

4.5.2 Most frequent methods and workflows for habitat and corridor identification

We studied 25 applied conservation projects in the Region to assess the methods and workflows they adopted (see further details in Appendix 1).

To achieve their objectives, projects in the Region generally rely on the analysis of remotely sensed and readily available geospatial data in GIS to derive maps of land cover, land ownership, land protection status, and other layers representing environmental or social measures considered relevant to conservation and connectivity. Important habitats or core areas can be established using simple land cover categories as done by the recent Vermont conservation design (Sorenson and Zaino 2018) or with elaborate multi-criteria evaluations combining multiple layers such as in the Staying Connected Initiative projects (Coker and Reining 2013). Currently, factors such as habitat patch area, distance from roads, or fragmentation, and constraints such as land cover type or land ownership are generally considered by these projects.

Once important patches of habitat are identified, the most common approach to identify linkages is to derive a resistance surface based on a combination of criteria considered to affect the movement or dispersal of species (presence of roads, agricultural and urban land cover etc.). This continuous resistance surface is then used to obtain least-cost pathways representing potential trajectories of movement or dispersal that minimize distance between patches while following a path of least-resistance. In many studies, potential corridors (contiguously connected areas of habitat) might be identified from the paths using a number of techniques including fixed-distance buffers. A smaller number of projects use methods based on set rules derived from literature or expert opinion to prioritize links or paths between patches. This is especially the case in projects studying freshwater connectivity since the dispersal links for fish and other aquatic organisms are restricted to known watercourses (Martin and Levine 2017, Noseworthy et al. 2019).

Software used to support corridor identification, such as Linkage Mapper, Zonation, Marxan or SITES are often used in the final assessment phase for optimal corridor design. Additional criteria such as budget constraints and feasibility are also used. A few projects also conducted workshops with local experts to validate and improve the design of their ENCs. The final proposed design is produced in the form of a vector GIS layer(s) and graphical map indicating the location of the corridors.

A number of projects followed a much simpler workflow and proposed general frameworks to identify core priority areas and linkage areas without adopting a typical habitat definition, linkage definition, or assessment workflow. This method, often applied at large scales, seems to be a first step toward the building of consensus around what habitat needs to be protected and linked, and which then provides grounds for more detailed analyses down the line.

4.6 Identification of key areas for ecological connectivity

KEY MESSAGE

Most projects agree on the large core natural areas and connectors to protect within the Region. The models provide valuable support to the identification and comparison of network priorities across the Region.

The identification of key areas for connectivity depends on spatial scale and resolution. At the scale of the entire region and at a coarse resolution, most projects agree about the major core areas that represent important natural habitats. These are concentrated in northern and western Maine, within the White Mountain National Forest, along the north–south axis of Vermont within the Green Mountain National Forest, in the Northern half of New-Brunswick, in a lot of the Gaspésie peninsula, and in North-Central Quebec. A good overview of these large zones of core natural areas are defined in the Eastern Wildway project (Reining et al. 2006), whose authors conclude that their proposed "[…] design provides important insights into the major regional patterns of high terrestrial conservation value and landscape linkages. Regardless of future adjustments, it is unlikely that concentrated areas of the most highly irreplaceable conservation features at the regional scale identified through this analysis will vary significantly. "

Interestingly, projects that were carried out at a finer resolution identified a much more intricate network of core areas, regardless of the scale of the analysis. For example, Nature's Network maps of terrestrial and aquatic cores (Figure 15) , or the Vermont Conservation Design outputs contain core areas that are much smaller and with more spatial complexity compared to projects like the Eastern Wildway. This indicates that resolution (e.g. pixels on raster) is a very important aspect of the analysis to consider when comparing key areas for connectivity.

When it comes to isolating areas that are specifically important for connectivity, the Staying Connected Initiative priority linkage areas project, while not performed consistently across the region, likely represents the most comprehensive assessment. Of the nine linkage areas they identified and documented, three overlap the US and Canada border and all nine cover more than one state or province. The conservation efforts focusing on these areas would form a core part of the collaboration focused on Resolution 40-3 and could be an ideal starting point for expansion into the north and south of the region for more complete coverage.

The TNC Resilient and Connected Landscapes project (Anderson et al. 2016) compiled 58 connectivity studies completed in Eastern North America that included areas from maritime Canada to Florida. They used visual comparisons and spatial overlays to compare the regional flow results from these studies. They identified studies that had spatially explicit results and were appropriate for comparison with their regional flow analysis. They excluded studies that focused on aquatic species as well as those conducted at very fine scales.

The project ended up selecting 30 sites; of these, 57% had good agreement with their regional flow results and 43% had moderate agreement. No study had poor agreement. Highest agreement was found between the regional flow results and species movement studies that did not start with a priori cores. However, this comparative analysis highlighted the difficulty of directly comparing results among studies conducted with different objectives, methodologies and presentation of results. Anderson et al. (2016) state that "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". This study thus made it clear that the identification of important corridors, linkage areas or regional flow areas is largely dependent on the scale, resolution, specific methodologies and the species assessed.

4.7 Major conclusions from existing projects

CONCLUSION 1

There remain large extents of connected natural habitats in the Region but anthropogenic pressure is increasing in these areas.

Our review of the literature and connectivity projects spanning the Region of Resolution 40-3 has clarified a number of points that we offer here as four major conclusions.

Several projects identify the Region as vital to connectivity at the scale of North America because it still contains large tracts of natural areas, and many of those areas are relatively well connected. Since some important key areas are close to large urban centers, they are increasingly vulnerable to urban sprawl, road development and resource extraction. In the US portion of the Region, Goetz et al. (2009) established that almost 80% of core areas are subject either to development or management activities that could modify habitat quality and connectivity. In Maine, for example, 22 percent of the land has changed hands since 1998, leading to intensive land use change pressures (Wildlands Network, Maine Wildlands Network Vision). The Vermont Conservation Design identifies 68% of the state's land base to be of the highest priority landscape conservation feature; 33% of this area is already protected, and 41% of the highest priority connectivity blocks are protected (Loeb and D'Amato 2020). Also, certain large natural areas that are in relatively close proximity to one another are not well connected due to major barriers such as highways or large agricultural zones. For example, TNC Resilient and Connected Landscapes identified 201 areas where major roads interfere with areas of high regional flow (Anderson et al. 2016). We have a window of opportunity to act at the scale of the Region to preserve large areas of connected forest and watersheds that will be essential for biodiversity as it shifts in space over time in response to climate change.

CONCLUSION 2

A large percentage of areas identified as key priority areas for connectivity conservation are not protected.

Over one third of the core habitat identified by Goetz et al. (2009) has no formal protection, and another 42% is subject to motorized recreation or timber extraction. Roughly 20% of the core areas identified are currently protected from development and have strict and use management. Similar findings are reported in the Adirondacks to Acadia study where about 14% of the total proposed network is in existing core protected areas, 23% is in proposed core areas and the remaining 63% is in lands of high biological significance. About 53% of their proposed network remains privately held and subject to potential development.

CONCLUSION 3

Many of the key connectivity areas cover multiple states and provinces

As seen from the Staying Connected Initiative, some of the important remnants of natural areas in the Region cross state-level boundaries or US-Canada borders. Note that projects that extended beyond the boundaries of the Region, for example by including New York state or Ontario, established corridors that connected parts of the Region to core areas outside of it. This highlights the need to include a relatively large buffer to assess the connectivity of the Region's network, and its contribution at the continental scale.

As stated in Resolution 40-3: "our region's forests and water resources cross provincial, state, and national borders. Effective action to sustain these assets, along with the invaluable ecosystem goods and services they provide, requires collaboration across borders". Recent research indicates that transboundary connectivity conservation is challenging due to differences between smaller scale connectivity initiatives such as methodology and priorities but that this collaboration is vital for effective conservation (Santini et al. 2016). Resolution 40-3 has enormous potential to reinforce ongoing efforts to protect the connectivity of the region's ecosystems and the many benefits we derive from them.

CONCLUSION 4

Connectivity conservation requires collaboration among all stakeholders and rightsholders across the jurisdictions of government and non-governmental organizations

Existing projects have shown that planning for an integrated ENC for the Region is a challenging task that requires rigorous methodologies and extensive, high quality, data sources that are not readily available. Crucially, some projects have highlighted that communication channels must be facilitated to work toward consensus building around the choice of core areas and corridors for conservation. As the Wildlands Network Adirondacks to Acadia report (Reining et al. 2006) states: "It is critical to involve regional stakeholders, such as scientists, infrastructure planners, and energy planners among others, in the process of designing and implementing a network design. The draft network design should also undergo rigorous expert reviews before a final design is released."

Initiatives such as the Wildlands Network's Eastern Wildway, or ongoing work in the Montérégie area of Quebec have organized workshops between experts and stakeholders to catalyze consensus building for regional ENCs. These projects have shown that consensus is possible, especially on the ecological and geographic priorities, but practical information needed to support action on the ground (e.g. which sites to prioritize first, restoration vs planting) and that the success of this action may vary greatly from region to region. Nevertheless, proper consultation, collaboration and the involvement of stakeholders are essential to bolster the political and social acceptability of the ENC.

5
Gap analysis

5.1 Regional gaps in connectivity conservation science

KEY MESSAGE
Large portions of the Region are covered by sophisticated connectivity analyses and represented by integrated projects. However, certain areas are not well covered by existing initiatives. There is an opportunity to conduct an integrated connectivity analysis for the entire Region.

As we have seen above, the spatial coverage of projects in the Region is relatively uneven. There are a number of collaborative efforts to identify core conservation priority areas and linkages over large extents of the Region, notably over the Northern Appalachian-Acadian ecoregion and Northeast and Mid-Atlantic regions of the USA. However, only the Wildlands Network Eastern Wildway project covers the entire extent of the region. Atlantic Canada, Gaspésie, Northern Quebec and Rhode Island are only covered by a limited number of projects or scientific studies (Figure 9 and Figure 32). As seen above, state or province-wide initiatives are carried out using a number of different frameworks. There is a clear opportunity to conduct a region-wide and multiscale analysis of functional and structural connectivity over the Region.

While projects in the region make recommendations for the conservation of a wide range of species, the spatial extent of these studies is rarely informed by the distribution of these species and their expected range shifts in the coming decades (Suárez-Seoane and Baudry 2002). Research is being done to study landscapes at multiple scales in order to capture the ecological needs of a larger range of species (Anderson et al. 2005, Resetarits 2005, Rayfield et al. 2018, Vanak and Gompper 2010). Within the surveyed literature on connectivity, we identified multiple studies which assessed connectivity at a minimum of two different scales (Foster et al. 2016, Carvalho et al. 2016, Boyle et al. 2017, Vanbianchi et al. 2018). For example, one of these assessed connectivity at a local scale using road surveys combined with a regional scale assessment using circuit theory (Boyle et al. 2017); this allows recommendations on large regions where efforts should be concentrated and specific locations where crossing structures should be planned. The applied connectivity projects surveyed did not consider multiple scales and, rather, chose to assess landscapes and connectivity at a single scale.

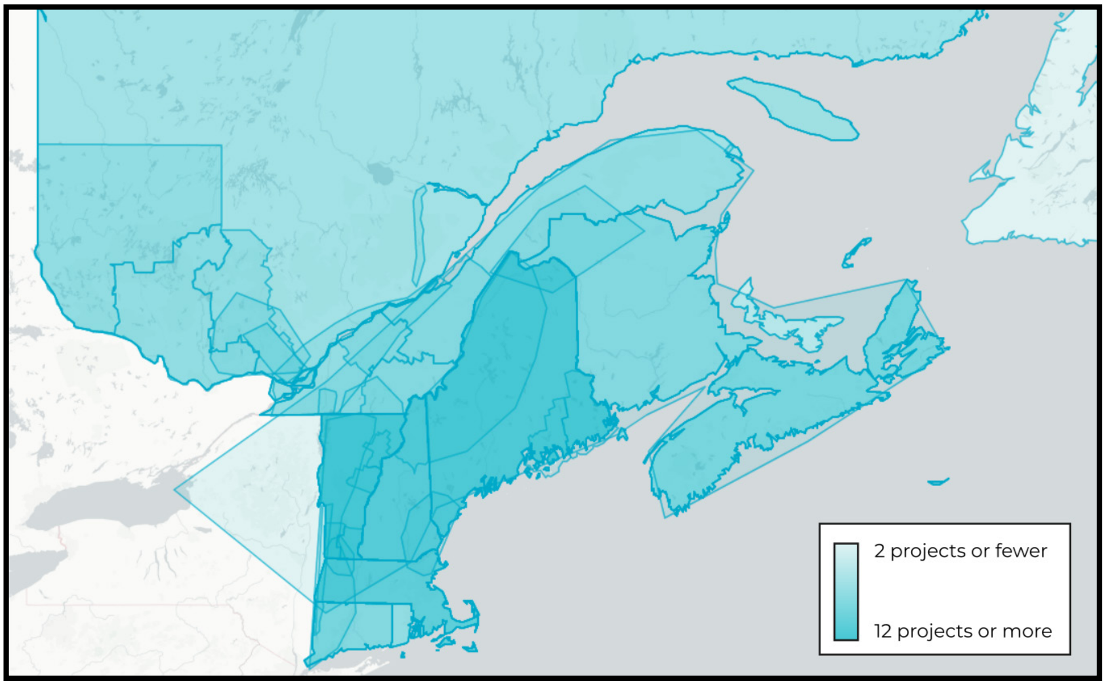


Figure 32. Map showing the overlay of the extents covered by connectivity projects in the Region and entered on the Ecological Connectivity web portal. Darker blue areas are covered by a larger number of projects.

5.2 Gaps in the coverage of ecosystems and species groups

KEY MESSAGE

Forests and aquatic systems are in general well represented by projects in the Region. However, some groups of species, such as insects and other invertebrates, are underrepresented by connectivity assessments in Region. There is an opportunity to assess the connectivity between aquatic and terrestrial ecosystems in future studies.

A majority of projects in the Region target the conservation of natural areas (forested areas, streams, undisturbed areas, etc.). Forest ecosystems are well represented in terrestrial studies (Figure 30), with relatively few studies considering grasslands, wetlands, watersheds or other ecosystem types. Projects could better integrate these ecosystem types as core areas of conservation value, and as potentially important nodes of connected networks.

Insects are generally neglected in connectivity studies in general and this is also true for the Region. Nevertheless, most insect species are affected by local-scale connectivity and there are a number of migratory insect species that are particularly affected by regional habitat connectivity (e.g. monarch butterflies). Studying the connectivity of insect habitats would help in conserving essential insect-driven ecosystem benefits such as pest control and pollination. In addition, these studies would likely improve our understanding of ecological connections such as insect-borne disease spreading, forest insect pest infestation potential, and the spatial variation in the food of insectivorous animals.

Few studies explicitly considered restoration opportunities in their connectivity analyses. For example, agricultural field abandonment, tree planting, or reconversion of industrial land to vegetated areas or wetlands in key areas are options for improving the overall ecological connectivity of a region.

Studies focused on aquatic connectivity generally take a species-agnostic approach and place their focus on the impact of infrastructure such as dams and culverts on structural connectivity. While these types of analyses can generate important conclusions about improper placement and/or installation of barriers, the life history of species which occupy these waterways are varied and should also be taken into consideration. For example, only Nature's Network considered the connectivity of lake habitats. Many regional species carry out their life-histories in lakes using streams to move between them. The degree of connectivity between these lakes is an important aspect of the landscape for the persistence of these lake-dwelling species.

Despite the large number of green or blue connectivity projects, few explicitly considered the joint connectivity of aquatic and terrestrial networks. However, work has been done to assess important riparian habitats which represent an important link between the two realms. TNC's Resilient and Connected Landscapes (Anderson, 2016) considered riparian corridors in their connectivity assessment. In addition, Vermont Conservation Design also addressed riparian and terrestrial connectivity, emphasizing the importance of riparian areas and their restoration to provide connectivity and many other ecological functions in highly fragmented landscapes. More research is needed to better understand and protect the linkages between these ecosystems types (Muehlbauer et al. 2019, Sullivan and Manning 2019). For example, the identification of streams important for aquatic connectivity might also lead to the protection of contiguous riparian habitat which represent an important corridor for terrestrial species movement. Aquatic insect resources arising from streams and rivers can support bird communities using riparian corridors. Similarly, the conservation efforts in the context of a terrestrial connectivity project might have important consequences for the flow of nutrients and energy into aquatic systems and the maintenance of its biodiversity.

5.3 Methodological gaps in connectivity projects in the Region

KEY MESSAGE
A number of important methods can be added to future connectivity studies in the Region, including spatial biodiversity models, multi-scale connectivity assessments, and scenario-based evaluations of uncertainty due to climate and land use change.

Here, we describe general gaps that we identified by comparing methodologies and workflows used in connectivity research worldwide.

5.3.1 Extending methods for defining habitats and links

BIODIVERSITY MODELING: A number of methods for biodiversity modeling and prediction have been developed in the scientific literature that could be included in future assessments by the projects in the Region. One of the most common methods used to define changes in the spatial distribution of diversity in the surveyed scientific literature is the species distribution model and more recent multispecies and multitrophic variants of these models (e.g. Talluto et al. 2018, Braga et al. 2019). Using knowledge of ecological and environmental requirements of the focal species, these methods allow researchers to predict the expected change in distribution and habitat use of large sets of species. Care should be given to the uncertainties associated with these models. However, while they cannot guarantee projections of where species will be in the future, they offer an opportunity to validate current network designs and inform future updates of these designs.

DATA-BASED VALIDATION: Of the reports inventoried, few indicate that field data are obtained to validate the selection of cores and linkages. One study incorporating field work was done at the relatively small scale of a buffer around a single large highway in Quebec (Gratton 2014). Two other studies collated data on species occurrence from multiple sources (Martin and Levine 2017, Noseworthy et al. 2019). Moreover, few studies validated the habitats and links defined with existing species occurrence data. The surveyed scientific literature also points to the value of genetic information to validate the links proposed among habitats (Marrotte et al. 2014, Thatte et al. 2018, Zeller et al. 2018). Somes species-specific genetic studies are underway in the Region. For example, there is an effort to characterize the genetic structure, diversity, and relatedness of wood turtle (Weigel and Whiteley 2018) and spotted turtle (**https://rcngrants.org/content/spotted-turtle-conservation**) populations in the Northeast U.S.. However, these types of studies are relatively rare, and are not conducted at the spatial extent of the Region.

5.3.2 Quantifying connectivity at multiple scales

In general, projects in the Region did not present how connectivity planning met movement needs at different spatial scales. Most applied connectivity projects aimed to identify a set of important patches and ecological corridors. Thus, in the final assessment phase of the analyses, these studies tended to obtain or validate an optimal corridor design by considering important factors such as budget constraints, feasibility, political factors and other important trade-offs, but not by the scales of connectivity they support.

In the projects that have been considered here, assessments which explicitly considered the trade-off between budget and benefits to multiscale connectivity were focused on freshwater systems and prioritized dam removals (Martin and Levine 2017, Noseworthy et al. 2019). A few projects presented conductance maps or benefit maps as a visual form of assessment.

Very few projects investigated the importance of within habitat connectivity. In a recent analysis, it was shown that a commonly used connectivity metric (Connectance Index) ignores within-patch connectivity and might lead to erroneous conclusions; for example that fragmentation leads to higher connectivity (Spanowicz and Jaeger 2019). The effective mesh size metric that includes both within-patch and between-patch connectivity is suggested as an alternative metric.

5.3.3 Dealing with uncertainty via scenario-based forecasts and adaptive monitoring

Major sources of uncertainty in the Region include climate change and land use change, and the likely impacts of their interaction on habitat quality and connectivity. These drivers will no doubt affect the future efficacy of a regional ENC. Future informed connectivity planning can be based on downscaled (regional) climate forecasts and from projections of land use change and development. These projections can be used to assess the erosion of an ENC's ability to protect connectivity into the future, but they can also be used to iteratively improve the design of the ENC to account for regions where change in habitat quality and connectivity is expected in the near to medium term (Gregory et al. 2014, Dilts et al. 2016, Hamilton et al. 2018, Carlson et al. 2019).

In the absence of accurate forecasts, major sources of uncertainty can be addressed with scenario-based modeling; an approach commonly used in conservation science, but seldom used in connectivity science (Hamilton et al. 2013, Mitchell et al. 2015, Lechner et al. 2017). Scenario-based planning has the potential to 1) allow the explicit inclusion of broad uncertainties in future land use in the decision making process 2) allow corridors and connected network designs to be more robust to changes in climate and land use, and 3) allow sets of solutions--rather than single corridor or networks designs--founded on an adaptive approach to managing connectivity in an uncertain world.

Ultimately, connectivity analyses need to better incorporate the feedbacks between people and nature, climate change, and land use change projections (Anderson et al. 2016, Albert et al. 2017, Gonzalez et al. 2018). Model-based projections of the region's future must be linked to adaptive monitoring of biodiversity (Lindenmayer and Likens 2009) and species' movements (Fraser et al. 2018) across the network so that data can inform models and guide the conservation of the Region's connected landscapes.

6
Recommendations

In this section we offer five recommendations based on our review of the literature, research methods, and connectivity projects in the Region. We have gathered these below into a set of five specific recommendations which we believe will support and strengthen science-based assessments of connectivity in the Region. Whenever possible, we follow these recommendations with specific tools, methods, and knowledge.

RECOMMENDATION 1
Building on existing initiatives, regular assessments are needed to evaluate the changing state of connectivity at the scale of the entire Region.

Several comprehensive ecological connectivity studies were carried out over a significant portion of the Region and can be used as strong building blocks for further analyses. The Staying Connected Initiative and the updated version of TNC's Resilient and Connected Network include a large part of the Region and represent scientifically thorough efforts to map connectivity and identify key areas for conservation and restoration. The Wildlands Network Eastern Wildway and Nature's Network projects also cover a large part of the Region but represent an integration of several studies and not a single unified analysis.

We recommend expanding some of these studies to cover the entire Region, including the southern states, Newfoundland and Labrador and Northern Quebec. A Region-wide analysis would allow us to better understand the possible connectivity pathways between Northern New England and Gaspésie and New-Brunswick to the East, and with the forests of the Laurentians and Northern Québec to the West and North. This would be important to understand the potential role of the Ste. Lawrence Lowlands, both as a barrier for regional connectivity and where targeted conservation efforts could improve regional connectivity.

It is also clear from our assessment that the inclusion of New York State, the Adirondack mountains and Eastern Ontario into the Region would be necessary to derive a connectivity assessment that better captures the habitat distribution and dispersal patterns of species at the regional scale. The Adirondacks, and the Algonquin Park area represent an important extent of protected and natural areas and a potentially important connectivity pathway at the regional scale for species to move north from New England and through the Ottawa region towards the large forested area of Northern Quebec.

Performing assessments at regular intervals would allow for the detection of changes and potential thresholds in connectivity metrics and allow for the re-evaluation of the efficacy of conservation measures in place to protect or restore connectivity.

RECOMMENDATION 2
Support for open sharing of methods and data for collaboration at the scale of the Region.

The development of the Ecological Connectivity project and online portal has addressed the need for better sharing of information, reports and methodologies among different stakeholders. We recommend continued development of this platform and continued updating of the projects listed on it. We further recommend focus on open-source technologies that might facilitate sharing of analysis workflows. Explicit partnerships can be established with the scientific community to share workflows and benefit from the highly qualified personnel and computational capabilities available in academic research environments.

We further recommend the alignment of data sources used to design and monitor the implementation of a Region-wide ENC. Precise and valid maps of detailed land cover, topography, stream and road networks and geological features should be generated for the entire Region. These data should be obtained from the integration of existing datasets, and can build on the work of partners who have already generated datasets for their jurisdiction or for large parts of the Region. These data should be complemented with data on the distribution of flora and fauna in the Region. This can be derived from data from partners such as NatureServe, provincial Conservation Data Centres, and state Natural Heritage Programs. Data can also be integrated from rapidly growing open online repositories and citizen science initiatives (e.g. GBIF, eBird, iNaturalist).

The use of these datasets requires appropriate computational resources and protocols. Thus, data pipelines for connectivity assessments and monitoring should be used to support the species distribution models, occurrence data, and statistical analysis and prioritization tools used to conduct connectivity assessments. These protocols will greatly enhance the comparison and synthesis of results across studies and therefore provide a firmer basis for future evaluations of the status and trends in the region's connectivity.

The co-design of ENCs with all relevant stakeholders is essential. This will be important if we are to address the social acceptability of connectivity conservation in the study region. To this end we must communicate the many benefits and costs associated with connectivity-based conservation strategies. Stakeholders at all levels should be consulted, including municipal, state and provincial, indigenous people, conservation agencies, landowners and citizens.

RECOMMENDATION 3
Integrate analytical methods and adopt a multi-scale approach that supports prioritization and the implementation of an ENC across jurisdictions and scales.

Studying the same species using multiple connectivity indices and criteria can result in different spatial prioritizations for an ENC (Théau et al., 2015, Meurant et al. 2018). Combining multiple methods produces more robust assessments that account for uncertainty in habitat preferences, movement ecology, and future environmental conditions (Finnegan et al. 2012). In our review, we saw that the scientific community makes use of a wider set of powerful tools and techniques to assess connectivity compared to the conservation community of the Region. We believe this provides an opportunity for an integration of the latest workflows used for research with those currently adopted by the conservation community.

Multi-scale connectivity assessments have been embraced by the scientific connectivity community and are now considered a more robust basis for connectivity assessments (Maciejewski and Cumming 2016). Multiscale assessments can also simultaneously guide conservation at the local scale (<1km2), while incorporating constraints and opportunities for management for the entire region. An analysis at the scale of the entire Region would represent a "coarse-filter" approach to identify threats, challenges and opportunities to connectivity conservation at the landscape and regional scales. This could be complemented with a fine filter approach to understand challenges at local scales.

Many of the reviewed connectivity conservation projects did not focus on particular species and rather focused on specific landscape features with the assumption that these would lead to prioritizations which conserve species depending on these features. However, without explicit consideration for these species it cannot be said with great certainty whether these actions will benefit threatened species in the region. On the other hand, focusing connectivity analyses on one species at a time is impractical and inefficient in terms of time and resources.

A middle ground which we recommend is the adoption of multiple species assessments combined with landscape geodiversity. This multispecies assessment could be complemented with the approach of landscape geodiversity (Anderson et al. 2016) to develop prioritization areas that are not only suitable for the target species habitat and movement, but that also contain a diversity of landforms and topographies, thereby potentially capturing important habitats for species of insects, fungi, bacteria and plants that are often ignored in a multispecies assessment.

The scientific community is actively developing methods to capture a large amount of biodiversity in a few well-chosen 'representative' species (Théau et al. 2015, Albert et al. 2017, Wang et al. 2018, Meurant et al. 2018, Freeman et al. 2019). Some of these methods have been used by researchers and applied to large areas within the Region (Théau et al. 2015, Albert et al.

2017, Meurant et al. 2018, Rayfield et al. 2018). There is much more work to do, especially on reducing uncertainties about how and where species are moving and using this information to validate species selection criteria. Nonetheless, representative species sets have the potential to identify ENCs adapted for a larger portion of the region's plant and animal diversity.

RECOMMENDATION 4

Incorporate uncertainty into assessments and future plans for a regional ecological network for conservation (ENC). Important uncertainties relating to climate change and land use change can be addressed via scenario-based analysis and planning.

Connectivity conservation planning and scientific connectivity assessments must deal with various sources of uncertainty. We recommend that these sources of uncertainty are reported and evaluated to support efforts to gather new information and data. For example, connectivity analyses need to better incorporate the uncertainty arising from the feedbacks between people and nature, climate change scenarios, and land use change simulations (Albert et al. 2017, Gonzalez et al. 2017). Indeed many people have written about the need to further address the uncertainty in conservation and have suggested many avenues for how this might be done (Regan et al. 2002, 2005, Burgman et al. 2005).

One optimistic avenue for this is scenario-based planning; this is a strategic planning method involving systems thinking that organizations use to make flexible long-term plans, it may involve both qualitative (plausible scenario storylines) and quantitative assessments (probabilistic projections from models) of the future (Symstad et al. 2017). An approach common in conservation, but less so in connectivity research, is to use a range of projections of land use and climate change to create robust conservation plans (Mitchell et al. 2015, Lechner et al. 2017). Scenario-based planning has the potential to:

1) Allow the explicit inclusion of broad uncertainties in future land use and climate in the decision making process;
2) Allow corridors and connected network designs to be more robust to changes in climate and land use; and
3) Allow sets of solutions--rather than single corridor or networks designs--founded on an adaptive approach to managing connectivity in an uncertain world.

A scenario-based assessment of the future of the Region's connectivity would greatly benefit the implementation of resolution 40-3.

RECOMMENDATION 5
Develop a connectivity monitoring network to support the adaptive management of the region's connectivity conservation.

We recommend the implementation of a connectivity monitoring network, building on existing initiatives, to measure trends in the connectivity across the region. Monitoring could fill data gaps across the region and support validation of the models. A combination of direct and indirect methods can be used to assess how organisms use the ecological network. For example, functional connectivity can be estimated from data obtained by camera traps, gps collars, eDNA, and genetics. Remote sensing can also be used to assess the ecological integrity of the network, and the development of threats from land use change and the development of transport networks. Monitoring can also support action on the ground to protect core areas and linkages across the Region.

7
Conclusion

Pressed by the severity and scale of the change in ecological connectivity worldwide, conservation biologists have developed much of the science and policy support (i.e. a IUCN connectivity conservation specialist group) required for the implementation of ecological networks for conservation (ENCs, Hilty et. al 2019) designed to protect and restore connectivity. Looking ahead we see great value in the formation of a regional connectivity conservation specialist group to guide the research and action needed to manage the science and implementation of an ENC for the Region.

Past and ongoing initiatives covered by this report have made great progress towards the identification of an ENC for the Region. Thankfully, future efforts can build from this rich and elaborate body of work to cover important under-represented natural areas, identify missing linkages and achieve an ENC design that is more robust to climate change, land use change and other threats to the integrity of Region's ecosystems. A regional ENC should also be viewed as a highly effective nature-based solution delivering a host of ecosystem benefits to the people living in the Region. An explicit assessment of these values would be a valuable addition to our body of knowledge.

Our review has shown that the science of ENCs is developing fast and involves a sophisticated integration of quantitative methods from landscape ecology, network science, spatial modeling and multicriteria prioritization and optimization research. Some caution against the view that connectivity is a panacea able to mitigate all threats to biodiversity (Boitani et al. 2007, Gippoliti and Battisti 2017). This is an important message and care must be taken to engage with the complex realities of biodiversity and connectivity conservation on the ground. Simplistic approaches and network designs targeting one or a few species may not be effective for biodiversity writ large, or robust to the effects of land use change and climate change. However, robust methods are available, and evidence points to the great value of conservation approaches that integrate connectivity as a fundamental and efficient design principle (Crooks and Sanjayan 2006, Worboys et al. 2010, Anderson et al. 2016, Albert et al. 2017).

The past and continued erosion of connectivity in the Region is creating ecological outcomes with impacts large enough to threaten local and regional biodiversity, and in conjunction with climate change, is expected to result in a considerable reorganization of our flora and fauna. The long-term sustainability of the Region's ecosystems and the processes that support the many benefits we derive from them also depend on connectivity. We can design an integrated ENC for the region, but its implementation and governance must be resilient to the long-term social and ecological changes expected for the region. The design must be comprehensive and include redundancy for all conservation target elements, including ecological connectivity. An adaptive approach to maintaining connectivity will be needed. The co-design of the Region's ENC with a diverse array of actors and stakeholders could be an effective means for creating broad support for connectivity conservation in the Region.

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Appendices

Appendices in separate documents include a table of surveyed scientific literature on connectivity and from connectivity projects in the Region (in Excel format), as well as a classification and details about the literature review we conducted to support the report.