Designing Sustainable Landscapes: Project Overview

A project of the University of Massachusetts Landscape Ecology Lab

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With support from:

- North Atlantic Landscape Conservation Cooperative (US Fish and Wildlife Service, Northeast Region)
- Northeast Climate Science Center (USGS)
- University of Massachusetts, Amherst

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1 Purpose

This document provides an overview of the *Designing Sustainable Landscapes* (DSL) project (McGarigal et al 2017) of the University of Massachusetts Landscape Ecology Lab, including a statement of goals and objectives and a general description of our approach. This working document should be useful to anyone interested in learning more about the scope of the DSL project. Note that this document is an executive summary of the full project and references other documents that provide the full technical details of our approach. The DSL project is supported principally by the *North Atlantic Landscape Conservation Cooperative* (NALCC), with additional support from the *Northeast Climate Science Center* (NECSC) and the University of Massachusetts.

2 Goals and Objectives

Our primary mission as conservationists and public stewards of fish and wildlife resources is to ensure the conservation of biological diversity. Thus, our primary over-arching goal is to maintain well-distributed viable populations of all native species and the ecosystem processes they perform and depend on. To achieve this goal, however, we face many serious challenges associated with human population growth, such as habitat loss and fragmentation, disruption of ecological processes, spread of invasive non-native species, and human disturbance, all of which are being overlain and exacerbated by global climate change. In the face of these serious challenges, our specific conservation objective is to maximize the quantity, quality, and connectivity of habitats and ecological systems, subject to the real world socio-economic constraints of human population growth and development. If we are to be successful, our conservation strategies must strive to protect, manage and restore as much habitat as possible, minimize the forces of habitat degradation, and design landscapes to ensure habitat connectivity, all within the limits imposed by the socio-economic realities of human population growth and development.

To achieve this overall conservation objective, the USFWS developed the *Strategic Habitat Conservation* (SHC) approach, which incorporates five key components in an ongoing process that changes and evolves in an adaptive framework (**Fig. 1**):

- Biological Planning (assessing status, trends and limiting factors for populations and setting targets)
- Conservation Design (developing plans and tools to guide conservation actions to meet the goals)
- Conservation Delivery (implementing conservation actions based on planning and design)
- Monitoring and Adaptive Management (measuring success and improving results)
- Research (increasing our understanding)

The Department of the Interior is working with partners to create a geographic network of ecologically-based *Landscape Conservation Cooperatives* (LCCs) to define, design and deliver landscapes that sustain natural resources using an SHC approach (**Fig. 2**). The NALCC was established in 2010 and encompasses ecoregions adjoining the mid and north

Atlantic coast, including all or part of 12 states from Virginia to Maine, plus Washington DC, and all or part of four eastern Canadian provinces (**Fig. 3**).

The mission of the NALCC is to provide a partnership in which the private, state, tribal and federal conservation community works together to address increasing land use pressures and widespread resource threats and uncertainties amplified by a rapidly changing climate. The partners and partnerships in the cooperative address these regional threats and uncertainties by agreeing on common goals for land, water, fish, wildlife, plant and cultural resources and jointly developing the scientific information and tools needed to prioritize and guide more effective conservation actions by partners toward those goals.

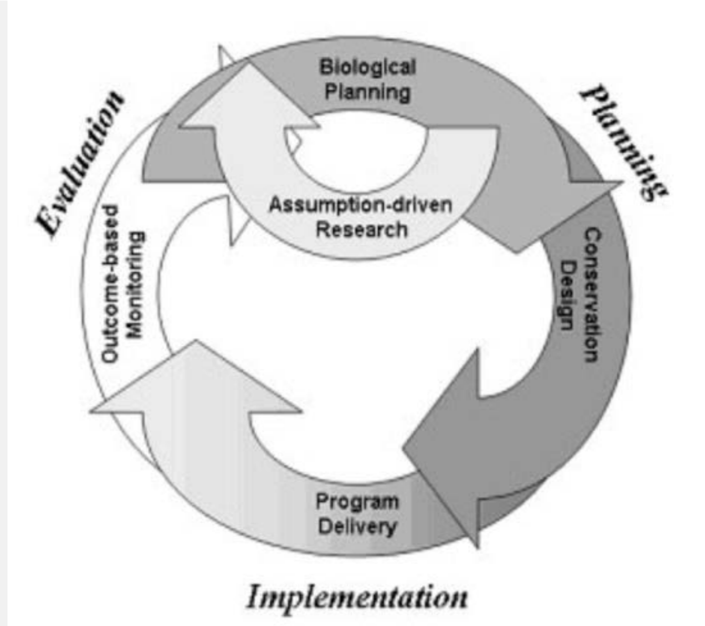

Figure 1 . Diagram of the Strategic Habitat Conservation (SHC) framework, a U.S. Fish and Wildlife Service science-based framework for making management decisions about where and how to deliver conservation efficiently to acheive specific biological outcomes.

To help achieve the NALCC mission, the DSL project was developed with the following objectives in mind:

1. Assess the current capability of habitats to support sustainable populations of wildlife and functioning ecosystems;
2. Predict the impacts of landscape-level changes (e.g., from urban growth, climate change, etc.) on the future capability of these habitats to support wildlife populations and ecosystem functions;
3. Target conservation programs to effectively and efficiently achieve objectives in State Wildlife Action Plans and other conservation plans and evaluate progress under these plans; and
4. Enhance coordination among partners during the planning, implementation and evaluation of habitat conservation through conservation design.

The DSL project described in this document is one of the science-development projects of the NALCC aimed at meeting these objectives. To this end, we developed a modeling framework to simulate landscape change, assess the ecological impacts of those changes and identify conservation priorities for land protection (i.e., what lands to protect to get the "biggest bang for the buck"), management (e.g., what should the management priorities be on conservation lands) and restoration (e.g., where should we place a wildlife road crossing structure or upgrade a stream culvert to improve landscape connectivity the most). The specific objectives of the DSL project are as follows:

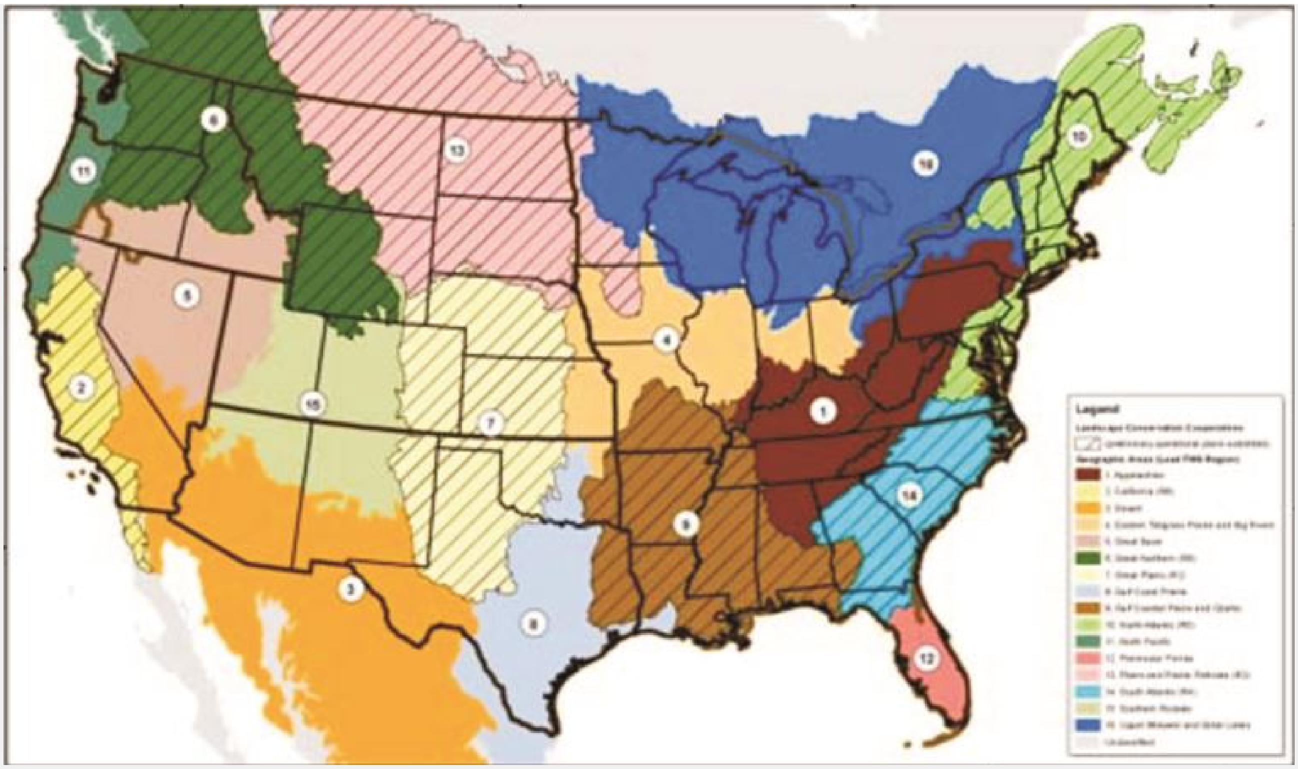

Figure 2. Map of the U.S. Fish and Wildlife Service Landscape Conservation Cooperatives (LCCs).

1. Develop a *Landscape Change, Assessment and Design* (LCAD) model for the Northeast Region that will allow us to simulate changes to the landscape under a variety of alternative future scenarios (e.g., climate change, urban growth), assess affects of those changes to ecological integrity and climate-habitat capability for focal species, and inform the design of conservation strategies (e.g., land protection, management and restoration) to meet conservation objectives.
2. Develop *landscape capability* models for a suite of representative (a.k.a. surrogate) species for evaluating the ecological consequences of landscape change in the LCAD model (#1).
3. Develop *ecological integrity* models for a suite of ecological systems as a coarse filter for evaluating the ecological consequences of landscape change in the LCAD model (#1).
4. Apply the LCAD model to the Northeast region, including the 12 US states and the District of Columbia (**Fig. 3**).

Note, these project objectives dovetail tightly with the first two steps of the SHC approach: (1) biological planning and (2) conservation design. Specifically, the LCAD model provides a landscape change and assessment tool that can inform biological planning and a landscape design tool that can inform conservation design.

3 LCAD Model Design

To meet objectives 1-3, we sought to develop a model based on the following design criteria:

1. *Computational feasibility* — The model must be practical to run given available computing resources. This involves simplifying the model as necessary so that it is practical to run. In essence, a "good" model that can run in days is better than a "great" model that needs a super computer and a year to run.
2. *Extant data* — The model input data must be based on extant data at the Northeast regional scale or data that can easily be compiled at the regional scale, and the model complexity must be scaled appropriately to match the quality of the data. In essence, the time or resources to develop raw data is not available, so the model input data has to be limited primarily to what already exists at the regional scale.

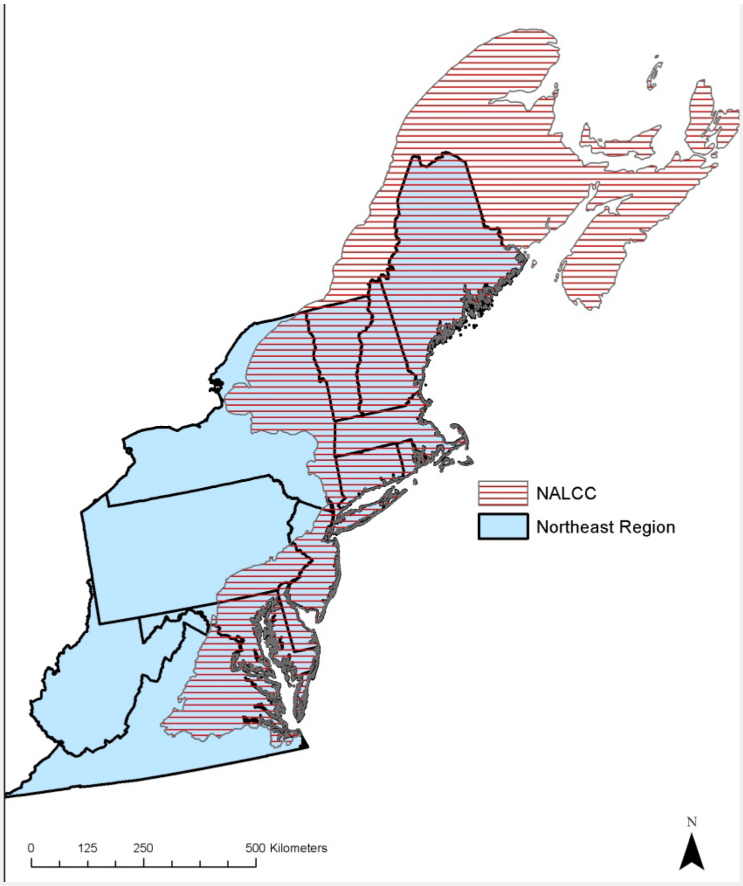

Figure 3. North Atlantic Landscape Conservation Cooperative (NALCC) extent and the Northeast region.

3. *Minimize subjective parameterization* — The model should require as few subjectively-derived parameter estimates as possible, and instead use empirically-derived parameter estimates wherever possible, resorting to expert opinion only when necessary. This has implications in the choice of methods for modeling various processes. For example, rather than use expert-based state transition models for vegetation development (succession), we opted to use statistically-derived models of continuous vegetation change based on Forest Inventory and Analysis (FIA) data.
4. *Model uncertainty* — The model must allow us to explicitly examine uncertainty in predictions (based on the uncertainty in model parameters). Note, assessing model uncertainty comes at the great cost of additional computations, so there is a real tradeoff between computational feasibility and modeling uncertainty, and thus a balance between these opposing forces must be achieved.
5. *Fisheries project compatibility* — The model should strive for compatibility with the NALCC-supported sea level rise and fisheries projects, particularly with respect to the spatial and temporal scale of the models and the particular ecological attributes tracked in these models. For example, the landscape change model should track the

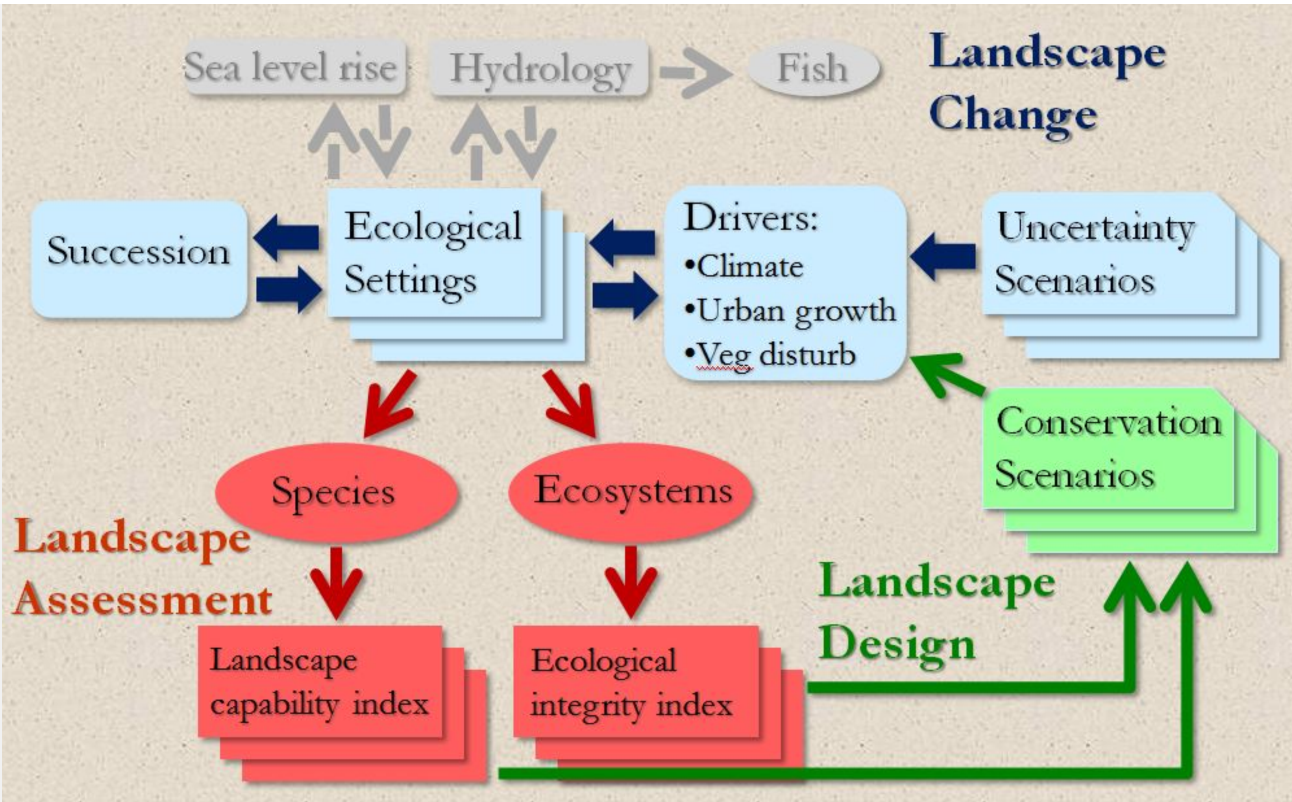

Figure 4. Diagram of the Landscape Change, Assessment and Design (LCAD) model for the Designing Sustainable Landscapes (DSL) project. Note, separate projects involve modeling sea level rise, freshwater stream hydrology and fish populations and are not described in this document. Blue elements represent the landscape change component; red elements represent the landscape assessment component and green elements represent the landscape design component.

important environmental variables needed as input to the hydrologic model, and conversely, the hydrological model should be structured to provide water flow and temperature at a spatial and temporal scale suitable for use in the LCAD model.

6. *Ecosystem- and species-based assessment capability* — The model must provide a framework for both species modeling and ecological integrity (coarse filter) assessments.
7. *Keep it simple* — The model should be kept as simple as possible at first without compromising the ability to add complexity later as time, resources and knowledge allow. For example, while we would like to incorporate a mechanistic model of the relationship between climate and vegetation development, we opted to adopt a much simpler approach at first that treats ecological systems as static, and then add complexity to this process as time, resources and knowledge permit.

Given these design criteria, we developed the LCAD model, which is outlined broadly in **figure 4**. Briefly, in addition to the spatial and nonspatial database, our model is conceptually comprised of three major components (each described below in more detail):

1. *Landscape change* — This is the core landscape change model, in which the landscape drivers including urban growth, climate change and vegetation disturbances and vegetation succession processes are implemented under a user-specified scenario or set of scenarios and a user-specified number of stochastic runs of each scenario. The landscape change model involves modifying the ecological setting variables (i.e., spatial data layers representing biophysical and anthropogenic attributes of the landscape) over time in response to the landscape drivers.
2. *Landscape assessment* — This is the ecological assessment of the landscape, including a two-pronged assessment of ecosystem integrity (coarse filter) and landscape capability for a suite of representative species at each timestep and summarized for the simulation run and scenario as a whole. This assessment is used to evaluate the ecological consequences of a future landscape change scenario by comparison to the baseline starting condition and to each other, and is the basis for informing landscape design.
3. *Landscape design* — This involves using the results of the landscape assessment to design conservation priorities for land protection, management, and/or restoration in order to maximize ecological performance criteria such as the landscape ecological integrity indices and landscape capability indices for representative species.

The LCAD model involves assessing the current ecological condition of the landscape or its predicted condition in the future under a landscape change scenario and using the results to inform landscape conservation design. The principal spatial data products include a set of ecological settings grids, a set of derived grids measuring ecological integrity and landscape capability for each representative species, and a set of derived grids that identify priorities for conservation action. Indeed, one way of conceptualizing LCAD is as a three-tiered set of spatial data products:

1. Tier 1 = primary data layers represented by the ecological settings variables, which represent important biophysical and anthropogenic attributes of the landscape;
2. Tier 2 = secondary data layers derived from the primary layers to measure ecological integrity and landscape capability for focal species (i.e., landscape assessment); and
3. Tier 3 = tertiary data layers derived from the secondary layers to identify priorities for conservation action (i.e., landscape design).

The LCAD model is entirely grid-based to facilitate modeling contagious processes (e.g., disturbance) and spatial dynamism in the environment. The spatial resolution of the model is 30 m, to be consistent with many of the input data sources. The temporal resolution is 10 years with a temporal extent of 70 years, 2010-2080 (although this is not a hard constraint). A 10-year resolution was deemed a sufficient compromise between realistically representing processes that operate at finer temporal scales (e.g., annual variability in climate) and vegetation dynamics (e.g., seral stage changes) that are much slower, and the need for computational efficiency. Lastly, the model is designed to be run on sub-landscape tiles to allow for parallel processing at the regional scale, but is flexible enough to work with any geographic extent (e.g., to accommodate application-specific conservation planning units) and/or any geographic tiling scheme.

4 Model Components

4.1 Spatial and Nonspatial Data

The LCAD model requires a variety of spatial and nonspatial (primary) inputs and generates a wide variety of spatial and nonspatial (secondary and tertiary) outputs. Important input data include nonspatial parameters that control all aspects of the landscape change simulation and affect the derivation of the ecological assessment measures and landscape conservation design products, in addition to spatial data (grids) that define the ecological setting of each cell.

4.1.1 Nonspatial input data

Required nonspatial input data consist of tabular data used to control the model run, such as length of the simulation (i.e., number of time steps), number of replicate runs, which drivers to include (e.g., climate and urban growth), and which timesteps to assess with the ecological measures. Nonspatial data also include the parameters for the individual component processes (e.g., succession); in other words, values for the parameters that control landscape change, assessment and design. This consists of a series of tables associated with each model component. The number and structure of the parameters vary among model components. For example, the succession component includes a suite of parameters describing the growth function for vegetation biomass indexed by ecological system. For other components, indexing by ecological system is not useful (e.g., urban growth) and the tables are structured accordingly.

The combined set of nonspatial data inputs represent a single scenario, and any one or combination of the parameters can be altered to create different scenarios. For example, the total amount of urban development could be varied among scenarios. Subject to the constraint imposed by the overall model structure, there is virtually no limit to the number and variety of scenarios that can be run with the LCAD model.

4.1.2 Spatial input data

Required spatial (GIS) input data consist primarily of a suite of ecological settings variables in addition to a few ancillary layers. Briefly, the *ecological settings variables* include a parsimonious suite of static as well as dynamic abiotic and biotic variables representing the natural and anthropogenic environment at each location (cell) at each time step (**Table 1**). Static variables are those that do not change over time (e.g., incident solar radiation, flow gradient). Dynamic variables are those that change over time in response to succession and the drivers (e.g., above-ground live biomass, temperature, traffic rate). Most of the settings variables are continuous and thus represent landscape heterogeneity as continuous (e.g., temperature, soil moisture), although some are categorical and thus represent heterogeneity as discrete (e.g., potential dominant life form, developed lands). Importantly, the settings variables include a broad but parsimonious suite of attributes that can be used to define the ecological setting of each cell at any point in time. As such, they play an important role in the landscape change processes (e.g., in the urban growth model to determine the probability of development). Moreover, the settings variables are considered the primary determinants of ecosystem composition, structure and function, and ultimately determine the ecological similarity between two locations. As such, the settings variables play a key role in both the coarse-filter ecological integrity assessment and the species' landscape capability models. Overall, the settings variables provide a rich, multivariate representation of important landscape attributes and represent the foundational data layers in the LCAD model.

In addition to the settings variables, we also assign each cell to a discrete ecosystem type, which can be based on any classification scheme that can be mapped, although here it is derived from The Nature Conservancy's Northeast Habitat Classification map (Ferree and Anderson 2013; Anderson et al. 2013; Olivero and Anderson 2013; Olivero-Sheldon et al 2014), but modified in several ways to better meet our needs as described elsewhere (see DSLland document, McGarigal et al 2017). Ecosystems are used as an organizational framework for scaling the ecological integrity metrics and in the species landscape capability models as described below.

Lastly, there are a variety of ancillary data layers that are variously used in the landscape change and assessment modules (e.g., in the calculation of individual ecological integrity metrics, downscaling climate, predicting urban growth, etc.), and to control the output of the analysis (e.g., to determine the spatial extent of an assessment). Note, some of these ancillary data layers are derived at each timestep (e.g., development intensity) and thus are dynamic.

Table 1. Ecological settings variables included in the LCAD model for the Northeast region. Note, settings variables are grouped into biophysical attributes for organizational purposes. A detailed description of each settings variable is available at the DSL website.

Biophysical attribute	**Stetting variable**	**Description**
Temperature	Growing season degree-days	Sum of the daily average temperatures above the threshold T_{base} = 10 °C and where temperatures above T_{max} = 30 °C are excluded; heuristic tool for predicting vegetation growth.
	Minimum winter temperature	Minimum air temperature (°C) reached in the winter (in January); sets the northern range limit for many plants and animals.
	Heat stress index 35	Sum of the daily average temperatures above the critical air temperature of 35°C; heuristic tool for predicting where heat stress may limit the geographic range and/or demographic performance for many plants and animals.
	Stream temperature	Mean annual water temperature (°C); important determinant of habitat conditions for many aquatic species.
Solar energy	Incident solar	Unitless measure derived from slope, aspect,

Biophysical attribute	Stetting variable	Description
	radiation	topographical shading and latitude; principal determinant of plant growth.
Chemical and physical substrate	Water salinity	Salt concentration (ppt rescaled) in aquatic ecosystems; important determinant of the ecological community in coastal ecosystems.
	Substrate mobility	Realized mobility of the physical substrate, due to both substrate composition (i.e., sand) and exposure to forces (wind and water) that transport material; important attribute of certain dynamic systems (e.g., coastal dune systems).
	$CaCO_3$ content	Calcium content (%) of the soil and water influences based on underlying bedrock material; affects buffering capacity (and hence susceptibility to acidification) among other things.
	Soil available water supply	Total volume of water (cm) that should be available to plants when the soil, inclusive of rock fragments, is at field capacity measured within the top 25 cm of the soil; principal determinant of plant growth.
	Soil depth	Soil depth (cm) to impervious layer; affects communities primarily because shallow soils (usually on steep slopes or ridgetops) limit deep-rooted plants.
	Soil pH	Soil pH within top 30 cm; measures acidity, which affects nutrient uptake by plants.
Physical disturbance	Wind exposure	Mean sustained wind speeds at 50 m above ground level (m/sec); exposure to high winds can be an important determinant of plant community development under extreme conditions (e.g., Krumholtz vegetation on mountaintops).
	Slope	Percent slope; the propensity for gravity-induced physical disturbance (e.g., talus slopes) can limit plant development.
Moisture & hydrology	Topographic wetness	Unitless measure derived from slope and watershed area; principal determinant of plant growth.

Biophysical attribute	**Stetting variable**	**Description**
	Flow gradient	Percent slope in lotic ecosystems; determines water velocity (and hence influences geomorphic processes) and is a principal determinant of lotic communities.
	Flow volume	Unitless measure of flow accumulation derived from elevation and preciptions; principal determinant of riverine communities.
	Tidal regime	Probability of tidal influence determined by the frequency, period and depth of tidal flooding; principal determinant of estuarine communities.
Vegetation	Potential dominant life form	Height (ordinal) of the dominant plant life from (e.g., barren, herbaceous, shrub, tree); principal attribute of ecological communities.
Anthropogenic	Developed	Indicator of development of any intensity; principal land use indicator for determining ecological integrity and habitat suitability.
	Hard developed	Indicator of hard (impervious) development; principal land use indicator for determining ecological integrity and habitat suitability.
	Gibbs traffic rate	Average number of vehicles per day on roads and railways, transformed to represent the probability of an animal crossing a road and being hit given the traffic rate; important determinant of landscape connectivity for mobile organisms.
	Imperviousness	Percentage of the ground surface area that is impervious to water infiltration; important determinant of ecological communities.
	Terrestrial barriers	Degree to which railroads and culverts may physically impede movement of terrestrial organisms; important determinant of landscape connectivity for mobile organisms.
	Aquatic barriers	Degree to which culverts and dams impede upstream and downstream movement of aquatic organisms; important determinant of aquatic connectivity for aquatic organisms.

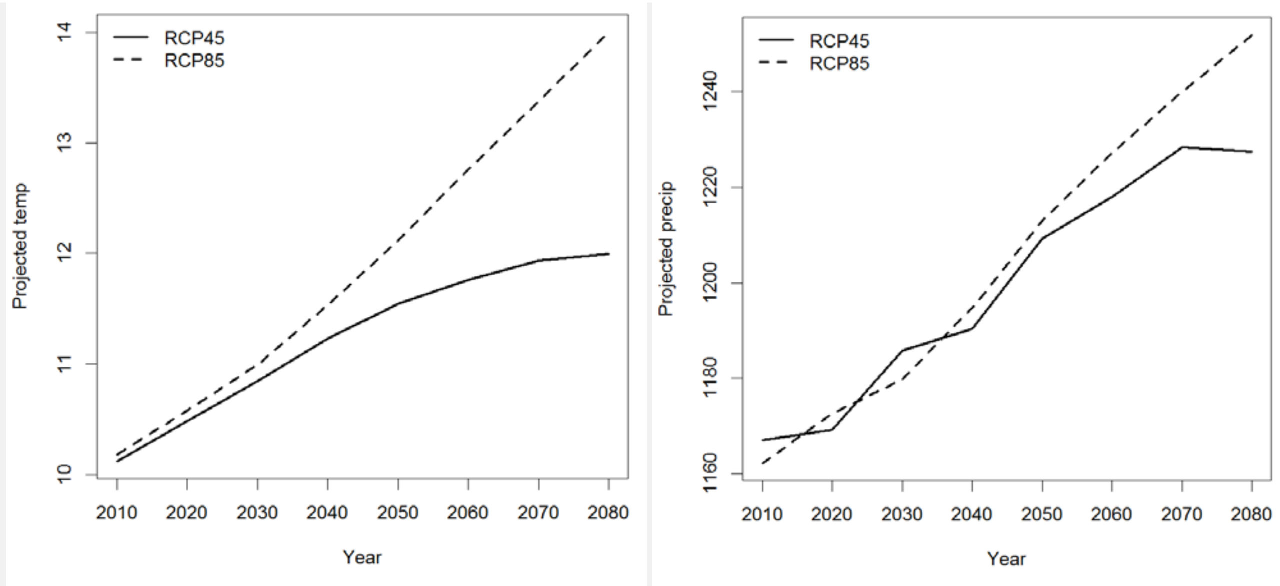

Figure 5. Projected annual average temperature (^{0}C) and precipitation (mm) throughout the Northeast Region from 2010 to 2080 under RCP 4.5 and RCP 8.5.

4.2 Landscape Change

Our landscape change model currently includes a suite of four major "drivers" (climate change, urban growth, vegetation disturbance-succession, and sea level rise) that operate sequentially within each timestep of the model to modify one or more of the ecological settings variables. Each driver is modeled separately, either as a deterministic or stochastic process, and acts differently depending on the settings variables; however, they all act to modify one or more of the settings variables. Uncertainty in the deterministic processes (climate change and sea level rise) is accounted for extrinsically by running multiple varying scenarios, whereas uncertainty in the stochastic processes (urban growth and disturbance-succession) is intrinsic to the process itself (via random variables) and is addressed by running multiple replicate simulations of the same scenario. The four major landscape change drivers currently included in the model are described in the following sections; additional potential drivers to be added in the future are briefly described in the **Appendix**.

4.2.1 Climate change

Climate change is modeled as a deterministic process by downscaling the climate predictions associated with monthly temperature and annual precipitation from an ensemble of Global Coupled Atmospheric-Ocean General Circulation Models (AOGCMs). The uncertainty in climate change predictions stems from using a suite of AOGCMs and a range of standard emissions scenarios set by the Intergovernmental Panel on Climate Change (IPCC). A detailed description of the climate model is provided in a separate technical document on climate (McGarigal et al 2017). Briefly, we used AOGCM data downscaled using the Bias Corrected Spatial Disaggregation (BCSD) approach (Wood et al. 2002, 2004) spatially to 1/8 degree (approximately 12km) and temporally to daily values provided by Eleonora Demaria of the Northeast Climate Science Center-UMass, Amherst

Table 2. Climate variables derived from AOGMC's and PRISM data and used in the DSL project as an ecological settings variable or in the climate niche envelop modeling for representative species (CNE).

Climate Variable	**Calculation Details**
Annual Precipitation (Input in soil wetness calculation, CNE)	Total precipitation for the year. The sum of the daily values across all days. mm/year. Note the "delta" in this case is actually a ratio.
Growing Season Precip (CNE)	Sum of daily precipitation for days in May through September mm/year. The "delta" is actually a ratio.
Average annual temperature (CNE)	Mean of daily min and max for every day of the year.
Mean Minimum Winter Temperature (Settings Variable, CNE)	Mean of the daily minimum temperatures for everyday in December, January, and February.
Mean Maximum Summer Temperature (CNE)	The mean of the daily maximum temperature for June, July and August.
Growing Degree Days (Settings Variable, CNE)	The sum across days of the number of degrees by which the mean daily temperature exceeds a threshold of 10 deg C. Where mean temperature is the mean of the min and max temp for the day. For prism data this is calculated from the 30 year mean temperature for each month by multiplying the exceedance by the number of days in the month.
Heat Index 35 (Settings Variable, CNE)	Uses the same general algorithm as gdd but with a threshold of 35 deg and based on the daily max temperature rather than the daily mean temp.

and derived from datasets publicly available through World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 5 (CMIP5). We averaged the results of 14 AOGCMs to create an ensemble average projection for each of two Representative Concentration Pathway (RCPs) emission scenarios (Moss et al. 2010): 1) RCP 4.5, in which the various models project an increase of 1-4 degrees Celsius and ~50 mm precipitation across the Northeast between 1995 and 2080; and 2) RCP 8.5, in which the projected increase is 3-6 degrees C and ~80 mm, respectively (**Fig. 5)**. We subtracted a baseline to create projected anomalies, resampled these data at 800 m cells, combined these data with 800 m resolution, 30-year normal temperature and precipitation PRISM data (Climate Group, Oregon State University) using the "delta method", and resampled and projected these data to 600 m cells, which aligned with the 30 m cells used in the LCAD model. Finally, we derived a suite of climate variables for each 10-year timestep of the model from 2010-2080 (**Table 2**).

In the LCAD model, climate change acts principally to modify the ecological settings variables associated with temperature and precipitation (a subset of the variables listed in

Table 1), and thus causes each cell to "migrate" through ecological settings space over time. The primary effect of climate change is in the assessment of ecological integrity (principally via the climate alteration, resiliency and adaptive capacity metrics, see below) and landscape capability for representative species (via the climate niche component, see below), and as a covariate affecting the magnitude and rate of succession in above-ground live biomass in forests.

4.2.2 Urban growth

Urban growth is modeled as a stochastic process by predicting the probability of several different types of development transitions at the cell level, and then stochastically building disturbance patches until the allocated amount of development is achieved. The uncertainty in urban growth predictions stems from the intrinsic stochasticity of the process itself and is realized by running multiple replicate simulations of the same scenario, in addition to the variation among scenarios that can be achieved by forcing relatively more or less total development and/or more or less sprawliness to the pattern of urban growth. A detailed description of the urban growth model is provided in a separate technical document urban growth (McGarigal et al 2017). Briefly, the projected amount of future development in an area (demand) is downscaled from county-level forecasts based on a U.S. Forest Service 2010 Resources Planning Act (RPA) assessment (Wear 2011) to individual application "panes" ~5 km on a side. Within an application pane the transition type (i.e., new low-, new medium-, new high-, low-to-medium, low-to-high, and medium-to-high intensity development) and spatial pattern of development at the cell level is based on statistical models of historical development and is influenced by factors such as geophysical conditions (e.g., slope, intensity of open water) and proximity and intensity of roads and urban development. Ultimately, based on a novel matching algorithm, each cell ends up with a probability of each type of development transition that reflects the total projected demand for development in the application pane and the relative likelihood of that type of development occurring on that cell given its spatial context in relation to the patterns observed historically in similar landscape contexts. Disturbance patches are built stochastically based on these surfaces until the total demand is met, with the distribution of patch sizes reflecting that observed historically in similar landscape contexts (**Fig. 6**). At the end of each 10-year timestep, once growth is realized, the resulting urban grid is fed back into the beginning of the process for the next timestep.

Importantly, due to our novel matching algorithm, the urban growth model is non-stationary across space and time; i.e., as an application pane becomes more urbanized in the future, its growth patterns change to match the way more urbanized panes grew historically, but all subject to the projected demand for growth based on the downscaled RPA forecasts.

In the LCAD model, urban growth acts principally to modify the ecological settings variables associated with human development such as impervious, traffic rates and development. The primary effect of urban growth is in the assessment of ecological integrity (via all of the intactness and resiliency metrics, see below) and landscape capability for representative species (via the habitat capability models, see below).

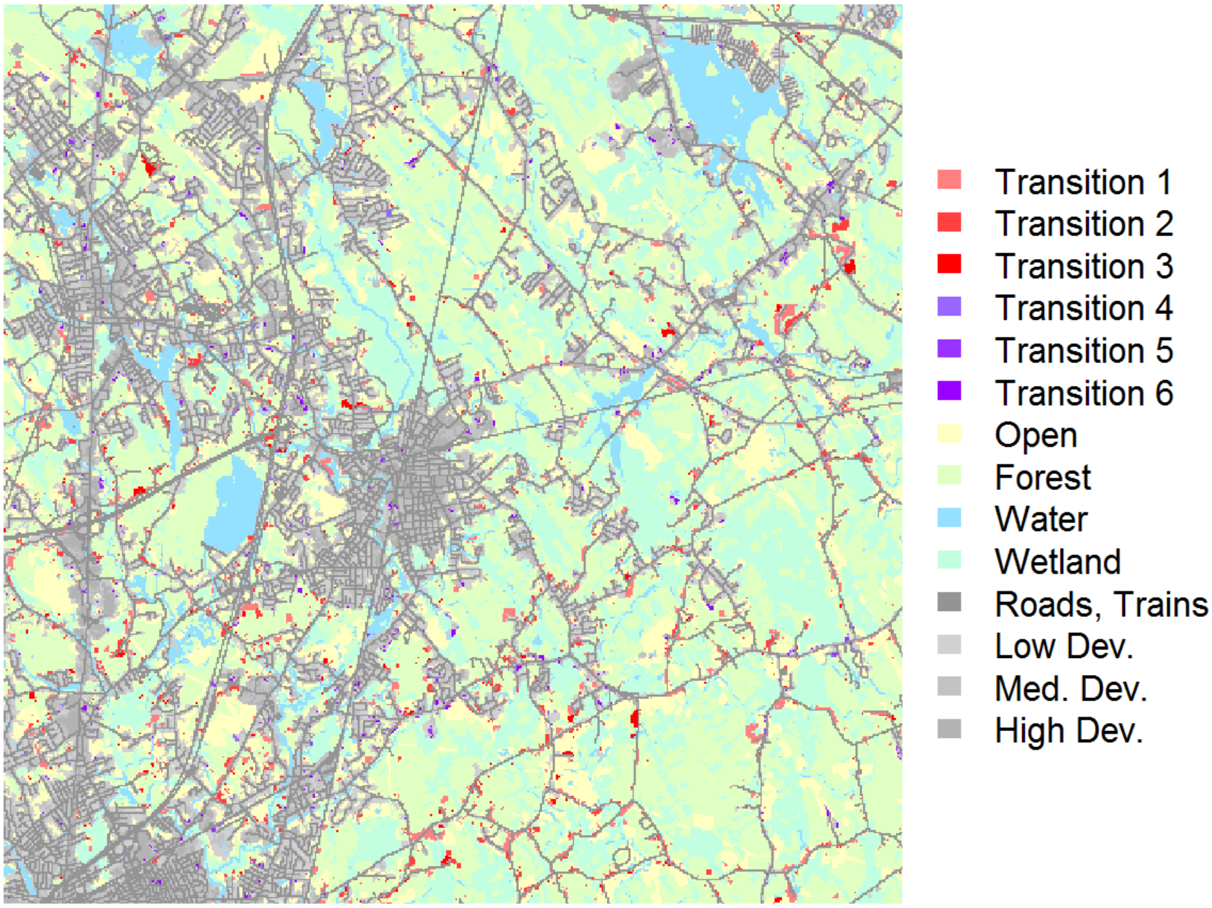

Figure 6. Urban growth simulation for a single 10-year timestep for a random application "window" (15 km on a side) in the Northeast, depicting the stochastic realization of six modeled transition types.

4.2.3 Vegetation disturbance-succession

Vegetation disturbance and succession are modeled as two separate processes that operate sequentially within each timestep: vegetation undergoes succession and then is subject to disturbance. Succession is modeled as a deterministic change in above-ground live biomass ("biomass" for short, as a proxy for seral stage) according to a set of growth functions established for each group of similar forested ecological systems (macrogroups); non-forested systems are treated as having no biomass and as static (i.e., constant over time). A detailed description of the succession model is provided in a separate technical document on disturbance and succession (McGarigal et al 2017). Briefly, to develop the growth functions we used USDA Forest Service Forest Inventory and Analysis (FIA) plot data to compute biomass of each forested FIA plot for its last sampling occasion. Pooling across all forested FIA plots within each macrogroup, we treated biomass as the dependent variable and suite of spatial covariates including estimated stand age from FIA, growing degree days, growing season precipitation, soil pH, soil depth, and soil available water supply as the independent variables, and fit a nonlinear function (Monomolecular or asymptotic exponential) using ordinary least squares estimation. This process fit a function to the average growth trajectory. Thus, for any given ecological setting, based on the independent covariates, the growth function predicts the corresponding average biomass (**Fig. 7**). At the beginning of each timestep, the biomass of each forested cell is updated based on the corresponding growth function.

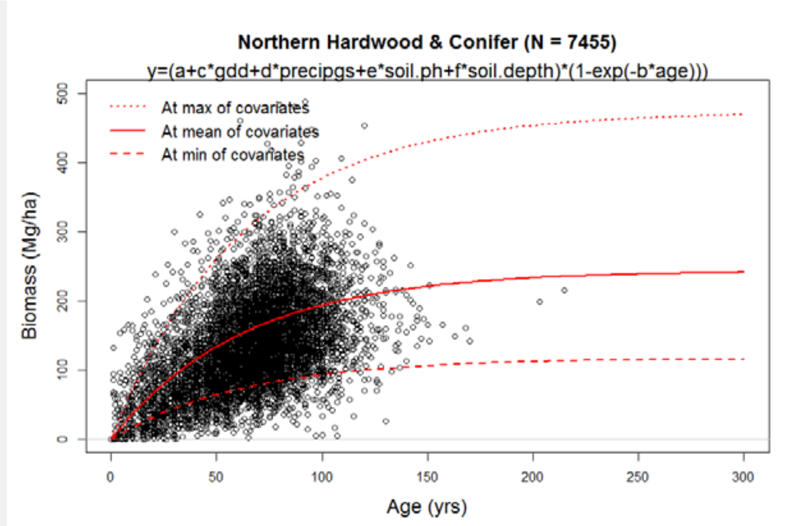

Figure 7. Scatter plot of above-ground live biomass (Mg/ha) against stand age (years) for 7,455 Forest Inventory and Analysis (FIA) plots distributed throughout Northern Hardwood and Conifer forests in the Northeast, along with the fitted monomolecular function given in the title at the mean, minimum and maximum of the covariates (growing degree days, growing season precipitation, soil pH, and soil depth.

As in interim solution for the current version of the LCAD model, we developed a generic vegetation disturbance driver that implements generic disturbances (i.e., not associated with any particular real-world process such as timber harvest or wildfire). Disturbance is modeled as a stochastic change in forest biomass according to a two-stage statistical model developed for each of 13 different ecoregions. The uncertainty in vegetation disturbance stems from the intrinsic stochasticity of the process itself and is realized by running multiple replicate simulations of the same scenario, in addition to the user-specified variation among scenarios in overall disturbance rate. A detailed description of the forest disturbance model is provided in the technical document referenced above. Briefly, we used FIA plot data to compute the probability of a forest disturbance at the cell level, defined as a net loss of biomass between sampling occasions, and given a disturbance, the severity of disturbance, defined as the proportional loss of biomass. Pooling across all forested FIA plots within each ecoregion, first we treated delta biomass between sampling occasions as a binomial response (i.e., negative delta = disturbance) and the starting biomass for the sampling period as the independent variable, and fit a logistic regression to predict the probability of disturbance given current biomass for a 10-year model timestep. Next, given that a disturbance occurred, we treated the proportional loss of biomass as a Beta-distributed random variable, essentially treating the severity of disturbance as purely stochastic and distributed according to a Beta distribution, which is appropriate for a proportional response variable. Based these fitted relationships, to simulate vegetation disturbances, we: 1) randomly initiate individual disturbance events based on the probability of disturbance surface, 2) spread outward from the initiating cell using a resistant kernel (whereby resistance is inversely related to the probability of disturbance) until a randomly selected patch size is met (based on the observed historical distribution of disturbance patch sizes within the ecoregion), 3) randomly impose a severity (whereby biomass is "set back" or moved to an earlier seral condition) based on the fitted Beta distribution, and 4) repeat the process above until an overall rate of disturbance (i.e., the proportion of forested vegetation that gets disturbed) is met within the ecoregion, which is controlled by a user-defined parameter but by default is based on the rate of disturbance observed in the FIA data for the corresponding ecoregion (**Fig. 8**).

Note, we recognize that a generic disturbance process such as the one we implemented here does not capture the many importance nuances of individual natural (e.g., fire, wind, insect and pathogens) and anthropogenic (e.g., timber harvesting) disturbance processes. In particular, the frequency, severity and size of disturbance events can vary substantially among disturbance processes and geographically across the region. Unfortunately, we did not have the resources in the current phase of this project to develop a more sophisticated model for vegetation disturbances that differentiates the various processes, but this remains an important priority for future phases of work. See the **Appendix** for a brief description of potential additional disturbance drivers to be added to the model in the future pending additional resources.

In the LCAD model, succession and disturbance act in concert to modify vegetation biomass in forested cells (i.e., cells initially mapped as a forested ecosystem and not subsequently developed via urban growth). Conceptually, biomass is an ecological settings variables, but we do not include it with the other settings variables (**Table 1**) due to its highly stochastic nature, and thus it is not involved in on our ecological integrity assessment (see below). Instead, the primary effect of succession and disturbance (via biomass) is in the assessment of landscape capability for representative species (via the habitat capability models, see below).

4.2.4 Sea level rise

Sea level rise (SLR) is being modeled separately by USGS Woods Hole Science Center. As in interim solution for the current version of the LCAD model, the output of the SLR model is being incorporated into the ecological integrity assessment as a stressor metric, as described below. The uncertainty in sea level rise is incorporated explicitly into the sea level inundation rise, which is given as the probability of the focal cell being unable to adapt to predicted inundation by sea level rise averaged between the RCP 4.5 and 8.5 climate scenarios (**Fig. 9**; see Lentz et al 2015 for a detailed description).

In future versions of LCAD, in collaboration with Woods Hole Science Center, we hope to incorporate predicted changes in the distribution of certain ecological settings variables (e.g., elevation-derived variables) and coastal ecosystems (e.g., salt marsh) in response to sea level rise and storm surge, but the details of how this process will be modeled and how uncertainty will be incorporated are not yet determined, and it will be primarily the responsibility of the Woods Hole Science Center.

In the current LCAD model, sea level rise acts solely as a stressor metric affecting coastal ecosystems. The primary effect of sea level rise, therefore, is in the assessment of future ecological integrity. Note, the sea level rise inundation metric is not used in the

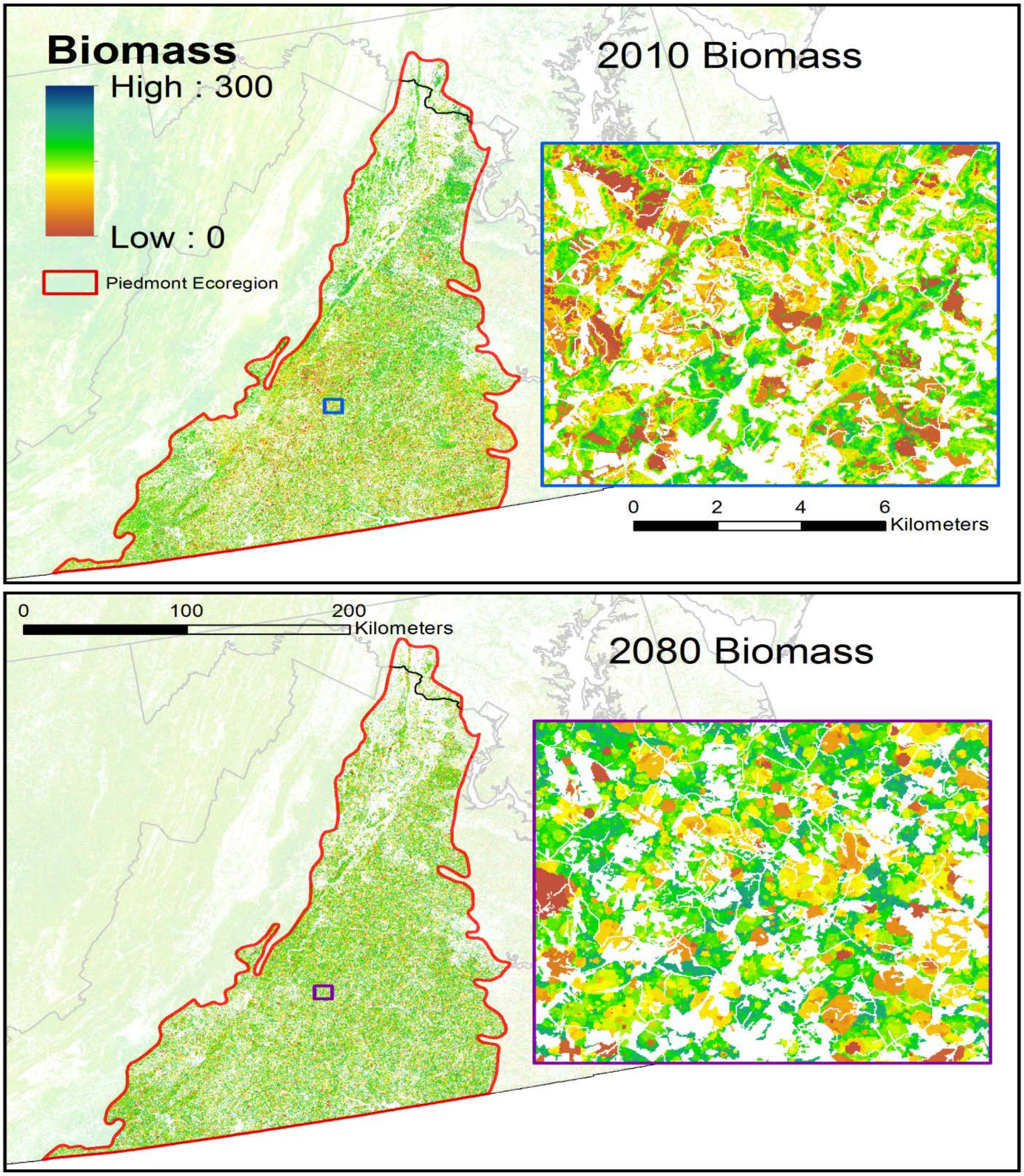

Figure 8. Initial (2010) biomass and simulated biomass in 2080 for the Piedmont ecoregion based on the disturbance rate observed in FIA data for the period 1997-2012 and the disturbance patch size distribution observed in the High-Resolution Global Maps of 21st-Century Forest Cover Change (Hansen et al. 2013) for disturbances between 2000-2012.

assessment of current ecological integrity (as measured by the *Index of Ecological Integrity, IEI,* see below), but rather it is used to compute future *IEI* in 2080 (see below).

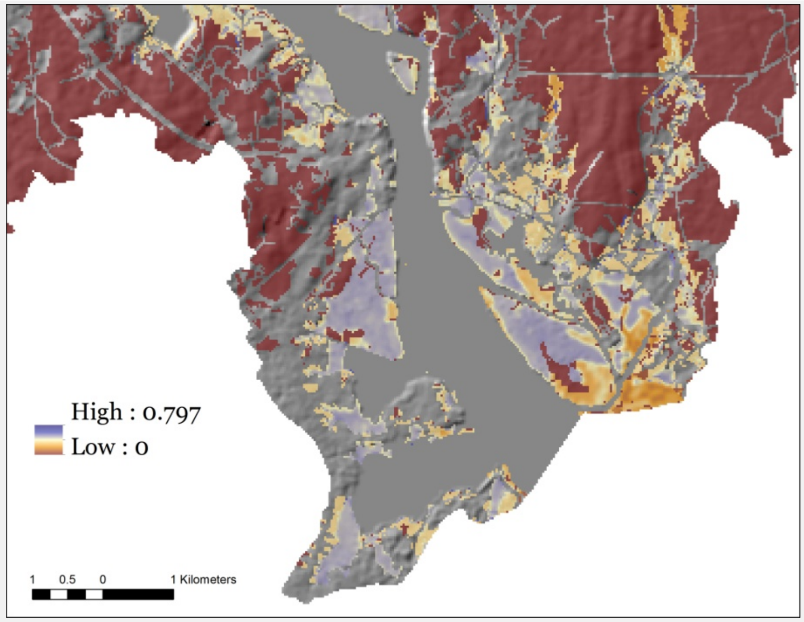

Figure 9. Sea level rise inundatation metric depicting the relative probability of being unable to adapt to sea level rise between 2010-2080 for the mouth of the Connecticut River, overlaid on a hillshade map in grayscale. Note, areas in purple are predicted to have a high likelihood of being inundated in the future and thus recieve a higher stressor score.

4.3 Landscape Assessment

Our landscape assessment includes a complementary two-pronged approach aimed at assessing impacts to: 1) biodiversity in general, based on ecosystem integrity, and 2) a suite of focal species (e.g., representative species), as follows:

4.3.1 Ecosystem-based assessment

We use a coarse-filtered, ecosystem-based approach as the overarching approach for the conservation of biodiversity, as described in detail in a separate technical document on integrity (McGarigal et al 2017). Briefly, the premise of our ecosystem-based approach is as follows:

1. Maintaining the integrity of ecosystems across the landscape will ensure that important ecological functions persist (to benefit the natural world and humans).
2. Protecting ecosystems as a coarse filter is an efficient and thus practical means of protecting the bulk of biodiversity, including most species, but especially the hidden biodiversity that can't easily be conserved on species-by-species basis.
3. The coarse filter alone is probably not sufficient to conserve all species since some species have special life history requirements, such as the juxtaposition of specific environments, that can easily "fall through the cracks" of the coarse filter, and thus a complementary fine filter to capture those biodiversity elements that are not captured by the coarse filter is ideally needed.

Given this premise, our coarse-filter approach depends on a clear definition of the coarse filter. While there are a variety of ways to define a coarse filter, the most common approach, and the one that we adopt, is as follows.

Our **coarse filter** involves protecting the *ecological integrity* of the full suite of ecological systems under consideration, with two important components to this definition:

1. Our coarse filter is based on a suite of ecological systems, which we treat as distinct ecological entities that can be mapped and assessed. Note, it is not necessary to assume discrete ecological systems, since an ecological gradient approach is also feasible (and we have implemented it elsewhere), but for practical reasons and for consistency with established practices, here we have opted to treat ecological systems as discrete entities for purposes of applying the coarse filter. Importantly, the use of a relatively small number of distinct ecological systems offers us an efficient and practical approach for implementing the coarse filter.
2. Our coarse filter is based on the concept of landscape ecological integrity, which we define as the ability of an area to sustain ecological functions over the long term; in particular, the ability to support biodiversity and the ecosystem processes necessary to sustain biodiversity over the long term, especially in response to disturbance and stress. Note, this definition of ecological integrity emphasizes the maintenance of ecological functions over the long term rather than the maintenance of a static composition and structure, and thus accommodates the modification or adaptation of systems (in terms of composition and structure) over time to changing environments (e.g., as driven by climate change). Moreover, this definition of ecological integrity can be decomposed into several measurable components, including intactness, resiliency and connectivity that can be measured for ecological systems and the landscape as a whole, as described below.

Based on this definition, we discern three major components of ecological integrity; i.e., measurable attributes that confer ecological integrity either to the landscape as a whole or to the site (cell) and thus, by extension, to the landscape as a whole:

- *Intactness* — refers to the freedom from human impairment (anthropogenic stressors); it is an intrinsic attribute of a site (cell) that contributes to the ecological integrity of the site itself and thus, by extension, confers ecological integrity to the landscape as a whole. Intactness is measured using a broad suite of stressor metrics (**Table 3**), each of which measures a different anthropogenic stressor and is intended to reflect a unique relationship between a human activity and an ecological function even though they may be empirically correlated in real landscapes. The stressor metrics are computed for all undeveloped cells, although some metrics apply only to certain ecological systems (e.g., watershed-based metrics apply only to aquatic and wetland systems) and may only be selected for application to some ecological systems (see ecological integrity models below), and some metrics only apply to the assessment of the future landscape condition (e.g., climate alteration and sea level rise inundation). Each stressor metric measures the magnitude of human stressor impacts at each cell based on its neighborhood context; in general, the value of each metric increases with increasing intensity of the stressor within the ecological neighborhood of the focal cell. Thus, the raw value of the intactness metric is inversely related to ecological integrity.

- *Resiliency* — refers to the capacity to recover from or adapt to disturbance and stress; more specifically, the amount of disturbance and stress a system can absorb and still remain within the same state or domain of attraction (e.g., resistance to permanent change in the function of the system) (Holling 1973, 1996). In other words, resiliency metrics deal with the capacity to maintain characteristic ecological functions.

Resiliency is both a function of the local ecological setting, since some settings are naturally more resilient to disturbance and stress (e.g., an isolated wetland is less resilient to species loss than a well-connected wetland because the latter has better opportunities for recolonization of constituent species), and the level of anthropogenic stress, since the greater the stressor the less likely the system will be able to fully recover or maintain ecological functions. Moreover, the concept of resiliency applies to both the short-term or immediate capacity to recover from disturbance and the long-term capacity to sustain ecological functions in the presence of stress, and the landscape attributes that confer short-term resiliency may not be the same as those that confer long-term resiliency. For example, short-term resiliency of a site may be a function of the amount and accessibility of similar ecological settings in the neighborhood of the focal cell, since having larger and more connected local populations should facilitate population recovery of the constituent organisms (and thus ecosystem functions) following disturbance, whereas long-term resiliency of a site may be a function of the amount and accessibility of diverse ecological settings in the neighborhood of the focal cell, since having a diverse assemblage of species nearby increases the opportunities for different organisms to fill the ecological niche space as the environment changes over time.

Given the above, it is evident that resiliency is a complex, multi-faceted concept that cannot easily be measured with any single metric. Consequently, we have conceived of a suite of metrics for measuring resiliency from different perspectives, although we have not yet implemented all of these metrics (**Table 3**). Like the stressor metrics, the resiliency metrics are computed for all undeveloped cells, although they may only be selected for application to some ecological systems (see ecological integrity models below). Each resiliency metric measures the capacity of each site (cell) to recover from or adapt to disturbance and stress over either the short or long-term based on its neighborhood context. In contrast to the stressor metrics, however, the value of each resiliency metric increases with increasing resiliency, so larger values connote greater integrity. In addition, in contrast to the stressor metrics, the value of the resiliency metric at any location is dependent on the particular ecological system or setting of the focal cell, since that determines the ecological similarity or dissimilarity of the neighborhood. Thus, the resiliency metrics are not particularly useful in their raw-scale form. Instead, they are best interpreted when rescaled by ecological system (see below) so that what constitutes high resiliency for a small patch-forming ecological systems (e.g., wetland) need not be the same as for a matrix-forming system (e.g., Northeastern upland forest).

- *Connectivity* — refers to the propensity to conduct ecological flows (including individual plants and animals) across the landscape. Connectivity it is a complex, multi-faceted concept that can be considered from several different perspectives and at different scales (locally and regionally). Connectivity is essential to individuals and populations to facilitate processes such as resource acquisition, dispersal and gene flow in the absence of disturbance and stress, but it is also essential to resiliency or the ability of individuals, populations, communities and ecosystems to recover from disturbance and stress. With regards to the latter, connectivity is incorporated directly into the connectedness and adaptive capacity resiliency metrics (above), but is also measured directly and more generally without regard to resiliency per se using a

Table 3. Ecological integrity metrics included in the LCAD model for the ecological integrity assessment of the Northeast region. Note, the final suite of metrics was based on available data. The metrics are grouped into broad classes for organizational purposes, as described in the text. A detailed description of each metric is available at the DSL website. Metrics shown in gray are currently under development.

Metric group	Metric name	Description
Intactness	Habitat loss	Measures the intensity of habitat loss caused by all forms of development in the neighborhood surrounding the focal cell based on a standard Gaussian kernel. Habitat loss has myriad effects, both direct and indirect, on the ecological integrity of the focal cell and in many ways subsumes the individual effects targeted by many of the other metrics. In particular, the loss of habitat in the neighborhood of the focal cell affects the occurrence and abundance of many organisms via their minimum area requirements.
	Watershed habitat loss	Measures the intensity of habitat loss caused by all forms of development in the watershed above the focal cell based on a time-of-flow kernel. Similar to habitat loss, watershed habitat loss has myriad effects, both direct and indirect, on ecological integrity and is perhaps more pertinent for aquatic and wetland systems where the ecological neighborhoods are more watershed based than circular.
	Road traffic	Measures the intensity of road traffic (based on measured road traffic rates) in the neighborhood surrounding the focal cell based on a standard Gaussian kernel. Road traffic is a direct source of animal mortality and a source of chemical and noise pollution.
	Mowing & plowing	Measures the intensity of agriculture (as a surrogate for mowing/plowing rates) in the neighborhood surrounding the focal cell based on a standard Gaussian kernel. Mowing and plowing are a direct source of animal mortality, especially for slow-moving terrestrial species such as turtles.
	Microclimate alterations	Measures the adverse effects of induced (human-created) edges on the microclimate integrity of patch interiors. The microclimate edge effects metric is based on the "worst" edge effect among all adverse edges in the neighborhood surrounding the focal cell, where each adverse edge is evaluated using a "depth-of-edge" function in which the "effect" is scaled using a standard

Metric group	Metric name	Description
		Gaussian kernel. Microclimate alterations along induced edges alter the physical environment for native plant and animal communities and exacerbate natural disturbance rates (e.g., windthrow) that together alter vegetation composition, structure and function.
	Watershed road salt	Measures the intensity of road salt application in the watershed above an aquatic focal cell based on road class (as a surrogate for road salt application rates) and a time-of-flow kernel. Road salt alters the chemistry of adjacent ecological systems and thus alters the suitability of the environment for native plant and animal communities, and is especially relevant to palustrine and lacustrine ecosystems.
	Watershed road sediment	Measures the intensity of sediment production in the watershed above an aquatic focal cell based on road class (as a surrogate for road sediment production rates) and a time-of-flow kernel. Road sediment and the pollutants carried by sediments alter the physical and chemical environment of adjacent ecological systems and thus the suitability of the environment for native plant and animal communities, and is especially relevant to palustrince, lacustrine and riverine ecosystems.
	Watershed nutrient enrichment	Measures the intensity of nutrient loading from non-point sources in the watershed above an aquatic focal cell based on land use class (primarily agriculture and residential land uses associated with fertilizer use, as a surrogate for nutrient loading rate) and a time-of-flow kernel. Nutrient enrichment, especially nitrogen and phosphorus derived from fertilizers, alters the chemistry of adjacent ecological systems and thus the suitability of the environment for native plant and animal communities, and can have an important influence on the trophic status of aquatic and wetland ecosystems.
	Domestic predators	Measures the intensity of development associated with sources of domestic predators (e.g., cats) in the neighborhood surrounding the focal cell weighted by development class (as a surrogate for domestic predator abundance) and a standard Gaussian kernel. Domestic predators, especially domestic cats, are a direct source of animal mortality, especially for small birds, mammals

Metric group	Metric name	Description
		and herpetofauna.
	Edge predators	Measures the intensity of development associated with sources of edge mesopredators (e.g., raccoons, skunks, corvids, cowbirds; i.e., human commensals) in the neighborhood surrounding the focal cell weighted by development class (as a surrogate for edge predator abundance) and a standard Gaussian kernel. Edge predators are a direct source of animal mortality, most notably for songbirds, and their populations are enhanced by induced (human-created) edges.
	Non-native invasive plants	Measures the intensity of development associated with sources of non-native invasive plants in the neighborhood surrounding the focal cell weighted by development class (as a surrogate for non-native invasive plant abundance) and a standard Gaussian kernel. Non-native invasive plants can substantially alter the physical and chemical environment and thus the suitability of the environment for native plant and animal communities.
	Non-native invasive earthworms	Measures the intensity of development associated with sources of non-native invasive earthworms in the neighborhood surrounding the focal cell weighted by development class (as a surrogate for non-native invasive earthworm abundance) and a standard Gaussian kernel. Non-native earthworms alter the physical and chemical environment and thus the suitability of the environment for native plant and animal communities, and effect myriad ecological processes (e.g., nutrient cycles, decomposition), with the most notable impacts on the native flora understory of many forests.
	Climate stress	Measures the magnitude of climate change stress at the focal cell based on the climate niche of the corresponding ecological system and the predicted change in climate (i.e., how much is the climate of the focal cell moving away from the climate niche envelope of the corresponding ecological system). Climate is a major attribute of the physical environment and a principal determinant of plant and animal distribution. Note, climate stress is only included in calculations of future *IEI*.

Metric group	**Metric name**	**Description**
	Watershed imperviousness	Measures the intensity of impervious surface (as a surrogate for hydrological alteration) in the watershed above an aquatic focal cell based on imperviousness and a time-of-flow kernel. Watershed imperviousness, by disrupting infiltration rates, has a major impact on watershed hydrology, which is a major determinant of the composition, structure and function of many aquatic ecosystems.
	Dam intensity	Measures the intensity of dams (as a surrogate for hydrological alteration) in the watershed above an aquatic focal cell based on dam size and a time-of-flow kernel. Dam intensity, by disrupting flows and impounding water, has a major impact on watershed hydrology, which is a major determinant of the composition, structure and function of many aquatic ecosystems.
	Sea level rise inundation	Measures the probability of the focal cell being unable to adapt to predicted inundation by sea level rise developed by USGS Woods Hole, Lentz et al 2015. Whether a site gets inundated by salt water permanently due to sea level rise or intermittently via storm surges associated with sea level rise clearly determines whether an ecosystem can persist at a site and thus its ability to support a characteristic plant and animal community. Note, sea level rise inundation is only included in calculations of future *IEI*.
	Tidal restrictions	Measures the magnitude of hydrologic alteration to the focal cell due to tidal restrictions based on the estimated tidal hydroperiod (ecological setting variable) and magnitude of tidal restriction (on the upstream side of a restriction).
	Salt marsh ditching	Measures the magnitude of temporal loss of open water habitat (i.e., loss of open water habitat during mid to low tides) around the focal cell due to ditching based on a standard Gaussian kernel. This metric is currently incomplete for the entire Northeast region due to missing data and thus it is not yet included in *IEI*.
Resiliency	Similarity	Measures the amount of similarity between the ecological setting at the focal cell and those of neighboring cells, weighted by a logistic function of distance. Similarity is based on the ecological distance

Metric group	Metric name	Description
		between the focal cell and each neighboring cell, where ecological distance is a multivariate distance across all ecological setting variables. Similarity is an important determinant of a site's resiliency or ability to recover from disturbance and stress, since it determines whether organisms from nearby similar ecological systems are available to recolonize the site or rescue declining populations, and it is especially relevant for highly vagile species in which movement among sites is not easily impeded (e.g., for many birds).
	Connectedness	Measures the disruption of habitat connectivity caused by all forms of development between each focal cell and surrounding cells. A hypothetical organism in a highly connected cell can reach a large area with minimal crossing of “hostile” cells. This metric uses a resistant kernel algorithm to determine the area that can be reached from each focal cell weighted by the ecological similarity to the focal cell. Connectedness, as a measure of local connectivity, is an important determinant of a site's resiliency or ability to recover from disturbance and stress, since it determines whether organisms from nearby similar ecological systems can recolonize the site or rescue declining populations, and it is especially relevant for less vagile species in which movement among sites is more easily impeded by unfavorable environments (e.g., many amphibians and reptiles).
	Aquatic connectedness (aqconnect)	Aquatic connectedness is identical to connectedness except that it is constrained by the extent of aquatic ecosystems, such that the connectivity being assessed pertains to flows within the aquatic network. Impediments to movement of aquatic organisms, such as culverts and dams, are especially relevant for aquatic connectedness but may be less important or unimportant for terrestrial connectivity. Aquatic connectivity, like terrestrial connectivity, is essential to the resiliency of aquatic communities and is often a principal determinant of the distribution and viability of many aquatic species.
Diversity	Diversity	Measures the diversity of multivariate ecological settings in the neighborhood of a focal cell. Diversity reflects the opportunities for organisms to move between the focal cell and neighboring cells with

Metric group	Metric name	Description
		different ecological settings than the focal cell in order to adapt to changing environmental conditions (e.g., changing climate) over the long term.
Adaptive capacity	Adaptive capacity	Measures the capacity to adapt to a changing environment (e.g., as driven by climate change). Like connectedness, it reflects the accessibility of ecologically similar settings from the focal cell, but here the resistance and similarity is based on the future environmental conditions rather than the current. As such, adaptive capacity is the long-term equivalent of connectedness.
Connectivity	Local conductance	Measures the total amount of ecological flow through a cell from neighboring cells as a function of the ecological similarity between the focal cell and the neighboring cells. Local conductance differs slightly from local connectedness in that conductance measures how much flow there is to and through a cell from neighboring cells independent of the ecological similarity of the focal cell to its neighbors, whereas connectedness measures how much flow there is to the focal cell from ecologically similar neighboring cells. Thus, the conductance of a focal cell is determined in a sense by the average resistance of its neighborhood across all the ecological settings, whereas the connectedness of a focal cell is determined largely by the ecological similarity of its neighborhood. Although in practice these two measures tend to be highly correlated, conceptually these two metrics have different interpretations and uses. Connectedness is a measure of ecological isolation. Connectedness confers resiliency to a site in the short-term, since being connected to similar ecological settings should promote recovery of the constituent organisms following a local disturbance. Conductance, on the other hand, is a measure of importance in promoting ecological flows across the local landscape, regardless of whether the cell itself is highly connected to an ecologically similar neighborhood.

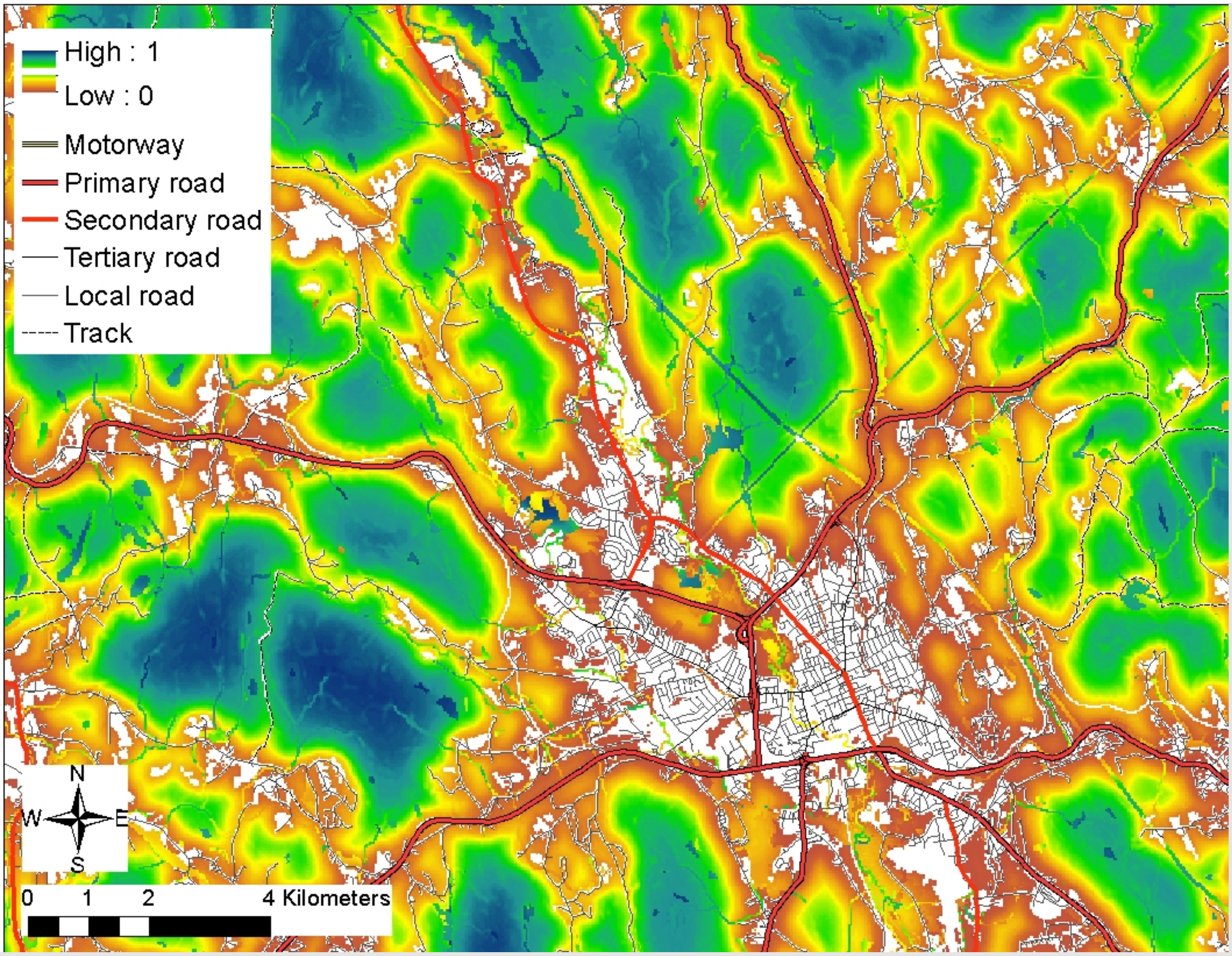

Figure 10. *Index of Ecological Integrity* (*IEI*) metric in 2010 scaled by ecosystem across the Northeast region (shown here for a random location). Note, developed lands are not assessed and are shown in white.

measure of conductance; i.e. the magnitude of ecological flows through a location. Importantly, in contrast to intactness and resilience, the conductance of a cell does not necessarily indicate a location with high ecological integrity, because the site itself may have low integrity but because of its landscape context play a vital role in conducting ecological flows from point A to point B. Thus, conductance is perhaps best interpreted as providing ecological integrity to the landscape as whole, rather to an individual site, and for this reason we use conductance primarily in the context of landscape design to identify places important to the integrity of the landscape.

Our ecological integrity assessment involves quantifying the attributes described above, which consists of a combination of spatial and nonspatial results. Spatial results include grids depicting the individual metrics (**Table 3**), as well as a composite local *Index of Ecological Integrity* (*IEI*), which is a weighted combination of the intactness and resiliency metrics. In order to combine the raw metrics into a single composite index, *IEI* is quantile-scaled by ecological system within various geographic extents (Northeast Region, state,

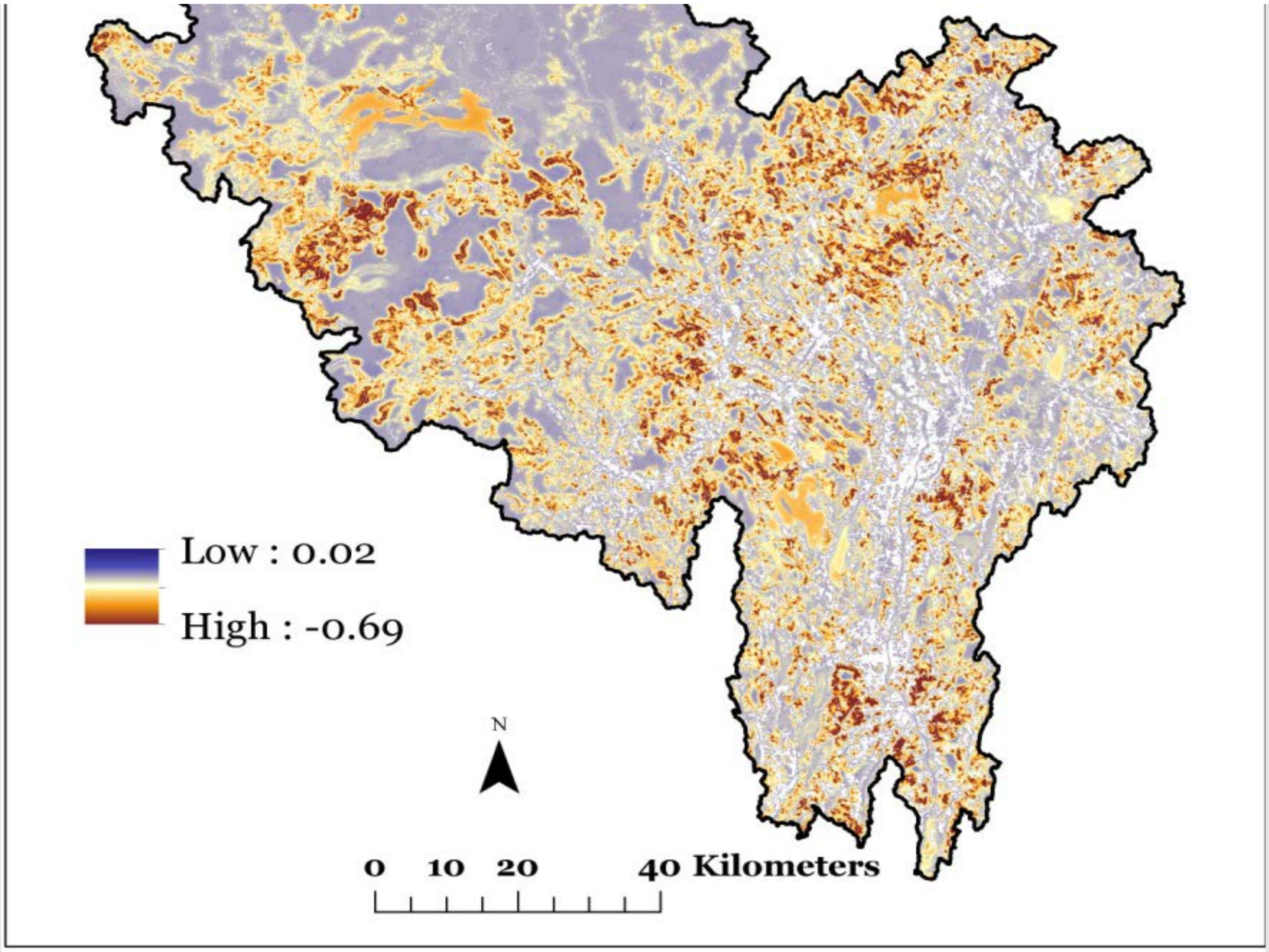

Figure 11. *Index of Ecological Impact* (*Impact*) metric in 2080 for the lower portion of the Kennebec River watershed in Maine averaged across replicate landscape change simulations. Large negative values indicate areas of high predicted ecological impact of the simulated landscape changes and represent places with high initial ecological integrity in 2010 and relatively large predicted loss of ecological integrity over time.

ecoregion and HUC6 watershed). Briefly, the individual raw metrics are first quantile-scaled by ecological system across the analysis extent (e.g., Northeast region), then combined in a weighted linear function specific to each ecological system, and then the composite *IEI* is again quantile-scaled by ecological system within each geographic extent to produce the final *IEI*. The end result is that within the extent considered the poorest cell within an ecological system gets a 0 and the best cell within that system gets a 1 (**Fig. 10**). Thus, forests are compared to forests and emergent marshes are compared to emergent marshes, and so on, within the corresponding geographic extent. It doesn't make sense to compare the integrity of an average forest cell to that of an average wetland cell, because wetlands have been substantially more impacted by human activities than forests. Rescaling by ecological system means that all the cells within an ecological system are ranked against each other in order to determine the cells with the greatest relative integrity for each ecological system. Similarly, it may not be that meaningful to compare the integrity of an average forest cell in Maine to that of a cell in, say, Maryland, if you are responsible

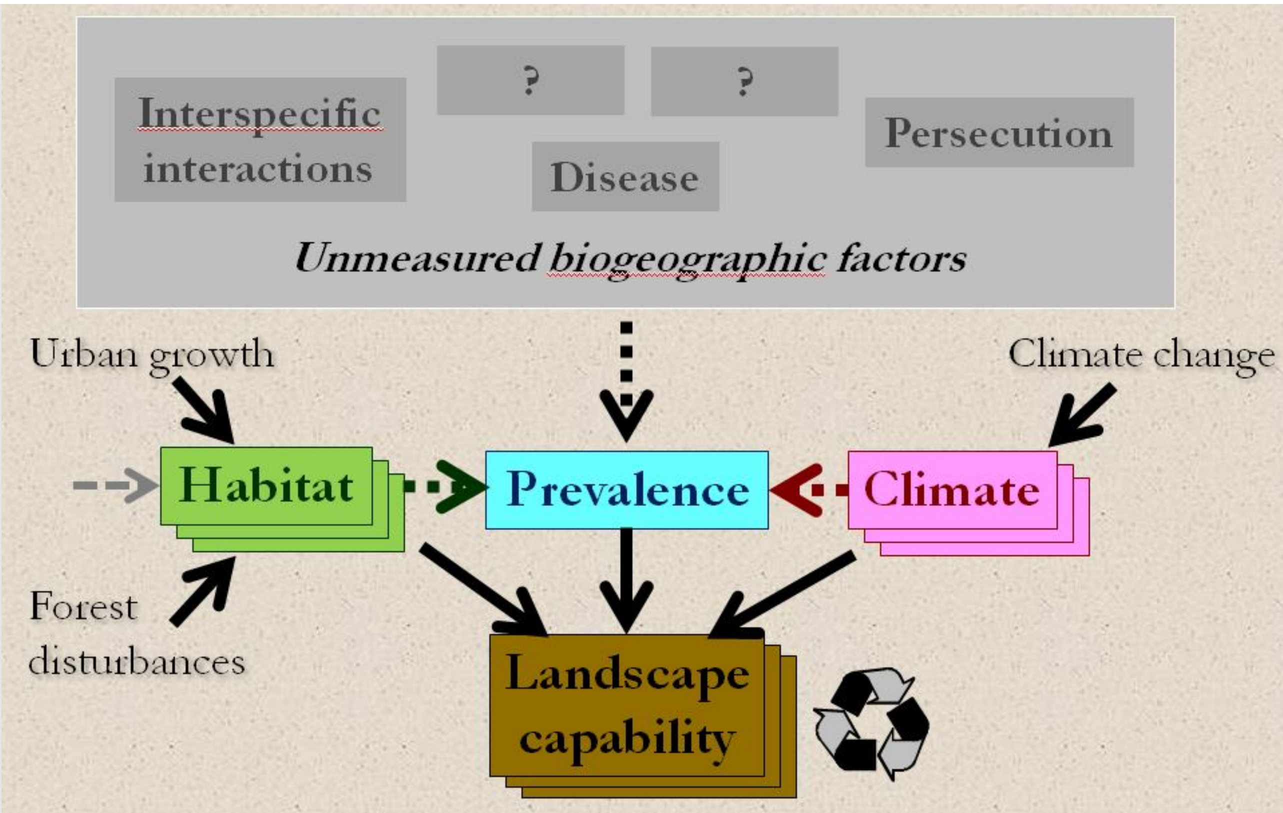

Figure 12. Schematic outline of the landscape capability modeling framework, in which we separately model the species' climate niche, habitat capability and prevalence, while recognizing that there are potentially other factors influencing the species' distribution, and then integrate these factors into single index.

for finding the best forest in Maine to conserve. Therefore, *IEI* is scaled not only by ecological system but also by various geographic extents, including the entire Northeast region, state, ecoregion and HUC6 watershed. *IEI* is our most synoptic measure of ecological integrity and, as such, it serves as the basis for our overall coarse-filter ecological assessment in the LCAD model. Moreover, it forms the basis for delineating core areas in the context of landscape design (see below).

In addition, we also compute a composite local *Index of Ecological Impact* (*Impact*), which is a measure of the change in *IEI* between the current and future timesteps relative to the initial *IEI* (i.e., delta *IEI* times initial *IEI*)(**Fig. 11**). A site that experiences a major loss of *IEI* due to urban growth has a high predicted ecological impact of the simulated landscape changes; a loss of say 0.5 *IEI* units reflects a greater relative impact than a loss of 0.2 *IEI* units. Moreover, the loss of 0.5 units from a site that has a current *IEI* of say 0.9 is much more important than the same absolute loss from a site that has a current *IEI* of 0.5. Thus, *Impact* reflects not only the magnitude of loss of *IEI*, but also where it matters most — sites with high initial integrity.

Nonspatial results of our ecological integrity assessment include numerical summary statistics for some of the ecological integrity attributes described above for each ecological

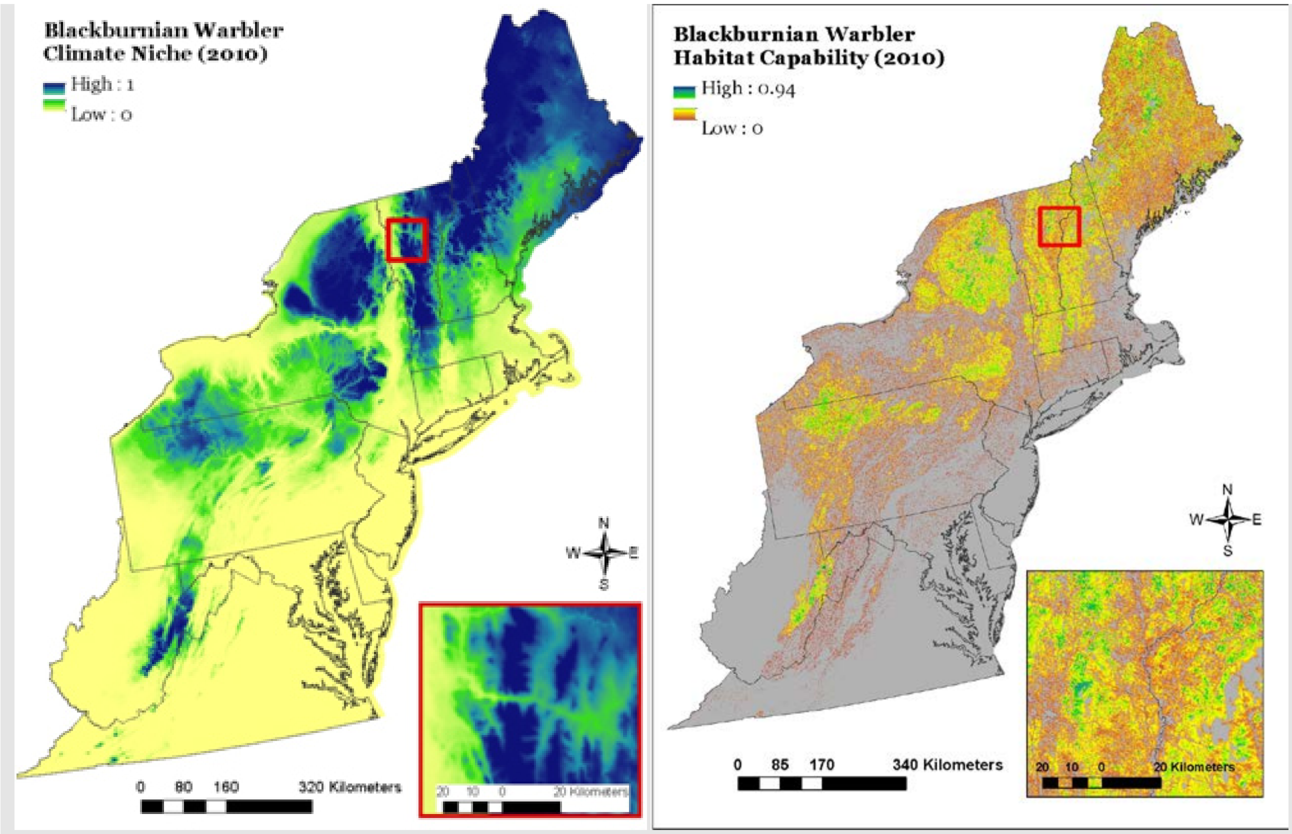

Figure 13. *Climate Niche* (*CN*) index, expressed as a continuous relative probability of climate suitability surface, and *Habitat Capability* (*HC*) index, expressed as a continuous relative probability of habitat suitability surface, shown here for the Blackburnian warbler in the Northeast in 2010.

system or for the landscape as a whole, and these are useful for quantitatively summarizing and comparing among scenarios.

The ecological integrity assessment is done at select timesteps of the simulation, and summarized for the entire run and across stochastic runs for each scenario. The ecological integrity assessment is useful as a means of comparing scenarios with regards to achieving biodiversity conservation, and it is also useful as a basis for landscape design.

4.3.2 Landscape capability for representative species

In addition to our coarse-filtered, ecosystem-based assessment, we also use a complementary individual species-based approach. Our species-based assessment is based on the concept of *landscape capability* and is described in detail in a separate document (DSL_documentation_species.pdf). Importantly, we developed a modeling framework for assessing landscape capability for any species regardless of the purpose of the selected species (e.g., representative or surrogate species, indicator species, threatened and endangered species, vulnerable species, flagship species, game species or any other species of conservation interest)(**Fig. 12**). However, for the current phase of the project we focused on developing models for a suite of 30 representative species under the assumption that

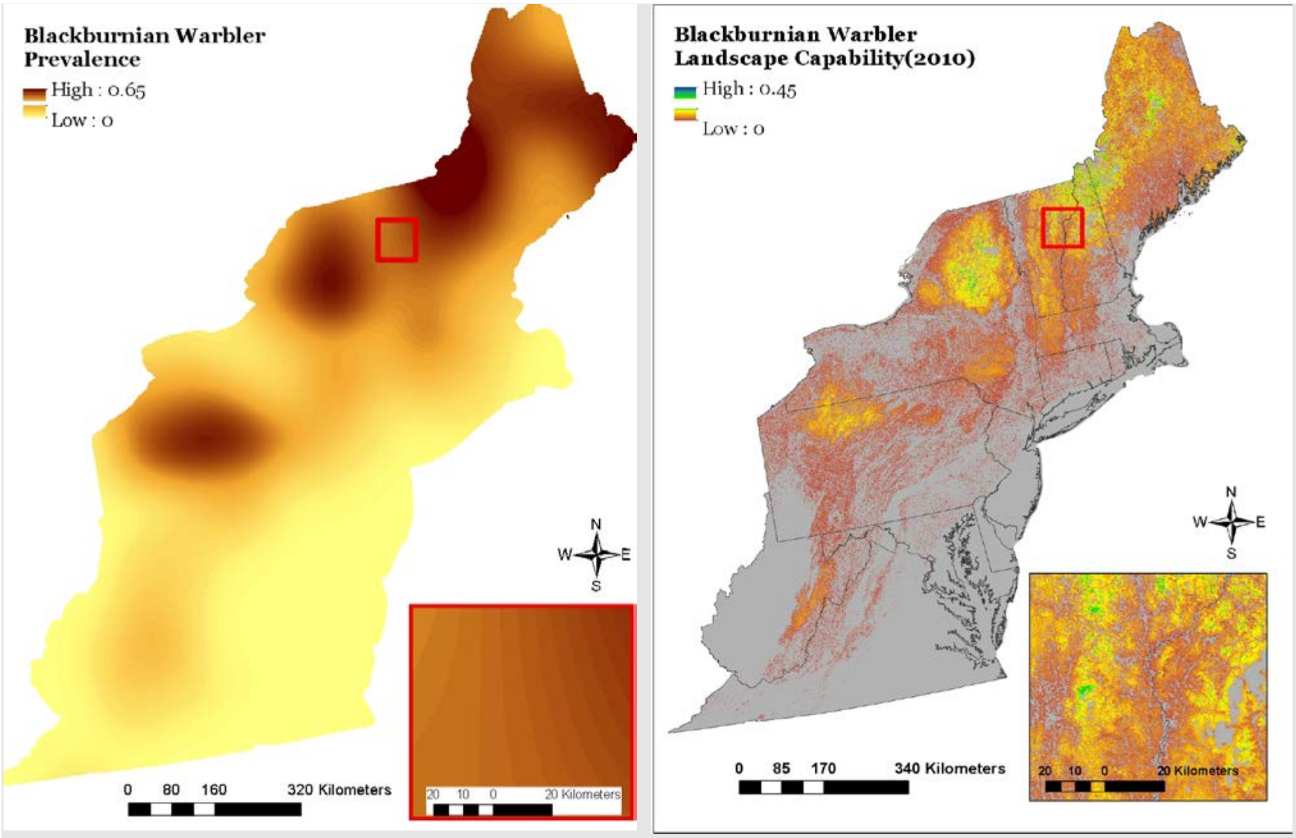

Figure 14. *Prevalence* index and composite *Landscape Capability* (*LC*) index, both expressed as continuous relative probability surfaces, shown here for the Blackburnian warbler in the Northeast in 2010.

these relatively few species can serve as surrogates for the much large suite of conservation priority species. Our landscape capability modeling approach has several key features:

- We use logistic regression methods to build species' *Climate Niche* (*CN*) models from downscaled climate data and independent species' occurrence data. These models predict the probability of climate suitability for each species based on their current geographic distribution in relation to several climate variables based on data representing the past 30 years (**Fig. 13**). We use these fitted models to predict the future distribution of the species' climate niche under alternative climate change scenarios. Importantly, we use these predictions to determine where the species might occur if they are able to immediately redistribute to remain within their current climate niche envelope (*CNE*), but they are not meant to predict where the species will actually occur because of our uncertainty in the species' ability to geographically track climate and the potentially limiting role of future habitat changes independent of climate, as well as time lags in habitat response to climate change.

- We use the program HABIT@, a spatially explicit, GIS-based wildlife habitat modeling framework developed in the UMass Landscape Ecology Lab, to build species' habitat capability models. These models produce an index of habitat capability that we refer to as the *Habitat Capability* (*HC*) index for each species based on the condition of the landscape represented by a suite of environmental variables (**Fig. 13**). We use these HABIT@ models to predict the future habitat capability of the landscape under alternative land use (e.g., urban growth) scenarios. Importantly, we use these predictions to determine where the species <u>might</u> occur if they are able to immediately redistribute to track suitable habitat conditions, but they are not meant to predict where the species will <u>actually</u> occur because of our uncertainty in the species' ability to geographically track habitat changes and the potentially limiting role of future climate independent of habitat.

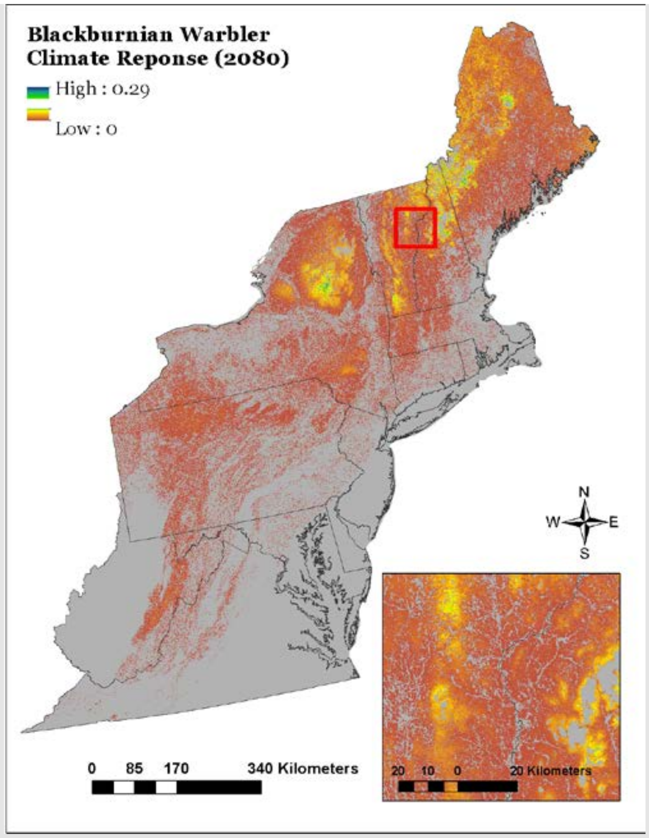

Figure 15. *Climate Response* (*CR*) index, defined as the future *Landscape Capability* (*LC*) index calculated with <u>current habitat</u> and predicted <u>future climate</u> in 2080 (averaged across RCP4.5 and RCP8.5 scenarios), shown here for the Blackburnian warbler in the Northeast.

- We use kernel density estimators to build species' *Prevalence* models based on species' occurrence data. These models predict the species' current relative probability of occurrence based solely on the species' observed spatial distribution independent of any explanatory variables. Prevalence is intended to capture biogeographic factors influencing species' distributions that are not accounted for by the climate niche and habitat capability models, such as interspecific interactions, human persecution, and disease that we cannot measure directly (**Fig. 14**). We use these prevalence models to affect the species' predicted landscape capability (below) separately from that of climate and habitat. This is particularly important in some species' distributions where prevalence is less than would be expected based solely on climate suitability and habitat capability, presumably due to other biogeographic factors.

- We synthesize the previous results for each species into a composite *Landscape Capability* (*LC*) index at each time step for each landscape change simulation. Specifically, we combine *CN*, *HC* and *Prevalence* into a single index (*LC*) scaled 0-1 (although distributed as an integer grid scaled 0-100)(**Fig. 14**) and use logistic regression to evaluate the predictive ability of the model based on independent species' occurrence data. Briefly, an *LC* model represents an index of the species' <u>relative</u> probability of occurrence based on climate, habitat and other biographic factors (as represented by prevalence); it is our best estimate of the species' likely distribution based on measurable factors. Importantly, *LC* models provide an index of species occurrence, not the true probability of occurrence. We acknowledge that there may be other factors influencing species' distributions, such as interspecific interactions, human persecution and disease, but these are outside the scope of modeling with extant data at the regional scale. Consequently, these predictions are used to determine where the species might occur based on climate suitability, habitat capability and prevalence, but they are not meant to predict where the species will actually for the reasons mentioned previously. In the context of the LCAD model, we use the species' LC to predict the current and future distribution of the species under alternative landscape change scenarios, and we use the intersection of a species' *LC* map at any future timestep in relation to the initial or baseline condition in 2010 as the basis for summarizing the potential impacts of habitat and climate changes on a species (see below).

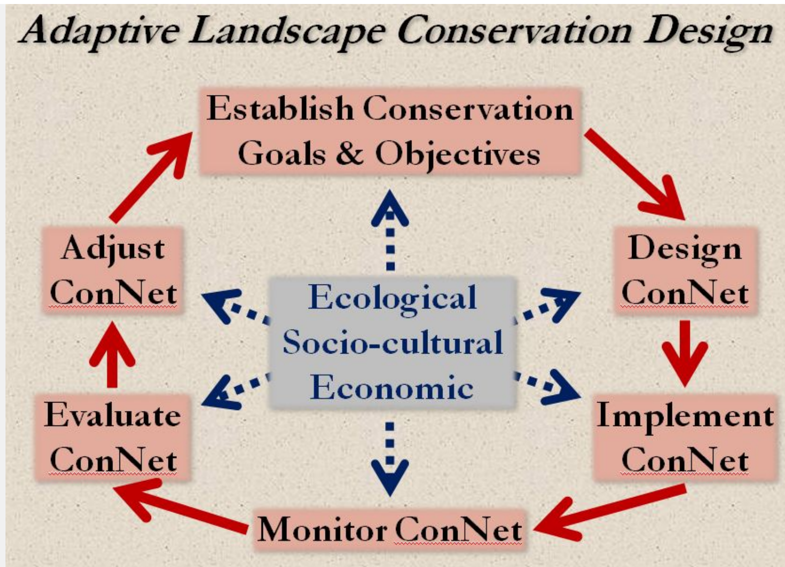

Figure 16. Diagram of the Adaptive Landscape Conservation Design (LCD) steps. Our landscape design model fits into step 2 — designing a conservation network (ConNet).

- Lastly, we assess the potential impacts of habitat and climate changes on each species using a variety of nonspatial and spatial indices. First, we compute a complementary set of nonspatial indices for each species based on the proportional change in *LC* due to climate change, habitat change, or both within the specified geographic extent. These nonspatial indices are primarily useful for establishing conservation objectives or targets for species in conservation design or for comparison among landscape change scenarios. Second, we derive a variety of spatial indices representing the species' potential response to climate change, habitat change or both based on changes in *LC* under different assumptions or for different purposes. For example, the species' *Climate Response* (*CR*) index depicts the species' future *LC* calculated with current habitat (*HC*) and predicted future climate (*CN*) in 2080 (averaged across RCP4.5 and RCP8.5 scenarios) within the project area (**Fig. 15**). This index emphasizes places with high current habitat and climate capability that maintain or increase in climate suitability over time but without regard to future changes in habitat capability. These spatial indices are useful for prioritizing locations for conservation action for each species in the context of landscape conservation design and for visualizing the potential changes in the distribution of a species due to climate change, habitat change or the combination of the two.

4.4 Landscape Design

Our landscape conservation design (LCD) approach includes a suite of tertiary products derived from the ecological assessment and aimed at identifying priorities for conservation action, as described in detail in a separate technical document on landscape design (McGarigal et al 2017). Briefly, for our purposes, we define LCD as:

> "A coordinated suite of conservation actions within a designated spatial and temporal extent intended to modify the landscape pattern for the purpose of conserving biodiversity while recognizing socio-cultural and economic constraints."

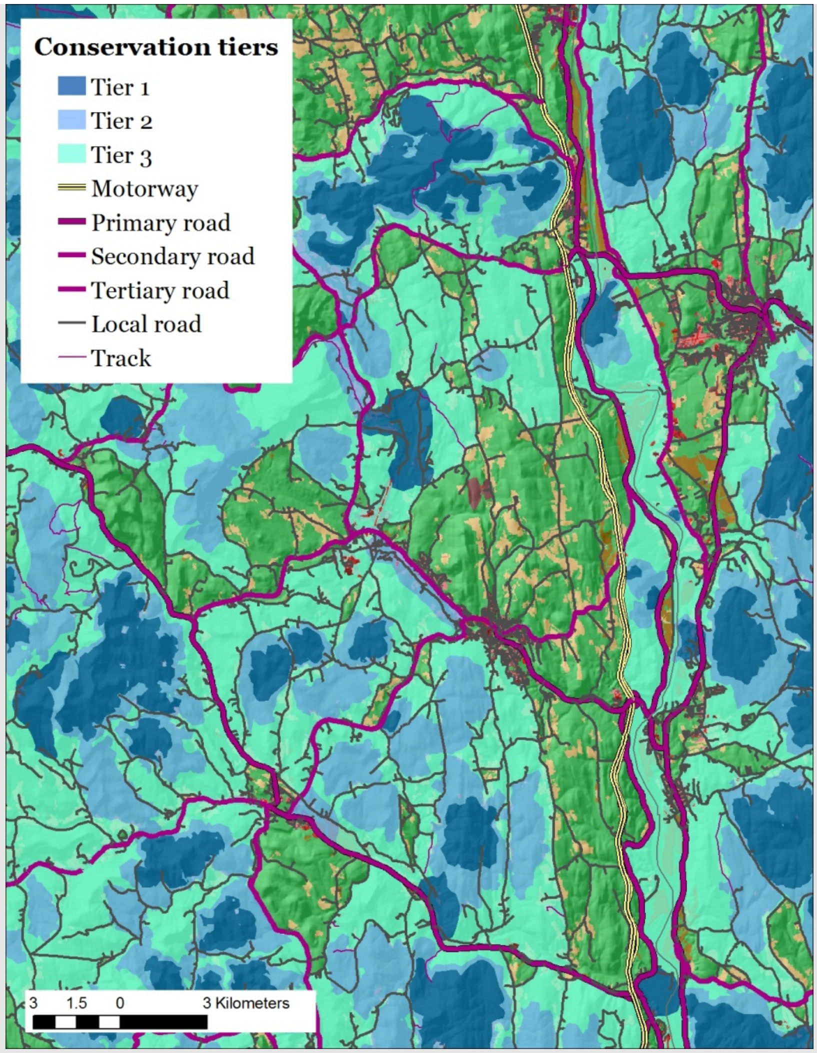

Figure 17. Tier 1 and 2 terrestrial core areas and the corresponding tier 3 supporting landscapes overlaid by roads and with land use (no legend) in the background.

We envision our LCD approach as contributing to one step in an adaptive landscape conservation design framework that consists of a sequence of six major steps implemented in an iterative cycle and operating within a multi-scale framework (**Fig. 16**). Our LCD approach focuses on the ecological component of the conservation design step (step 2) in the adaptive framework and is primarily a spatial strategy for conservation actions designed to achieve a set of user-defined conservation goals and objectives. Importantly, the conservation design is merely a hypothesis about what conservation actions need to be taken and where for the objectives (and thus the goals) to be met, and thus its success can only be determined through objective-based monitoring.

Our LCD has four major components: 1) establishing a set of conservation "core areas" to spatially represent the ecological network designed to provide strategic guidance for conserving natural areas, and the fish, wildlife, and other components of biodiversity that they support within the landscape; 2) identifying places critical to promoting ecological connectivity independent of and between the core areas to ensure adaptive capacity of ecosystems and species in the face of climate and land use change; 3) determining conservation priorities and active management needs of individual core areas, supporting

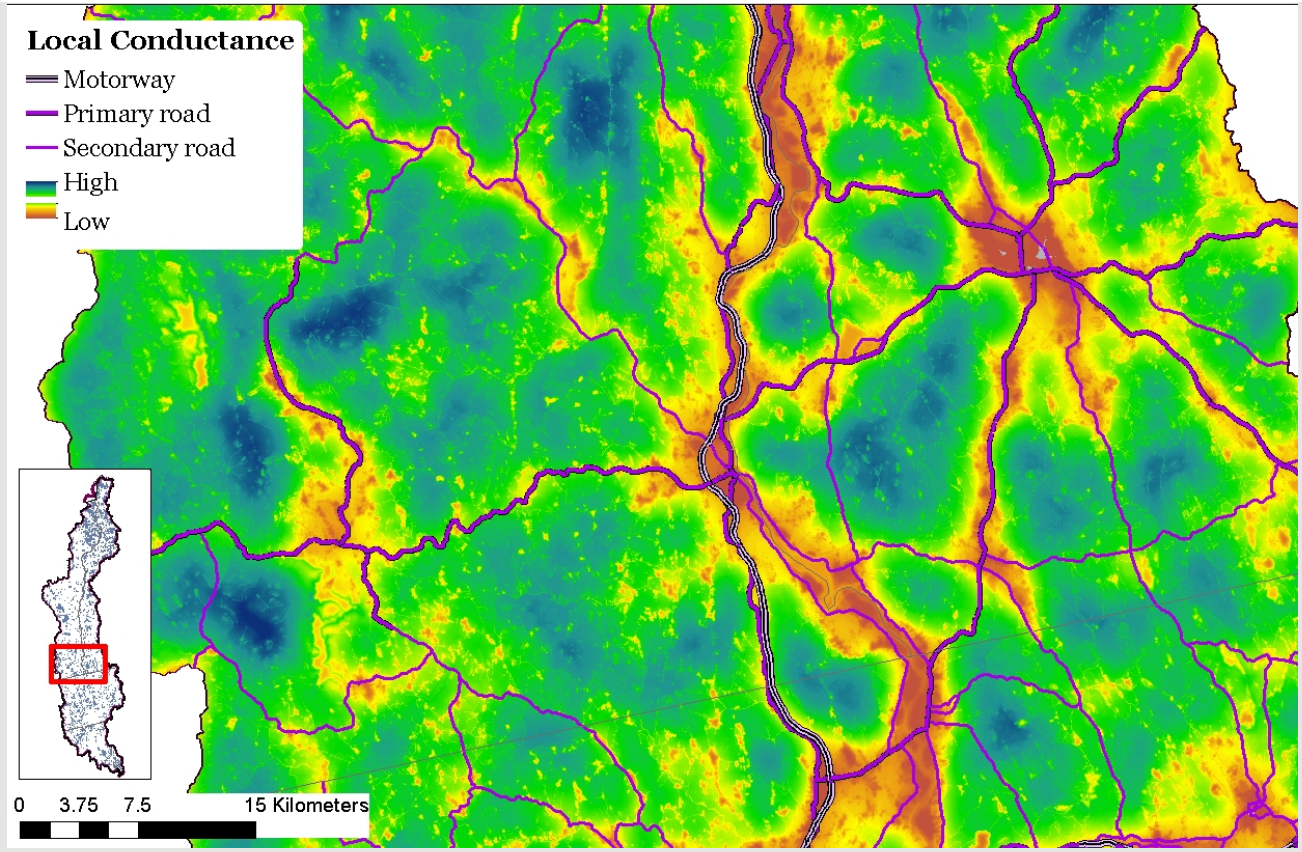

Figure 18. Illustration of the local conductance metric. The areas shown in blue depict relatively high local conductance, whereas the areas shown in red depict relatively low local conductance; major roads are depicted by class.

landscapes and/or connectors; and 4) prioritizing opportunities for restoring ecological patterns and processes, with an emphasis on restoring connectivity. Importantly, each of these components can be initially developed from the primary and secondary LCAD data products, but the final design of each component must be accompanied by field verification (e.g., to confirm that the assigned ecological value to a location is not the result of a spatial data error) and consideration of other ecological, socio-cultural, and economic considerations that lie outside the current scope of the DSL project. Here, however, we will focus on the LCD components that are based on the LCAD data products.

4.4.1 Establishing core areas

The first major design component is the most critical element and involves identifying and protecting a network of (potentially tiered) conservation *core areas* separately for terrestrial and aquatic ecosystems and species within each sub-unit of the landscape, with the aim of protecting the lands and waters with the highest ecological value base on one or more criteria, including: 1) high ecological integrity across all ecological settings, emphasizing areas that are relatively intact (i.e., free from human modifications and disturbance) and resilient to environmental changes (e.g., climate change); 2) high capability to support a suite of focal wildlife species, emphasizing areas that provide the best habitat and climate conditions for each species; and 3) any number of other factors

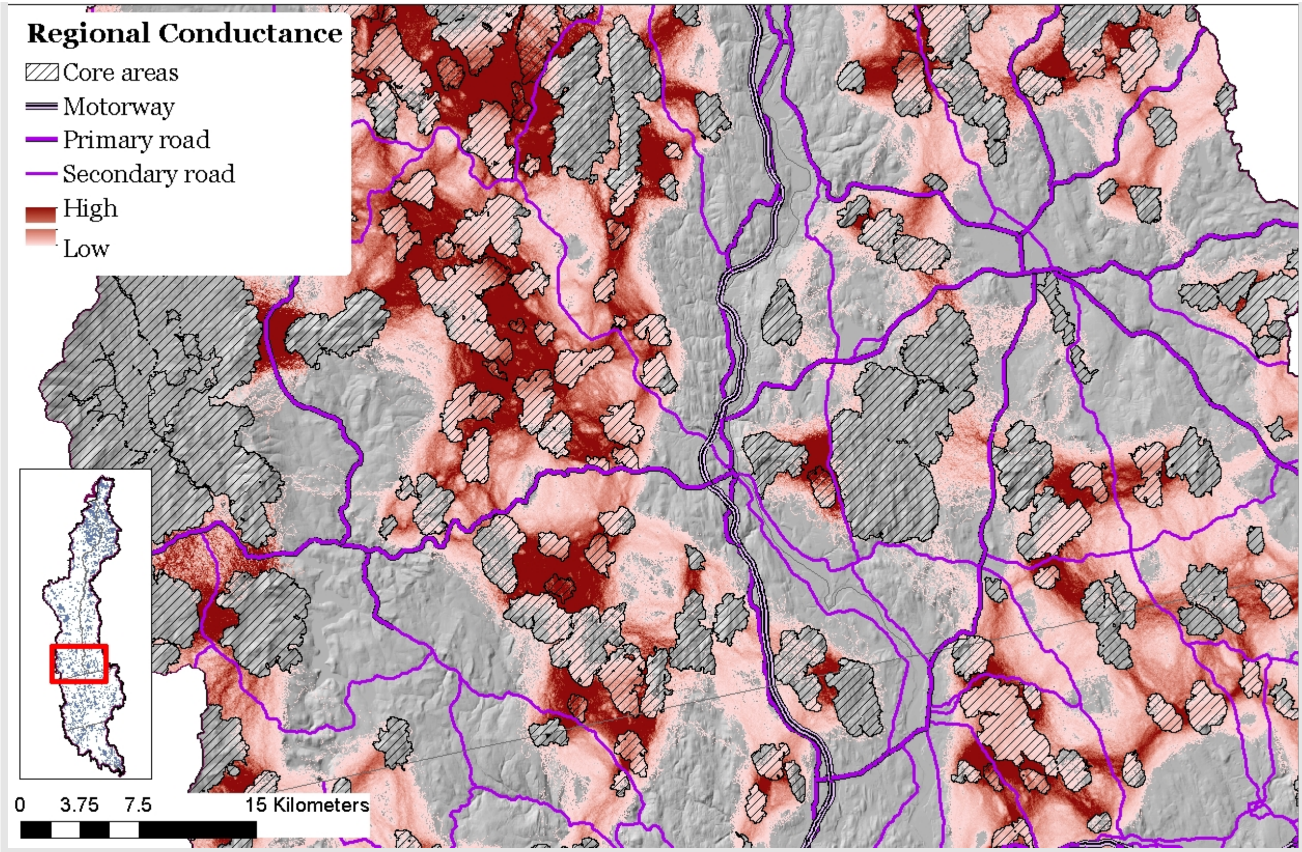

Figure 19. Illustration of the regional conductance metric, shown here for a designated core area network and a small portion of the Connecticut River watershed. Conductance is given by the intensity of red and depicts areas of relatively high predicted ecological flows between designated core areas; major roads are depicted by class.

such as rare natural communities that support unique biodiversity, and floodplains and riparian areas that perform critical functions in the interface between terrestrial and aquatic ecosystems. Note, the criteria for selecting core areas is flexible and can include anything so long as the data are consistent over the extent of the landscape. In addition, the exact composition and extent of the core area network will depend on user-specified conservation targets dictated by the goals and objectives (e.g., how to weight ecosystems and focal species, how much of the landscape to include in core areas, minimum size of core areas, etc.), but the final network of core areas, however they are defined, can be considered the most important locations for achieving the objectives.

Importantly, cores areas represent the best or most urgent places to start conserving, but by themselves are unlikely to be sufficient to fully achieve the objectives. Moreover, core areas are places of particularly high ecological value based on the criteria above without regard to existing protected lands, and as delineated may not always represent logical or practical conservation units since they do not correspond to parcel boundaries or any other practical scheme such as roadless blocks. In addition, core areas can be generated in tiers to reflect different conservation targets (e.g., 25% versus 50% of the landscape) or to provide "buffers" or "supporting landscapes" for the highest priority tier 1 cores (e.g., **Fig.**

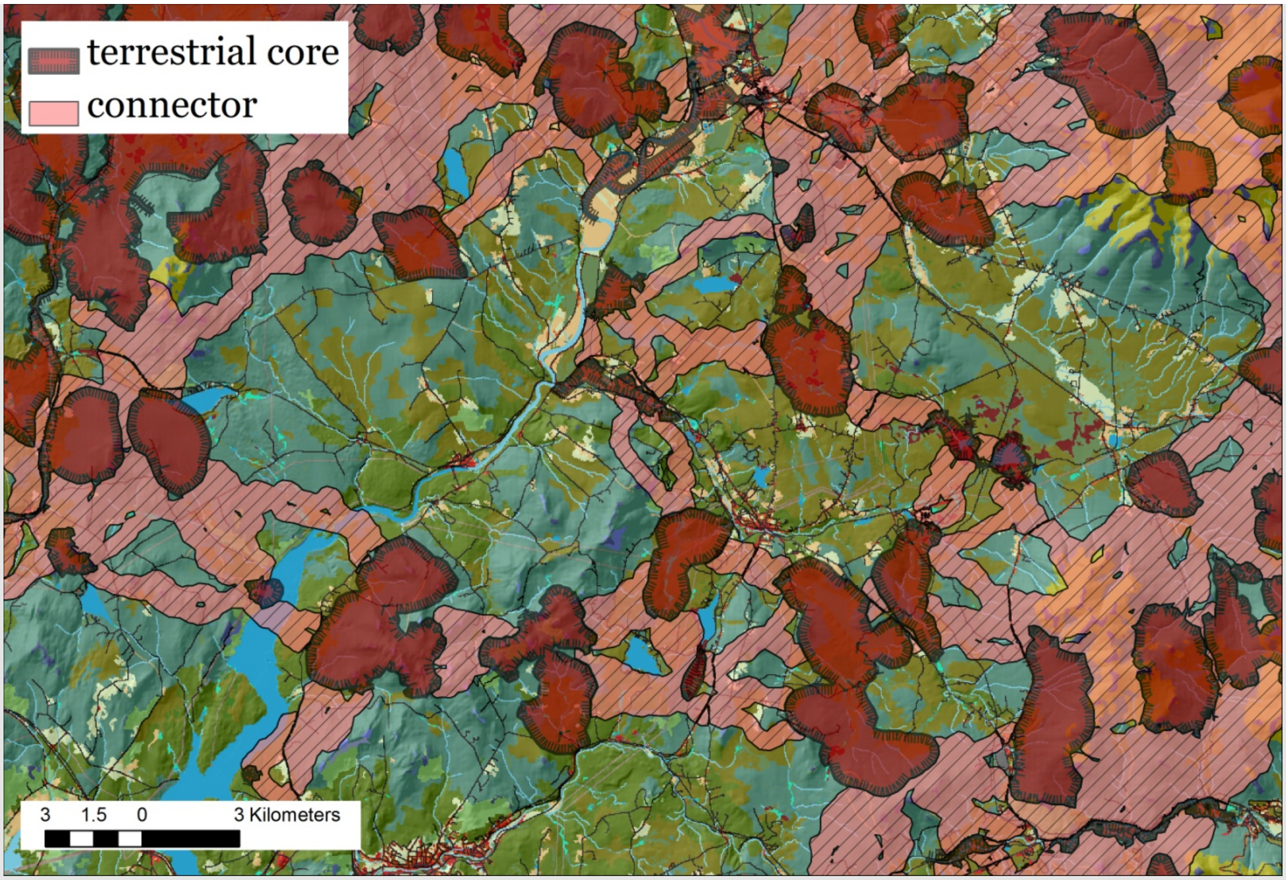

Figure 20. Terrestrial cores and connectors, shown here for a small portion of the Connecticut River watershed on a background of the ecological systems map (without a legend).

17). The latter may be important for preventing the future degradation of the core area values caused by adverse human land uses impinging on the cores.

4.4.2 Promoting ecological connectivity

The second major design component involves identifying places critical to promoting ecological connectivity (i.e., the propensity to facilitate ecological flows, including organism dispersal and gene flow) across the landscape. While there are many aspects to connectivity and ways to represent it and promote it, here we focus on local and regional *conductance* and connecting the designated core areas via *connectors*:

- *Local conductance* — measures the total potential amount of ecological flow through a cell from neighboring cells as a function of their proximity and ecological similarity to the focal cell at the scale of a few to several kilometers. Local conductance measures the importance of a cell in promoting ecological flows across the local landscape, regardless of whether the cell itself is highly connected to an ecologically similar neighborhood (**Fig. 18**). Thus, a cell itself may not have particular high integrity but because of its position in the landscape may serve an important role as a thruway for ecological flows.

- *Regional conductance* — measures the total potential amount of ecological flow through a cell from nearby designated terrestrial core areas at the scale of a few to ten kilometers, and is a function of the size, composition and proximity of the adjoining core areas and the resistance of the intervening landscape and the focal cell itself. Importantly, this metric is contingent upon the a prior designation of terrestrial core areas, and thus is it only meaningful when referenced to those designated terrestrial cores (**Fig. 19**).

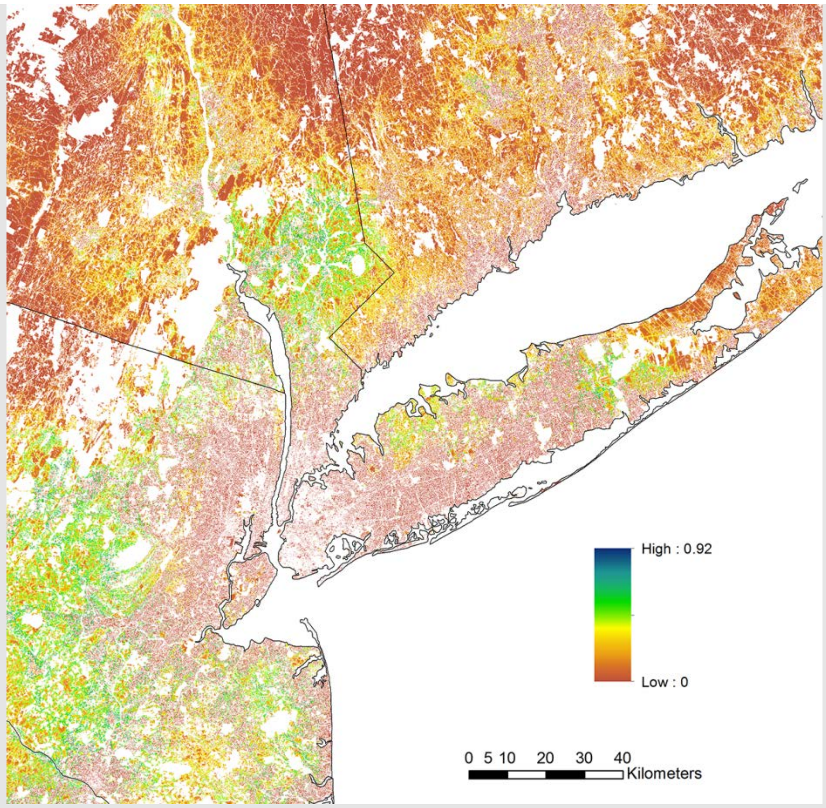

Figure 21. Integrated probability of development occurring between 2010-2080 for the area in the vicinity of New York. Areas shown in white are unbuildable (e.g., water, barren, secured).

- *Core area connectors* — essentially a discrete representation of regional conductance, whereby the connectors delineate potential "corridors" that could facilitate the movement of plants and animals (i.e., ecological flow) between designated terrestrial core areas (**Fig. 20**). By providing connectivity between core areas, these connectors increase the resiliency of the core area network to uncertain land use and climate changes. The connectors are wider where more movement between cores is expected because of larger, higher-quality, and closer core areas and where a more favorable natural environment exists between them. Connectors primarily link adjoining core areas along routes that possess the greatest ecological similarity to the ecosystems in the adjoining cores; they do not necessarily represent travel corridors for any individual species.

4.4.3 Conservation priorities and management needs within the ecological network

The third major design component involves determining conservation priorities and active management needs within the ecological network of core areas, supporting landscapes and connectors. While there are numerous ways to prioritize conservation actions and management needs within the ecological network, here we focus on identifying places within the network that are most *vulnerable* to the loss of value due to future urban development and identifying *management* needs within the core areas:

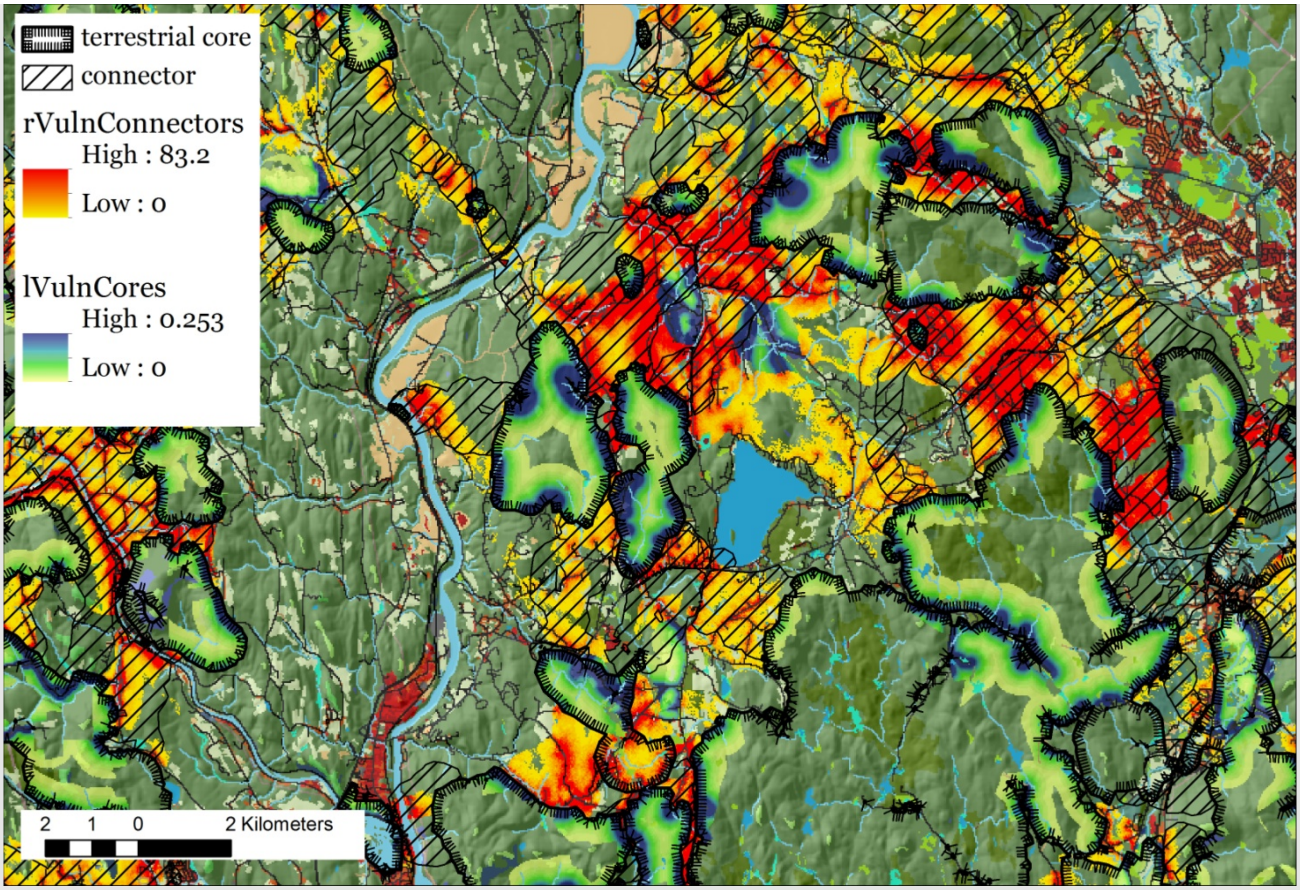

Figure 22. Vulnerability of conductance to future development depicted by a combination of the local vulnerability index within terrestrial core areas (lVulnCores) and the regional vulnerability index within connectors (rVulnConnectors). Areas in dark blue within cores and dark red within connectors have a high risk of future development. Shown here for a small portion of the Connecticut River watershed on a background of the ecological systems map (without a legend).

- *Vulnerability* — An important by-product of the urban growth model is an index representing the relative probability of development integrated across all of the possible development transitions (e.g., undeveloped to low-intensity development, low- to high-intensity development, etc.) occurring sometime between 2010 and 2080 at the 30 m cell level (**Fig. 21**). We can use this probability of development metric in combination with any of the ecological assessment and design products to identify high-valued places that are vulnerable to future development. For example, we can combine this metric with the local and regional conductance metrics described above to identify places important for promoting connectivity that are most vulnerable to future development; moreover, these two metrics can be used in a complementary fashion to identify vulnerable places within the terrestrial cores (*local vulnerability*) and between the terrestrial cores (*regional vulnerability*)(**Fig. 22**).
- *Management needs* — There are many management actions (e.g., silvicultural treatments, hydrological controls, prescribe burning, etc.) designed to actively

manipulate ecological systems and/or populations to achieve conservation objectives. For example, vegetation management may be the most effective way to achieve habitat objectives for certain terrestrial species requiring early-seral vegetation; hydrologic management may be critical to the maintenance of habitat for certain aquatic species (e.g., regulation of river discharge to effect habitat for shortnose sturgeon); and prescribed fire may be the only feasible way to maintain this keystone process in certain ecosystems (e.g., pine barrens). In all of these cases, the value assigned to a particular core area, supporting landscape or connector may be the result of certain past management activities, and the maintenance of that value may be dependent on sustained management activities. Consequently, it is important to identify these management needs as part of the conservation design process. Unfortunately, it is not clear how best to explicitly incorporate management needs into the conservation design process, at least within the LCAD modeling framework without additional relevant spatial data. For example, currently we are not modeling prescribed burning, timber harvesting and water management as explicit landscape change processes, so there is no simple way to evaluate these management practices in the model. However, we can identify the important ecosystems and focal species in each core area, for example, as the necessary first step in determining its management needs. To do this we developed several different indices to evaluate the importance of each core for each ecosystem and species. Once the important ecological systems and/or species are identified for a particular core area (e.g., **Fig. 23**), it is incumbent on the manager to determine the appropriate management activities needed to maintain the core area value.

4.4.4 Ecological restoration opportunities

The fourth major design component involves prioritizing opportunities for *ecological restoration*. While there are myriad types of restoration actions that could be identified and prioritized, here we focus on a few types of activities designed to actively restore ecological connectivity — what we refer to as "critical local linkages". Our critical local linkages products measure the relative potential to improve local connectivity through restoration activities including dam removals, culvert upgrades, and creating terrestrial road passage structures. Each dam, road-stream crossing and road segment is scored based on its potential to improve local connectivity through the corresponding restoration action, but only where it matters -- in places where the current ecological integrity is not already seriously degraded too much.

Our critical local linkages assessment is based on the *connectedness* metric and its aquatic counterpart, *aquatic connectedness*, in combination with the composite *IEI* metric, which were mentioned previously and are described in detail in the technical document on ecological integrity (McGarigal et al 2017). Importantly, connectedness and aquatic connectedness represent the amount of ecological flow to the focal cell from neighboring cells, weighted by their accessibility and ecological similarity (as represented by the ecological settings variables). Underlying this metric is the assumption that ecological flows from similar ecological communities are more important to local connectivity (at least in the short term) than those from dissimilar communities, but only if they are accessible (i.e., there are no major impediments to movement between the neighboring cells and the focal cell). In the calculation of resistance to ecological flows, anthropogenic landscape features

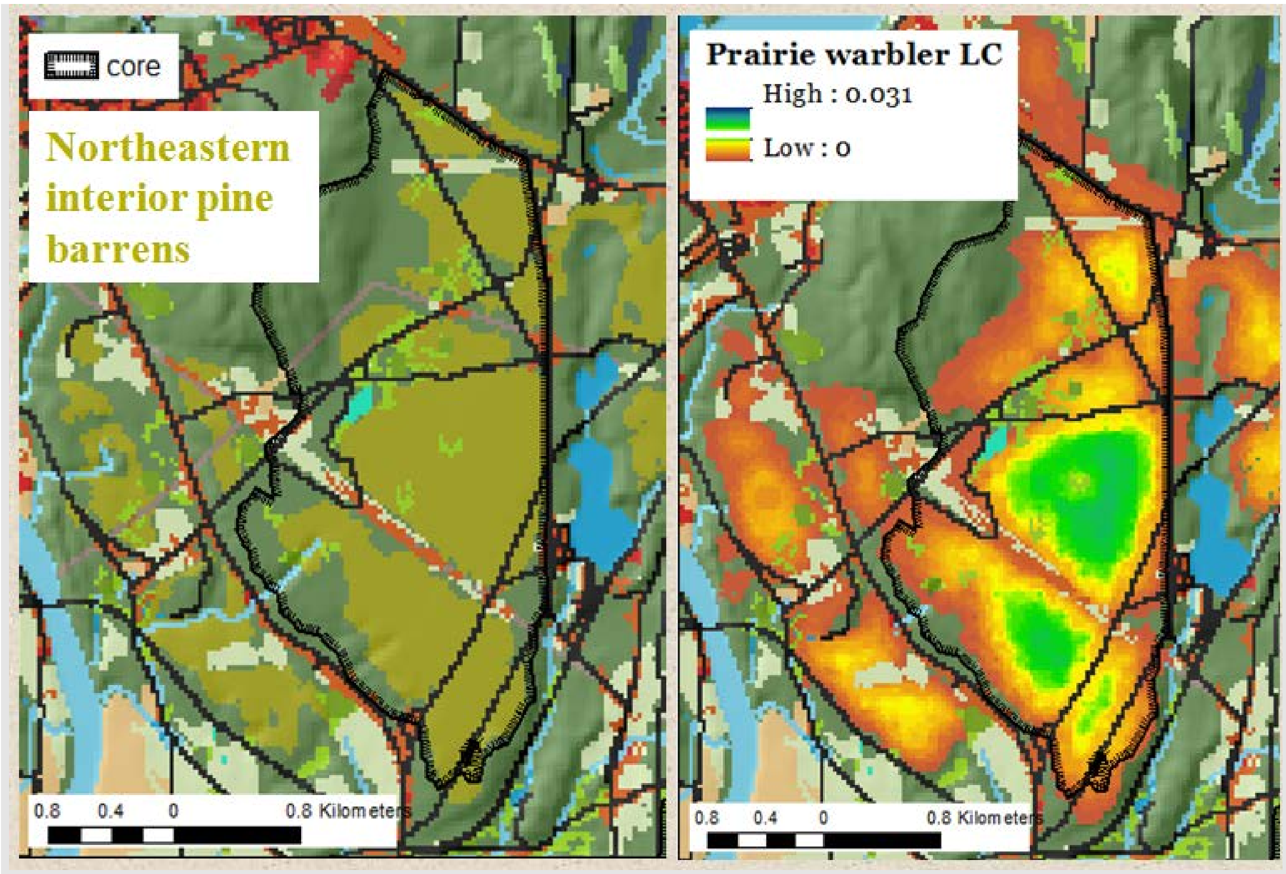

Figure 23. Sample core area centered on the Montague sand plains in Turners Falls Massachusetts: left panel depicts the ecological systems map (without a complete legend), but highlighting the most important ecosystem in this core; right panel depicts the same map but with the most important focal species' landscape capabilityindex overlaid.

are weighted very heavily. In particular, terrestrial barriers along with road traffic, impervious surface and development all weigh most heavily in determining terrestrial connectedness, and aquatic barriers (i.e., dams and road-stream crossings) weighs most heavily in determining aquatic connectedness.

Our current critical local linkage assessment involves evaluating the restoration potential of: 1) culvert upgrades, 2) dam removals, and 3) construction of terrestrial wildlife passage structures on roads, as follows:

- *Culvert upgrades* -- With culvert upgrades, each road-stream crossing is scored based on its potential to improve local aquatic connectivity by upgrading a culvert to a bridge, but only where it matters — in places where the current ecological integrity is not already seriously degraded too much. Our measure of local connectivity for culvert upgrades is the aquatic connectedness metric. Aquatic barriers (i.e., dams and road-stream crossings) is one of several ecological settings variables that determines the ecological distance between the focal cell and neighboring cells, and it weighs very heavily in determining aquatic connectedness. Aquatic barriers is a measure of the degree to which road-stream crossings (i.e. , culverts and bridges) and dams are

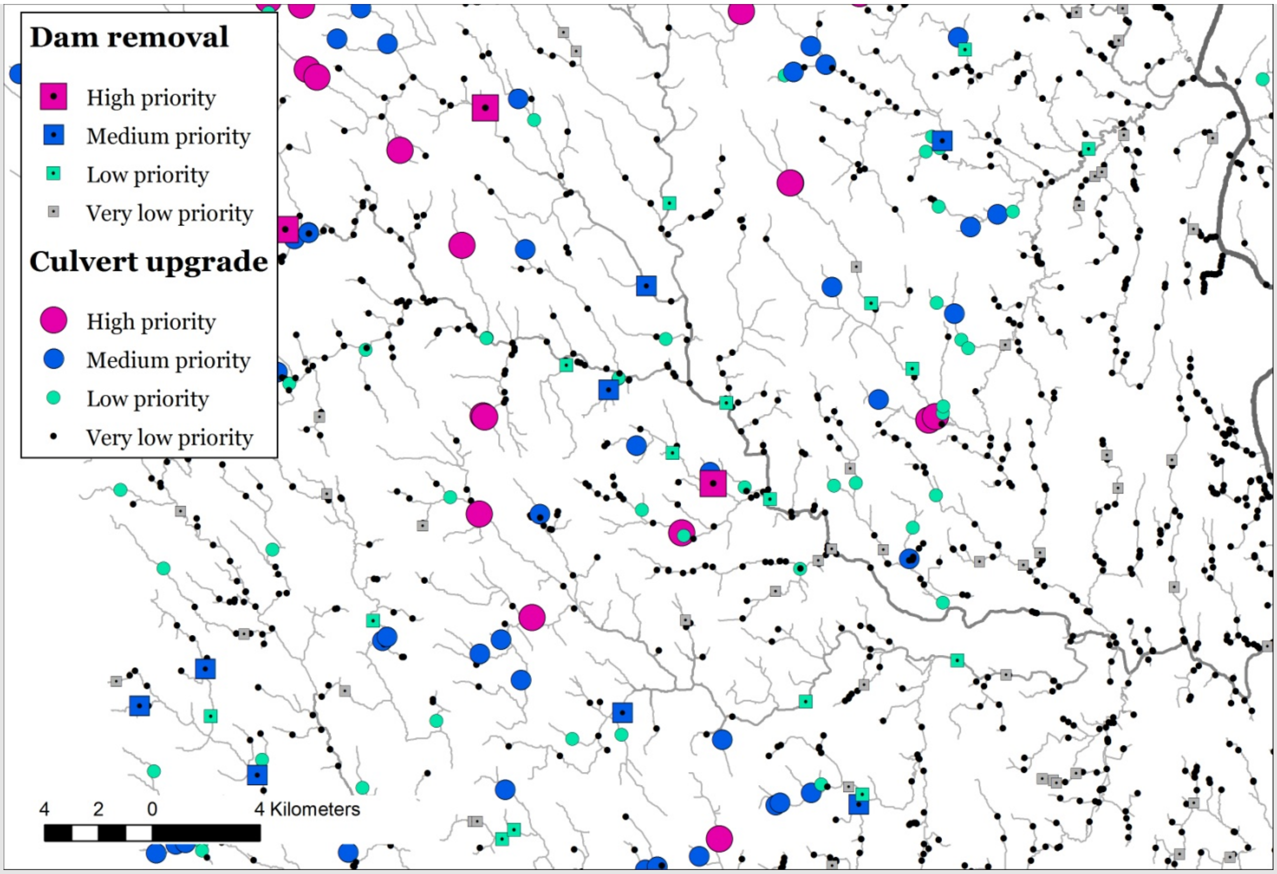

Figure 24. Critical local linkage scores for dam removals and culvert upgrades for a portion of the Connecticut River watershed. The size of the symbol represents the relative magnitude of increase in local aquatic connectivity from removing the dam or upgrading the culvert to the equivalent of a bridge.

estimated to act as impediments to ecological flows in aquatic systems. Thus, aquatic connectedness measures the degree of local aquatic connectivity for each focal cell as principally affected by nearby road-stream crossings and dams. The culvert upgrade metric measures the improvement in aquatic connectedness from upgrading a road-stream crossing from a culvert with its estimated degree of passability for aquatic organisms to a bridge with minimal impediment to ecological flows, but the delta in aquatic connectedness is multiplied by the initial *IEI* for all cells within the affected neighborhood so that the end result is a an estimate of the effect of upgrading the crossing to a bridge in places where the current ecological integrity is not already degraded too much. These scores can be used to prioritize culverts for upgrades (**Fig. 24**).

- *Dams* -- With dam removals, each dam is similarly scored based on its potential to improve local aquatic connectivity by removing the dam, but again only where it matters — in places where the current ecological integrity is not already seriously degraded too much. Our measure of local connectivity for dam removals is again the aquatic connectedness metric, as described above. The dam removal metric measures the improvement in aquatic connectedness from removing a dam with its estimated

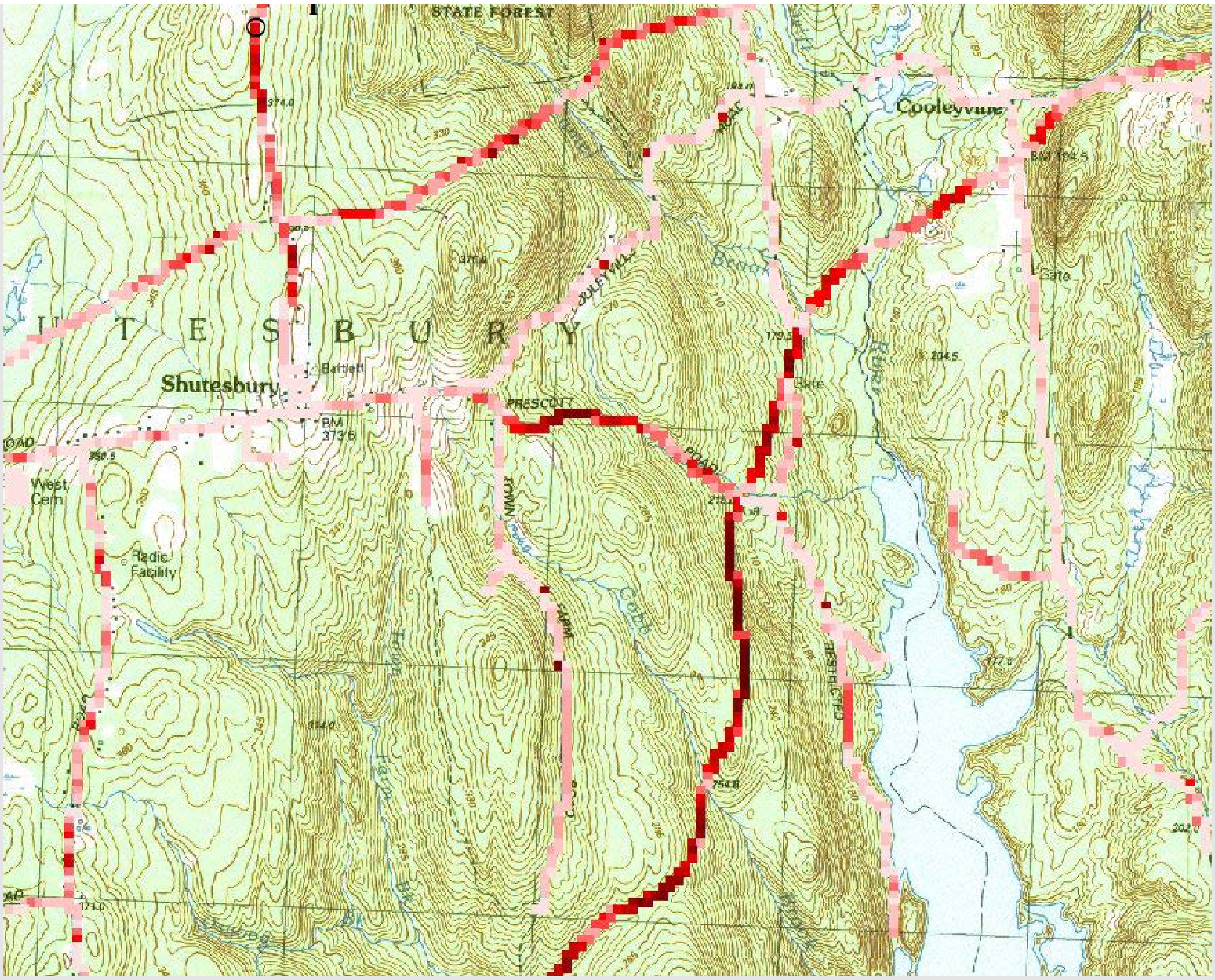

Figure 25. Critical local linkage scores for road passage structures for a portion of the Connecticut River watershed. The color intensity represents the relative magnitude of increase in terrestrial connectedness from installing a wildlife road passage structure.

degree of passability for aquatic organisms to a free-flowing river with no impediment to ecological flows, but the delta in aquatic connectedness is multiplied by the initial *IEI* for all cells within the affected neighborhood so that the end result is an estimate of the effect of removing the dam on the delta in aquatic connectedness in places where the current ecological integrity is not already degraded too much. These scores can be used to prioritize dams for removal (**Fig. 24**).

- *Road passage structures* -- With terrestrial road passage structures, each 300 m section of road (in areas that are not already too developed) is scored on its potential to improve local terrestrial connectivity by installing a road passage structure — in places where the current ecological integrity is not already seriously degraded too much. Our measure of local connectivity for terrestrial road passage structures is the connectedness metric. The terrestrial road passage structure metric measures the improvement in connectedness produced by reducing the value of the terrestrial barrier and Gibbs traffic settings variables by 90% for the road cells associated with the road segment, but the delta in connectedness is multiplied by the initial IEI for all cells within the affected neighborhood so that the end result is an estimate of the effect of installing a road passage structure on the delta in connectedness in places where the current ecological integrity is not already degraded too much. These scores can be used to prioritize dams for removal (**Fig. 25**).

5 Model Application

Our LCAD model currently can be applied to any reasonably large extent (say, State or HUC6 watershed or larger) within the Northeast region for which we have developed the required input data. For example, we have applied to the LCAD model to develop products for the Connect the Connecticut LCD (www.connecttheconnecticut.org, which represents a 2.9 million hectare (7.2 million acre) HUC4 watershed (comprised of two HUC6 watersheds), and for the Nature's Network LCD (www.naturesnetwork.org) that encompasses the entire Northeast region (64.5 million ha/159 million acres). However, our LCAD modeling approach is generalizable to any geography as long as the required input data are developed.

6 Scope and Limitations

While the current suite of products derived from our LCAD model (reviewed above) provide tremendous decision support for biodiversity conservation, there is much more to be done to improve the quality of the products (e.g., by improving the quality of the input data) and to expand the scope of the products. The most serious

6.1 Scope

The following is a list of important considerations regarding the scope of our LCAD modeling approach, with particular attention to where and when our approach should be used.

1) We developed our LCAD model for application in northeastern North America. Specifically, we devised an approach that makes sense for the ecological and anthropogenic setting of the Northeast, and this permeates all aspects of the approach. For example, human land use, in particular urban growth, and climate change are deemed to be the overriding drivers of landscape change and the principal threats to biodiversity in the Northeast. Consequently, the landscape change and assessment model focuses on these stressors and landscape change drivers; other potential stressors and drivers such as human-altered natural disturbance regimes (e.g., fire), which are major drivers in other areas (e.g., western North America), are not included at this time. Note, while our approach is developed for application in the Northeast, with appropriate modifications and/or extensions (e.g., including natural disturbance regimes and their modification as a major stressor/driver), our approach could be extended to have broader geographic application.

2) Our approach emphasizes landscape change, assessment and design at regional to sub-regional spatial scales. Specifically, although we devised an approach that incorporates information across a broad range of spatial scales (from local to

regional), we emphasized building an approach that provides a consistent regional or sub-regional perspective on biodiversity conservation. From a practical standpoint, this means including relevant ecological data that is consistently available at the regional scale and excluding otherwise highly relevant ecological data that is available only locally. For example, many states maintain spatial databases with much improved data layers (e.g., improved roads data) and additional data layers (e.g., maps of unique ecological features such as vernal pools or rare and endangered species locations) that are not consistently available at the regional scale. We chose to build an approach that relies on data consistently available across the region, which comes at the cost of not always making use of the best available information that exists locally. Note, as these improved data layers and additional data layers become available at the regional scale, our approach can easily be modified to incorporate this information. Importantly, because of the regional perspective embodied in our approach, it is intended to complement and supplement local conservation planning efforts that rely on detailed and specific local information.

3) Our approach is currently limited to the ecological dimension of landscapes. Specifically, we devised an approach that (at least currently) considers only ecological information and does not explicitly consider socio-cultural and economic information. Of course, the latter is ultimately critical to the successful implementation of LCD, as conservation does not happen in a socio-cultural and economic void. In part, the choice to focus exclusively on the ecological dimension of landscapes is practical, owing to the expertise of the DSL team and the difficulty of obtaining relevant socio-cultural and economic information at relevant spatial and temporal scales, but it also reflects a desire to build an approach that is in some sense "ideal" for the conservation of biodiversity. In other words, we sought an approach that would provide a benchmark for biodiversity conservation unfettered by the socio-cultural, economic and political realities of real-world conservation. This may be viewed as both a strength and a weakness.

4) Related to the previous item, our approach emphasizes using ecological data at ecologically relevant spatial/temporal scales without bias towards the existing conservation real estate. Specifically, our approach seeks to identify the places with the greatest ecological value with respect to ecological integrity and landscape capability for representative wildlife species using the highest resolution data available (i.e., mostly 30 m), but without explicit regards to what is already in the conservation real estate portfolio (e.g., existing secured lands). We recognize that one approach to LCD is to account for what already exists in the conservation real estate and then add to this portfolio in a complementary fashion. This has the appeal that it builds on the de facto conservation design that is already in place. However, because many of the existing secured lands that are part of the de facto conservation design do not offer much in the way of assessed ecological value, we did not want to bias the design in this manner. Instead, our approach seeks to identify an "ideal" conservation portfolio, and while this does not explicitly incorporate the existing conservation real estate, it does provide perhaps a better design target for meeting the biodiversity conservation goals. Note, this does not mean that existing secured lands should be ignored in practice, but rather that they can and should be used as an overlay to our design to inform local conservation actions.

5) Our approach to landscape assessment and design involves a complementary ecosystem- and species-based approach. Specifically, our approach emphasizes the use of ecological integrity as a coarse filter for biodiversity conservation, but accommodates the use of individual focal species (e.g., representative species) as a complement. The choice of ecosystems versus species as the basis to identify conservation priorities is fundamental to any LCD approach, and is often a point of disagreement among conservation practitioners. Neither approach is more right or wrong, they are simply different ways to achieve the goal of biodiversity conservation and each has strengths and weaknesses. Our approach is flexible in this regard and allows for the use of either approach by itself or the complementary use of both.

6) Our approach ultimately emphasizes conservation actions directed at land protection and ecological restoration, with only minor attention to land management. Specifically, our landscape design focuses on identifying places of high ecological value for ecosystems and representative wildlife species, including for example creating a network of core areas, for which land protection is the implied conservation tactic. In addition, our landscape design identifies opportunities for restoring aquatic and terrestrial connectivity (e.g., dam removals, culvert upgrades, terrestrial road passage structures). Unfortunately, our design currently offers little in terms of direct guidance for land management actions, other than identifying which ecosystems and/or species are important in any particular area. This largely stems from the complexity of determining where and what kind of management action is most needed to meet the multi-facetted ecological goals of the design. However, we recognize the importance of management to meet conservation goals; therefore, this should be a focus of future work to improve our approach.

7) Our approach emphasizes short- to moderate-range planning on the order of one to several decades. Specifically, our landscape change and assessment currently involves forecasting landscape changes and ecological conditions to the year 2080. Ultimately, nothing in the model structure constrains us to that timeframe, but to extend the model further in time would require urban growth demands and climate change projections that extend beyond 2080. However, as these projections are developed, our model can be extended accordingly. We recognize the need to consider even longer-term forecasts and the need to conserve biodiversity for future generations in perpetuity, but our current data and ability to make reliable forecasts limits us to a shorter planning horizon.

6.2 Major Limitations

The following is a list of some of the major limitations of our LCAD modeling approach. Note, this is not a comprehensive list of all the limitations, as that list would be too extensive. Rather, this is a list of the most important limitations that affect the use and interpretation of the results and that should be the focus of future efforts to improve the LCAD approach.

1) Our approach relies entirely on models to assess ecological values. For example, we use a model to assess the ecological integrity of every location and another model to assess the landscape capability to support of each representative wildlife species. And one thing that is true of all models is that they are only as good as the input data.

Unfortunately, the spatial data (GIS data) that these models rely on are fraught with errors, including both misclassifications and misalignments. This is especially true for many of the regional datasets that we employ, because there is usually a trade-off between extent and local accuracy; broader spatial coverage (e.g., regional or national extent) usually means lower accuracy at the finest spatial resolution (e.g., 30 m grid cell). Consequently, the results are often wrong at the finest resolution of the data (30 m) even though they may be quite meaningful at a slightly coarser resolution. For this reason, the LCD products should not be scrutinized for accuracy too carefully at the finest resolution of the data (30 m), and any depicted boundaries (e.g., core area and connector boundaries) should be viewed as "fuzzy" boundaries (i.e., merely general places to focus attention).

2) As noted above, our approach relies heavily on models to assess ecological values. We deem models necessary and useful because they are the only way to assign values to places that have not been sampled/observed in the field and they are the only way to make forecasts of future landscape conditions. Moreover, we recognize that "essentially, all models are wrong, but some are useful" (Box 1976). Implied in this quote is that models are necessary simplifications of reality and thus do not, indeed cannot, mathematically represent the full complexity of reality. The models employed in our LCAD approach are no different; they are incomplete and overly simplified representations of reality. For example, our model for computing *IEI* contains from 6-16 individual stressor and resiliency metrics (out of 20 currently for the Northeast region) that capture many different aspects of the landscape that affect ecological integrity. Each of these metrics makes use of the best available, regionally consistent spatial data and uses state-of-the art algorithms to summarize the data, but in most cases the metric is nonetheless a gross simplification of the particular stressor-response function. For example, the road salt metric measures the intensity of road salt application in the watershed above an aquatic focal cell based on road class (as a surrogate for road salt application rates) and a time-of-flow kernel. Clearly, road class is not a perfect surrogate for salt application rates that can vary dramatically among towns based on local policies and bylaws, information that is not readily available across the region, and the time-of-flow model certainly does not account for all the real-world intricacies of topography, soils and vegetation that affect how water and suspended materials move across the surface and sub-surface. Thus, the road salt metric is an incomplete representation of this particular stressor. Nevertheless, it is the best that we can do with existing spatial data and this is deemed better than not considering road salt as a stressor.

In addition, there are known stressors that are not explicitly being represented in *IEI* due to the lack of available data or the complexity of modeling the particular stressor-response process. For example, alteration of instream flow by dams and culverts is an important process affecting aquatic ecosystems, yet this is an exceedingly difficult thing to quantify given available data, especially because the anthropogenic modification of flow must be decoupled from the natural factors affecting flow. As a result, this important stressor is not included in the current suite of metrics. Consequently, *IEI* is an incomplete representation of the factors affecting local ecological integrity, and it always will be because we will never be able to perfectly and completely represent all the factors affecting ecological integrity.

The important point here is that our models are imperfect and therefore they will often not get it quite right, and this will lead to an imperfect and imprecise landscape design. This is OK if we accept that the design can be wrong, but still useful.

3) As mentioned above, our approach currently considers urban growth, climate change and sea level rise as the major stressors and landscape change drivers, which we deemed appropriate as the initial focus for the Northeast. However, we recognize that there are other important stressors and drivers in the Northeast that should be addressed for a more comprehensive solution to LCAD. For example, timber harvest is a major anthropogenic disturbance to forests in the Northeast, especially in some parts of the Northeast (e.g., northern New England), and it can play a significant role in regulating vegetation composition and structure and thus habitat conditions for many wildlife species. Our current approach treats timber harvest collectively with other natural vegetation disturbance processes (e.g., ice/wind, insects/pathogens) as a purely stochastic and generic process, which does not adequately account for the spatial predictability of timber harvest in areas managed intensively for wood products (e.g., industrial forest lands). Consequently, our current ecological assessment may overestimate or underestimate the ecological values assigned to each location. Adding these additional anthropogenic and natural vegetation disturbance processes to the landscape change and assessment model should be a priority for future improvements to our LCD approach.

7 Literature Cited

Anderson MG, M Clark, CE Ferree, A Jospe, A Olivero-Sheldon, and KJ Weaver. 2013. Northeast Habitat Guides: A companion to the terrestrial and aquatic habitat maps. The Nature Conservancy, Eastern Conservation Science, Eastern Regional Office. Boston, MA. http://nature.ly/HabitatGuide.

Ferree C, and MG Anderson. 2013. A Map of Terrestrial Habitats of the Northeastern United States: Methods and Approach. The Nature Conservancy, Eastern Conservation Science, Eastern Regional Office. Boston, MA.

Holling CS. 1973. Resilience and stability of ecological systems. Annual Review of Ecology and Systematics 4:1–23.

Holling CS. 1996. Engineering resilience versus ecological resilience. In P. C. Schulze, editor. Engineering within ecological constraints. National Academy Press, Washington, D.C., USA.

Lentz EE, SR Stippa, ER Thieler, NG Plant, DB Gesch, and RM Horton. 2015. Evaluating coastal landscape response to sea-level rise in the northeastern United States—Approach and methods: U.S. Geological Survey Open-File Report 2014–1252, 26 p., http://dx.doi.org/10.3133/ofr20141252 ISSN 2331–1258 (online).

McGarigal K, Compton BW, Plunkett EB, DeLuca WV, and Grand J. 2017. Designing sustainable landscapes products, including technical documentation and data products. https://scholarworks.umass.edu/designing_sustainable_landscapes/

Moss RH, JA Edmonds, KA Hibbard, MR Manning, SK Rose, DP van Vuuren, TR Carter, et al. 2010. “The Next Generation of Scenarios for Climate Change Research and Assessment.” *Nature* 463 (7282) (February 11): 747–756.

Olivero A, and MG Anderson. 2013. Aquatic Habitat Classification System. The Nature Conservancy, Eastern Conservation Science, Eastern Regional Office. Boston, MA.

Olivero-Shedon A, A Jospe, and MG Anderson. 2014. Northeast lake and pond classification. The Nature Conservancy, Eastern Conservation Science, Eastern Regional Office. Boston, MA.Box GEP. 1976. Science and Statistics. Journal of the American Statistical Association 71: 791-799.

Wear DN. 2011. Forecasts of county-level land uses under three future scenarios: a technical document supporting the Forest Service 2010 RPA Assessment. Gen. Tech. Rep. SRS-141. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station. 41 p.

Wood AW, EP Maurer, A Kumar, and DP Lettenmaier. 2002. Long-range experimental hydrologic forecasting for the eastern United States. Journal of Geophysical Research-Atmospheres 107: 4429.

Wood A, LR Leung, V Sridhar, and D Lettenmaier. 2004. Hydrologic implications of dynamical and statistical approaches to downscaling climate model surface temperature and precipitation fields. Climate Change 62:189–216.

Appendix. Other potential landscape change drivers

In addition to the landscape change drivers described previously (climate change, urban growth, vegetation disturbance and succession, and sea level rise), we have identified several additional drivers for future incorporation into the LCAD model, including the following:

- Timber harvest – we hope to model timber harvest as a stochastic process similar to urban growth. The details of this process have not been developed. However, it will probably involve randomly harvesting (as opposed to a deterministic schedule) random spatial units (as opposed to a priori defined treatment units) on lands deemed eligible for timber harvest according to varying management scenarios based on ownership, geographic location, forest type and other factors. Unfortunately, harvest policies vary among ownerships (e.g., industrial, non-industrial private, state, USFS, NPS, etc.), state agencies, and states, and can change radically in short amounts of time in response to economic and political winds. In addition, timber harvesting, in terms of types of treatments and intensity of harvest, is extremely variable and thus somewhat unpredictable. This suggests the need for many scenarios. Our approach will likely allow for complex spatial and temporal variation in management. Timber harvest will act principally to modify the vegetation settings variables (e.g., biomass).
- Agriculture development/loss – we hope to model agricultural development and loss as a stochastic process. The details of this process have not been developed. Agricultural development may be important in some portions of the region. Shifting agricultural land use, for example shifting from cropland to pasture, could be included, but is highly unpredictable. Agricultural loss is more likely throughout the region and will be modeled as a probability of agricultural land reverting to wetlands or forest. Note, agricultural loss to urban development is currently allowed in the urban growth model. Agriculture development/loss depends on the economy, soil suitability, urbanization, land costs, taxes, and distance to markets and other factors. Given the complex nature of this process, modeling agriculture development/loss is probably a low priority among the list of potential drivers.
- Natural disturbances – we hope to model natural disturbances as a suite of stochastic processes using a common algorithm that simulates initiation, spread, termination, and effects. There are several natural disturbance processes under consideration, including the following:
    - *Fire* – probably too rare to matter in the northeast (return intervals at the cell level are much longer than the simulation length of 70 yrs), but may be more important in the southern portions of the region.
    - *Wind* – downbursts and tornadoes may be frequent enough in some portions of the region (e.g., Adirondaks) to model; hurricanes may also be frequent enough in some portions of the region to model, perhaps separately from downbursts and tornadoes.
    - *Insects/pathogens* – native insects and pathogens are largely endemic and generally do not cause stand replacement; non-native invasive insects and pathogens may be worth considering on a case by case basis. Hemlock woolly

adelgid and emerald ash borer may be worth modeling; spruce budworm is another possibility, but we are unsure whether enough stand replacement occurs to warrant inclusion. Note, model parameterization for any insect/pathogen disturbance is going to be extremely challenging.

- *Floods* – ecologically important to riverine and riparian ecosystems, but largely doesn't cause stand replacement in riparian systems (perhaps due to regulation of rivers via dams), and geomorphic impacts to streams and riparian areas, while important, may be too difficult to model.
- *Beavers* – important driver in riverine and riparian ecosystems; may be possible to model.

Storm surge/overwash – important geomorphic disturbance in coastal ecosystems (especially barrier beaches); may be too difficult to model, or it may be accounted for in the future seal level rise model developed by USGS Woods Hole.