Designing Sustainable Landscapes: Project Overview

A project of the University of Massachusetts Landscape Ecology Lab

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1 Purpose

This document provides an overview of the *Designing Sustainable Landscapes* (DSL) project of the *North Atlantic Landscape Conservation Cooperative* (NALCC), including a statement of goals and objectives and a general description of our approach. This working document is directed to our scientific steering committee, but should be useful to anyone interested in learning more about this project. This document is something of an executive summary of the project in its current state and makes reference to other documents that provide the technical details of the approach and summarize the results in phases.

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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. Consequently, 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.

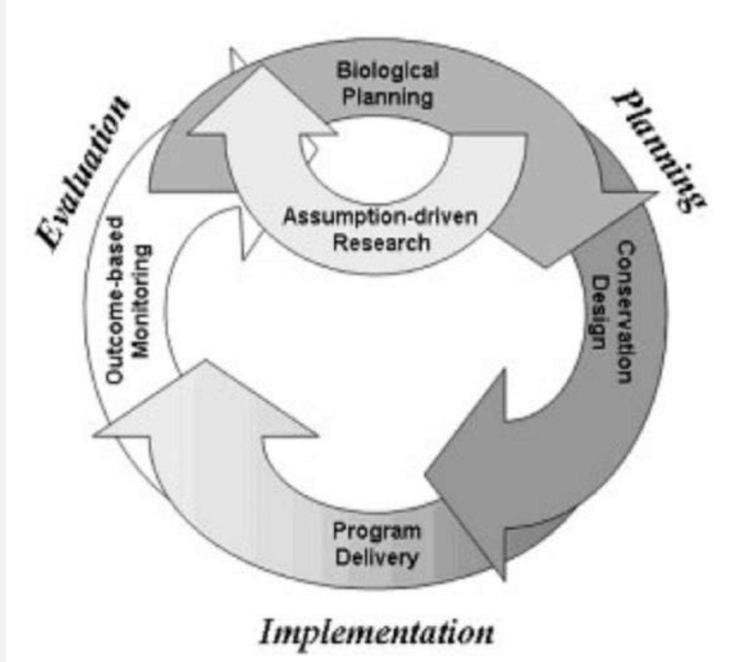

Figure 1 . Diagram of the Strategic Habitat Conservation (SHC) framework, a U.S. Fish and Wildlife Service science-based framework for making management decisions about where and how to deliver conservation efficiently to acheive specific biological outcomes.

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 project described in this document is one of the science-development projects of the NALCC. While the focus of this particular project is #1 and #2 above, the results of the model provide the basis for #3 and stimulate #4 in the long term. Thus, the DSL modeling framework allows us to simulate landscape change, assess changes in ecological integrity and habitat capability for representative species, and identify 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 existing 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 are as follows:

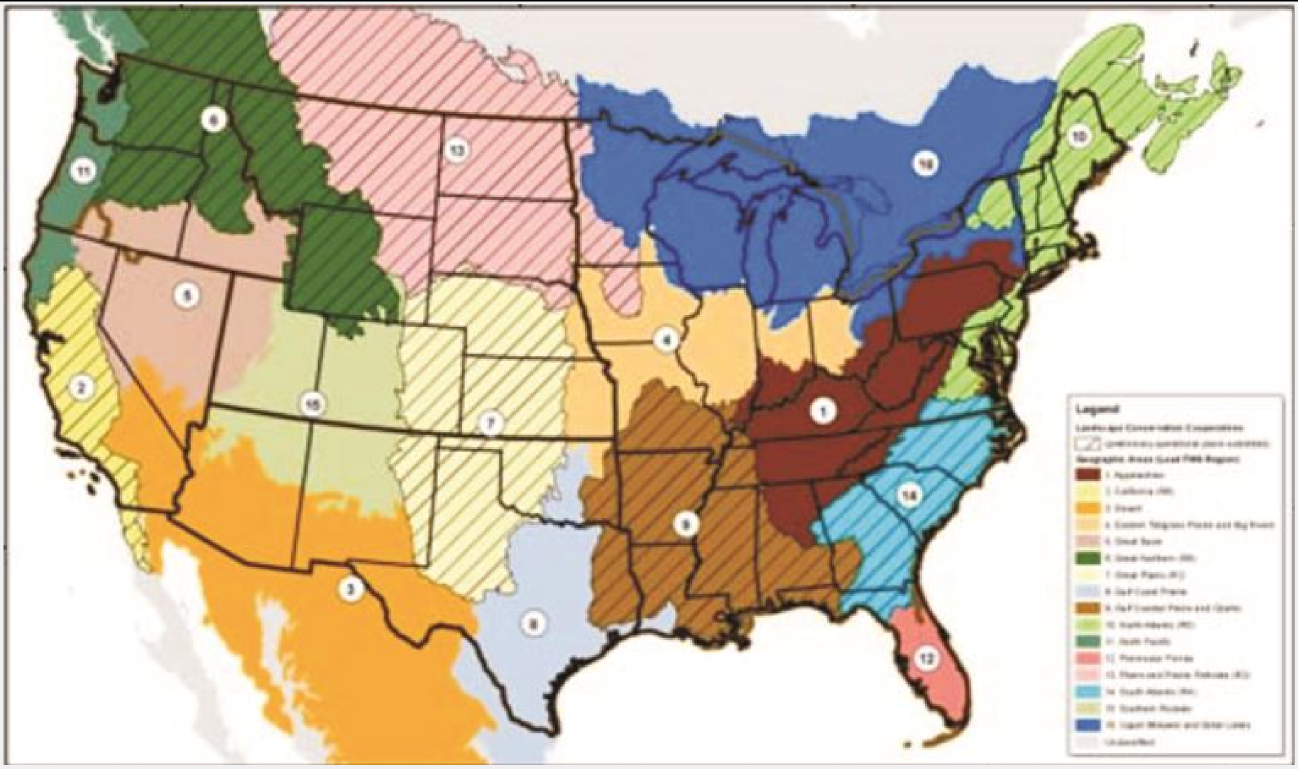

Figure 2. Map of the U.S. Fish and Wildlife Service Landscape Conservation Cooperatives (LCCs).

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 representative species, and inform the design of conservation strategies (e.g., land protection, management and restoration) to meet conservation objectives.
2. Develop *habitat capability* models for a suite of representative 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 and unique environments as a coarse filter for the 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**).
5. Assess the nature and magnitude of differences and similarities between areas identified as important habitat for the representative species and areas identified as having high ecological integrity (coarse filter) within the Northeast; describe the implications for strategic habitat conservation planning and make recommendations for effectively combining the ecosystem- and species-based approaches to habitat conservation.

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.

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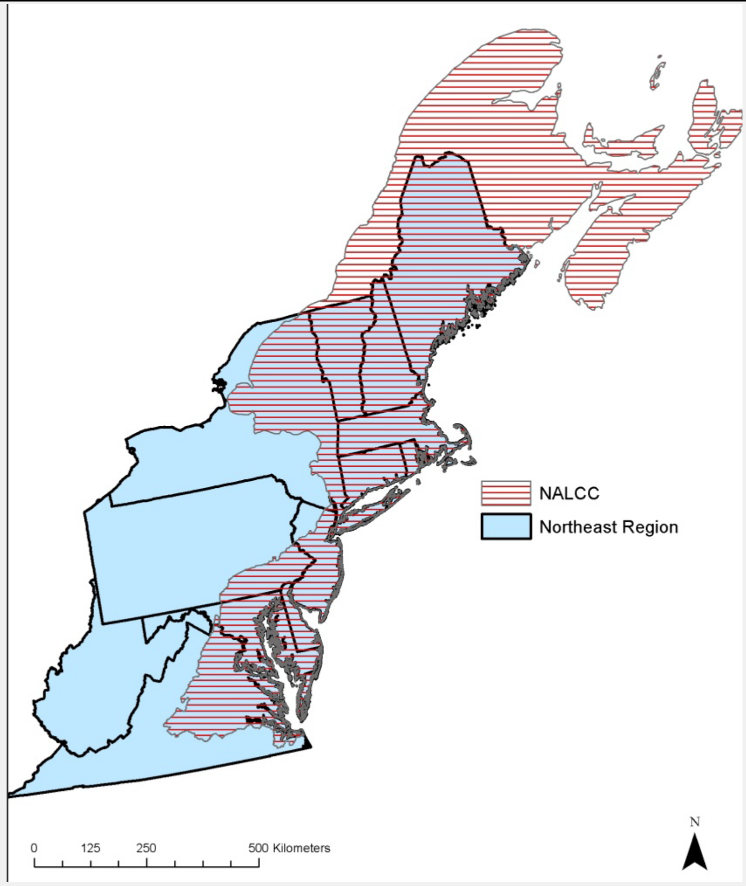

Figure 3. North Atlantic Landscape Conservation Cooperative (NALCC) extent and the Northeast region.

3 Model Design

To meet objectives 1-3, the LCAD model was developed 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.
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 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 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 the considerations above, the broad LCAD modeling framework is illustrated in **figure 4**. Briefly, in addition to the spatial and non-spatial database, the model is conceptually comprised of three major components (described below), including:

1. *Landscape change*.--This is the core landscape change model, where the landscape drivers (e.g., urban growth, climate change, and vegetation disturbances) and vegetation succession processes are implemented under a user-specified scenario or set of scenarios and user-specified number of stochastic runs of each scenario. This is where the ecological setting variables (i.e., spatial data layers representing biophysical and anthropogenic attributes of the landscape) are modified over time in response to the landscape drivers.
2. *Landscape assessment*.--This is the assessment of landscape ecological integrity (coarse filter) and landscape capability for 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 designing a suite of spatially-explicit conservation actions including land protection, management, and/or restoration scenarios to maximize ecological performance criteria such as the landscape ecological integrity indices and landscape capability indices for representative species.

The LCAD model involves iteratively implementing landscape change and assessment processes over timesteps for one or more scenarios, repeated many times to realize the stochasticity of the model processes, and then using the results to design a landscape conservation plan. The raw results are a set of settings grids and an assessment of ecological integrity and landscape capability for each representative species for each timestep for each stochastic run of each scenario. The summary results are a set of grids depicting ecological integrity, landscape capability for representative species and conservation priorities for each scenario and a set of tables summarizing the landscape

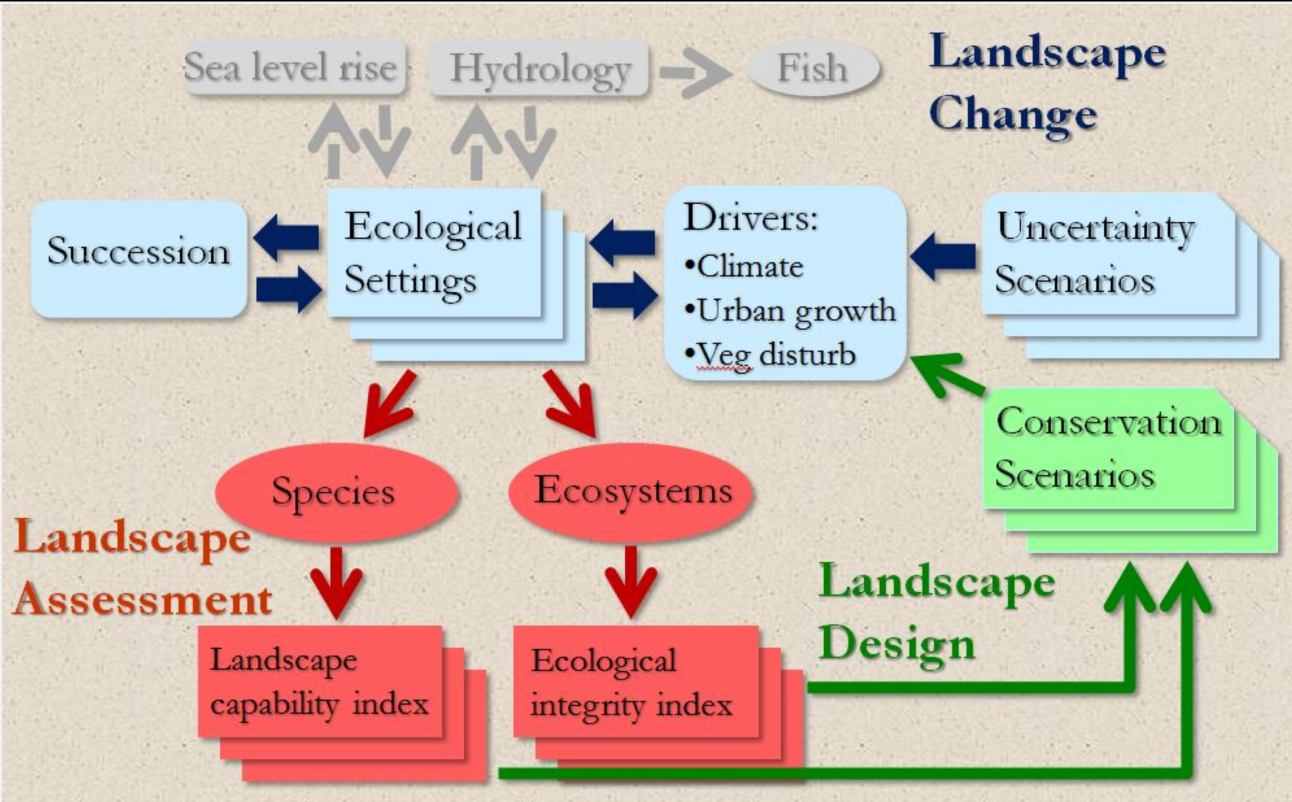

Figure 4. Diagram of the Landscape Change, Assessment and Design (LCAD) model for the Designing Sustainable Landscapes (DSL) project. Note, separate projects involve modeling sea level rise, freshwater stream hydrology and fish populations and are not described in this document. Blue elements represent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

ecological integrity and landscape capability indices for each ecological system and representative species across scenarios.

The 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 (although this is not a hard constraint). A 10 year resolution is 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 and to integrate well with the fisheries project, 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.

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4 Model Components

4.1 Input Data

The input data includes user-defined scenarios comprised of both nonspatial parameters (that control the simulation and the component processes) and spatial data (maps) representing ecological settings variables and other ancillary variables used in the landscape change and/or assessment models.

4.1.1 Non-spatial run parameters

This represents tabular (nonspatial) input data used to control the model run, including basic control over the length of the model run (i.e., number of time steps), the number of replicate runs, which drivers to include (e.g., climate and urban growth), and which timesteps to assess with the ecosystem- and species-based assessments. Here is where the user specifies whether to run a single scenario or a range of scenarios to reflect uncertainty in the drivers. For example, multiple scenarios might represent a range of estimates of climate change and urban growth rates.

4.1.2 Non-spatial component parameters

This represents the tabular (nonspatial) input data used to control the individual LCAD model component processes (e.g., succession and drivers); 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 each vegetation variable (e.g., 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.

4.1.3 Spatial data (grids)

This represents the spatial (GIS) data used in the LCAD model and consists of ecological settings variables and ancillary GIS data. A detailed description of the spatial data is provided in a separate document (DSL_documentation_spatial_data.pdf). 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. 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 system at any point in time; they are considered primary determinants of ecosystem composition, structure and function, and determine the ecological similarity between two locations. As such, they play a key role in the coarse-filter ecological integrity assessment, they are used in species' climate-habitat models to represent important climate-habitat components, and are used in the landscape change model processes (e.g., to determine the probability of development). Thus, the settings provide a rich, multivariate representation of important landscape attributes.

In addition to the settings variables, the spatial database includes a variety of ancillary data layers that are variously used in the landscape change 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..

4.2 Landscape Change

The landscape change model includes a suite of "drivers" that act to modify one or more of the ecological settings variables. These processes operate sequentially within each timestep of the model. Each of these drivers 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 deterministic processes (e.g., climate change) is accounted for extrinsically by running multiple varying scenarios; uncertainty in stochastic processes (e.g., urban growth) is intrinsic to the process itself (via random variables) and is addressed by running multiple replicate simulations. The LCAD currently includes the following drivers: 1) climate change, 2) urban growth, 3) generic vegetation disturbance-succession, and 4) sea level rise (via collaboration with USGS Woods Hole); the remaining drivers are intended for implementation in subsequent phases.

4.2.1 Climate change

Climate change is modeled as a deterministic process by simply 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 (GCMd) is provided in a separate document (DSL_documentation_climate.pdf). 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 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 2 emission scenarios based on Representative Concentration Pathways (RCPs)(Moss et al. 2010), subtracted a baseline to create projected anomalies, and resampled these data at 800m cells. We then combined these data with 800m resolution, 30-year normal temperature and precipitation data (PRISM Climate Group, Oregon State University) using the “delta method”. Finally, these data were further resampled and projected to 600m cells which aligned with 30m cells used in the LCAD model.

Climate change acts principally to modify the ecological settings variables associated with temperature and precipitation, and thus causes each cell to migrate through ecological settings space over time. Thus, the primary effect of climate change is in the assessment of ecological integrity (principally via adaptive capacity metrics, see below) and climate-habitat capability for representative species (via the climate niche envelopes, 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 each type of development (e.g., low-, moderate- and high-density) at the cell level, determining the total amount of development based on human population projections, and allocating the development among types, all within local windows scaled to account for spatial heterogeneity in development rates and patterns. A detailed description of the urban growth model (SPRAWL) is provided in a separate document (DSL_documentation_urban.pdf). Briefly, urban growth is modeled statistically based on historical land use data to derive a locally-varying, relative probability of each of six types of development transitions (e.g., undeveloped to low-, medium-, and high-density development, low-density to medium- and high-density development, and medium-density to high-density development). Predictors include a variety of spatial variables, including resistant kernels based on sources of jobs (e.g., urban areas), transportation infrastructure, and suitability of land (e.g., slope, wetlands, soils, secured land). The result of this step is a surface depicting the relative probability of each type of development for each timestep. The actual amount of development at each timestep is based county-level projections from a USDA Forest Service Resources Planning Act (RPA) assessment (Wear 2011) and allocated among transition types according to observed distributions at the local scale. Development patches are implemented randomly based on the probability of development surface and the historic distribution of patch sizes. The uncertainty in urban growth predictions stems from the intrinsic stochasticity of the process itself and is realized by running multiple runs of the same scenario, in addition to the variation among scenarios that can be achieved forcing relatively more or less sprawliness to the pattern of urban growth.

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

4.2.3 Vegetation disturbance-succession

As in interim solution for the current version of the LCAD model, we developed a generic vegetation disturbance-succession driver that implements generic disturbances (i.e., not associated with any particular real-world process such as timber harvest or wildfire) designed to roughly maintain the current distribution of vegetation seral stages and disturbance patch sizes. Briefly, vegetation disturbance is modeled as a stochastic process by randomly disturbing a patch of forested cells, whereby the severity of the disturbance (i.e., the degree to which above-ground live biomass as a proxy for seral stage are "set back" or moved to an earlier seral condition) and the size of the disturbance patch is selected randomly from the current distribution of patch sizes. The overall rate of disturbance (i.e., the proportion of forested vegetation that gets disturbed) is controlled by a user-defined parameter, which by default is based on the rate of disturbance observed over the past couple of decades (see below). The uncertainty in vegetation disturbance stems from the intrinsic stochasticity of the process itself and is realized by running multiple simulation of the same scenario, in addition to the user-specified variation among scenarios in overall disturbance rate.

Succession is modeled as a deterministic change in above-ground live biomass (or 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 (i.e., macrogroup); non-forested systems are treated as having no biomass and as static (i.e. constant over time). A detailed description of the succession model (GROW) is provided in a separate document (DSL_documentation_succession.pdf). Briefly, 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 (e.g., 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.

Disturbance is modeled as a stochastic change in forest biomass according to a two-stage statistical model developed for each of 13 different ecoregions. A detailed description of the forest disturbance model (DISTURB) is provided in a separate document (DSL_documentation_succession.pdf). Briefly, we used the FIA plot data to compute the probability of a forest disturbance, defined as a net loss of biomass between sampling occasions, and given a disturbance, the intensity 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 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 intensity of disturbance as purely stochastic and distributed according to a Beta distribution, which is appropriate for a proportional response variable. Note, while we recognize that the intensity of disturbance is not purely stochastic, we were not charged to develop a more complete model for vegetation disturbances in the current phase of this project, e.g., to better account for timber harvesting practices, but this remains an important priority for future phases of work.

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. Ultimately, 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 will be primary responsibility of the Woods Hole Science Center.

4.2.5 Other potential drivers

In addition to the drivers described above, 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.), among state agencies, among 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, canopy cover).

- Agriculture development/loss – we hope to model agriculture 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. 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 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 may be worth modeling; spruce budworm is another possibility, but 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.

4.3 Landscape Assessment

The landscape assessment model includes a two-pronged approach aimed at assessing impacts to: 1) biodiversity in general based on ecosystem integrity, and 2) a suite of conservation priority species, as follows:

4.3.1 Ecosystem-based assessment

We use a coarse-filter, ecosystem-based approach as an overarching approach for the conservation of biodiversity and not of individual species per se, as described in detail in a separate document (DSL_documentation_integrity.pdf). Briefly, the premise of the ecoystem-based approach to biodiversity conservation is as follows:

1. Maintaining the integrity of ecosystems and 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 its own.
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 fine filter to capture those biodiversity elements that are not captured by the coarse filter is needed.

Given this premise, the 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**.** There are two important components to this definition.

First, 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.

Second, 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, there are 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.
- *Resiliency* – refers to the capacity to recover from or adapt to disturbance and stress; more specifically, it refers to 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). Resiliency is measured using a suite of metrics, including: 1) *similarity*, which refers to the ecological similarity of the neighborhood of a focal cell and reflects the capacity for organisms to move into the focal cell from neighboring cells with a similar ecological setting as the focal cell; 2) *connectedness*, which refers to the ecological similarity and accessibility of the neighborhood of a focal cell; 3) *ecosystem diversity (or diversity for short)*, which refers to the variety and abundance of ecological settings in the neighborhood of a focal cell and reflects the opportunities for organisms to adapt to changing environmental conditions via movement to a different nearby location; and 4) *adaptive capacity*, which refers to the accessibility of diverse ecological settings in the neighborhood of a focal cell and reflects the opportunities for organisms to move between the focal cell and neighboring cells with different ecological settings than the focal cell.
- *Connectivity* – refers to the propensity to conduct ecological flows (including individuals) 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 metrics (above), but is also measured directly and more generally without regard to resiliency per se using a measure of conductance; i.e. the magnitude of ecological flows through a location.

Our ecological integrity assessment involves quantifying the attributes described above, which consists of a combination of spatial and non-spatial results. Spatial results include grids depicting the individual metrics as well as a composite local *Index of Ecological Integrity* (IEI), which is a weighted combination of the intactness and resiliency metrics, and these are useful for visually depicting the consequences of alternative landscape change scenarios and for choosing sites for conservation action (e.g., land protection) in the context of landscape design. Non-spatial results include numerical summary statistics for some of the ecological integrity attributes described above for each ecological system (or macrogroup) 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

To compliment the coarse-filtered, ecosystem-based assessment, we also use an 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 climate and habitat capability for any individual species regardless of the purpose of the selected species. For example, individual species models can be developed for representative species, indicator species, threatened and endangered species, vulnerable species, flagship species, game species or any other species of conservation interest. Currently, we are focusing on developing models for a suite of representative species under the assumption that these relatively few species can serve as surrogates for the much large suite of conservation priority species.

First, 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 occurrence of each species based on their current geographic distribution in relation to several climate variables based on data representing the past 30 years. 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.

Second, 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 in relation to a suite of environmental variables. 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 might occur if they are able to immediately redistribute to track suitable habitat conditions, but they are not meant to predict where the species will actually 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.

Third, we use kernel density estimators to build species' *Prevalence* models based on species' occurrence data. These models predict the species' current distribution based solely on the species' observed spatial distribution independent of any explanatory variables and are intended to capture biogeographic factors influencing species' distributions that are not accounted for by the climate niche and habitat capability models. We use these prevalence models to regulate the species' predicted probability of occurrence 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 such as interspecific interactions and disease that we cannot measure directly.

Fourth, 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 the species' *CN*, *HC* and Prevalence into a single index (*LC*) scaled 0-1 (although distributed as an integer grid scaled 0-100) and use logistic regression to evaluate the predictive ability of the model based on independent species' occurrence data. Importantly, the *LC* models provide an index of species occurrence, not the true probability of occurrence. 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.

Lastly, we assess the potential impacts of habitat and climate changes on each species using a variety of non-spatial and spatial indices. First, we compute a complimentary set of non-spatial 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 non-spatial 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. 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.

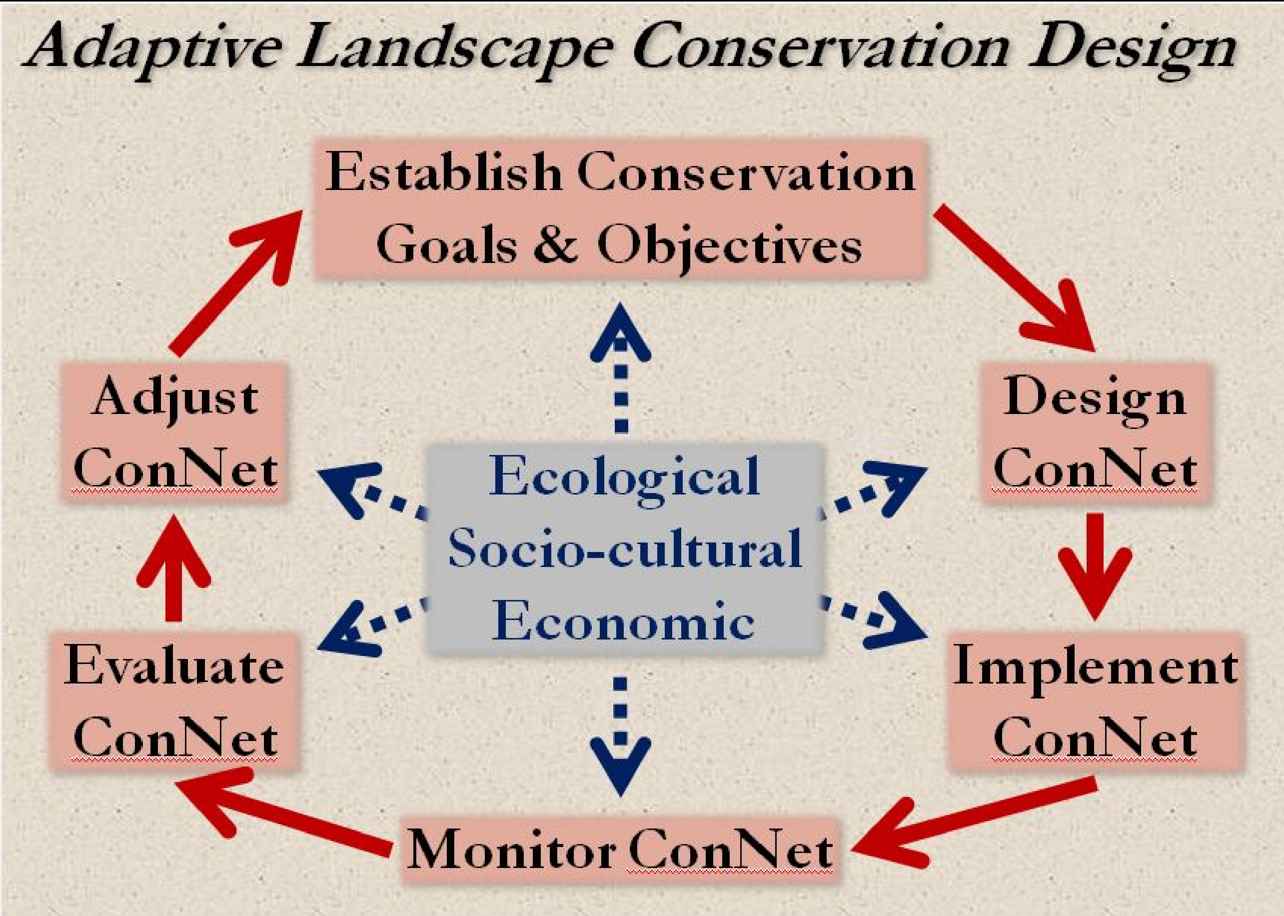

Figure 5. Diagram of the Adaptive Landscape Conservation Design (LCD) steps.

4.4 Landscape Design

The landscape conservation design (LCD) model is based on an adaptive management framework and consists of a sequence of six major steps implemented in an iterative cycle and operating within a multi-scale framework (**Fig. 5)**. Here we will briefly describe the conservation design step of the adaptive LCD framework since this is the step involving the modeling.

Given a set of user-defined goals and objectives, the conservation design is a spatial strategy based on a set of user-specified conservation targets intended to achieve the conservation goals and objectives. Here, "design" refers to a comprehensive spatial strategy outlining what conservation actions to take and where. Importantly, the 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 conservation network has five major components: 1) establishing a tiered set of conservation core areas to protect a representative diversity of integral ecological settings and persistent populations of a suite of focal species; 2) buffering the core areas from future degradation caused by human land uses; 3) connecting the core areas to ensure adaptive capacity of ecosystems and species in the face of climate and land use change at multiple scales; 4) prioritizing opportunities for restoring ecological patterns and processes, with an emphasis on restoring connectivity; and 5) determining the active management needs of individual core areas, buffers and/or corridors. Each of these components can be initially designed via modeling, 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 socio-cultural and economic considerations that lie outside the current scope of the DSL project. Therefore, here we focus on the ecological components as informed by the LCAD model and other data products.

4.4.1 Core areas

The first major design component is the most critical element and involves identifying and protecting a network of tiered conservation *core areas* within each sub-landscape unit of the focal landscape with the aim of protecting the lands with the highest ecological integrity and landscape capability across ecological settings and focal species, respectively, today and most likely to maintain their value in the future in light of climate change and development. The exact composition and cumulative extent of the core area network will depend on user-specified conservation targets (e.g., how much of the landscape to include in core areas, how many cores, minimum size of core areas, etc.).

4.4.2 Buffers

The second major design component involves *buffering* each of the core areas from future degradation caused by human land uses surrounding the cores. Typically, core areas derive their relatively high ecological integrity and species' habitat-climate capability from their relative isolation from anthropogenic stressors. However, if anthropogenic stressors are allowed to encroach upon the core areas, e.g., if development is allowed to occur up to the boundary of the core areas, the quality of the core areas will degrade over time. Buffering refers to the capacity to help high-valued core areas retain their value over time (i.e., buffer them from sources of human impairment). The buffer around each core area should be of sufficient ecological condition, width and configuration to minimize negative anthropogenic intrusions into the core.

4.4.3 Connectivity

The third major design component involves *connecting* the core areas across the entire region in order to ensure relatively unimpeded ecological flows (e.g., organism dispersal, gene flow) across the core area network (i.e., to ensure landscape connectivity) at all levels of the hierarchy. There are many ways to achieve landscape connectivity. Increasing the number and extent of core areas is perhaps the most direct way to increase connectivity. However, given real-world limits on the extent of the core area network, other strategies such as corridors and stepping stones will be required. We focus on the creation of broad conservation corridors between core areas, including likely pathways of concentrated ecological flows (i.e., high conductance) between core areas and areas of high conductance that are irreplaceable (i.e., limited alternative pathways) and vulnerable to development. Note, corridors may not have high local ecological integrity; their value stems from their role in conducting flows between areas of high ecological integrity (i.e., core areas); thus, high conductance rather than high ecological integrity is the criterion for selecting corridors.

4.4.4 Ecological restoration

The fourth major design component involves prioritizing opportunities for *ecological restoration*, of which there are several classes of activities designed to actively restore critical ecological functions (e.g., connectivity). For practical reasons we currently limit our consideration of ecological restoration to four classes of activities, as follows:

1) *Road-stream crossings* -- Prioritizing road-stream crossings for culvert upgrades to improve aquatic connectivity, as described below.
2) *Dams* -- Prioritizing dams for removal or installation of aquatic passage structures to improve aquatic connectivity, as described below.
3) *Road passage structures* -- Prioritizing placement of terrestrial road passage structures to improve terrestrial connectivity, as described below.
4) *Wetland restoration* -- Prioritizing agricultural lands for wetland restoration to improve the extent of wetlands, as described below.

Importantly, here we are referring to the restoration of ecological function via management actions designed to reduce or eliminate a stressor that is currently degrading ecological function. Each of these types of restoration activities involves a finite and well-defined set of landscape features (i.e., culverts, dams, road segments, agricultural parcels on hydric soils) that allows us to identify the full collection of opportunities a priori and then evaluate each in turn, as described below. A common theme for most of these restoration activities is that they are intended principally to restore connectivity. In each of the proposed restoration activities, we use a "coarse-filter" to assess connectivity; i.e., one that does not involve any particular focal species, but instead holistically considers macro-ecological systems or settings. A restoration scenario analysis involves computing one or both of these metrics before and after the restoration activity and comparing results to determine the loss (or gain) in specific metric units. Restoration opportunities (e..g., culverts) can then be prioritized based on which produce the greatest improvement in connectivity.

4.4.5 Land management

The fifth major design component involves determining active *land management* needs of individual core areas, buffers and/or corridors. 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. Similarly, 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, buffer or corridor may be the result of certain past management activities, and the maintenance of the core area value may be dependent on sustained management activities. It is important to identify these management needs as part of the conservation design process. Unfortunately, it is not clear how best to incorporate management needs into the conservation design process given current limitations in the LCAD model and relevant spatial data. For example, prescribed burning, timber harvesting and water management are not modeled as explicit processes, so there is no way to implement these as prescribed management activities in the landscape change model. Therefore, in the interim until these processes are included in the LCAD model, the active management needs of individual core areas, buffers and corridors will have to be identified separately, perhaps in step-down conservation plans for each site.

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5 Model Application

We are currently in the process of applying the LCAD model to the entire Northeast Region and intend to have a complete set of regional data products available by the end of 2016. In addition, we will be working to improve communication and delivery of the LCAD regional conservation products, and working with other conservation partnerships to implement LCD and lay the groundwork for the development of a stand-along decision-support software tool for LCD.

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