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# FINAL REPORT -- Phase 1
## *Middle Connecticut River watershed*

# Designing Sustainable Landscapes in the North Atlantic Landscape Conservation Cooperative

***UMass Landscape Ecology Lab**: Kevin McGarigal, Brad Compton, Ethan Plunkett, Bill DeLuca, Liz Willey and Joanna Grand*

This document is the final report on phase 1 of the ongoing *Designing Sustainable Landscapes* (DSL) Project of the *North Atlantic Landscape Conservation Cooperative* (NALCC) and includes the following:

1) Executive summary of the more detailed documentation (referenced herein) on the *Landscape Change, Assessment and Design* (LCAD) model developed for the NALCC.
2) Summary of preliminary LCAD model results for the middle Connecticut River watershed pilot study area in Massachusetts and portions of Vermont and New Hampshire.
3) Summary of a comparison of the coarse- and fine-filter ecological assessments in the pilot study area, including preliminary recommendations regarding the complimentary use of the coarse (ecological integrity) and fine (species) filters.

## 1. Goals and objectives

The overall goal of the NALCC is to:

1) Assess the current capability of habitats to support sustainable populations of wildlife;
2) Predict the impacts of landscape-level changes (e.g., from urban growth, conservation programs, climate change, etc.) on the future capability of these habitats to support wildlife populations;
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.

This DSL project is one of the ongoing science-development projects of the NALCC aimed at achieving this goal. While the focus of this DSL project is #1 and #2 above, the results of the modeling to accomplish #1 and #2 described in this report provide the basis for #3 and stimulate #4 in the long term. The specific objectives of this project are as follows:

1) Develop a model (LCAD) for the NALCC 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 (coarse filter) and climate-habitat capability for representative species (fine filter), and eventually (in phase 2) allow us to design conservation strategies (e.g., land protection, management and restoration) to meet conservation objectives.
2) Develop *habitat capability* models for a suite of representative species to be used as a fine filter for evaluating the ecological consequences of landscape change in the LCAD model (#1).
3) Develop *ecological integrity* models for a suite of ecological systems to be used as a coarse filter for evaluating the ecological consequences of landscape change in the LCAD model (#1).
4) Pilot the LCAD model by simulating landscape change and evaluating the effects on ecological integrity and habitat capability for the representative species in three representative watersheds distributed throughout the NALCC (**Fig. 1**).
5) Assess the nature and magnitude of differences and similarities between areas identified as important habitat for the representative species (fine filter) and areas identified as having high ecological integrity (coarse filter) within the pilot watersheds; describe the implications for strategic habitat conservation planning and make recommendations for effectively combining fine- and coarse-filtered approaches to habitat conservation.

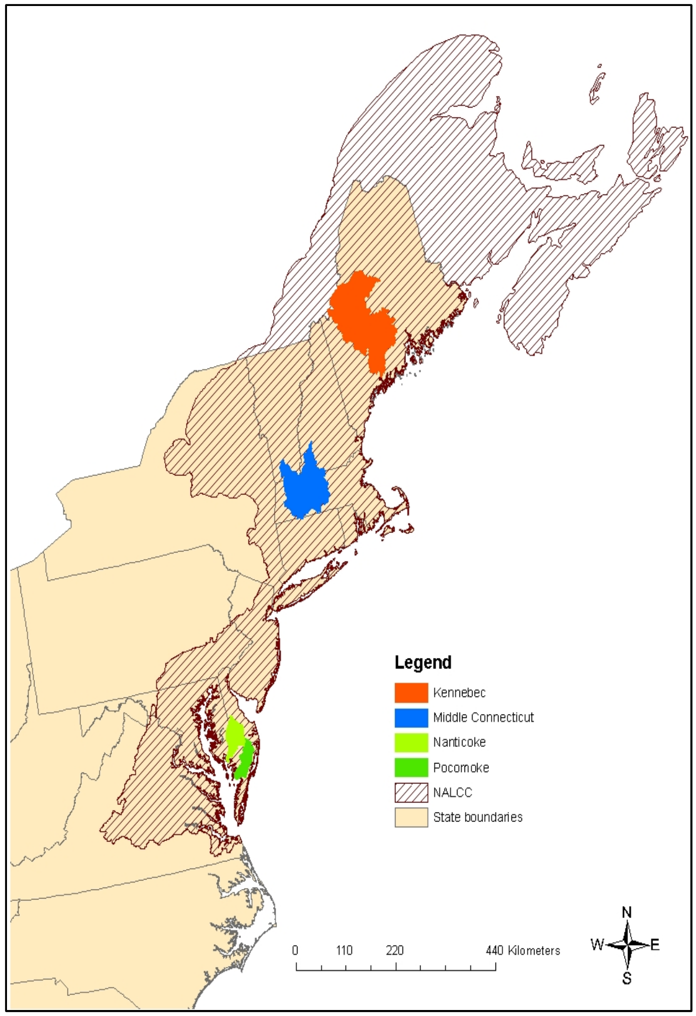



***Figure 1.*** *North Atlantic Landscape Conservation Cooperative (NALCC) extent and the three pilot study areas for phase 1.*

The purpose of this document is to report on our progress towards meeting these project objectives; specifically, to provide preliminary results of phase 1 model for the middle Connecticut River watershed pilot study area.

# 2. Landscape Change, Assessment and Design Model

The LCAD model is described in detail elsewhere (NALCC_documentation_overview.pdf). A review of this more detailed document and the sub-documents referenced within it is required to fully understand our modeling framework and the results reported in the next section. Here, we provide only a brief summary of the model, with an emphasis on factors affecting the interpretation of the preliminary model results reported in the next section. Briefly, the model is conceptually comprised of three major components:

## *2.1. Landscape Change*

The landscape change component of the model is where we simulate landscape change driven by climate change, urban growth, and vegetation succession under a user-specified scenario or set of scenarios and user-specified number of stochastic runs of each scenario. This is where we modify the ecological setting variables (i.e., spatial data layers representing biophysical and anthropogenic attributes of the landscape) over time to reflect the landscape drivers and succession. For a detailed description of the landscape change model, see the following technical documents:

- Spatial data (NALCC_documentation_spatial_data.pdf)
- Climate change (NALCC_documentation_climate.pdf)
- Urban growth (NALCC_documentation_urban.pdf)
- Vegetation disturbance and succession (NALCC_documentation_succession.pdf)

There are several important considerations regarding the landscape change simulation in phase 1 that have bearing on the interpretation of the preliminary results in the next section:

1) First, the spatial database of the LCAD model includes a suite of 23 ecological settings variables. However, there are several other potentially important settings variables (e.g., soil depth, texture and pH, water temperature, etc.) that are not currently available or reliable for the NALCC; these will be added as they become available and reliable in subsequent phases. Nevertheless, the existing suite of variables is sufficiently rich to provide a meaningful basis for both the coarse- and fine-filter assessments.

2) Second, the only landscape drivers explicitly modeled in phase 1 were climate change and urban growth, owing to their overarching importance in the Northeast. While there are many other important vegetation disturbance processes in the Northeast, such as timber harvest, fire, wind, and insects/pathogens, these were not included in phase 1 due to limitations in time and resources. However, as an interim solution, to capture the combined effects of these disturbances, we included a "generic" disturbance driver that implemented stochastic vegetation disturbances aimed at roughly maintaining the current vegetation age distribution and patch size distribution. Thus, the generic disturbance driver sought to produce a shifting-mosaic steady-state in vegetation attributes associated with stand age (i.e., above ground biomass, quadratic mean stem diameter, and stem density) and thus emulate

the effects of these other disturbance processes without explicitly modeling them as separate processes. In actuality, the net result was an age distribution that shifted somewhat to the older age classes and allowed some proportion of the forest to age beyond the current maximum age, which we deemed realistic, at least for phase 1. The main implications of this approach are with the interpretation of the spatial results of the species' habitat models (see below). To the degree to which vegetation age and related attributes are incorporated into a species' habitat model, there is increased randomness to the spatial distribution of predicted habitat. Note, because these disturbance processes are all stochastic in the real world (at least at the level we are able to observe them), there will be a random component to the spatial distribution of predicted habitat even if these processes are modeled explicitly.

3) Third, the "current" landscape represents the year 2010. The model operates on a 10 year timestep and simulates landscape change for a 70 year period through the year 2080. The final timestep of 2080 is constrained by the availability of current climate change predictions. However, as climate change predictions are extended, the landscape change simulation period can be extended accordingly. For the sake of parsimony, in phase 1 we summarized the landscape setting in 2010 (starting condition) and at 2030 (20-year forecast) and 2080 (70-year forecast).

4) Lastly, there is considerable uncertainty in future climate change and urban growth -- the two explicitly modeled landscape drivers. Consequently, there are dozens and dozens of alternative future scenarios that could be simulated in an attempt to account for this uncertainty. Unfortunately, practical constraints in running the simulation seriously limit the number of scenarios that can be run. Consequently, we defined three alternative future scenarios in climate change and urban growth, corresponding to the standard emissions scenarios set by the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES, Nakicenovic et al. 2000). Specifically, we chose the A2, A1B and B1 SRES scenarios, which represent a range in predicted temperature and precipitation increases and human population growth over the NALCC. The urban growth rates corresponding to these scenarios were estimated to be 15.6%,17.5%, and 11.8% per decade, respectively, for the middle Connecticut River watershed. We ran each of these scenarios three times to account for the stochastic nature of the urban growth process. Thus, we ran a total of nine simulations to account for uncertainty in future landscape change. While this clearly does not capture the full range of uncertainty in future landscape change, we believe that it is minimally sufficient for our purpose and strikes a reasonable balance between the desire to run hundreds of simulations and the computational cost of running each simulation.

## *2.2. Landscape assessment*

The landscape assessment component of the model is where we evaluate the ecological consequences of the simulated landscape change with respect to the integrity of the extant ecological systems (coarse filter) and the climate-habitat capability of the landscape for representative species (fine filter). 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.

Similar to the landscape change description, for the sake of parsimony, we assessed the landscape condition in 2010 (initial condition) and at 2030 (20-year forecast) and 2080 (70-year forecast) for each of the nine uncertainty simulations (see above), and then summarized the results across uncertainty simulations.

### 2.2.1. Ecological integrity assessment (coarse filter)

Our coarse filter landscape assessment is based on the concept of landscape ecological integrity and is described in detail in a separate document (NALCC_documentation_integrity.pdf). Briefly, *landscape ecological integrity* refers to 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. For our purposes, an integral landscape has a green infrastructure (i.e., undeveloped lands) containing a diversity of highly connected ecosystems with high intactness, resiliency and adaptive capacity. Based on this definition, there are five key attributes of landscape ecological integrity: 1) intactness, 2) resiliency, 3) adaptive capacity, 4) diversity, and 5) connectivity. These measurable attributes 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.

There are a couple of important considerations regarding the ecological integrity assessment in phase 1 that have bearing on the interpretation of the preliminary results in the next section:

1) First, due to time and resource constraints, the ecological integrity assessment was limited to two of the five the integrity attributes: intactness and resiliency. Intactness and resiliency represent local attributes that confer ecological integrity to the cell itself and thus, by extension, to the landscape as a whole, and can be evaluated for the landscape at a single point in time (i.e., a single snapshot). Consequently, these two attributes, and their corresponding metrics, can be used to assess the intrinsic ecological integrity of each cell and can be combined into a composite local *Index of Ecological Integrity* (*IEI*).

2) Second, *IEI* involves quantile-rescaling individual raw metrics within ecological systems, combining the rescaled metrics into *IEI* based on community-specific models (i.e., weighted linear combination of the metrics defined for each ecological system), and further quantile rescaling within specified geographic extents (e.g., by state, ecoregion, watersheds). The end result is an index that scales from 0 (least integrity within ecological system and extent) to 1 (most integrity within ecological system and extent). The use of quantiles means that the results are dependent on the extent of the analysis area, because the quantiles rank cells relative to other cells with the analysis area. Therefore, quantile-rescaling of the raw metrics must be done separately for each analysis area. The best of the NALCC is not the same as the best of the Connecticut River watershed or the state of Maryland. Consequently, the analysis area used for the quantile-rescaling must be explicit. In phase 1, we scaled

*IEI* to each study area extent since the study areas weren't large enough to encompass multiple states, ecoregions or watersheds. It is important to recognize that these extents may or may not be the best extent for any particular conservation application.

### 2.2.2. Climate-Habitat capability for representative species (fine filter)

Our fine filter landscape assessment is based on the concept of climate and habitat capability for a focal species and is described in detail in a separate document (NALCC_documentation_species.pdf). Importantly, we opted not to model species distributions based on habitat and climate combined into a single model because it is unclear to what extent habitat and climate function independently or jointly to limit a species' distribution. Consequently, there is no consensus on how to meaningfully incorporate both habitat and climate variables into a species distribution model for forecasting a species' future distribution under climate change. For example, it is unclear whether a species will track future climate conditions that are characteristic of their current distribution given the novel conditions that may be encountered in the future, unknown time lags in the species population response, and unknown interactions with environmental factors unrelated to climate. Instead, we opted to model habitat capability and climate suitability separately, which allowed us to make predictions based on different assumptions regarding the relative role of habitat and climate in limiting a species future distribution, as described below.

Briefly, *habitat capability* refers to the ability of the environment to provide the local resources (e.g., food, cover, nest sites) needed for survival and reproduction in sufficient quantity, quality and arrangement to meet the life history requirements of individuals and local populations. Habitat capability for a representative species is assessed using HABIT@, a multi-scale GIS-based system for modeling wildlife habitat. The details of the model vary among species depending on the species' habitat requirements, but include an assessment of the availability of one or more local resources (e.g., nesting, cover, food) based on the ecological settings database, summarized at the home range level as the *Home Range Capability* (*HRC*) index, and indexed for the landscape as a whole (see below). Note, these are largely expert-derived models, but statistically validated against empirical data on known species' occurrences.

Climate suitability is based on the concept of a *Climate Niche Envelope* (*CNE*). The "envelope" is a predicted distribution estimated to capture the vast majority of the species' known occurrences based solely on climate variables. Based on the species' current *CNE* model, the species' potential future distribution (based on climate only) is projected via the statistical model to future timesteps based on the projected climate variables.

The final result for each representative species is a coupled prediction of the species' *CNE* and habitat capability at each timestep under a particular landscape change scenario. The joint distribution of a species' predicted climate niche and habitat capability maps at any future timestep in relation to the initial or baseline condition in 2010 is the basis for summarizing the potential impacts of habitat changes and climate changes on a species. Among the myriad possibilities for summarizing these results, we use two basic approaches. First, we compute a *Landscape Capability* (*LC*) index in a couple of different ways, leading to either a graphical or tabular summary, depending on the assumptions we are willing to make regarding the species' responsiveness to climate change, as described below. In either case, it is important to note that *LC* is merely an index of population size based on habitat and climate; it is not an estimate of actual population size or density, since the translation of habitat capability into population size depends on home range size and overlap, habitat occupancy rate and many other factors. Second, we use the intersection of a species' predicted *CNE* and binary habitat capability maps as the basis for delineating distinct *Zones of Uncertainty* in the predicted future distribution of a species. We map these zones and compute a corresponding non-spatial index based on the area in each zone:

There are a couple of important considerations regarding the species assessment in phase 1 that have bearing on the interpretation of the preliminary results in the next section:

1) First, due to time and resource constraints, the species assessment was limited to 10 representative species across the pilot study areas, and all were terrestrial species. Thus, the preliminary results presented below cannot be deemed a comprehensive fine-filter assessment. However, the species' modeled do serve to illustrate the fine-filter approach and do point to some interesting comparisons with the coarse-filter results (see below).

2) Second, the range of most species, including those modeled here, greatly exceeds the extent of the pilot study areas. Thus, the changes in species' habitat capability or climate suitability within any of the pilot study areas may not reflect the changes occurring throughout the species' range. To fully understand the consequences of predicted landscape changes on a species, it is necessary to evaluate the entire range of the species. Our results reflect the changes occurring within a limited focal geographic area, which may or may not be the basis for making conservation decisions regarding the species.

## *2.3. Landscape design*

The landscape assessment component of the model is where we use the results of the landscape change assessment to inform landscape design and is described in detail in a separate document (NALCC_documentation_landscape_design.pdf). This component was not officially part of phase 1 and is to be developed fully in phase 2. It will likely involve designing land protection, management, and/or restoration scenarios to maximize ecological performance criteria such as the landscape ecological integrity indices and habitat capability indices for representative species. Here, we present preliminary results pertaining to optimal conservation reserve networks associated with our comparison of the coarse- and filter-filter approaches to conservation planning, but this is by no means meant to be a comprehensive approach to landscape design.

# 3. Preliminary Results for the Pilot Study Area

One of the objectives of phase 1 was to pilot the LCAD model by simulating landscape change and evaluating the effects on ecological integrity and habitat capability for the representative species in three representative watersheds distributed throughout the NALCC (**Fig. 1**). In consultation with NALCC partners, we selected the Kennebec River watershed in Maine (15,264 $km^2$)(**kenn**), the middle Connecticut River watershed in Massachusetts and southern New Hampshire and Vermont (8,579 $km^2$)(**midconn**), and the combined Pocomoke and Nanticoke Rivers watershed in Maryland, Delaware, and Virginia (3,730 $km^2$)(**pocnan**).

Here, we provide a summary of the results for the **Middle Connecticut River watershed** pilot study area. Specifically, we briefly describe and illustrate by example each of the major types of results, focusing on how to interpret the data products that we are making available to our NALCC partners and others. In addition, here we present preliminary results for the landscape change and assessment portions of the LCAD model; the landscape design portion of the model is being fully developed in phase 2, so here we present only some initial findings associated with our assessment of the coarse-versus fine-filter results.

## *3.1. Ecological settings*

The ecological settings variables represent spatial biophysical and anthropogenic attributes of the landscape (NALCC_documentation_spatial_data.pdf), many of which are dynamic and thus change over time in response to the drivers and succession, and are the basis for the ecological integrity assessment and the species' habitat capability modeling.

### 3.1.1. Current ecological settings grids

The ecological settings grids in 2010 represent the baseline or current condition of the landscape and, as such, are the starting condition for the landscape change simulations. We included 23 different settings grids in the following package:

- midconn_settings_current.zip

A description of each of the settings grids is beyond the scope of this document, but can be found in the document referenced above. However, the *Ecological Systems Map* (ESM) layer is particularly important to the interpretation of the ecological integrity results (below) and worth briefly describing here.

Ecological systems are defined by NatureServe as follows:

> "Ecological systems represent recurring groups of biological communities that are found in similar physical environments and are influenced by similar dynamic ecological processes, such as fire or flooding. They are intended to provide a classification unit that is readily mappable, often from remote imagery, and readily identifiable by conservation and resource managers in the field."

At the coarsest level, ecological systems are divided into terrestrial and aquatic systems. NatureServe defines terrestrial ecological systems, for example, as follows:

> "Terrestrial ecological systems are specifically defined as a group of plant community types (associations) that tend to co-occur within landscapes with similar ecological processes, substrates, and/or environmental gradients. A given system will typically manifest itself in a landscape at intermediate geographic scales of tens to thousands of hectares and will persist for 50 or more years. This temporal scale allows typical successional dynamics to be integrated into the concept of each unit. "

The Nature Conservancy mapped ecological systems across the Northeast. Despite the many challenges associated with the concept of ecological systems and their use in the LCAD model (see NALCC_documentation_ecological_systems.pdf for a detailed discussion), we use ecological systems as an organizational framework for the coarse-filter ecological integrity assessment and they also play an important role in most species' habitat capability models. To meet our purposes, we modified the original ecological systems map somewhat to include roads, multiple development classes and streams, and we refer to this settings layer as *Ecological Systems Map Plus* (ESM+). In addition, we maintain several versions of the ESM+ map that differ in subtle ways as necessary for various uses in the LCAD model. One of these versions we refer to as *Postland*, which is simply the ESM+ map version in which stream cells are placed on top of roads, culverts and dams (i.e., streams take precedence), and in which streams are classified into stream orders and gradient classes. The landcover classes present in *Postland* are the classes we use for quantile scaling the ecological integrity metrics; i.e., these are the "ecological systems" for which we assess ecological integrity, and thus we deemed this the most important map layer to disseminate (instead of the original ESM+) along with the other settings variables.

**Figure 2** depicts an example of the *Postland* map in 2010 for a portion of the middle Connecticut River watershed study area. The area shown encompasses a portion of urban and rural land located near the city of Springfield, Massachusetts, and depicts the urban to rural gradient in land use that is characteristic of most of the study area. Note, the map is colored at the 'formation' level, which is the broadest grouping of ecological systems in the hierarchical classification scheme, because there are too many ecological systems to discern at this scale with any clarity and the legend is too long to display. Hence, this map merely shows the coarse distribution of broad land cover categories, and mainly distinguishes the roads (shades of gray) and developed classes (shades of red) and agricultural land (yellow-green) from the aquatic (shades of blue) and forest classes (shades of green).

**Figure 3** depicts an example of the *Postland* map in 2010 for a small portion of the rural land southwest of the city of Springfield, Massachusetts. The map is colored at the 'ecological system' level, which is the finest level of mapping systems and is the level that it used to scale the ecological integrity metrics for purposes of evaluating landscape ecological integrity.

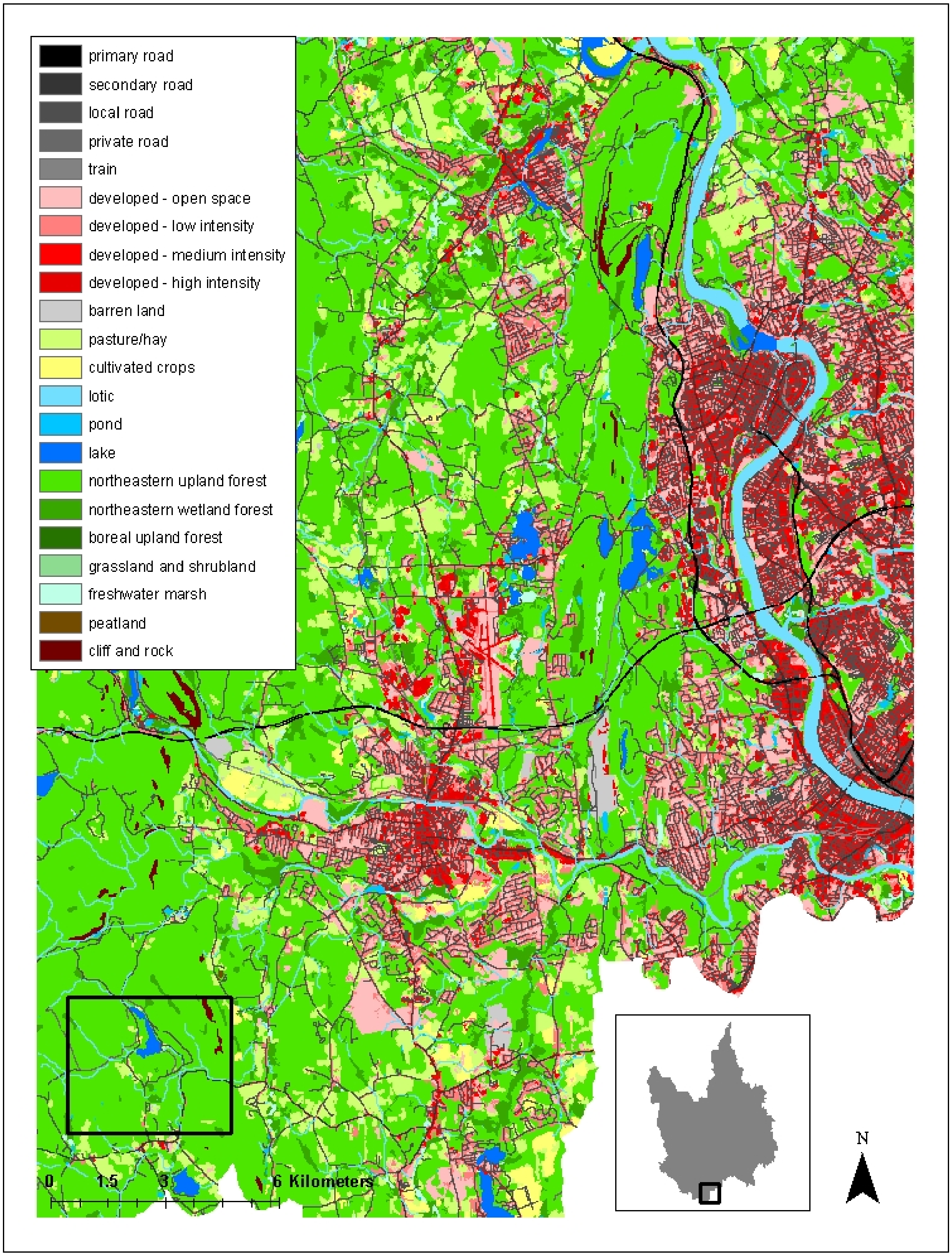



***Figure 2.*** *Ecological systems map with modifications (Postland, see text for details), displayed here at the 'formation' (coarsest) level, in 2010 for a portion of the middle Connecticut River watershed study area.*

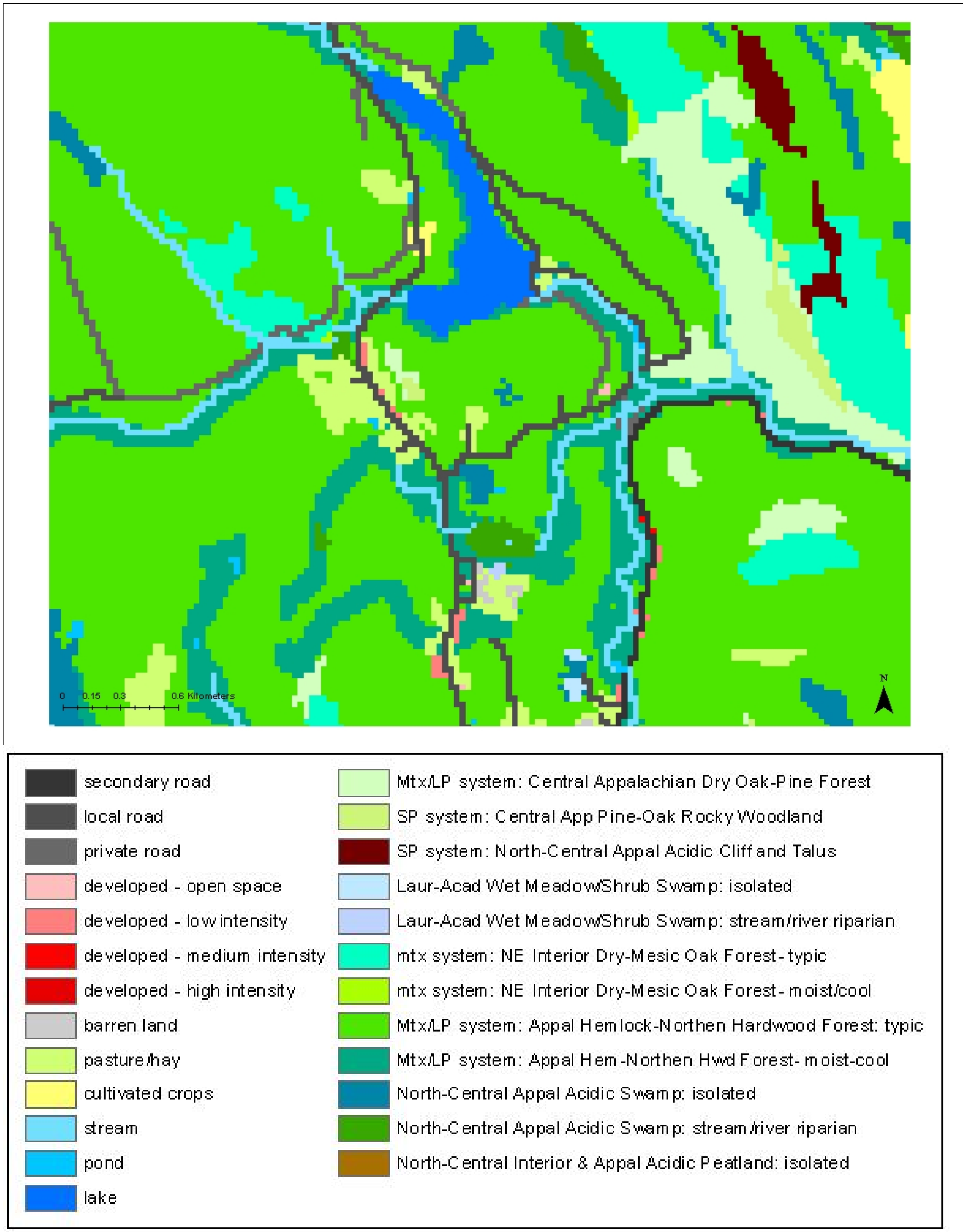



***Figure 3.*** *Ecological systems map with modifications (Postland, see text for details), displayed here at the 'systems' (finest) level, in 2010 for a portion of the middle Connecticut River watershed study area (i.e., depicted by the open box in figure 2).*

### 3.1.2. Future Postland grids

We deemed it impractical to store and distribute the full suite of ecological settings grids for every timestep under every simulation. Consequently, in the package below, we limited the output to the *Postland* grid for the timesteps representing the years 2030 and 2080 under each of the nine uncertainty simulations:

- midconn_settings_future.zip

**Figure 4** depicts a sample of three simulated *Postland* maps for the year 2080 for a portion of the middle Connecticut River watershed study area in the vicinity of North Hampton, Massachusetts, but highlighting the development classes. The differences among the maps illustrate the stochastic nature of urban growth -- each simulation produces a slightly different stochastic realization of urban growth. The amount of growth depicted in this example corresponds to the projected growth rate for this portion of the region associated with the SRES A2 climate change scenario (6.4% per decade). More specifically, the growth shown here was allocated from among the region's growth based on similarity to historical growth allocation across the region, and the spatial pattern of growth was governed by statistical models derived from historical growth patterns for similar landscapes. Importantly, most of the growth is in close proximity to the city, but there is some sprawl occurring away from the city; growth is mostly along side roads; the sizes of the individual developments reflect the distribution of historical patches of development in the region; and development is excluded from water bodies and secured land.

The primary use of the grids in this package are to get a sense of what the amount of growth (4.2-7.3% per decade in the middle Connecticut River watershed) and spatial pattern of growth might look like in the future and to highlight the uncertainty in where individual developments will occur. Importantly, these grids are not intended to show whether a particular parcel will get developed or not in the future, since this is the result of a stochastic process. In other words, we cannot predicted whether an individual parcel will actually get developed or not, only the probability that it will get developed. The realized (or "hard") development shown in these grids is the result of lots of coin tosses. Instead, these grids are intended to show the general patterns of development that might occur in the future.

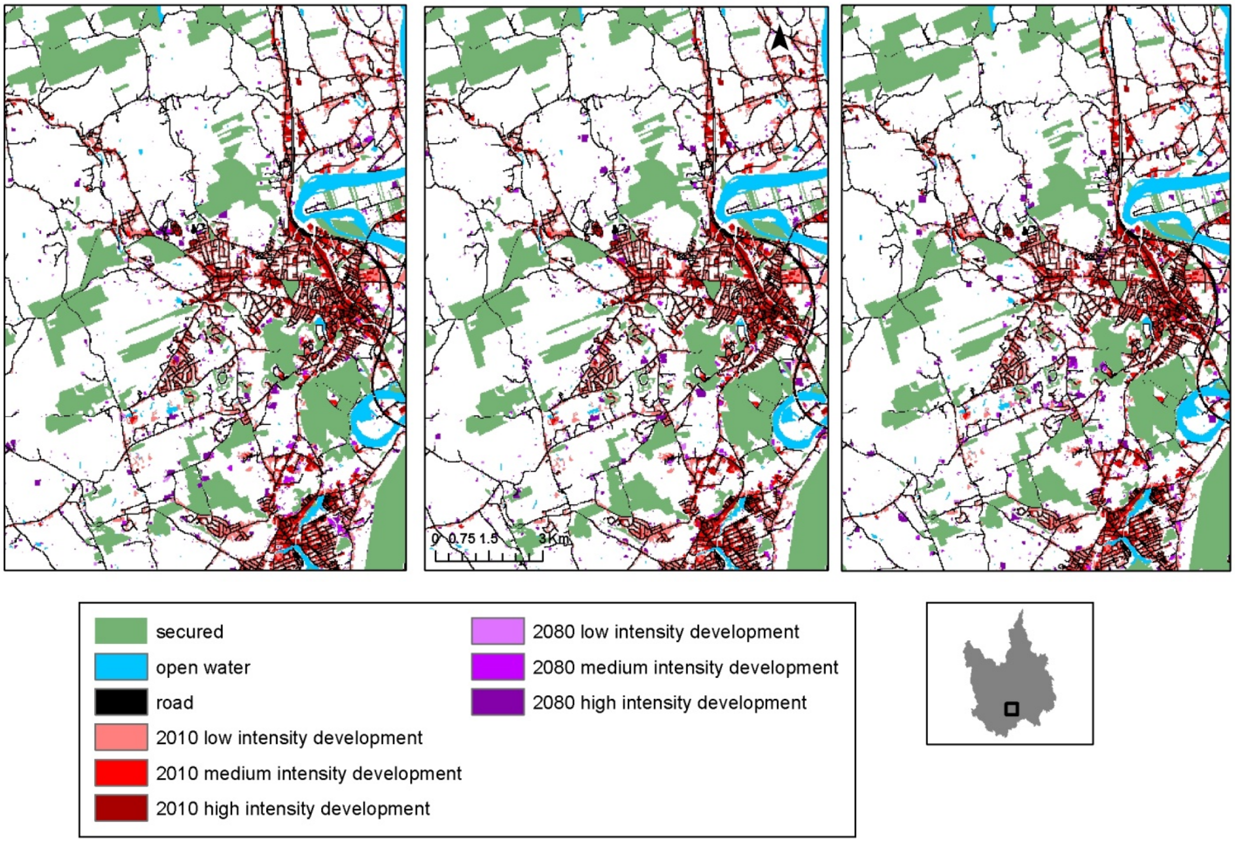



***Figure 4.*** *Land cover map depicting existing development and projected future development in 2080 for a portion of the middle Connecticut River watershed study area (as shown) in the vicinity of North Hampton, MA. Note, the sub-figures represent three different stochastic realizations of the urban growth model and the amount of development reflect the projections associated with the SRES A2 climate change scenario.*

## *3.2. Ecological integrity (coarse filter)*

The ecological integrity results represent our coarse-filter assessment of the ecological consequences of current land use and predicted future landscape changes (NALCC_documentation_integrity.pdf).

### 3.2.1. Current landscape condition

Ecological integrity in 2010 represents a coarse-filter spatial assessment of the current landscape condition and, as such, provide a baseline for comparison with future timesteps (below). Note, the current (2010) ecological integrity assessment does not depend on modeling landscape changes due to climate change, urban growth and vegetation disturbance and succession; therefore, these results have much less uncertainty than those based on the future landscape condition assessment. Indeed, the current landscape condition assessment is independent of the future landscape condition assessment and thus these results can be used for conservation planning, management and restoration without any consideration of the future landscape condition results.

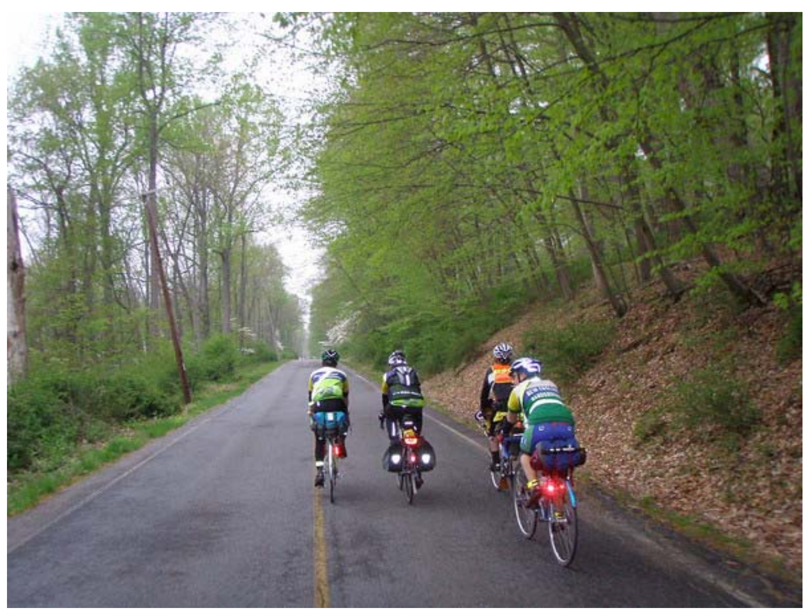
The results of the current ecological integrity assessment are in the form of grids (or maps) representing different ecological integrity metrics. Specifically, we included 16 different metrics representing the *intactness* and *resiliency* components of ecological integrity, along with *IEI*, in the following package:

- midconn_integrity_current.zip

The individual intactness and resiliency metrics represent different perspectives on the negative impacts of human land use on ecological integrity of a site (cell). Each metric reflects a different mechanistic relationship between human activity and ecological integrity and is distributed here in the raw scale of the metric, which varies among metrics and thus must be interpreted individually. Some metrics decrease in value as the integrity increases (e.g., traffic), whereas some metrics increase in value as the integrity increases (e.g., connectedness). Moreover, many of these metrics have a scale and measurement unit that is intuitive and thus interpretable in the raw scale form -- hence, our choice to distribute the raw scale form of the metrics. Importantly, these individual metrics provide a detailed decomposition of the factors most affecting local ecological integrity, and thus can be quite useful when trying to understand why some sites have high integrity and others have low integrity.

**(1) *Traffic [Grid]*** -- *Traffic* is an example of an intactness metric and reflects the assumption that as traffic intensity increases in the neighborhood of a cell that local ecological integrity will decrease, because many organisms will suffer higher rates of mortality due to vehicle collisions. Importantly, all of the intactness metrics, like *Traffic*, are computed without explicit reference to ecological systems; they quantify the magnitude of human stressors, which generally emanate outward from human development (e.g., roads, buildings, dams, etc.) independent of the specific ecosystem context. For example, *Traffic* is computed from the estimated traffic rate along roads. First, each cell of road is assigned a traffic rate from the traffic settings variable, in which the estimated traffic rate has already been transformed to range 0-1. Next, for every undeveloped cell, we place a standard logistic kernel of fixed width (inflection=800 m, scale=100 m) over the cell. Note, the standard kernel has a volume of 1; the logistic kernel assigns a weight to each neighboring cell within the kernel according to the shape of the logistic curve, such that they sum to 1. Next, the kernel is multiplied by the traffic rate, such that road cells end up with the product of the logistic kernel weight (which is a function of Euclidean distance) and the road traffic rate, and all other cells end up with zero. Finally, we sum the resulting values of the kernel and place this value in the focal cell. The final value ranges from 0 (no traffic within the kernel) to 1 (all cells have a traffic rate of 1 within the kernel), and represents the magnitude of "exposure" to traffic within the ecological neighborhood of the focal cell. We repeat this process for every undeveloped cell.

**Figure 5** depicts an example of *Traffic* in 2010 for the middle Connecticut River watershed study area. Note, the areas in white represent developed classes and they receive no value, since we ultimately don't compute ecological integrity for these cells. The areas in red depict large areas of very low to no road traffic, at least at the scale of the kernel. These areas may have lots of rural (or local) roads, but they realize very low levels of traffic. The areas in blue depict narrow zones largely around the urban centers in which road traffic rate is at the maximum within the study area; in this case, the maximum observed is 0.52, which is roughly one-half the theoretical maximum that could have been observed. The areas in yellow and green pick up the major transportation corridors associated with primary and secondary roads and also nicely reveal the scale of the kernel used to evaluate road traffic intensity. Lastly, keep in mind that *Traffic*, like all other intactness metrics, is distributed in its raw scale. Hence, the computed values are independent of the study area extent; i.e., there is no rescaling of the metric by ecological system or extent. Consequently, the traffic values shown in **figure 5** will not change as the study area expands in phase 2.



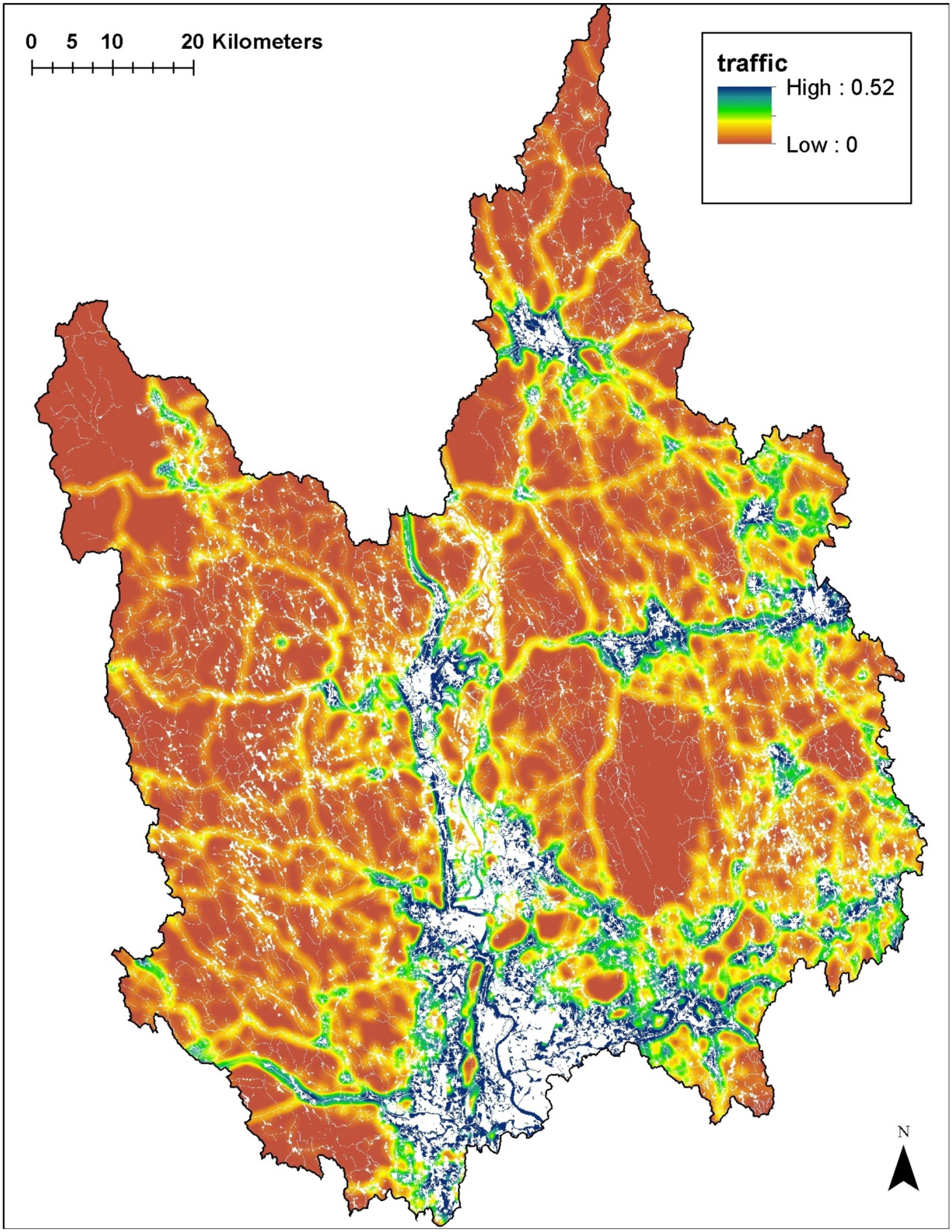



***Figure 5.*** *Traffic metric in 2010 for the middle Connecticut River watershed study area.*

**(2)** ***Connectedness [Grid]*** -- *Connectedness* (Connect) is an example of a resiliency metric and reflects the assumption that as local connectivity increases, local ecological integrity increases, because many organisms will be better able to recover from disturbances via rescue and/or recolonization from nearby populations and thus be better able to maintain their populations over time. Connectedness ranges from 0 (single isolated cell of a particular ecological system) to 1 (ecological neighborhood comprised of the same ecological setting as the focal cell and without anthropogenic impediments to movement). Importantly, all of the resiliency metrics, like *Connectedness*, are affected by both the human infrastructure (i.e., roads and development) and the natural ecological setting; they quantify the extent and configuration of similar ecological settings (e.g., a cell of emergent marsh surrounded by an abundance of emergent marsh is more resilient to disturbance and stress) and the degree to which human infrastructure has reduced the extent of the focal setting (e.g., loss of emergent marsh through drainage and filling reduces resiliency of the remaining marsh) and/or disrupted the flow of organisms and material across the landscape (e.g., an expressway between two emergent marshes decreases the resiliency of both marshes). For example, *Connectedness* is computed using a complicated process involving resistant kernels. Briefly, for every undeveloped cell, we build a resistant Gaussian (i.e., normal) kernel. Basically, this involves spreading outward from the focal cell according to a Gaussian kernel (similar to *Traffic* but with a normal curve instead of a logistic curve), but discounting each cell during the spreading by its resistance to ecological flow. Here, resistance is a function of the ecological dissimilarity to the focal cell based on the suite of settings variables. Moving through a cell of a very different ecological system or through development or across a road confers relatively high resistance, whereas moving through a cell of a similar ecological setting confers relatively little resistance. The end result is a resistant kernel whose shape reflects the pattern of local resistance to ecological flows. Next, the kernel is multiplied by the ecological similarity to the focal cell. Thus, a cell that is perfectly similar to the focal cell is multiplied by 1 and unchanged, whereas a cell that is very different from the focal cell is multiplied by a number much less than 1, asymptotically approaching 0 as the dissimilarity increases. In other words, weight is only given to destination cells that are ecologically similar to the focal cell. Finally, for each undeveloped cell, we sum the values of all the overlapping kernels and place this value in the focal cell. The final value ranges from 0 (completely isolated cell) to 1 (perfectly similar and accessible ecological neighborhood), and represents the local connectivity of the focal cell.

**Figure 6** depicts an example of *Connectedness* in 2010 for the middle Connecticut River watershed study area. Note, the areas in white represent developed classes and they receive no value. The areas in brown depict areas surrounded by intensive development and roads that confer high resistance to ecological flows. Conversely, the areas in blue largely depict remote areas far from development and roads, but also reflect natural settings with a relative high degree of ecological similarity. In this case, the maximum observed value is 0.63 (the theoretical maximum that could have been observed is 1) associated with a single large water body, the Quabbin Reservoir, which is an extensive area of similar ecological setting surrounded by very little development. Lastly, keep in mind that *Connectedness*, like all other resiliency metrics, is distributed in its raw scale. Hence, the computed values are independent of the study area extent.

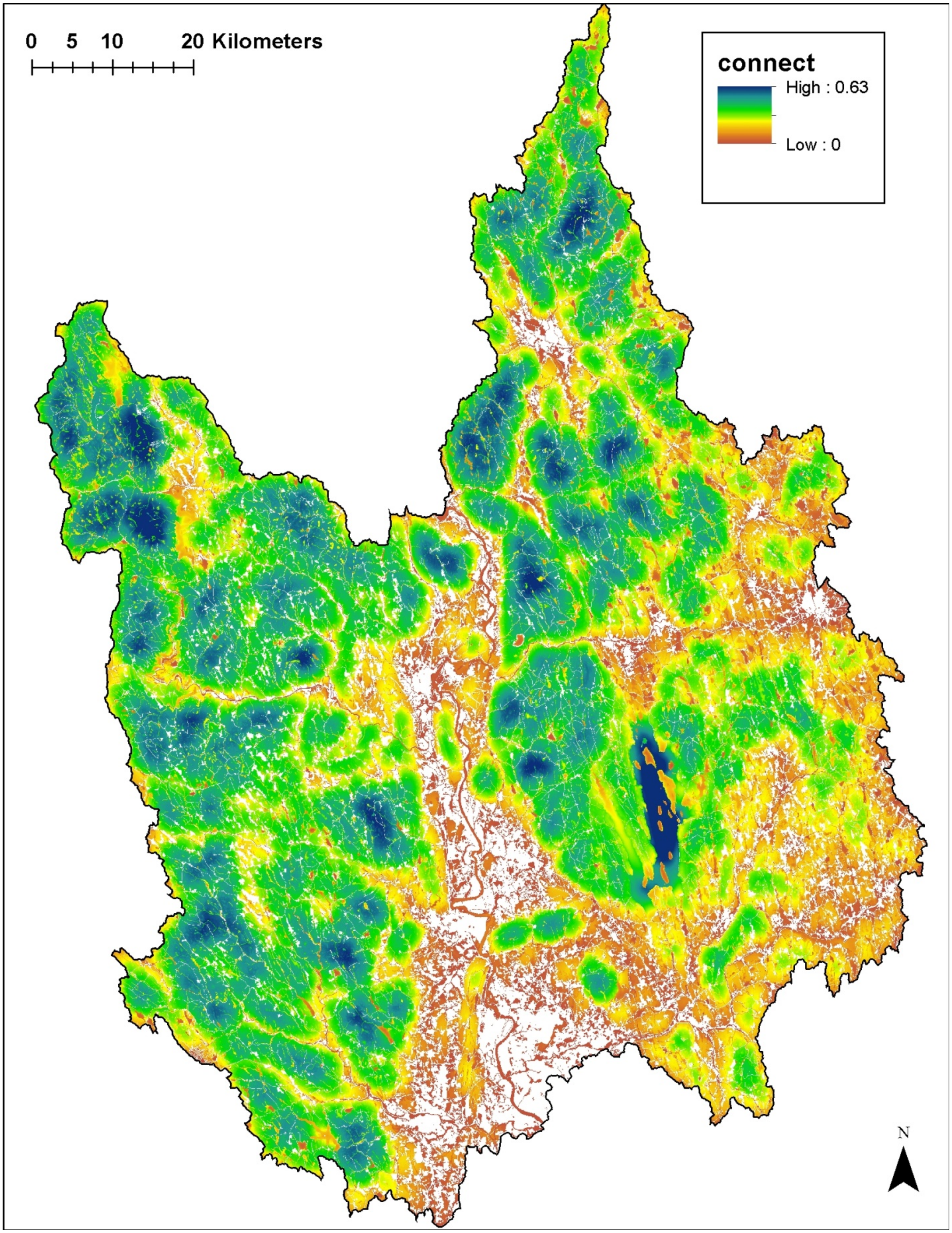
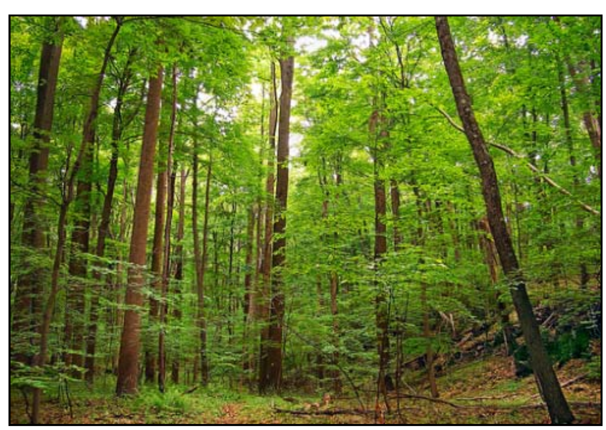



***Figure 6.*** *Connectedness (Connect) metric in 2010 for the middle Connecticut River watershed study area.*

**(3) *Index of Ecological Integrity [Grid]*** -- *IEI* is a composite index derived from the individual intactness and resiliency metrics; it is a synoptic measure of local ecological integrity and thus represents the primary coarse-filter result. In contrast to the individual component metrics, *IEI* is quantile-scaled by ecological system and extent. The individual metrics are first quantile-scaled by ecological system within an extent (in this case, each pilot study area), then combined in a weighted linear function specific to each ecological system, and then the composite raw *IEI* is quantile-scaled by ecological system and 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. Thus, forests are compared to forests and emergent marshes are compared to emergent marshes, and so on. 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.

It is critically important to recognize the relative nature of *IEI*; a value of 1 does not mean that a site has the maximum absolute ecological integrity (i.e., completely unaltered by human activity), only that it is the best of that ecological system within the analysis area. In an absolute sense, the best within an analysis area may still be pretty impacted. Consequently, *IEI* is best used as a comparative index to compare one site to another. To compare the same site to itself over time, however, we must use a different scaling scheme, as discussed below. In addition, the final *IEI* has a nicely intuitive interpretation, because the quantile of a cell expresses the proportion of cells with a raw value less than or equal to the value of the focal cell. Thus, a cell with a 0.9 value has a value that is greater than or equal to 90% of all the cells, and all the cells with >0.9 quantile values comprise the best 10% within the analysis area. For these reasons, the *IEI* maps are best interpreted in conjunction with the *Postland* maps, since the latter depicts the landcover classes by which the quantile-scaling was conducted.

**Figure 7** depicts an example of the *IEI* map in 2010 for the middle Connecticut River watershed study area. Note that values for undeveloped cells range from near 0 (minimum integrity) to 1 (maximum integrity) over the full extent of the study area, and this is true separately for each ecological system. Because *IEI* is based on quantile scaling, it can easily be thresholded to show the top x% of the landscape. For example, in **figure 7** the top 20% of the landscape in terms of *IEI* is depicted by areas shown in blue. Importantly, these "top 20%" areas are distributed across all ecosystems in proportion to their abundance in this landscape. Thus, the majority of the top 20% is composed of northeastern upland forest (of various flavors), since this formation is the dominant undeveloped land cover classes in this landscape (comprising roughly 84% of the study area).



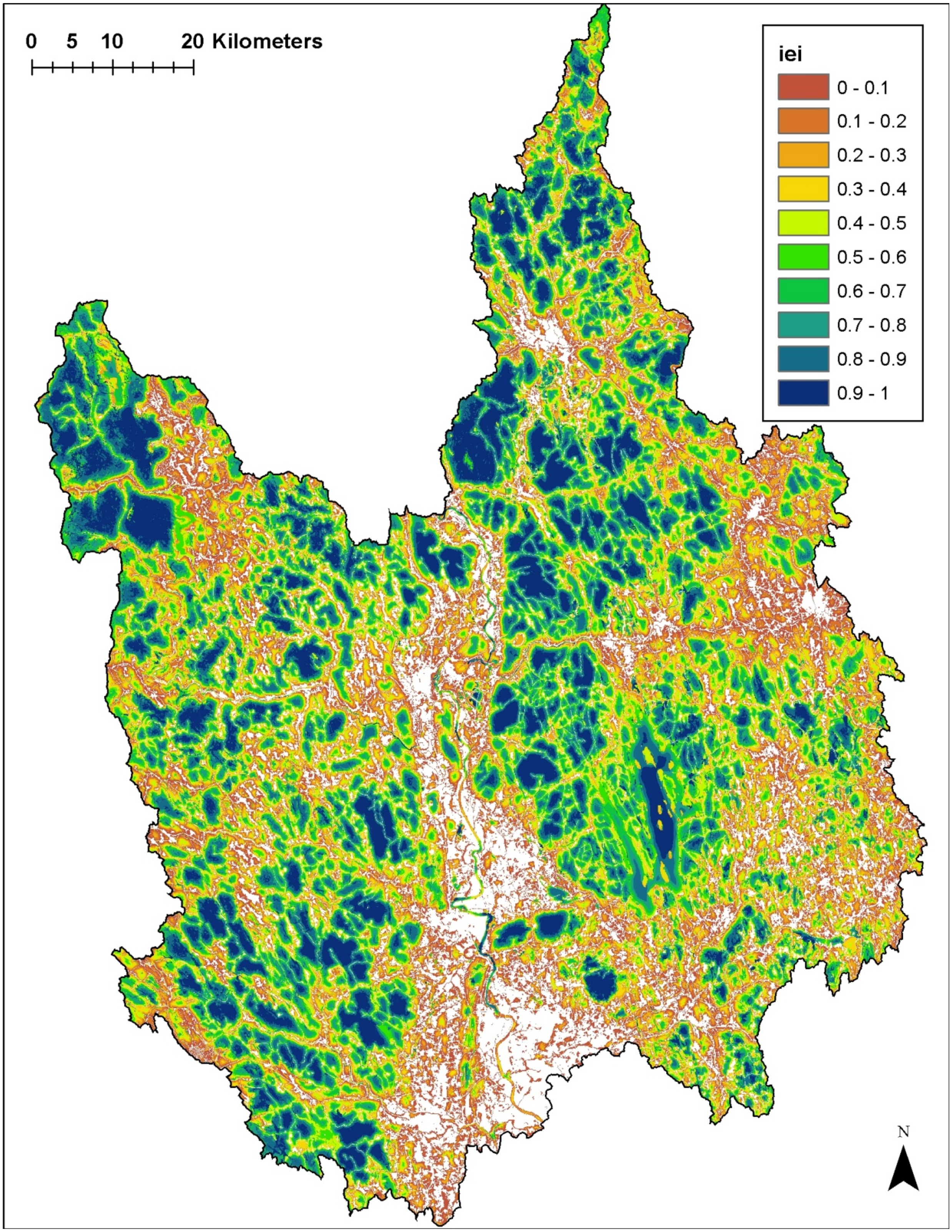



***Figure 7.*** *Index of Ecological Integrity (IEI) metric in 2010 for the middle Connecticut River watershed study area.*

Given the previous discussion, when viewing the *IEI* map it is important to recognize that the eye naturally will be drawn to the areas of high integrity associated with the dominant ecosystem(s). For example, if 90% of the landscape is composed of a particular forest type, then 90% of the *IEI* greater than some threshold, say 0.8, will be composed of that forest type due to the quantile-scaling by ecological system. In the study area depicted in **figure 7**, there is a preponderance of forest; therefore, the high-integrity streams and wetlands, for example, are easily "lost" or overwhelmed by the preponderance of high-integrity forest. Indeed, the problem is not restricted to aquatic and wetland ecosystems. Given the many different "flavors" of forest that exist at the ecosystem level, the patterns of variation in particular forested ecosystem types is also swamped by the pattern of the dominant forest ecosystem type. Consequently, it is often useful to mask all but the focal ecological system(s) of interest. For example, in **figure 8**, the *IEI* for only the "North Central Appalachian Acidic Swamp: Smaller Stream Riparian" ecological system is displayed for a portion of the middle Connecticut River watershed study area and reveals the integrity gradient for this system without being overwhelmed by the integrity of the dominant systems.

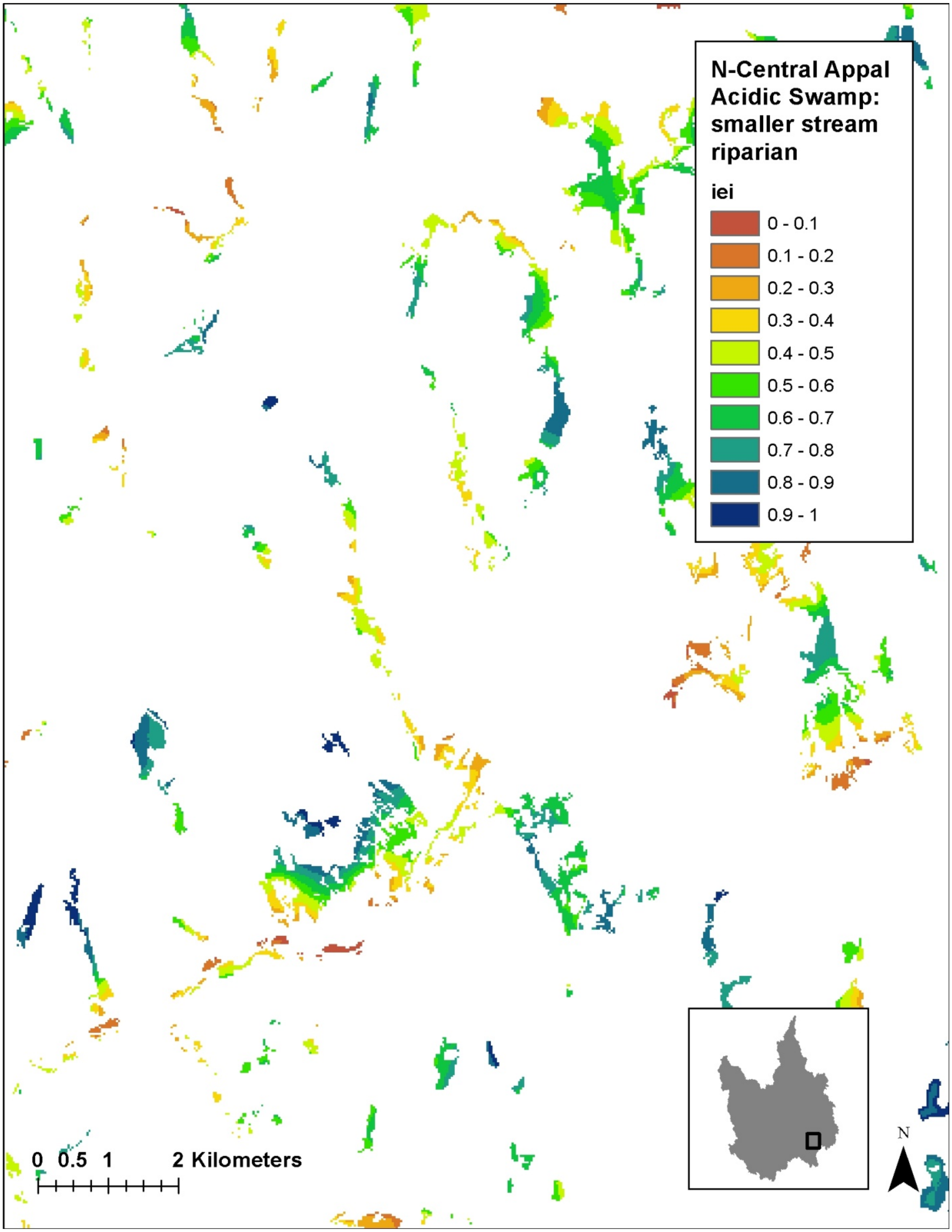



***Figure 8**. Index of Ecological Integrity (IEI) metric for the North Central Appalachian Acidic Swamp: Smaller Stream Riparian ecological system in 2010 for a portion of the middle Connecticut River watershed study area.*

### 3.2.2. Future landscape condition

Ecological integrity in 2030 and 2080 represents a coarse-filter spatial assessment of the future landscape condition for a 20-year forecast (2030) and 70-year forecast (2080), respectively, in light of predicted landscape changes driven by climate change, urban growth and vegetation disturbance and succession. Because of the uncertainty in the landscape change drivers (e.g., uncertainty in amount and pattern of urban growth that will be realized), these results have much greater uncertainty than those based on the current (2010) ecological integrity assessment. Thus, these results should be used with caution for conservation planning, management and restoration in combination with the more certain current ecological integrity results.

The results of the future ecological integrity assessment are in the form of grids (or maps) representing different ecological integrity metrics and a non-spatial summary in tabular form. For the sake of parsimony, we included only two grids, *IEI* and *Impact*, along with a non-spatial summary of *Impact* in tabular form in the following package:

- midconn_integrity_future.zip

**(1) *Index of Ecological Integrity [Grid]*** -- *IEI* is defined as above, but here it is computed for the landscape condition in 2030 or 2080. An important distinction between the *IEI* grid in 2010 and the *IEI* grid in 2030 or 2080 distributed here is that the future *IEI* represents the mean across the nine uncertainty simulations. Note, each uncertainty simulation results in a unique landscape change projection and a corresponding ecological integrity assessment for each timestep. Thus, the *IEI* grid in 2030 (or 2080) in any one of the uncertainty simulations is a merely an assessment of a stochastic realization of the future landscape condition. Although the variation in *IEI* across simulations may be of some interest, it can be challenging to interpret, so we opted for simplicity sake to distribute just the mean across simulations.

Importantly, the future *IEI* cannot be compared directly to the current *IEI* due to the use of quantile-scaling, as discussed in the technical document on ecological integrity. Briefly, the use of quantile-scaling suffers from the "Bill Gates" effect when used for scenario comparison (e.g., comparing a future timestep to the current timestep). The "Bill Gates" effect occurs when the value of the raw metric is decreased in a cell but it remains the highest valued cell -- the quantile is unchanged. This is analogous to taking millions of dollars away from Bill Gates, and yet he remains the richest man around. The issue is actually more pervasive than just this extreme case. For example, when the raw values are all very low, even a small absolute change can result in a large quantile change. All this makes quantile-scaling unsuited for scenario comparison. To address this issue, we developed *delta-scaling* as an alternative to quantile-rescaling that is more meaningful when comparing among scenarios, and this is the scaling that is used to index ecological impact (i.e., the change in *IEI* over time), as described below. Thus, the future *IEI* should be interpreted independently as an index of the relative integrity of sites in the future, without explicit comparison to the present.

**Figure 9** depicts an example of the mean *IEI* in 2080 for the middle Connecticut River watershed study area. In general, there is a subtle but inevitable decrease in *IEI*

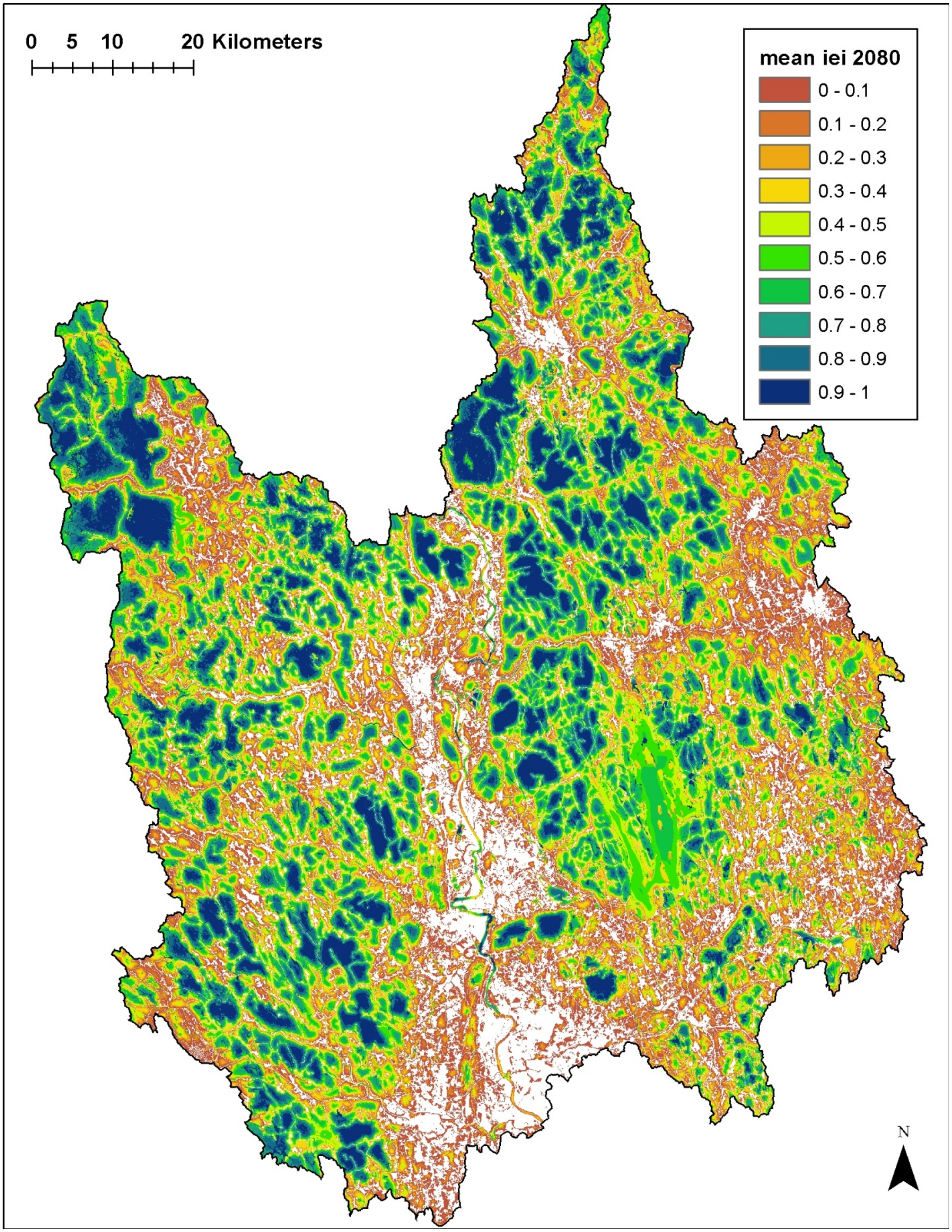



***Figure 9.*** *Index of Ecological Integrity (IEI) metric in 2080 for the middle Connecticut River watershed study area, averaged across nine uncertainty simulations.*

values over time due to urban growth, but remember that we cannot directly compare the *IEI* in 2080 with the *IEI* in 2010 due to the use of quantile-scaling -- we must leave that for *Impact* (below). If we had a crystal ball and could look ahead 70 years, the mean *IEI* in 2080 represents our expected distribution of local ecological integrity values given the uncertainty in our forecasts and, as such, depicts areas that we expect to have high integrity in 2080.

**(2) *Impact [Grid]*** -- *Impact* is a composite index like *IEI*, but derived to represent the change in *IEI* over time. Specifically, *Impact* is based on a weighted linear combination of the *delta*-scaled intactness and resiliency metrics (reflecting the difference between the baseline in 2010 and the future timestep), multiplied by the *IEI* in 2010. Thus, *Impact* is interpreted as the magnitude of change in *IEI* where it matters the most -- places currently with high integrity that are most likely to be degraded by future urban growth. These might be considered priorities for land protection. Like *IEI*, each simulation produces a unique *Impact* grid for each future timestep, reflecting the stochastic nature of urban growth. Similar to the *IEI* grids for future timesteps, the *Impact* grids distributed here represent the mean across the nine uncertainty simulations.

**Figure 10** depicts an example of the mean *Impact* in 2080 for the middle Connecticut River watershed study area. The larger the negative index, the greater the effective loss in ecological integrity between 2010 and 2080; in other words, the loss in ecological integrity from cells that currently have high ecological integrity -- where it matters the most. It is clearly evident that the greatest impacts on ecological integrity are patchily distributed throughout the watershed owing to the dispersed development in the future. Note the concentration of relatively high *Impact* in the major urban growth areas around the Connecticut River valley and along the major east-west transportation corridors where the development is close to areas of high *IEI* (dark blue areas in **figure 7** and **9**). The high impact here is a function of the future development footprint directly reducing IEI and indirectly reducing the IEI of adjacent undeveloped high-value land.

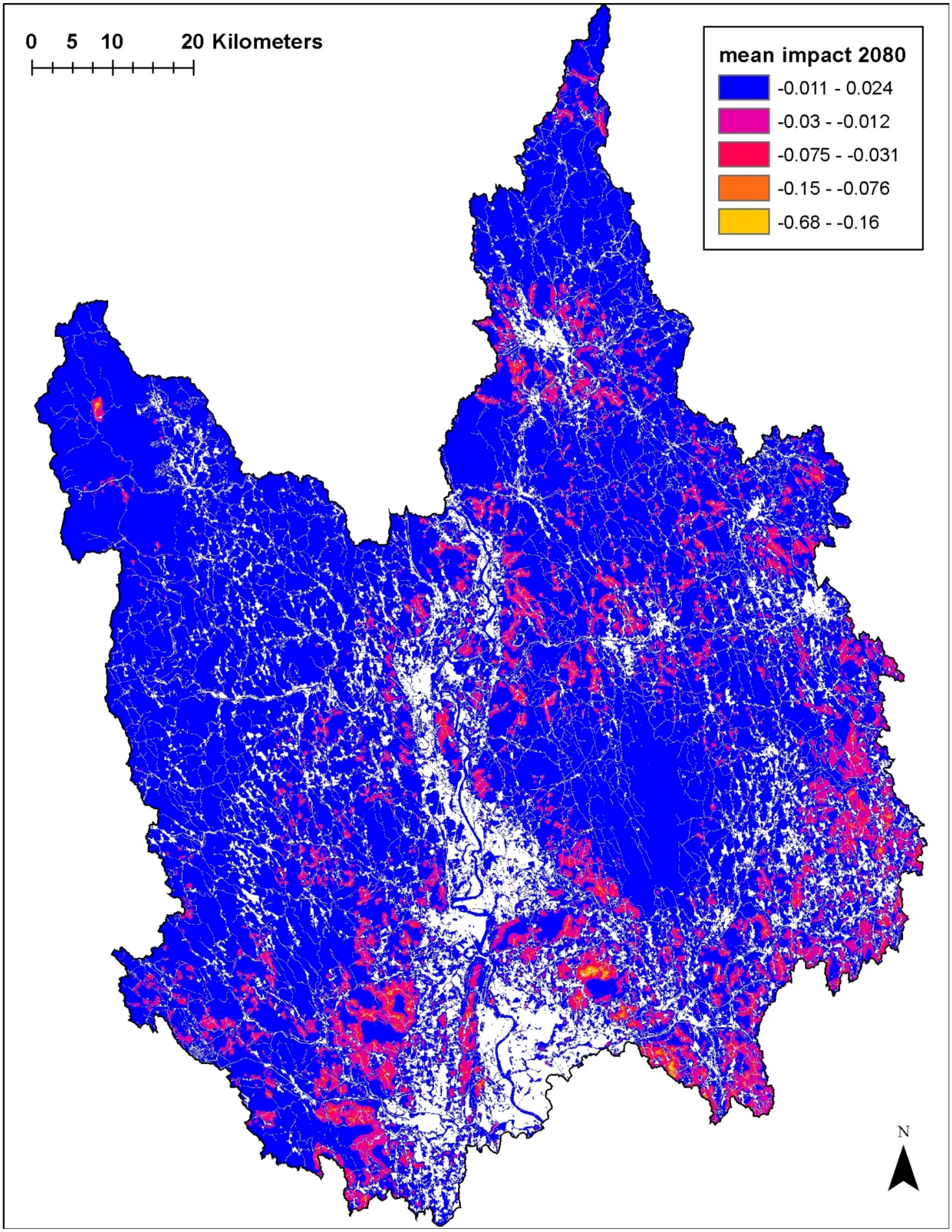



***Figure 10.*** *Index of Ecological Impact (Impact) metric in 2080 for the middle Connecticut River watershed study area, averaged across nine uncertainty simulations.*

**(3) *Impact [Table]*** -- The ecological integrity results can be summarized non-spatially in tabular form. *IEI* does not lend itself to a meaningful non-spatial summary due to the quantile scaling by ecological system. However, *Impact* can be meaningfully summarized for the landscape non-spatially in a couple of different ways, as follows:

- *Total Impact* -- First, *Impact* is summed across all cells and converted to hectares within each ecological system to quantify the *Total Impact* on each ecological system and the landscape as a whole. *Total Impact* is interpreted as the maximum *Impact* equivalent hectares. This index is useful for determining which ecological systems are expected to be impacted the most in aggregate by development, and can be quite useful for comparing the impact of different landscape change scenarios on individual ecological systems, but comparisons among ecological systems is seriously compromised by the varying extents of individual ecological systems. For example, an impact of 10 units in an ecological system that covers 100 hectares is not the same as an impact of 10 units in an ecological system that cover 1,000 hectares, except in an absolute sense. A wetland system that loses 10 units of integrity is probably more disconcerting than an extensive forested system that loses the same 10 units of integrity.

- *Average Impact* -- Second, given the considerations above, we also compute the *Average Impact* across all cells (multiplied by 100) within each ecological system and the landscape as a whole. *Average Impact* ranges from 0 (no impact) to -100 (maximum impact). This index is useful for determining the average or expected impact to a cell of a particular ecological system, and has the same utility as *Total Impact* for comparing the impact of different landscape change scenarios on individual ecological systems. However, *Average Impact* is particularly useful for comparing the impacts among ecological systems, since the differences in area among ecological systems is controlled for. Of course, the average impact says nothing about the total impact to an ecological system. Consequently, neither the *Total Impact* or the *Average Impact* provide a complete picture of the impact to the ecological systems, and thus they are probably best interpreted in conjunction.

**Table 1** depicts an example of the *Total* and *Average Impact* of the simulated landscape change in 2030 and 2080 for the middle Connecticut River watershed study area. Note, **table 1** gives *Impact* statistics for ecological formations; i.e., aggregations of ecological systems into broader categories, as defined in table 3 in the technical document on ecological integrity. However, *Impact* statistics are also reported for individual ecological systems and distributed in this data product package. **Table 1** is sorted by the area (ha) of ecological formations. Northeastern upland forest comprises the majority of the undeveloped landscape at 84%, and not surprisingly also suffers the greatest total and average impact over time. Northeastern wetland forest and freshwater marsh, on the other hand, comprise much less area (<8% combined) than Northeastern upland forest and thus much less total impact, but nonetheless suffer almost as high an average impact, suggesting that these ecological formations are being disproportionately impacted.

***Table 1**. Impact of landscape change on the ecological integrity of each ecological system (shown here for system groups, or formations) in the middle Connecticut River watershed study area in 2030 and 2080. Area (ha and percentage of landscape) of each ecological system is for 2010. Impact is measured at the cell level as the change in the index of ecological integrity between 2010 and 2030 or 2080, multiplied by the index of ecological integrity in 2010, and both summed (Total Impact) and averaged (Average Impact) across cells of the corresponding ecological system. Impact is reported here as the mean and range across uncertainty simulations.*

| | **Area** | | **Total impact** | | **Average impact** | |
|---|---|---|---|---|---|---|
| Ecological formation | ha | % | 2030 | 2080 | 2030 | 2080 |
| Northeastern Upland Forest | 589,017 | 83.85 | -2,759.3 (-3,352.7, -2,078.7) | -10,582.9 (-12,924.0, -7,762.1) | -0.47 (-0.57, -0.35) | -1.80 (-2.19, -1.32) |
| Northeastern Wetland Forest | 40,196 | 5.72 | -194.8 (-250.2, -138.9) | -681.3 (-824.4, -517.0) | -0.48 (-0.62, -0.35) | -1.69 (-2.05, -1.29) |
| Lentic | 25,994 | 3.70 | -90.4 (-108.7, -61.8) | -338.8 (-431.9, -237.6) | -0.35 (-0.42, -0.24) | -1.30 (-1.66, -0.91) |
| Lotic | 24,878 | 3.54 | -26.5 (-31.6, -20.1) | -99.1 (-120.0, -71.9) | -0.11 (-0.13, -0.08) | -0.40 (-0.48, -0.29) |
| Freshwater Marsh | 11,899 | 1.69 | -52.7 (-66.2, -38.2) | -198.5 (-248.0, -140.9) | -0.44 (-0.56, -0.32) | -1.67 (-2.08, -1.18) |
| Boreal Upland Forest | 4,042 | 0.58 | 0.0 (0.0, 0.0) | 0.0 (0.0, 0.0) | 0.00 (0.00, 0.00) | 0.00 (0.00, 0.00) |
| Cliff and Rock | 3,285 | 0.47 | -3.1 (-4.9, -1.8) | -12.1 (-18.4, -6.5) | -0.09 (-0.15, -0.05) | -0.37 (-0.56, -0.20) |
| Grassland and Shrubland | 2,325 | 0.33 | -0.2 (-0.3, -0.1) | -0.9 (-1.4, -0.6) | -0.01 (-0.01, 0.00) | -0.04 (-0.06, -0.03) |
| Peatland | 801 | 0.11 | -4.9 (-8.5, -3.1) | -19.9 (-24.6, -13.6) | -0.62 (-1.06, -0.38) | -2.48 (-3.07, -1.70) |

| | | | | | | |
|---|---|---|---|---|---|---|
| Total | 702,435 | 100.00 | -3,132.0 (-3,823.0, -2,342.6) | -11,933.5 (-14,592.7, -8,750.3) | -0.45 (-0.54, -0.33) | -1.70 (-2.08, -1.25) |

## 3.3. Species climate-habitat capability (fine filter)

The species results represent our fine-filter assessment of the ecological consequences of current land use and predicted future landscape changes (NALCC_documentation_species.pdf). we implemented models for the following species in the middle Connecticut River watershed study area:

1. Blackburnian warbler (*Setophaga fusca*)
2. Blackpoll warbler (*Setophaga striata*)
3. Louisiana waterthrush (*Parkesia motacilla*)
4. Marsh wren (*Cistothorus palustris*)
5. Northern waterthrush (*Parkesia noveboracensis*)
6. Ovenbird (*Seiurus aurocapilla*)
7. Red-shouldered hawk (*Buteo lineatus*)
8. Wood thrush (*Hylocichla mustelina*)
9. Wood turtle (*Glyptemys insculpta*) [CNE models not included]

### 3.3.1. Current landscape condition

The species results in 2010 represent a fine-filter spatial assessment of the current landscape and, as such, provide a baseline for comparison with future timesteps (below). Like the coarse-filter results, the current (2010) species' climate-habitat assessment does not depend on modeling landscape changes; therefore, these results have much less uncertainty than those based on the future landscape condition assessment. Thus, as with the coarse filter, these results can be used for conservation planning, management and restoration without any consideration of the future landscape condition results.

The results of the current species' climate-habitat assessment are in the form of grids (or maps) representing each species' habitat capability, climate suitability and predicted distribution in 2010. Specifically, we included three grids representing *Home Range Capability* (HRC), *Climate Niche Envelope* (CNE) and *Current Optimal Area* (COA) for each species in 2010 in the following package:

- midconn_species_current.zip

**(1) *Home Range Capability [Grid]*** -- *HRC* is an index of the capability of a potential homerange area centered on a focal cell to support an individual based on solely on habitat; i.e., the quantity, quality and accessibility of local resources needed to support survival and reproduction. *HRC* ranges from 0 (no habitat) to 1 (optimal habitat), and unlike *IEI* that involves quantile scaling, it does not depend on the extent of the analysis area; it is an intrinsic property of the local landscape context. It is important to recognize that *HRC* is not a function of the composition of the focal cell, but rather of the area around the focal cell. Thus, the *HRC* of a cell can be high even if the local resource value of the focal cell itself is low, so long as the area surrounding the focal cell provides an abundance of high-quality and accessible resources. The exception to this rule is that *HRC* is set to zero for cells of hard development (e.g., roads, development).

**Figure 11** depicts an example of the *HRC* map in 2010 for the blackburnian warbler for the middle Connecticut River watershed study area. Note that values range from 0 (no habitat) to some number less than 1, and do not necessarily approach 1 anywhere within the study area, because optimal habitat conditions may not exist within the study area. Indeed, in this example, the best habitat appears to fall in the 0.5-0.7 range of *HRC* and is patchily distributed throughout the study area at the higher elevations in the northern and western portions of the landscape.

**Figure 12** depicts an example of the *HRC* map in 2010 for four representative species (including the ovenbird) for the middle Connecticut River watershed study area, but shown only for a small portion of the study area for clarity (see the open box in **figure 11** for the location). Note, we selected the species shown here to illustrate the range of variability in *HRC* maps among representative species. The marsh wren (mawr) inhabits dense vegetation typically associated with fresh, brackish and saltwater marshes and thus non-zero *HRC* values are associated with the patchy distribution of marshes. The Louisiana waterthrush (lowa) most commonly breeds along clear, perennial, first to third order streams that flow through deciduous forest, but in lower densities than along faster-flowing, coarse-bottomed streams and thus the non-zero *HRC* values reveal the linear nature of riparian zones. The blackburnian warbler (blbw) is rather broadly distributed in upland forests in this study area and thus shows a contiguous distribution of *HRC* values across the study area. The blackpoll warbler (blpw) is restricted in distribution to the highest elevation forests in this study area and thus shows a much more limited distribution of non-zero *HRC* values.

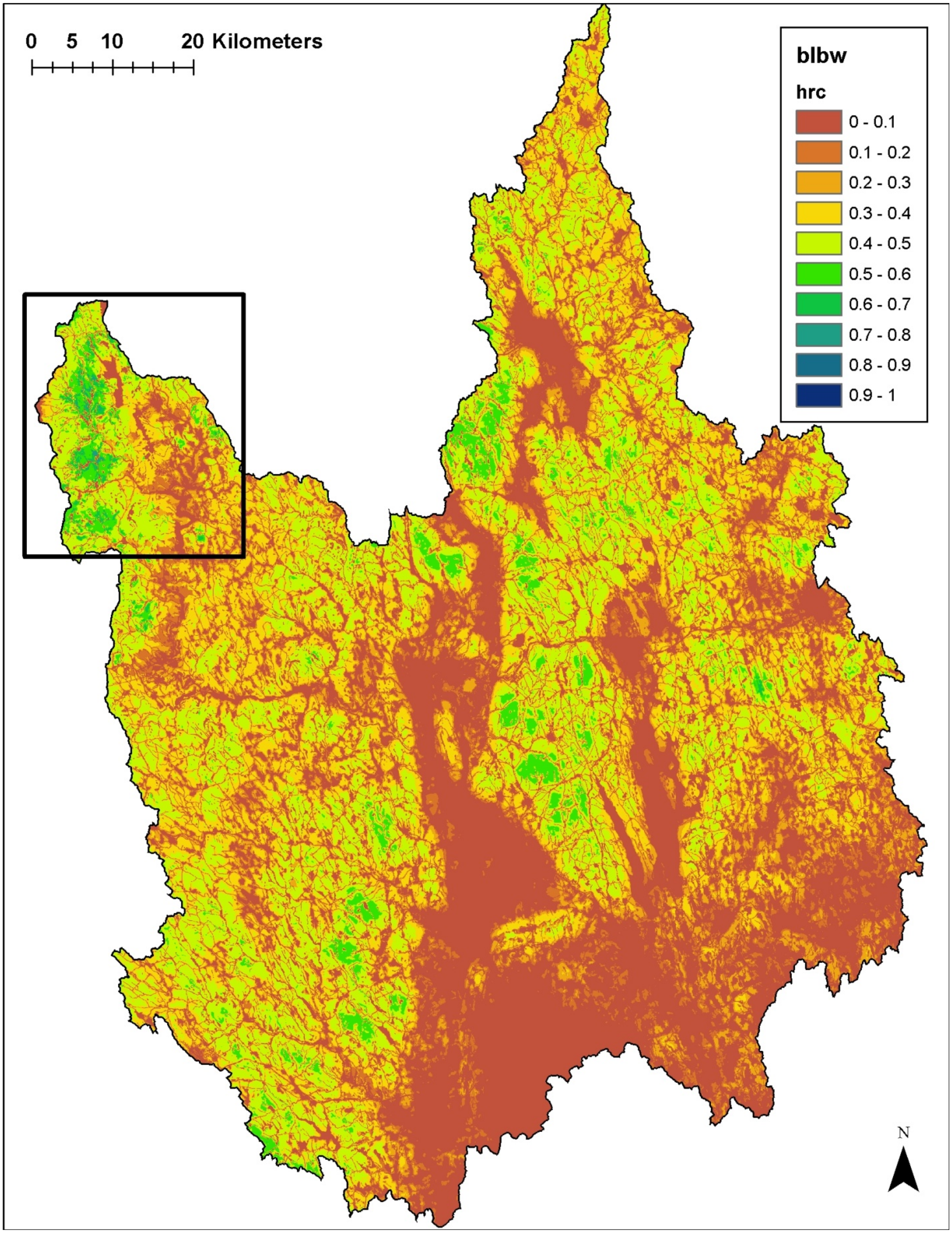



***Figure 11.*** *Home Range Capability (HRC) index for the blackburnian warbler in 2010 for the middle Connecticut River watershed study area.*

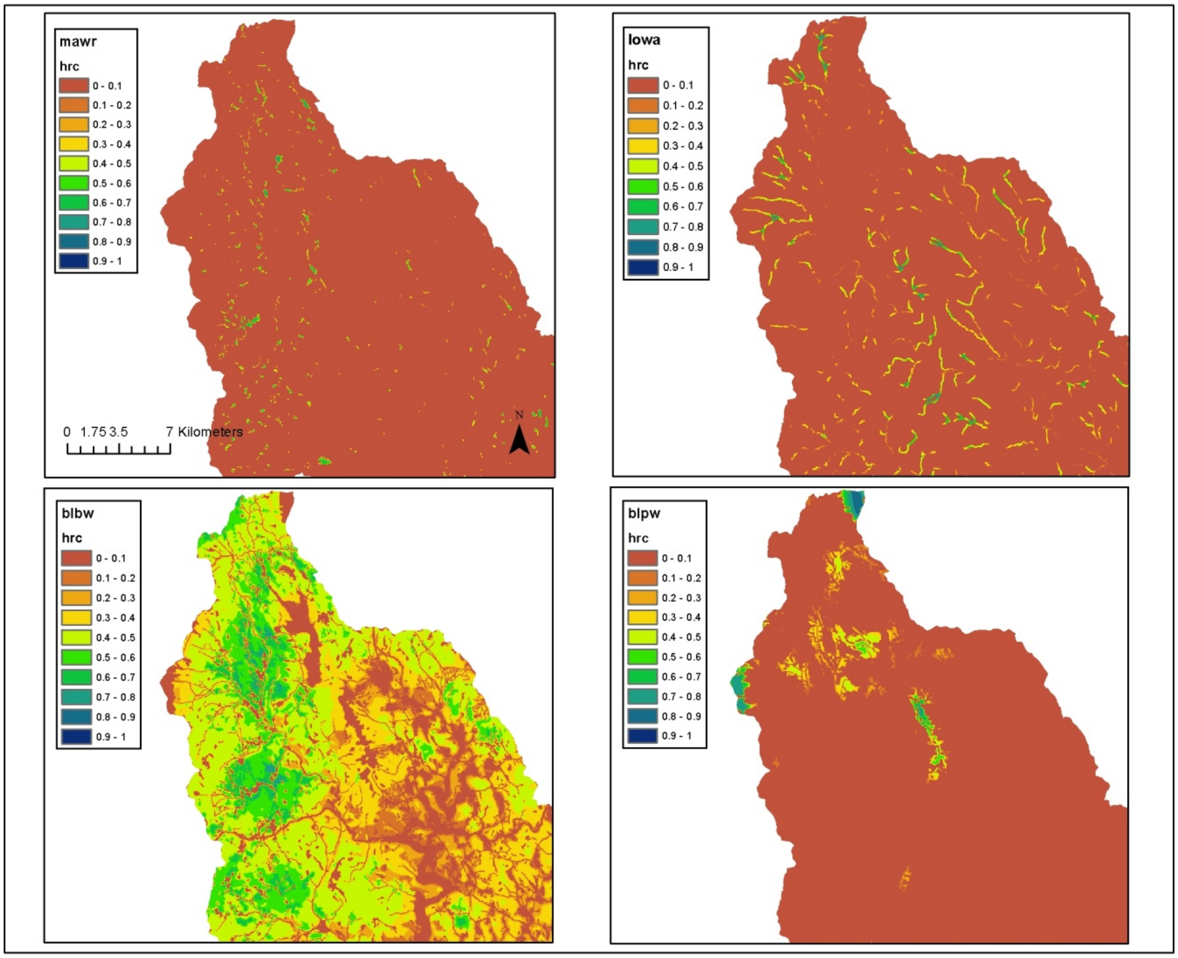



***Figure 12.*** *Home Range Capability (HRC) index for the marsh wren (mawr), blackburnian warbler (blbw), Louisiana waterthrush (lowa) and blackpoll warbler (blpw) in 2010 for a portion (the area depicted by the open box in* ***figure 11****) of the middle Connecticut River watershed study area.*

Because the *HRC* maps are not based on quantile scaling, we cannot simply threshold the *HRC* values to look at the top x% of the landscape. However, we can use a somewhat arbitrary cutoff of *HRC*≥0.5 to depict the likely distribution of the species based on habitat (**Fig. 13**). Importantly, it is not necessary that this binary map depict the actual distribution of the species, so long as it is correlated strongly with the species' distribution. Note, the binary map shown in **figure 13** is not included as a separate grid in this package because it is easily derived from the continuous *HRC* grid that is provided. This binary map is especially useful for its ease of comparison among species and/or among scenarios (see below). For example, it is clear from **figure 13** that "good" blackburnian habitat (i.e., *HRC*≥0.5) is rather uncommon and patchily distributed throughout the middle Connecticut River watershed study area.

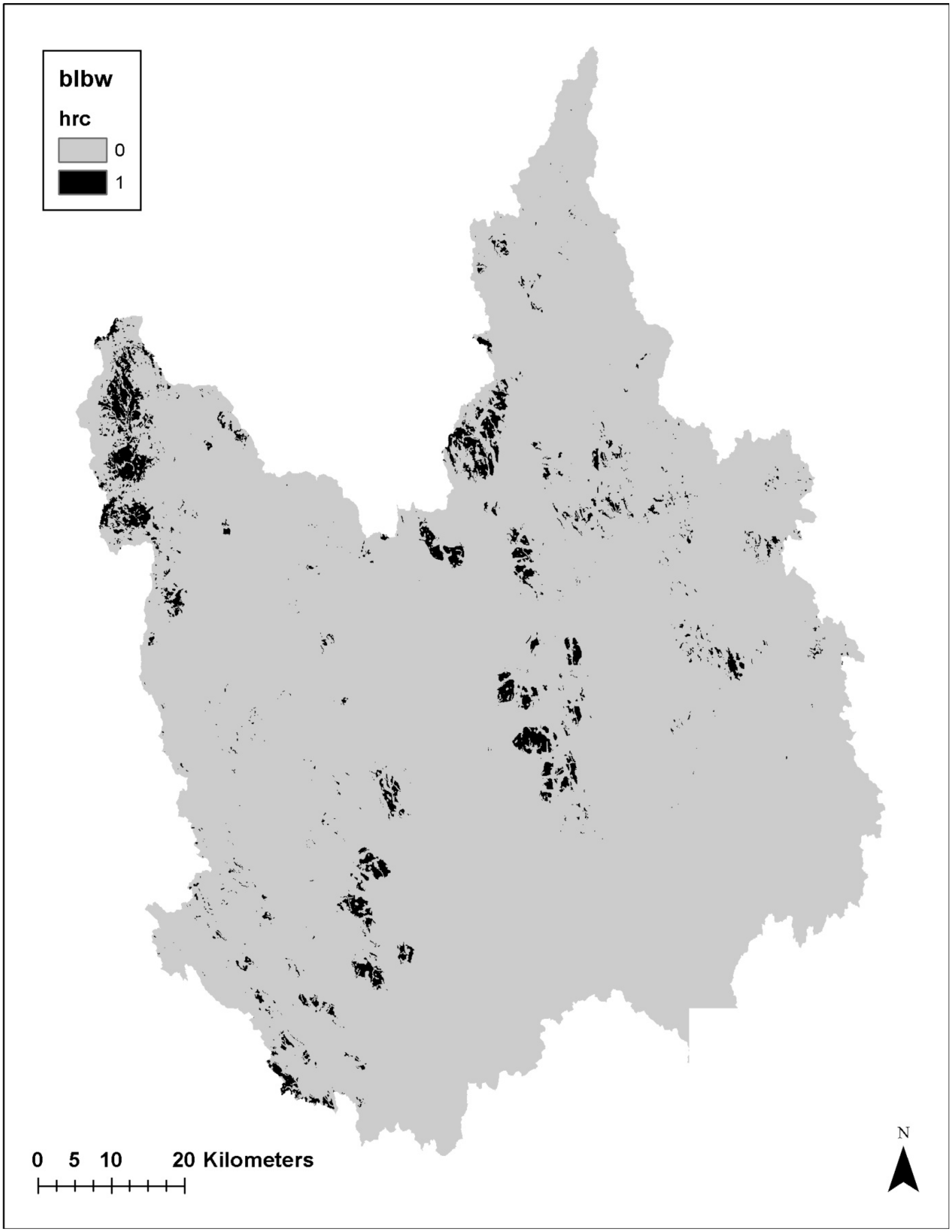



***Figure 13.*** *Home Range Capability (HRC) index for the blackburnian warbler in 2010 for the middle Connecticut River watershed study area, thresholded to show areas of high (HRC≥0.5) versus low (HRC<0.5) habitat capability.*

**(2) *Climate Niche Envelope [Grid]*** -- *CNE* is an estimate of the area containing suitable climate for a species based on its known current distribution. Specifically, it is statistical prediction of the area that is expected to encompass 95-99% of the species' occurrences. *CNE* is a binary map depicting 0 where the climate is predicted to be unsuitable and 1 where the climate is predicted to be suitable. In contrast to *HRC*, *CNE* is a function of the climate at the focal cell and not the area surrounding the focal cell; although given the coarse spatial resolution of the climate data (effectively 800 m), there is a very high degree of spatial autocorrelation in the *CNE*.

**Figure 14** depicts an example of the *CNE* maps in 2010 for a suite of representative species for the middle Connecticut River watershed study area. In this case, the *CNE* for the Louisiana waterthrush (lowa) encompasses the entire study area, and thus the species' distribution is not predicted to be limited by climate -- at least within this study area. In contrast, the *CNE* for the blackpoll warbler is limited largely to the northwestern portion of the study area. Clearly, this species is at the southern limit of its distribution in this study area, and thus we would expect climate to play a significant role in limiting the species' distribution within the study area.

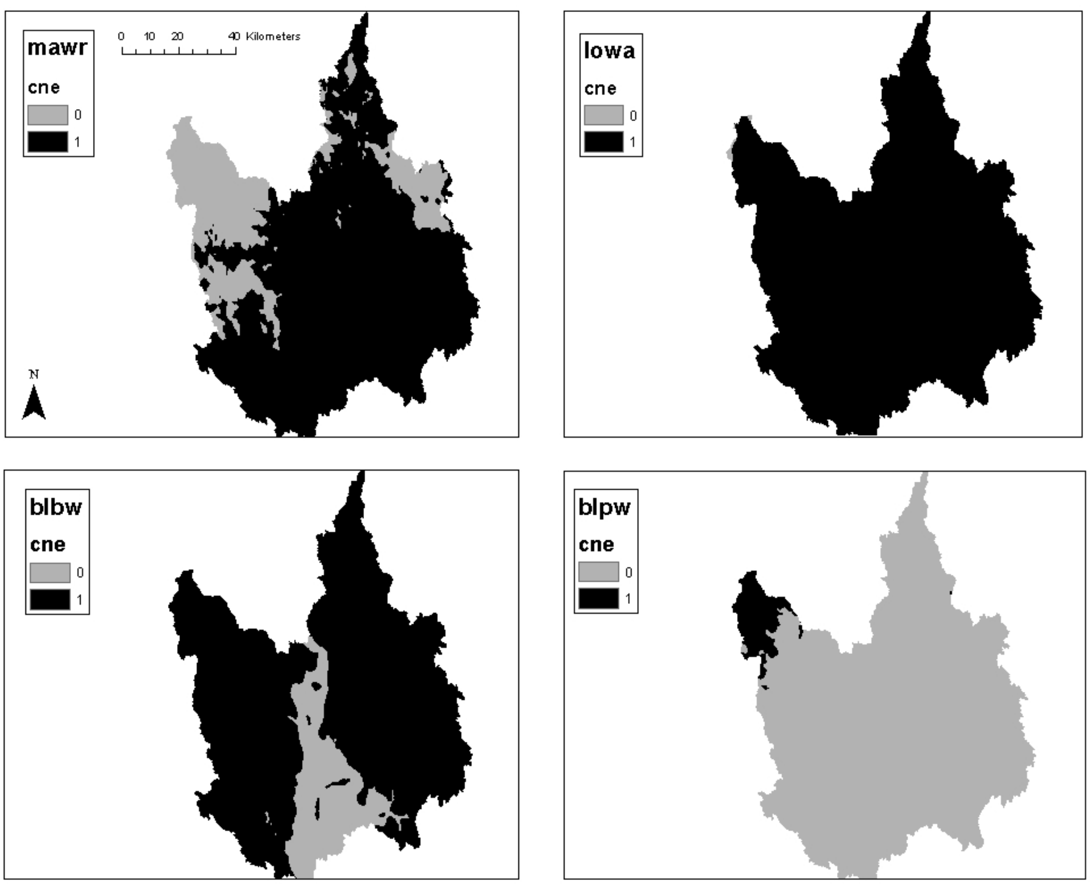



***Figure 14.*** *Climate Niche Envelope (CNE) for the marsh wren (mawr), blackburnian warbler (blbw), Louisiana waterthrush (lowa) and blackpoll warbler (blpw) in 2010 for the middle Connecticut River watershed study area.*

***(3) Current Optimal Area [Grid]*** -- *COA* is simply the intersection of the species' binary *HRC* map (*HRC*≥0.5) in 2010, binary *CNE* map in 2010, and published range map. *COA* is essentially our best estimate of the species' current distribution. Note, because the *HRC* threshold of 0.5 is somewhat arbitrary, the *COA* map is also somewhat arbitrary. Importantly, it is not necessary (or even possible) that the *COA* map depict the species' true distribution, so long as it is correlated strongly with the species' actual distribution, which we verify during the development and assessment of each species' model. This binary map is especially useful as a baseline for calculating a number of metrics associated with our zones of uncertainty, which we will discuss in the next section.

**Figure 15** depicts an example of the *COA* maps (which are always for 2010) for a suite of representative species for the middle Connecticut River watershed study area. Note, the *COA* map is merely the binary *HRC* map (**Fig. 13**) restricted to the *CNE* (**Fig. 14**), and in some cases the species' published range further restricts the *COA*, but this is not the case here in any of the examples shown. Note, the marsh wren has capable habitat (*HRC*≥0.5) in the area shown (**Fig. 12**), but it is outside the species' 2010 *CNE* (**Fig. 14**), thus nothing in the area shown is considered *COA* (**Fig. 15**). The blackpoll warbler has capable habitat (*HRC*≥0.5) in the area shown (**Fig. 12**) that extends beyond its 2010 *CNE* (**Fig. 14**), thus its *COA* is constrained by the *CNE* (**Fig. 15**).

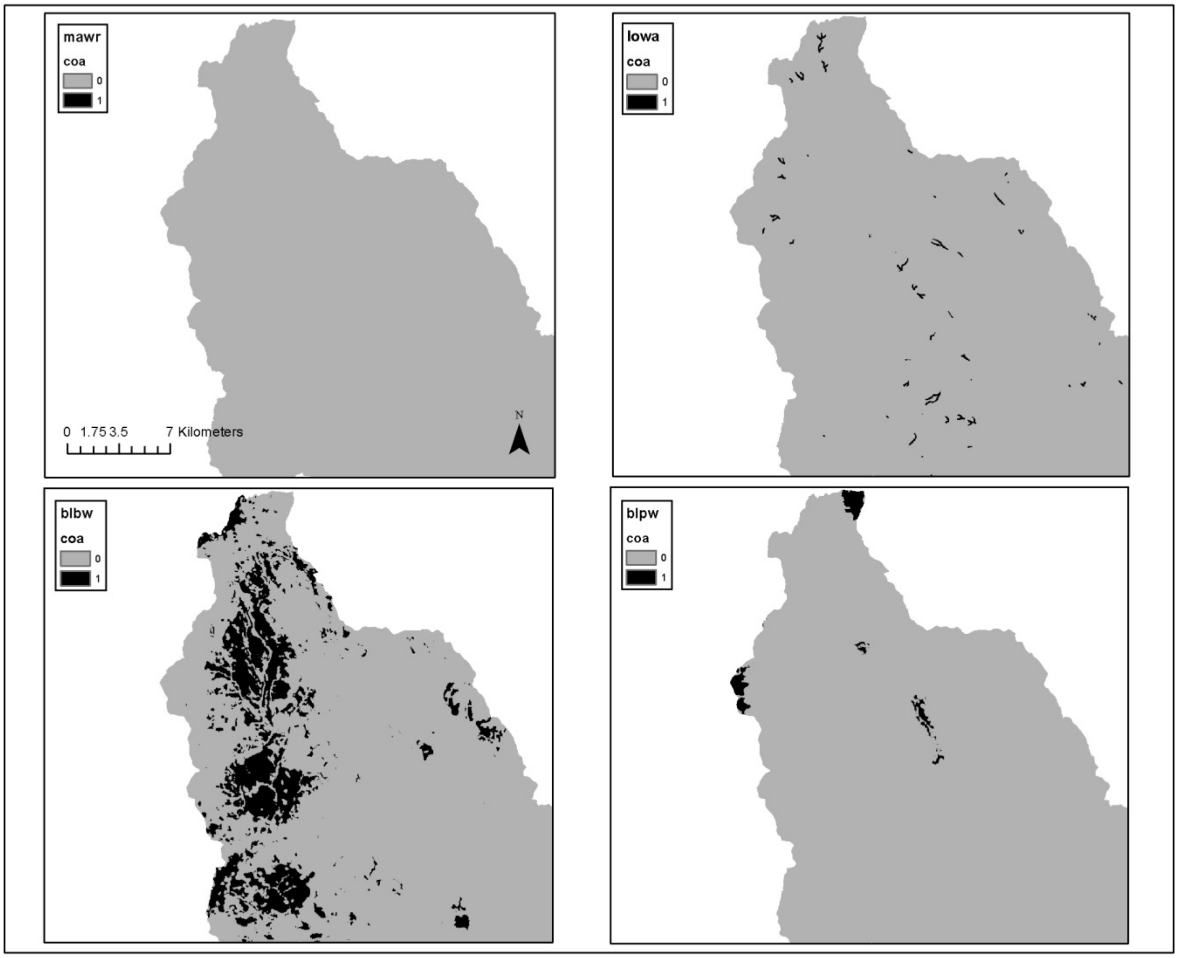



***Figure 15.*** *Current Optimal Area (COA) for the marsh wren (mawr), blackburnian warbler (blbw), Louisiana waterthrush (lowa) and blackpoll warbler (blpw) in 2010 for a portion (the area depicted by the open box in **figure 11**) of the middle Connecticut River watershed study area.*

### 3.3.2. Future landscape condition

The species' results in 2030 and 2080 represent a fine-filter spatial assessment of the future landscape condition for a 20-year forecast (2030) and 70-year forecast (2080), respectively, in light of predicted landscape changes driven by climate change, urban growth and vegetation disturbance and succession. Like the coarse-filter results, because of the uncertainty in the landscape change drivers, these results have much greater uncertainty than those based on the current (2010) species' climate-habitat assessment. Thus, as with the coarse filter, these results should be used with caution for conservation planning, management and restoration in combination with the more certain current species' climate-habitat results.

The results of the future species' climate-habitat assessment are in the form of grids (or maps) representing habitat capability, climate suitability and zones of uncertainty in the predicted future distribution of each species along with a suite of non-spatial summary statistics provided in tabular and graphical form. Specifically, we included five different grids representing *Home Range Capability* (HRC), *Climate Niche Envelope* (CNE) and three different zones of uncertainty: Zone of Persistence (PERSIST), Zone of Contraction (CONTRACT), and Zone of Expansion (EXPAND), for each species in 2030 and 2080, along with a suite of non-spatial summary tables and figures in the following package:

- midconn_species_future.zip

**(1) *Home Range Capability [Grid]*** -- *HRC* is defined as above, but here it is computed for the landscape condition in 2030 or 2080. An important distinction between the *HRC* grid in 2010 and the *HRC* grid in 2030 or 2080 distributed here is that the future *HRC* represents the mean across the nine uncertainty simulations. Recall that each uncertainty simulation results in a unique landscape change projection and a corresponding ecological integrity assessment for each timestep. Thus, the *HRC* grid in 2030 (or 2080) in any one of the uncertainty simulations is a merely a stochastic realization of the future landscape condition. Although the variation in *HRC* across simulations may be of some interest, it can be challenging to interpret, so we opted for simplicity sake to distribute just the mean across simulations, similar to *IEI*.

**Figure 16** depicts an example of the *HRC* map in 2010 and the mean *HRC* in 2080 for the ovenbird warbler for a portion of the middle Connecticut River watershed study area. Note the change in *HRC* over time; in this example it reveals a mild decreasing quality of habitat owing principally to development, but this is balanced against a slightly increasing quality of habitat due to a shifting seral-stage distribution to older forest age classes. Of course, if natural and anthropogenic disturbances (e.g., fires, timber harvest) had caused a shift to younger stand ages, then we would have observed a more dramatic decrease in *HRC* over time for this species. Much depends on the vegetation disturbance regime and its effects on the seral-stage distribution.

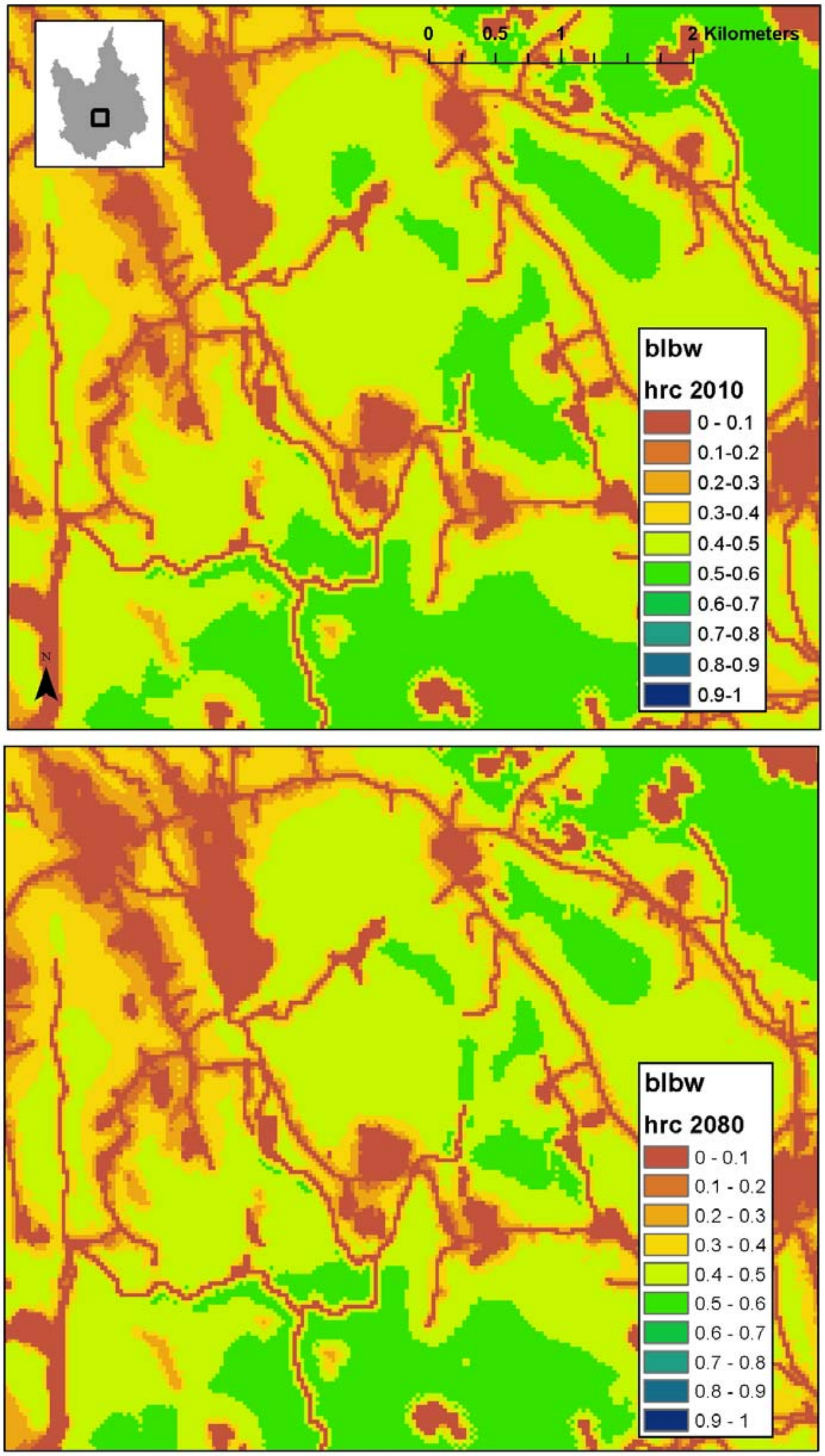



***Figure 16.*** *Homerange Capability (HRC) map in 2010 paired with the mean HRC in 2080 for the blackburnian warlber for a portion of the middle Connecticut River watershed study area.*

**(2) *Climate Niche Envelope [Grid]*** -- *CNE* is defined as above, but here it is computed for the climate conditions in 2030 or 2080. Like *HRC* above, the *CNE* for 2030 and 2080 is the mean across uncertainty simulations, only here there are only three uncertainty simulations (rather than nine) based on the three different SRES climate change scenarios we considered. Note, in the LCAD model, we treated each SRES climate scenario as a deterministic process; i.e., we did not account for stochastic variation within a particular SRES scenario. We incorporated uncertainty in climate solely through implementation of different SRES scenarios. This was a practical constraint given the computational costs of running the model many times to capture the full range of climate uncertainty.

**Figure 17** depicts an example of the *CNE* map in 2010 and the mean *CNE* in 2080 across the three SRES climate scenarios for the blackburnian warbler for the middle Connecticut River watershed study area. Note the change in *CNE* over time and the differences among the SRES scenarios. Specifically, the species' *CNE* is dramatically reduced over the 70-year period regardless of SRES scenario. The northwestern-most portion of the study area is in the 2080 *CNE* under all three SRES scenarios (i.e., mean *CNE*=1), and thus we have the most confidence in this area having suitable climate in 2080 given our uncertainty in climate change. Conversely, the areas depicted as having a mean of zero in 2080 are the areas where we have the most confidence in them NOT having suitable climate in 2080. And the areas with 0.33 and 0.67 mean *CNE* values in 2080 are intermediate in this respect.

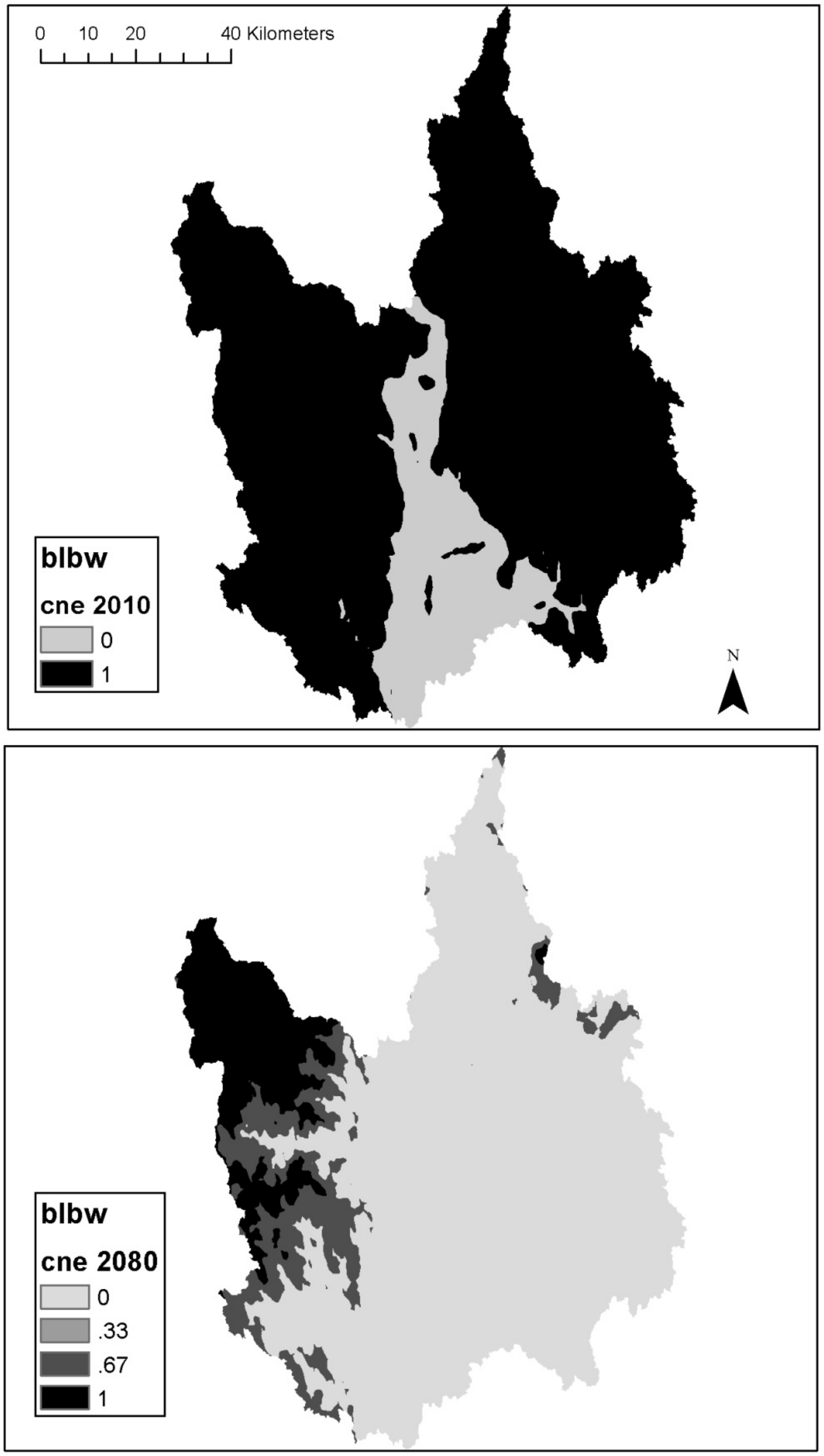



***Figure 17.*** *Climate Niche Envelope (CNE) in 2010 and the mean CNE in 2080 across the three SRES climate scenarios for the blackburnian warbler for the middle Connecticut River watershed study area.*

In addition to the habitat and climate capability maps above, we also use the species' binary HRC map (>0.5) and binary *CNE* map in relation to the species' *COA* map (also binary) to further address our uncertainty in the role of climate in limiting a species' future distribution. Specifically, by comparing the species *COA* to its predicted future distribution based on future habitat capability and climate suitability, we create three zones of uncertainty in the species' predicted future distribution (that also provide the basis for deriving non-spatial indices discussed below), as follows:

**(3)** ***Zone of Persistence [Grid]*** -- *PERSIST* is the portion of the species' *COA* that is still predicted to be habitat in the future (*HRC*≥0.5) and where the climate is still predicted to be suitable (*CNE*=1). In other words, this is the area currently predicted to be occupied that is still predicted to have suitable habitat and climate in a future timestep. This is the area where we have the highest confidence in the species' predicted future occurrence. Note, this zone (and the corresponding non-spatial index, see below) does not account for potential habitat gain or expansion of suitable climate; rather, it focuses on where we have the highest likelihood of the species being present in the future -- places where the species is found today and that maintain habitat and climate suitability over time. Similar to *HRC* above, *PERSIST* for 2030 and 2080 is the mean across the nine uncertainty simulations.

**Figure 18** depicts an example of the *COA* in 2010 and *PERSIST* in 2080 for the blackburnian warbler for the middle Connecticut River watershed study area. Note that non-zero values in *PERSIST* are restricted to the *COA* in 2010, and represent our most conservative estimate of where a species is likely to occur in the future. The areas with the highest probability of persistence are the areas where the species most likely occurs today and where it is most likely to occur in the future given our uncertainty in climate and habitat changes. Based on our landscape change projections, the blackburnian warbler is most likely to persist only in the northwestern portion of the watershed by 2080 (depicted by the light green polygons in **figure 18**), assuming of course that it contracts its range in response to the expected climate changes.

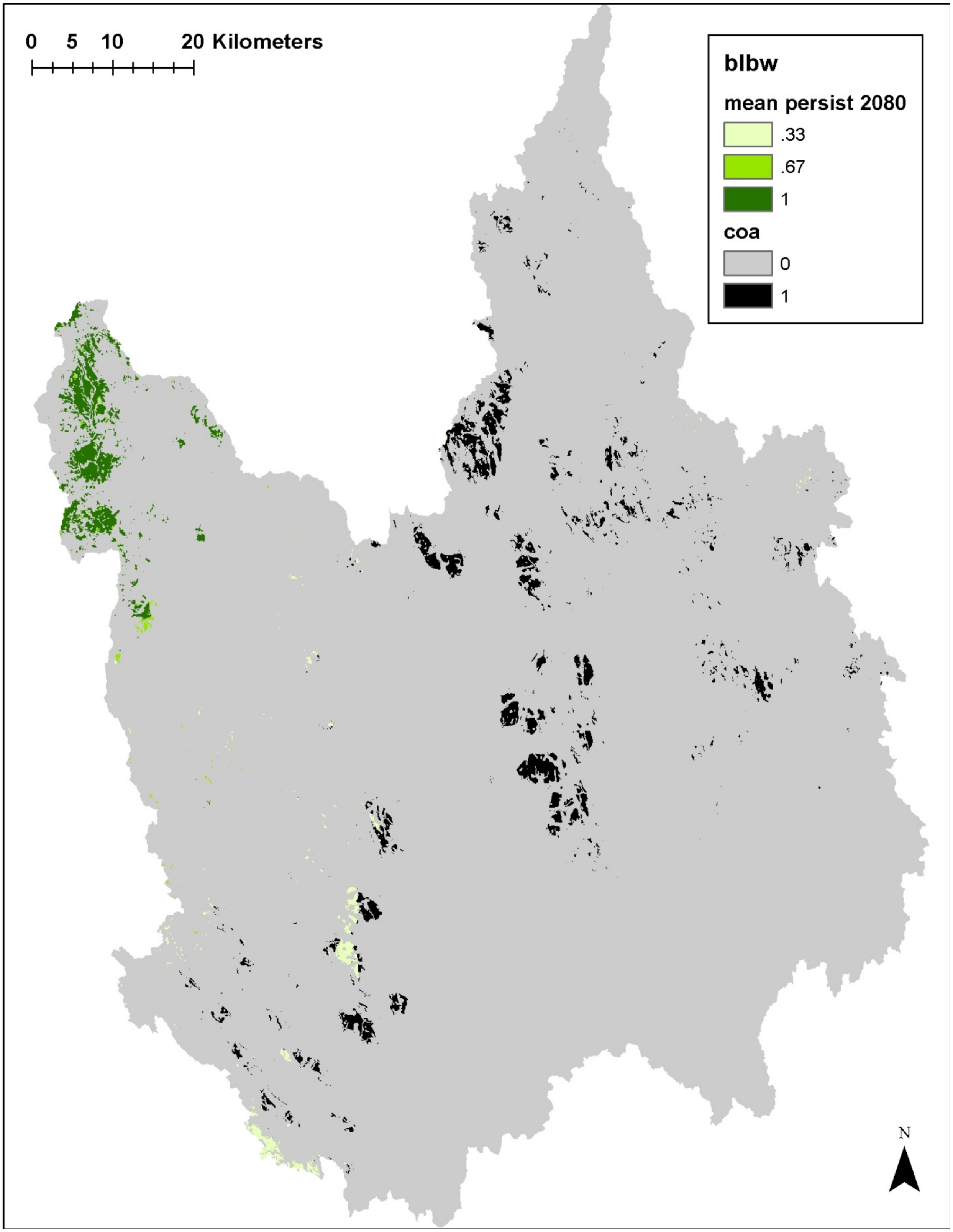



***Figure 18.*** *Probability of persistence (PERSIST) of the blackburnian warbler in 2080 in the middle Connecticut River watershed study area within the Current Optimal Area (COA).*

**(4) *Zone of Contraction [Grid]*** -- *CONTRACT* is the portion of the species' *COA* that is no longer predicted to be habitat (*HRC*<0.5) or suitable climate (*CNE*=0) in the future. In other words, this is the area currently predicted to be optimal that is no longer predicted to have suitable habitat or climate in a future timestep; i.e., the compliment of *PERSIST*. In this zone we have lower confidence in the species' predicted future occurrence. Whether or not the species occupies this zone in the future will depend on how quickly, if at all, it is able to respond to either habitat loss or climate change. If the species' exhibits very long (>70 years) time lags in population response to habitat loss or climate change, or is insensitive to climate change (i.e., climate is not limiting the species' distribution), then it is likely to persist in this zone. On the other hand, if the species' exhibits immediate response to habitat loss or climate change, then it is unlikely to persist in this zone. Given that any particular species is likely to exhibit a response somewhere in between these two extremes, we place relatively lower confidence on its occurrence in this zone compared to the zone of persistence. Note, like the zone of persistence, this zone (and the corresponding non-spatial index, see below) does not account for potential habitat gain or expansion of suitable climate; rather, it focuses on where we have a moderate likelihood of the species being present in the future -- places where it is found today but that experience loss of habitat and/or climate suitability over time. This zone represents the area of potential contraction in the species' future distribution and it is the compliment of the zone of persistence (i.e., *PERSIST* + *CONTRACT* = *COA*). Similar to above, *CONTRACT* for 2030 and 2080 is the mean across the nine uncertainty simulations.

**Figure 19** depicts an example of the *COA* in 2010 and *CONTRACT* in 2080 for the blackburnian warbler for the middle Connecticut River watershed study area. Note that non-zero values in *CONTRACT* are restricted to the *COA* in 2010, and represent a liberal estimate of the potential impact of habitat loss and climate change. Moreover, note that *CONTRACT* is the spatial compliment of *PERSIST*, since the *COA* is divided into the portion that persists and the portion that is lost to habitat loss or climate change. The areas with the highest probability of contraction are the areas where the species most likely occurs today and where it is most likely to be lost from in the future given our uncertainty in climate change. Consequently, the blackburnian warbler is most likely to exhibit range contraction throughout most of the watershed with only a moderate likelihood of range contraction in the northwestern-most portion of the watershed.

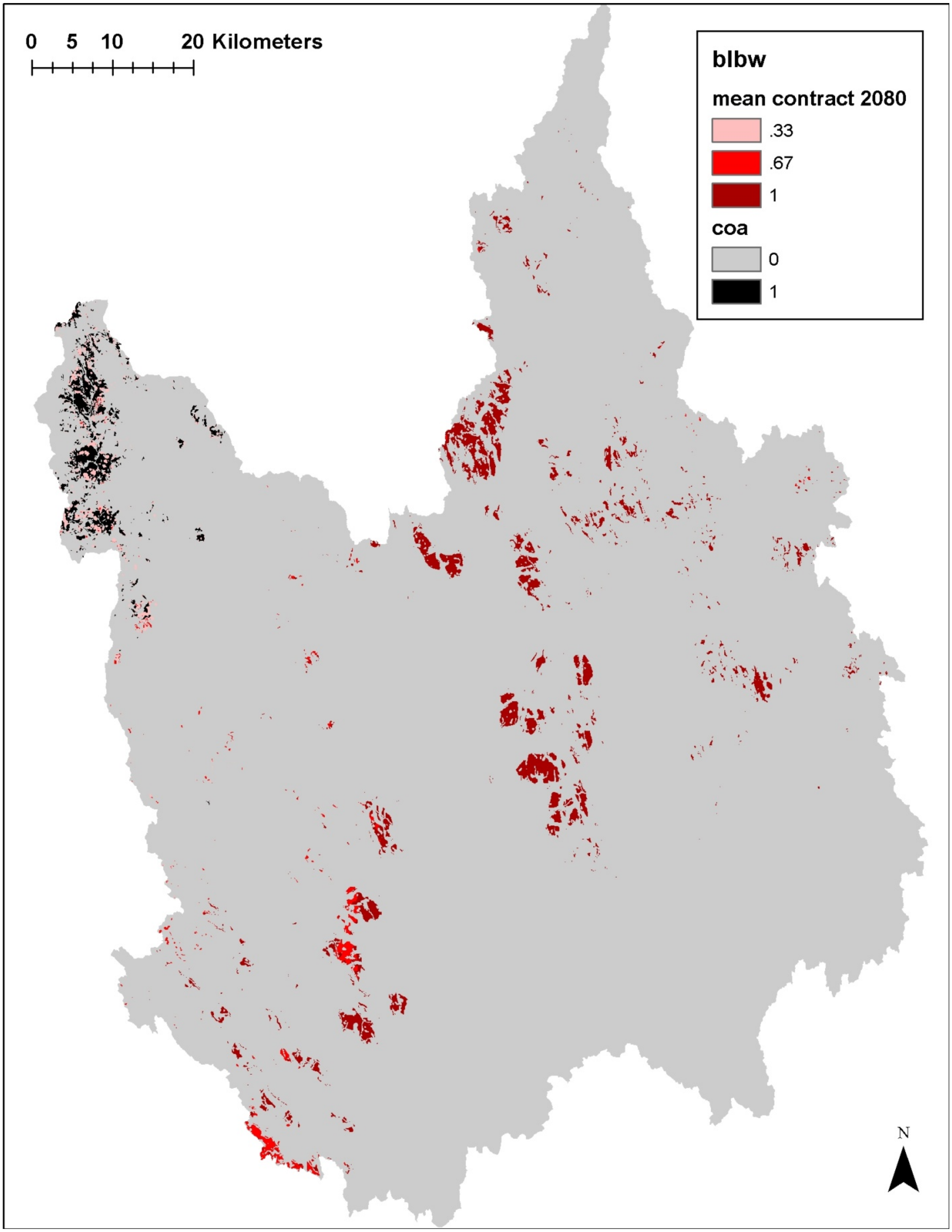



***Figure 19.*** *Probability of contraction (CONTRACT) of the blackburnian warbler in 2080 in the middle Connecticut River watershed study area within the Current Optimal Area (COA).*

**(5) *Zone of Expansion [Grid]*** -- *EXPAND* is the area outside of the species' *COA* that is predicted to be habitat (*HRC*≥0.5) and suitable climate (*CNE*=1) in the future. In other words, this is the area where future habitat and climate is predicted to be suitable but occurs outside the species' COA. In this zone we have the lowest confidence in the species' predicted future occurrence, because occupancy of this zone depends on the species' colonizing new sites. Whether or not the species occupies this zone in the future will depend on how quickly, if at all, it is able to respond to either habitat gain or climate change, but perhaps more importantly on its ability to colonize new sites, which is largely a function of the species' vagility. Given the challenges associated with finding and colonizing new sites, we place our lowest confidence on the species' occurrence in this zone compared to the other two zones. Note, this zone (and the corresponding non-spatial index, see below) does not account for potential habitat loss; rather, it focuses on where there are opportunities for the species to expand its distribution in the future -- places outside its current distribution that become suitable habitat and climate over time. Similar to above, *EXPAND* for 2030 and 2080 is the mean across the nine uncertainty simulations.

**Figure 20** depicts an example of the *COA* in 2010 and *EXPAND* in 2080 for the wood thrush for the Kennebec River watershed study area in Maine. Note that non-zero values in *EXPAND* fall outside the *COA* in 2010, and represent a liberal estimate of the impact of climate change (i.e., under the assumption that a species will actually track suitable climate conditions). The areas with the highest probability of expansion are the areas where the species is most likely to expand its future range given our uncertainty in climate change. In **figure 20**, the areas in black depict the species' *COA*; the areas in blue depict areas of potential range expansion. Based on this model, the wood thrush appears to be a potential beneficiary of expected climate change, with its distribution expanding substantially in the Kennebec River watershed over the next 70 years.

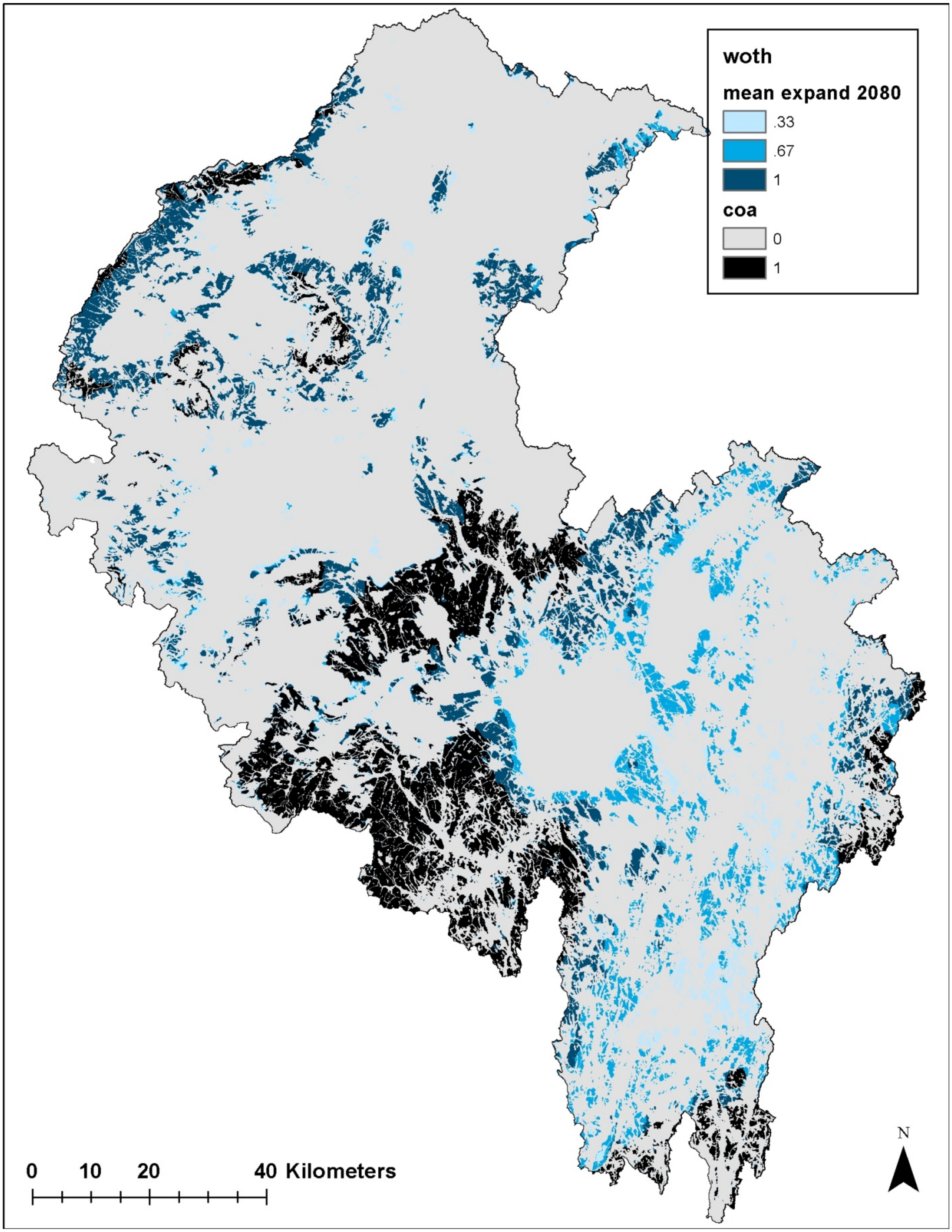



***Figure 20.*** *Probability of expansion (EXPAND) of the wood thrush in 2080 in the Kennebec River watershed study area outside the Current Optimal Area (COA).*

**(6) *Climate Niche Envelope area [Table]*** -- *CNE* can be summarized as the area (ha) of the envelope within the study area in any given year. Note, because *CNE* does not take into account habitat factors, it is not a particularly useful landscape capability index for a species, since we know habitat is critically important to a species and often limiting. However, *CNE* area does provide an index to the potential impact of climate changes on a species distribution. A decreasing *CNE* area is an indicator that climate may be increasingly acting as a stressor on the species and increasingly limiting the species' distribution.

**Table 2** depicts an example of the *CNE* area for six representative species in the middle Connecticut River watershed study area in 2010, 2030 and 2080. *CNE* for 2030 and 2080 represent the mean and range across the three uncertainty scenarios. Based on our analysis, the ovenbird and wood thrush are likely to experience major loss of suitable climate area over the next 70 years (95% and 35%, respectively), whereas the brown-headed nuthatch is likely to see roughly an 11% gain of suitable climate area. The wood thrush, for example, is on the southern edge of its range within the study area and the predicted temperature increase is likely to act as an increasing stressor on the species' distribution over time, resulting in a dramatic loss of suitable climate. Conversely, the brown-headed nuthatch is on the northern edge of its range within the study area and the same predicted climate change is likely to make the area more conducive to the species over time.

***Table 2****. Species' Climate Niche Envelope (CNE) area (ha) in the middle Connecticut River study area in 2010, 2030 and 2080 and the proportional change. CNE is the area predicted to contain suitable climate based on a model built from the species' known distribution in 2010, and ranges from 0 (no suitable climate) to the extent of the study (all suitable climate). Statistics reported for 2030 and 2080 are the mean and range across three climate uncertainty scenarios and the proportional change in area relative to the CNE in 2010.*

| | | 2010 | 2030 | | 2080 | |
|---|---|---|---|---|---|---|
| Species | Statistic | Area (ha) | Area (ha) | Change | Area (ha) | Change |
| blbw | mean | 722,737 | 552,261 | -0.24 | 121,043 | -0.83 |
| | min | | 512,409 | -0.29 | 67,875 | -0.91 |
| | max | | 574,962 | -0.20 | 193,574 | -0.73 |
| blpw | mean | 40,288 | 34,976 | -0.13 | 5,065 | -0.87 |
| | min | | 33,799 | -0.16 | 1,012 | -0.97 |
| | max | | 35,800 | -0.11 | 11,364 | -0.72 |
| glin | mean | 857,855 | tbd | tbd | tbd | tbd |
| | min | | tbd | tbd | tbd | tbd |
| | max | | tbd | tbd | tbd | tbd |

| | | | | | | |
|---|---|---|---|---|---|---|
| lowa | mean | 856,489 | 856,880 | 0.00 | 857,278 | 0.00 |
| | min | | 856,495 | 0.00 | 856,800 | 0.00 |
| | max | | 857,157 | 0.00 | 857,594 | 0.00 |
| mawr | mean | 669,433 | 796,669 | 0.19 | 854,192 | 0.28 |
| | min | | 794,690 | 0.19 | 846,953 | 0.27 |
| | max | | 800,024 | 0.20 | 857,855 | 0.28 |
| nowa | mean | 857,855 | 844,746 | -0.02 | 496,667 | -0.42 |
| | min | | 835,602 | -0.03 | 275,520 | -0.68 |
| | max | | 850,424 | -0.01 | 714,119 | -0.17 |
| oven | mean | 857,855 | 857,753 | 0.00 | 818,462 | -0.05 |
| | min | | 857,692 | 0.00 | 763,955 | -0.11 |
| | max | | 857,855 | 0.00 | 856,600 | 0.00 |
| rsha | mean | 843,875 | 843,007 | 0.00 | 843,654 | 0.00 |
| | min | | 842,840 | 0.00 | 842,661 | 0.00 |
| | max | | 843,113 | 0.00 | 845,554 | 0.00 |
| woth | mean | 851,958 | 853,108 | 0.00 | 854,213 | 0.00 |
| | min | | 852,168 | 0.00 | 853,073 | 0.00 |
| | max | | 853,941 | 0.00 | 855,338 | 0.00 |

**(7)** ***Distribution of HRC values [Plot]*** -- One way to assess changes in landscape capability for each species over time is to plot the frequency distribution of *HRC* cell values. Here, the frequency distribution is given as a kernel density distribution, which is essentially a smoothed histogram in which the y-axis shows the relative probability of observing any particular value of *HRC*. We derive the kernel density distribution for the area defined by the species *CNE* in 2010, and this area is held constant over time to focus on changes in habitat capability independent of climate change. **Figure 21** depicts an example of the *HRC* distribution for the blackburnian warbler for the baseline (2010) and the years 2030 and 2080 for the middle Connecticut River watershed area. The 2010 curve depicts the current distribution of *HRC* values; the 2030 and 2080 curves depict the future distribution of habitat capability values including the average (solid line) and range (shaded envelope) across the uncertainty simulations. Note, each uncertainty simulation produces a unique distribution of *HRC* values for each future timestep. Here, we simply take the average and the range across simulations for the years 2030 and 2080. The shift in the curves from the current to the future timesteps is indicative of two things: 1) direct loss of habitat due to the footprint of development, and 2) change habitat quality due to the indirect effects of development and vegetation structure changes dues to disturbance and succession. Direct habitat loss is indicated by the increase in the probability of cells with *HRC*=0, since developed cells are assigned a zero habitat value. Changes in habitat quality is indicated by a shift in the curves over time. A shift to the left (towards lower values of *HRC*) is indicative of habitat degradation. A shift to the right (towards higher values of *HRC*) is indicative of habitat improvement, for example as might be caused by vegetation disturbances and succession shifting the seral-stage distribution in the species' favor. In addition, the range envelopes provide a means to judge whether the changes are "significant" given our uncertainty in future landscape changes. Specifically, if the envelope for a future timestep does not overlap the baseline curve, then it is an indication that the differences are "significant" and that we can have confidence that the predicted change in habitat capability is likely to be real.

***Figure 21.*** *Plot showing the Homerange Capability (HRC) distribution within the current Climate Niche Enveolope (CNE) area for 2010, 2030 and 2080 for blackburnian warbler in the middle Connecticut River watershed study area. Note, this figure is under development.*

**(8) *Landscape Capability indices [Table]*** -- Another way to assess changes in landscape capability for each species over time is via a non-spatial landscape capability index. *LC* is based on the <u>sum</u> of HRC across cells within a defined area, where the defined area varies depending on the assumptions we are willing to make regarding the species' response to climate change. It is important to note that *LC* is merely an index of population size based on habitat; it is not an estimate of actual population size or density, since the translation of habitat capability into population size depends on home range size and overlap, habitat occupancy rate and many other factors. Thus, an index of say 100 for two different species does not imply similar population sizes, only that the habitat conditions within the landscape are, on average, relatively similar for the two species. Consequently, *LC* is best interpreted as a species-specific index for comparison across land use scenarios (e.g., different landscapes under the same land use scenario, or the same landscape under different land use scenarios) or across landscape change scenarios (i.e., same landscape at different times under the same or different land use scenarios).

**Table 3** depicts an example of the *LC* index for nine representative species under three different assumptions regarding their response to climate change for the middle Connecticut River watershed study area, as follows:

- *Current* -- the current (baseline) *LC* index is equal to the sum of *HRC* values across cells in 2010 within the 2010 *CNE* of the species, expressed in hectares; it ranges from 0 (no habitat) to the study area extent in number of cells (when the entire study area is within the *CNE* and is all optimal habitat). For example, the blackburnian warbler has an *LC* index in 2010 of 184,281 ha. This can be interpreted as the equivalent of 184,281 ha of optimal habitat (*HRC*=1), even though it is actually comprised of a much larger area containing lower *HRC* values, because two hectares of 0.5 *HRC* equals one *LC* ha. In contrast, the blackpoll warbler has an LC index of only 943 ha.

- *None* -- under the assumption that the species' will exhibit no response to climate change, either due to very long (>70 years) time lags in population response or insensitivity to climate change, the *LC* index is defined as the proportional change in the species' *LC* index in the future within the 2010 *CNE* of the species. Specifically, the index is computed as the sum of future *HRC* values across cells within the 2010 *CNE* of the species, divided by the *LC* in 2010. In essence, climate change is disregarded in this scenario. If you are a climate change skeptic (i.e., don't believe climate change is real), or distrust the climate change models (i.e., don't trust the accuracy of the model results), then this scenario provides an estimate of the change in *LC* over time and ultimately provides a baseline for comparison with other land use scenarios. *LC* for 2030 and 2080 is the mean across the nine uncertainty simulations. Based on our analysis, for example, the blackburnian warbler (and most of the other species) is expected to experience a slight increase in *LC* over the next 70 years if they maintain their current distribution despite climate change. In other words, the habitat capability within their current *CNE* is expected to increase slightly owing to the shifting vegetation age distribution to older forest despite loss of some habitat to development. Of course, if natural and anthropogenic disturbances (e.g., fires, timber harvest) cause a shift in the seral-stage distribution to younger stand ages, then the combined effect of direct habitat loss to development and reduced habitat capability of younger forest stands would result in a decrease (rather than a decrease) in *LC* over time for this and other late-seral species. Much depends on the vegetation disturbance regime and its effects on the seral stage distribution.

- *Immediate range contraction* -- under the assumption that the species' will exhibit an immediate response to climate change through range contraction, due to a zero time lag in population response in areas where the climate is no longer suitable, but is incapable of quickly expanding its range to take advantage of newly suitable climate, at least within the 70-year projection, the *LC* index is defined as the proportional change in the species' *LC* index in the future within the intersection of the 2010 and future *CNE* of the species. Specifically, the index is computed as the sum of future *HRC* values across cells within the intersection of the 2010 and future *CNE* of the species, divided by the *LC* in 2010. In other words, anywhere within the species' 2010 *CNE* that no longer has suitable climate in the future, the *HRC* is set to zero. This assumption may be appropriate for species with extremely low vagility and for which climate actively limits the species distribution (e.g., many reptiles and amphibians). *LC* for 2030 and 2080 is the mean across the nine uncertainty simulations. Based on our analysis, for example, the blackburnian warbler is expected to experience a substantial decrease (~79%) in *LC* over the next 70 years within the portion of their *COA* that is likely to maintain suitable climate. In contrast, the red-shouldered hawk is expected to experience a minor increase (1%) in *LC* over the same period.

- *Immediate range shift* -- under the assumption that the species' will exhibit an immediate response to climate change through range contraction and/or expansion, the *LC* index is defined as the proportional change in the species' *LC* index in the future across cells within the future *CNE* of the species. Specifically, the index is computed as the sum of future *HRC* values across cells within the future *CNE* of the species, divided by the *LC* in 2010. In other words, in this scenario we are simply summarizing the *HRC* values within the species future *CNE*. This assumption may be appropriate for species with extremely high vagility, such as birds, and for which climate actively limits the species distribution. *LC* for 2030 and 2080 is the mean across the nine uncertainty simulations. Based on our analysis, for example, the marsh wren is expected to experience a moderate increase of 28% in *LC* over the next 70 years if the species' immediately shifts its distribution to exploit the expanded distribution of suitable climate.

Importantly, regardless of the assumption made about the species response to climate change, the proportional change in the *LC* index for 2030 and 2080 represents the mean and range across the nine uncertainty scenarios in the habitat capability of the landscape. Thus, under all three assumptions we are accounting for changes in habitat; climate is in essence treated as an "additive" effect. In all likelihood, none of the assumptions made here are likely to be correct; the truth is probably somewhere in between. However, the *LC* results under the three assumptions do represent benchmarks for comparison and may provide some insight into the potential relative role of habitat versus climate change on a species predicted distribution. For example, the blackburnian warbler has an *LC* index of 1.01 in 2080 under the assumption of no response to climate change ("none" in **Table 3**), indicating no habitat loss or degradation within its current distribution. However, its *LC* index is 0.21 under the assumption of immediate range contraction or range shift. Together, these results indicate that the most likely cause of the reduction in *LC* for this species is climate change and not habitat changes.

***Table 3***. *Species' Landscape Capability (LC) index in the middle Connecticut River study area in 2010 and the proportional change in LC in 2030 and 2080 under three different assumptions regarding the species' response to climate change (see text for details). LC in 2010 is equal to the Home Range Capability (HRC) index summed across cells within the species' Climate Niche Envelope (CNE) in 2010, expressed in hectares, and it ranges theoretically from 0 (no habitat) to the extent of the study area (the entire study area is within the CNE and is all optimal habitat). Statistics reported for 2030 and 2080 are the mean and range across nine uncertainty simulations.*

| | | | Species Response to Climate Change | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | None | | Immediate Range Contraction | | Immediate Range Shift | |
| Species | Statistic | 2010 (ha) | 2030 | 2080 | 2030 | 2080 | 2030 | 2080 |
| blbw | mean | 184,281 | 1.01 | 1.01 | 0.87 | 0.21 | 0.87 | 0.21 |
| | min | | 1.01 | 1.00 | 0.83 | 0.12 | 0.83 | 0.12 |
| | max | | 1.01 | 1.01 | 0.90 | 0.32 | 0.90 | 0.32 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| blpw | mean | 943 | 1.00 | 1.00 | 0.99 | 0.48 | 0.99 | 0.48 |
| | min | | 1.00 | 0.99 | 0.99 | 0.32 | 0.99 | 0.32 |
| | max | | 1.00 | 1.00 | 0.99 | 0.63 | 0.99 | 0.63 |
| glin | mean | 11,982 | 1.00 | 0.99 | tbd | tbd | tbd | tbd |
| | min | | 1.00 | 0.99 | tbd | tbd | tbd | tbd |
| | max | | 1.00 | 0.99 | tbd | tbd | tbd | tbd |
| lowa | mean | 16,651 | 1.00 | 0.99 | 1.00 | 0.99 | 1.00 | 0.99 |
| | min | | 1.00 | 0.99 | 1.00 | 0.99 | 1.00 | 0.99 |
| | max | | 1.00 | 0.99 | 1.00 | 0.99 | 1.00 | 0.99 |
| mawr | mean | 3,633 | 0.99 | 0.98 | 0.99 | 0.98 | 1.20 | 1.28 |
| | min | | 0.99 | 0.97 | 0.99 | 0.97 | 1.20 | 1.28 |
| | max | | 1.00 | 0.98 | 1.00 | 0.98 | 1.20 | 1.29 |
| nowa | mean | 14,734 | 1.00 | 1.00 | 0.99 | 0.54 | 0.99 | 0.54 |
| | min | | 1.00 | 0.99 | 0.98 | 0.31 | 0.98 | 0.31 |
| | max | | 1.00 | 1.00 | 1.00 | 0.77 | 1.00 | 0.77 |
| oven | mean | 424,205 | 1.01 | 1.00 | 1.01 | 0.98 | 1.01 | 0.98 |
| | min | | 1.01 | 1.00 | 1.01 | 0.94 | 1.01 | 0.94 |
| | max | | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 |
| rsha | mean | 182,978 | 1.02 | 1.01 | 1.02 | 1.01 | 1.02 | 1.01 |
| | min | | 1.02 | 1.00 | 1.02 | 1.00 | 1.02 | 1.00 |
| | max | | 1.02 | 1.02 | 1.02 | 1.01 | 1.02 | 1.01 |
| woth | mean | 398,441 | 1.00 | 0.99 | 1.00 | 0.99 | 1.00 | 0.99 |
| | min | | 1.00 | 0.98 | 1.00 | 0.98 | 1.00 | 0.99 |
| | max | | 1.00 | 0.99 | 1.00 | 0.99 | 1.00 | 1.00 |

**(9)** ***Zones of uncertainty indices [Table]*** -- Another way to assess changes in landscape capability for each species over time given uncertainty in how species will respond to climate change is by intersecting the species' future *CNE* and binary habitat capability maps with the species' *COA* (defined previously) map. The intersection of these maps creates three distinct zones that can be mapped (as described above) and summarized with corresponding non-spatial indices, as follows:

- *Index of Persistence* (*PERSIST*) -- is equal to the area of the zone of persistence (defined above) as a proportion of *COA* and represents the species' potential vulnerability to loss of both suitable habitat and climate; it is bounded 0-1 and increases with the likelihood that the species' COA will continue to have suitable habitat and climate in the future. *PERSIST* for 2030 and 2080 is the mean across the nine uncertainty simulations.

- *Index of Contraction (CONTRACT)* -- is equal to the area of the zone of contraction (defined above) as a proportion of *COA* and is simply the compliment of *PERSIST*; consequently, it is also bounded 0-1, but increases as the future habitat or climate increasingly becomes unsuitable within the species' *COA*. *CONTRACT* for 2030 and 2080 is the mean across the nine uncertainty simulations.

- *Index of Expansion (EXPAND)* --is equal to the area of the zone of expansion (defined above) as a proportion of COA and represents the species' potential opportunity to capitalize on habitat gains and/or areas of newly suitable climate; it is bounded zero on the lower end and is unbounded on the upper end and increases as the future habitat and climate increasingly become suitable outside the species' COA. *EXPAND* for 2030 and 2080 is the mean across the nine uncertainty simulations.

**Table 4** depicts an example of the indices derived from the zones of uncertainty for nine representative species in the middle Connecticut River watershed study area in 2030 and 2080. The indices for 2030 and 2080 represent the mean and range across the nine uncertainty scenarios. Based on our analysis, for example, the blackburnian warbler is expected to experience a 68% decrease in its distribution based on where it is most likely to persist (i.e., Persist:2080=0.32); i.e., where we have the greatest confidence in its future distribution given climate and habitat changes. However, if the species is able to rapidly expand its distribution to take advantage of newly suitable climate areas in the future, it might be able to exploit an additional area equal to 9% of its current distribution (Expand:2080=0.09). Similarly, the marsh wren could experience a 30% increase in the extent of suitable habitat if it is able to rapidly expand its range in response to shifting distribution of suitable climate.

***Table 4***. *Species Current Optimal Area (COA)(ha) in 2010 and the Index of Persistence (PERSIST), Index of Contraction (CONTRACT) and Index of Expansion (EXPAND) in the middle Connecticut River study area in 2030 and 2080 (see text for details). Statistics reported for 2030 and 2080 are the mean and range across nine uncertainty simulations.*

| | | | Persist | | Contract | | Expand | |
|---|---|---|---|---|---|---|---|---|
| Species | Statistic | COA (ha) | 2030 | 2080 | 2030 | 2080 | 2030 | 2080 |
| blbw | mean | 27,425 | 0.91 | 0.32 | 0.09 | 0.68 | 0.19 | 0.09 |
| | min | | 0.87 | 0.28 | 0.07 | 0.62 | 0.18 | 0.07 |
| | max | | 0.93 | 0.38 | 0.13 | 0.72 | 0.20 | 0.11 |
| blpw | mean | 560 | 1.00 | 0.86 | 0.00 | 0.14 | 0.00 | 0.00 |
| | min | | 1.00 | 0.65 | 0.00 | 0.00 | 0.00 | 0.00 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | max | | 1.00 | 1.00 | 0.00 | 0.35 | 0.00 | 0.00 |
| glin | mean | 1,474 | tbd | tbd | tbd | tbd | tbd | tbd |
| | min | | tbd | tbd | tbd | tbd | tbd | tbd |
| | max | | tbd | tbd | tbd | tbd | tbd | tbd |
| lowa | mean | 6,347 | 0.99 | 0.97 | 0.01 | 0.03 | 0.01 | 0.01 |
| | min | | 0.99 | 0.96 | 0.01 | 0.02 | 0.01 | 0.01 |
| | max | | 0.99 | 0.98 | 0.01 | 0.04 | 0.01 | 0.01 |
| mawr | mean | 2,531 | 0.99 | 0.97 | 0.01 | 0.03 | 0.20 | 0.30 |
| | min | | 0.99 | 0.96 | 0.00 | 0.02 | 0.20 | 0.28 |
| | max | | 1.00 | 0.98 | 0.01 | 0.04 | 0.20 | 0.30 |
| nowa | mean | 4,982 | 0.99 | 0.56 | 0.01 | 0.44 | 0.01 | 0.01 |
| | min | | 0.99 | 0.35 | 0.01 | 0.25 | 0.01 | 0.01 |
| | max | | 0.99 | 0.75 | 0.01 | 0.65 | 0.01 | 0.01 |
| oven | mean | 483,010 | 0.99 | 0.96 | 0.01 | 0.04 | 0.02 | 0.02 |
| | min | | 0.99 | 0.93 | 0.00 | 0.01 | 0.02 | 0.02 |
| | max | | 1.00 | 0.99 | 0.01 | 0.07 | 0.02 | 0.02 |
| rsha | mean | 48,940 | 0.98 | 0.97 | 0.02 | 0.03 | 0.11 | 0.12 |
| | min | | 0.98 | 0.96 | 0.01 | 0.02 | 0.10 | 0.11 |
| | max | | 0.99 | 0.98 | 0.02 | 0.04 | 0.11 | 0.14 |
| woth | mean | 433,950 | 0.99 | 0.98 | 0.01 | 0.02 | 0.01 | 0.02 |
| | min | | 0.99 | 0.98 | 0.01 | 0.02 | 0.01 | 0.01 |
| | max | | 0.99 | 0.98 | 0.01 | 0.02 | 0.01 | 0.02 |

# 4. Comparison of the Coarse- and Fine-Filter Ecological Assessments

One of the objectives of phase 1 was to assess the nature and magnitude of differences and similarities between areas identified as important habitat for the representative species (fine filter) and areas identified as having high ecological integrity (coarse filter) within the pilot watersheds, and to describe the implications for strategic habitat conservation planning and make recommendations for effectively combining fine- and coarse-filtered approaches to habitat conservation. Here, we provide a brief summary of our approach and preliminary findings; a detailed description of our approach and results is provided elsewhere (NALCC_documentation_filters.pdf).

## *4.1. Approach*

Briefly, all analyses were conducted on each of the pilot study areas separately with two sets of planning units; intact roadless blocks and subdivided roadless blocks with a maximum size of 300 ha. **Figure 22** is an example of the intact planning units for the middle Connecticut River watershed area.

We summarized the conservation value of each planning unit by summing the square of the *Index of Ecological Integrity* (*IEI*) across cells for each ecological system (coarse filter) and summing the square of the *Homerange Capability Index* (*HRC*) in all cells within each species' current climate niche envelope. Here, each ecological system was treated as a separate conservation feature for the coarse filter analysis and each species was treated as a separate conservation feature for the fine filter analysis.

We used Marxan version 2.43 (Game & Grantham 2008), a decision support tool for reserve system design, to generate 1,000 alternative reserve network solutions using the adaptive simulated annealing algorithm, with coarse-filter, fine-filter, and combined coarse- and fine-filter input data (from above). We then compared the distributions of proportional area overlap of selected planning units, both within coarse- and fine-filter alternative solution sets and between them, to assess the level of intra-scenario versus inter-scenario redundancy/complementarity of the two reserve design approaches.

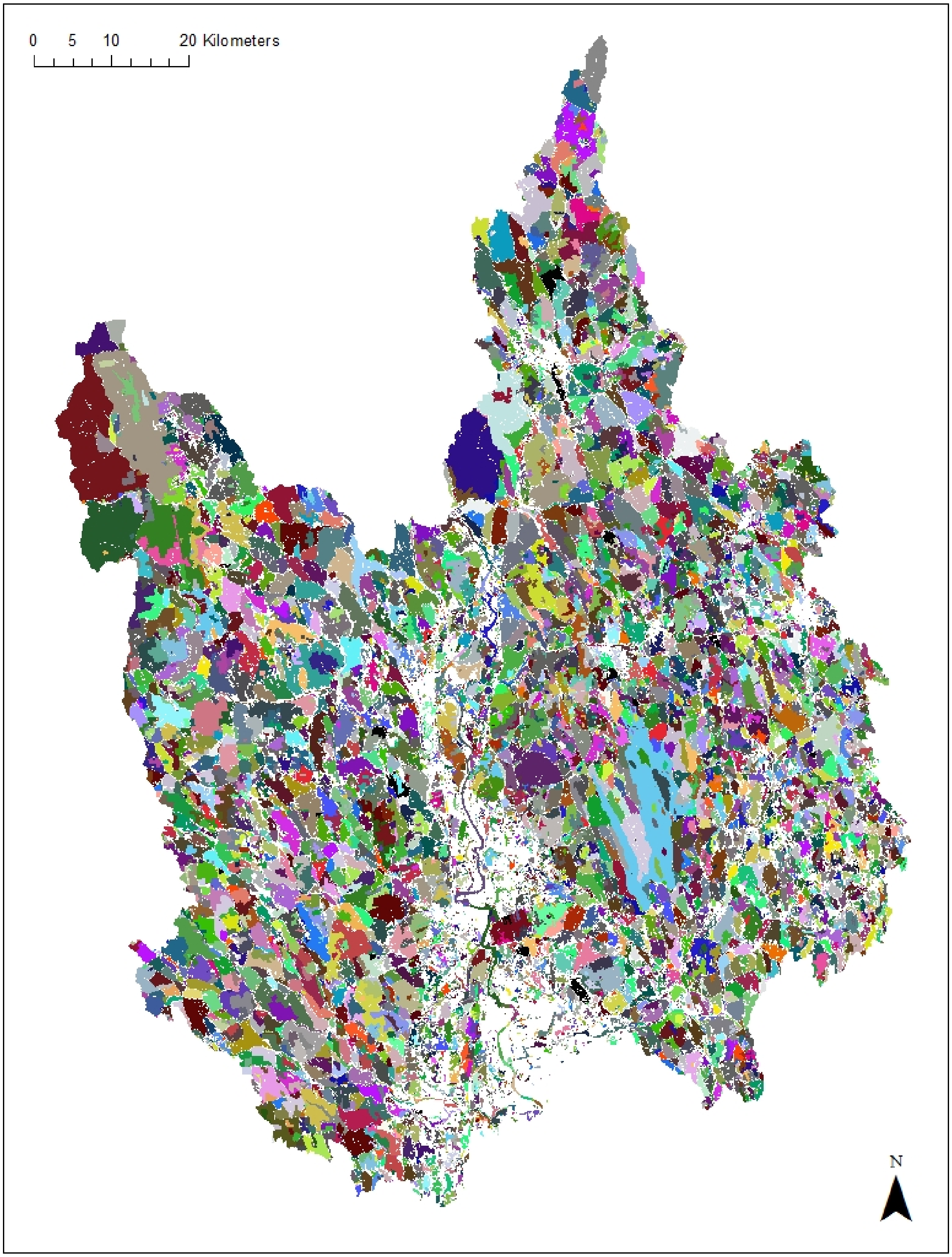



***Figure 22.*** *Intact planning units defined as roadless blocks for the middle Connecticut River watershed study area as used in the Marxan analysis to identify optimal reserve networks.*

## *4.2. Coarse- versus fine-filter results*

Overlap between alternative coarse-filter reserve network solutions and between alternative fine-filter reserve network solutions (i.e., intra-scenario comparison) was relatively low. For example, mean overlap among all combinations of 100 coarse-filter reserve network solutions and among all combinations of 100 fine-filter reserved network solutions based on the intact planning units in the middle Connecticut River watershed area was roughly 35% in both cases (**Fig. 23**), and the results were generally similar for the subdivided planning units, indicating that the level of flexibility among alternative coarse and fine-filter reserve network solutions was fairly high (i.e. there were few irreplaceable planning units). In other words, there was considerable flexibility in finding an optimal reserve network solution using either the coarse filter targets or the fine filter targets regardless of planning unit size. This is good news for conservation planners because it means they have lots of flexibility in finding good solutions and adapting to land protection opportunities that arise.

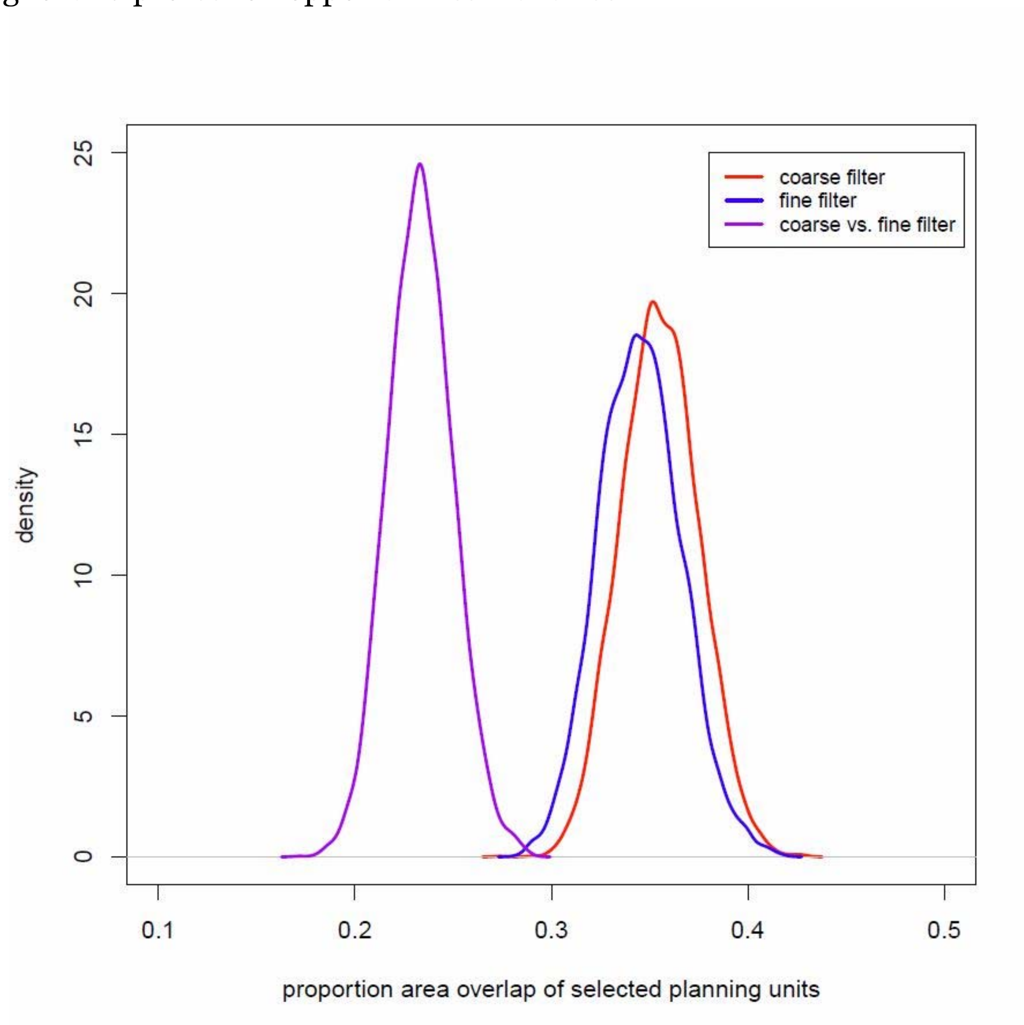



***Figure 23**. Kernel density plot of proportional area overlap within 100 coarse- and 100 fine-filter solutions (intra-scenario) and between 100 coarse- and 100 fine-filter solutions (inter-scenario) using intact planning units for the middle Connecticut River watershed study area (**Fig. 22**).*

Mean overlap between all combinations of 100 coarse and 100 fine-filter reserve network solutions (i.e., inter-filter solutions) was only 23% (**Fig. 23**), and the results were similar for subdivided planning units, indicating relatively low overlap, or high complementarity, between the coarse and fine-filter solutions. This result suggests there is substantial complementarity between the two reserve design approaches and provides support for the combined use of both methods in conservation planning. However, these results must be interpreted cautiously given the relatively few (n=6) and biased (proportionately more forest interior species) selection of representative species comprising the fine filter.

### *4.3. Prioritizing lands for conservation*

Marxan is principally designed to identify spatial solutions to the reserve network problem; i.e., it seeks to find a spatial network of reserves that best meets the conservation targets (whatever they may be). While we used this approach to compare coarse- and fine-filtered approaches to conservation planning, a principal output of this analysis is the reserve network solutions derived using the coarse, fine and combination coarse-fine filters, and these can be used to help set conservation priorities for land protection. Specifically, the results of our Marxan analysis are in the form of grids (or maps) representing conservation reserve priorities based on the coarse filter (ecological integrity) assessment, fine filter (species' habitat capability) assessment, and combined coarse-fine filter assessment for the current landscape condition in 2010. We included 14 grids representing potential *Conservation Planning Units* (CPUs; 2 grids: intact and subdivided planning units), *coarse filter solutions* (n=4: single best solution and selection frequency based on intact and subdivided planning units), *fine filter solutions* (n=4: single best solution and selection frequency based on intact and subdivided planning units), and *complementary coarse-fine filter solutions* (n=4: single best solution and selection frequency based on intact and subdivided planning units) in the following package:

- midconn_marxan_current.zip

For each of the scenarios (coarse filter, fine filter, and complementary coarse-fine filters), we include a grid depicting the single best solution based on the intact planning units and the subdivided units. For example, **figure 24** depicts the single best solution based on the complimentary coarse-fine filter approach (i.e., using the integrity of each ecological system as conservation targets in stage one and the habitat capability for each representative species as conservation targets in stage two) for the middle Connecticut River watershed study area. Note, this is merely one spatial solution, albeit the best among 1,000 iterations, that minimally meets all the conservation targets. In this case, the identified reserve network includes a cumulative ecological integrity score for each ecological system roughly proportionate to total integrity across the entire the landscape (i.e., there is more forest land protected than wetlands because the total integrity of forest is greater than the total integrity of wetlands, which is largely a function of the greater spatial extent of forest compared to wetlands). Thus, each ecological system has a proportionately equivalent degree of protection. Importantly, there are many other comparable reserve network solutions that also meet the overall conservation goal and that for all practical purposes are equivalent. Thus, this is not "the" solution, but "a" solution. **Figure 23** illustrates this point nicely. Among 100 optimal solutions based on either the coarse filter alone or the fine filter alone, there was only 35% spatial overlap, indicating that there are many spatially different solutions that meet the conservation goal. Although not shown in **figure 23**, the result for the complementary coarse-fine filter solutions is similar.

Given the high degree of flexibility in optimal reserve designs, it is useful to look at the planning unit frequency of selection among alternative solutions. **Figure 25** depicts the frequency of selection for the intact planning units in the middle Connecticut River watershed study area based on the complementary coarse-fine filter approach. While it is clear from this figure that many planning units are irreplaceable (or nearly so; i.e., dark red units) and thus play a critical role in meeting the conservation goals, it is equally clear that most planning units are involved in at least some of the solutions. Thus, almost any planning unit can contribute to an effective reserve network, if complemented properly with the right mix of other planning units. This implies that conservation planners have considerable flexibility in designing a reserve network that will meet the overall conservation goal.

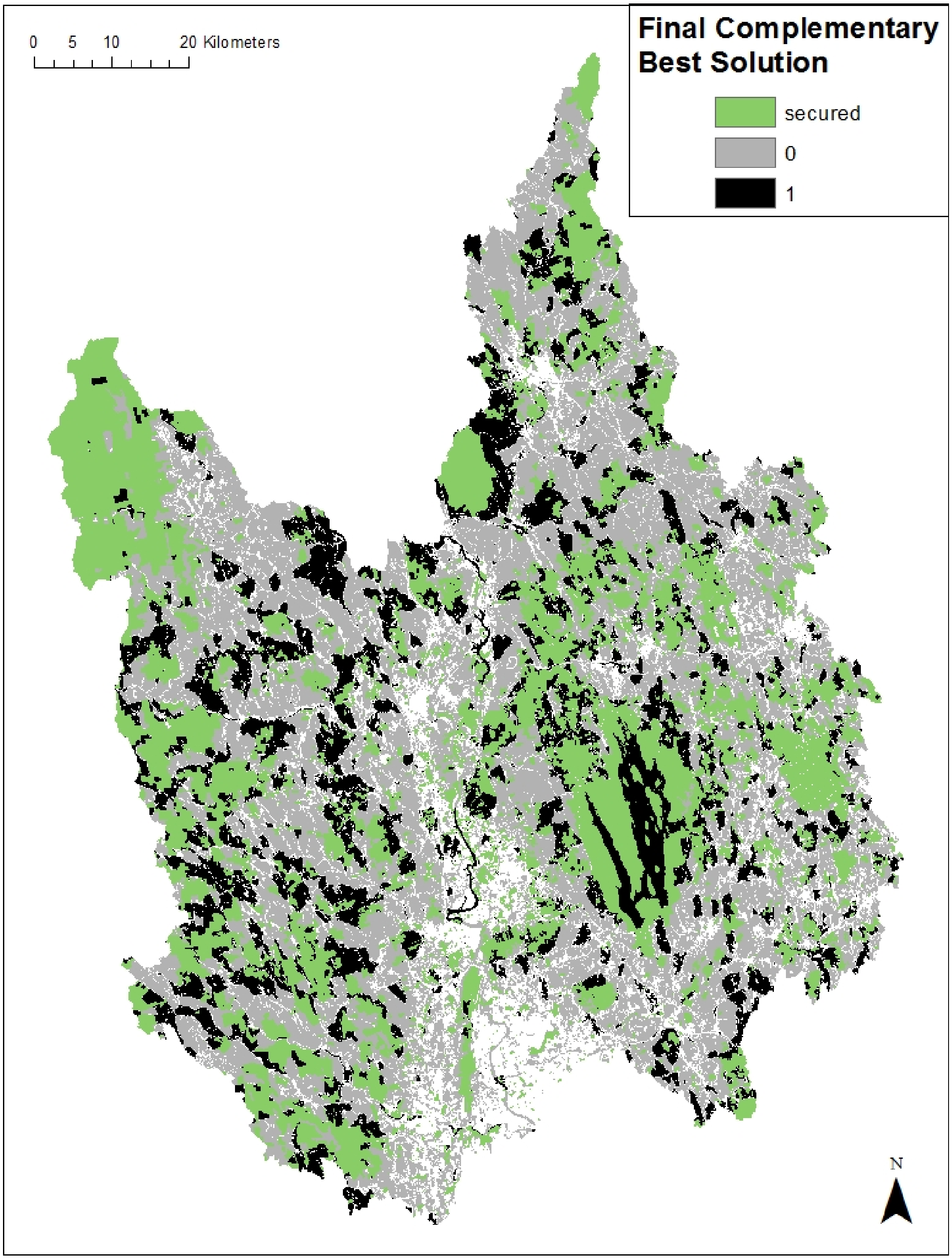



***Figure 24.*** *Final complementary approach 'best' solution using intact planning units for the middle Connecticut river watershed study area. Areas shown in black are included in the final reserve network along with the existing secured lands (green).*

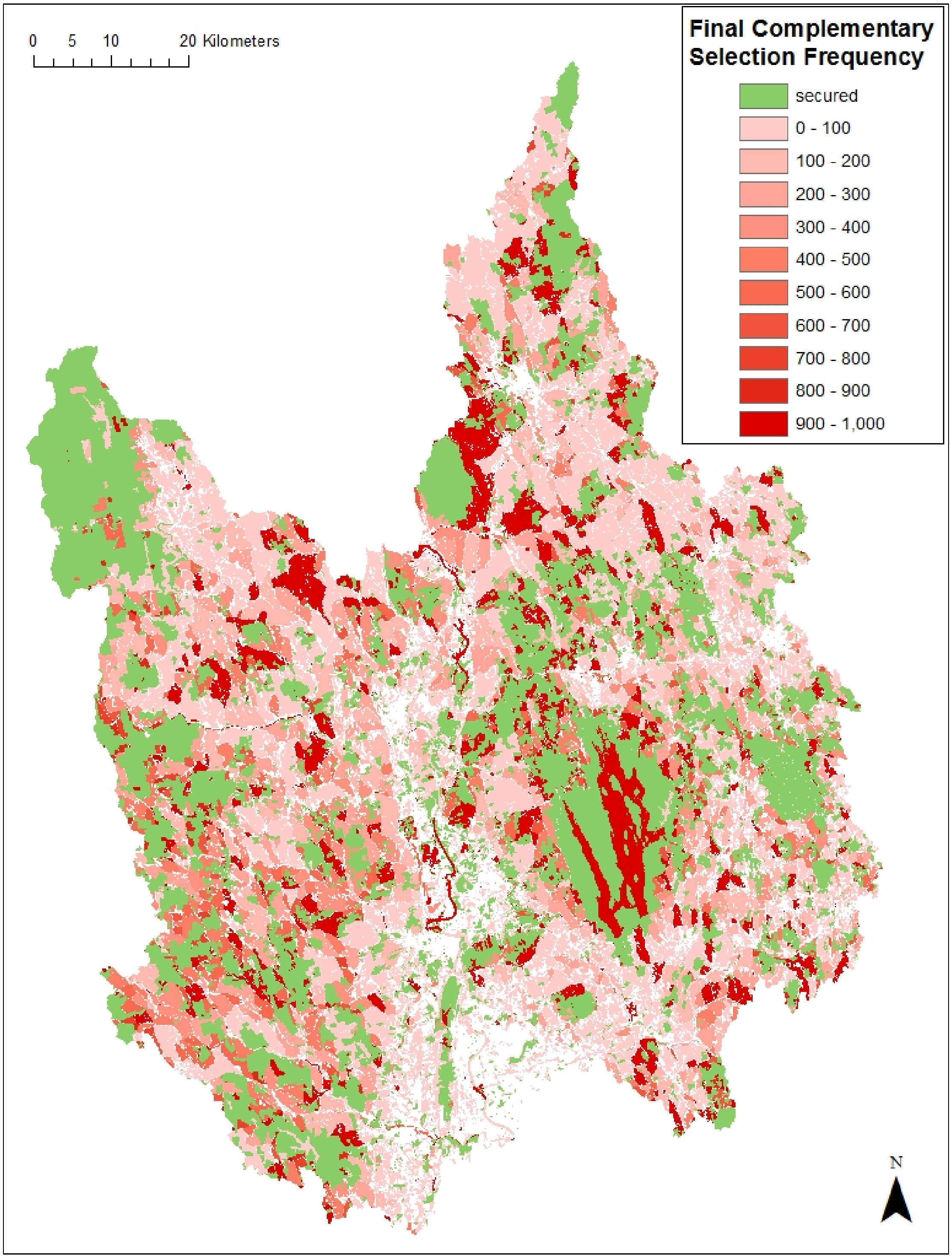



***Figure 25.*** *Final complementary approach selection frequency using intact planning units for the middle Connecticut river watershed study area. Selection frequency ranges from 0-1000 for units selected in no solutions to units selected in every solution (i.e., irreplaceable units).*

## *4.4. Implications and Recommendations*

Our results suggest there is substantial complementarity between the coarse- and fine-filtered approaches to conservation design and provide preliminary support for the combined use of both methods in conservation planning. However, we recognize several limitations to our preliminary assessment that must be considered when interpreting these results and should be considered in future applications of this analytical approach.

- Our fine filter included only 10 species (actually 6-9 depending on the study area) and was biased towards forest interior species; a more comprehensive set of species is needed to fully evaluate the fine filter approach and to make legitimate comparisons to the coarse filter results.

- There are many potential approaches to weighting conservation features. In the present analysis, we assigned all conservation features equal weight in proportion to their representation in the landscape; however, one might choose to weight some features more heavily than others. Moreover, our conservation features were based on the current landscape; however, one might choose to incorporate predictions of the future landscape condition. These are subjective decisions that must be driven by the specific goals of the user, and could have a significant impact on the results.

- Our complementary, two-stage, coarse-fine filter approach is only one of many possible approaches for combining the two strategies. We define 'complementary' here as the fine filter complementing the coarse filter which is selected first under the supposition that most conservation planning efforts start with relatively cheap and readily available data. In theory, our combined coarse-fine filter approach will be most effective when the species used in the analysis require juxtaposition of diverse ecological systems, or have a propensity for edge habitats.

- We defined planning units as roadless blocks or arbitrary subdivisions of roadless blocks. Ideally, one would use real parcel boundaries as planning units since these are the units by which land is purchased, but these data are not yet available in digital form for the entire region. It is unclear how the use of arbitrary units affects the results and thus more experimentation is needed.

- Our analysis did not consider the spatial aggregation of reserve network solutions or connectivity among reserves, nor the buffering of reserves that will be needed to maintain the ecological integrity of the reserves over time. More elaborate analyses are required to incorporate these considerations into an optimal landscape design.