

**CRITICAL LINKAGES: ASSESSING CONNECTIVITY RESTORATION POTENTIAL
FOR CULVERT REPLACEMENT, DAM REMOVAL AND CONSTRUCTION OF
WILDLIFE PASSAGE STRUCTURES IN MASSACHUSETTS**

Scott D. Jackson, Program Director UMass Extension's Natural Resources and Environmental
Conservation Program
Department of Environmental Conservation
Holdsworth Hall
University of Massachusetts
Amherst, MA 01003
(413) 545-4743
sjackson@umext.umass.edu

Bradley W. Compton, Research Associate
Department of Environmental Conservation
Holdsworth Hall
University of Massachusetts
Amherst, MA 01003
(413) 577-2179
bcompton@eco.umass.edu

Kevin McGarigal, Professor
Department of Environmental Conservation
Holdsworth Hall
University of Massachusetts
Amherst, MA 01003
(413) 577-0655
megarigalk@eco.umass.edu

CRITICAL LINKAGES: ASSESSING CONNECTIVITY RESTORATION POTENTIAL FOR CULVERT REPLACEMENT, DAM REMOVAL AND CONSTRUCTION OF WILDLIFE PASSAGE STRUCTURES IN MASSACHUSETTS

ABSTRACT

The University of Massachusetts Amherst, working in partnership with The Nature Conservancy and state agencies, has integrated data related to landscape connectivity and human development and completed a comprehensive analysis of areas in Massachusetts where connections must be restored to support biodiversity and minimize vehicle-wildlife collisions. The Critical Linkages project has been developing spatially explicit tools, including maps and scenario-testing software, to mitigate impacts of roads on the environment and help inform the design of new roads. The project built on the existing Conservation Assessment and Prioritization System (CAPS), a computer model developed by UMass that incorporates biophysical and anthropogenic data to develop an index of ecological integrity. Within the framework of CAPS the connectedness and aquatic connectedness metrics were used to model various scenarios and quantify the differences among them. Using this approach we conducted a comprehensive statewide assessment of restoration potential for 1) dam removals, 2) culvert replacements and 3) construction of wildlife passage structures on roads and highways. A baseline assessment of connectedness and aquatic connectedness provided a statewide base scenario for comparison of restoration options. Scenario-testing software was developed to efficiently assess restoration potential for large numbers of possible restoration projects and then applied statewide to identify road segments, road-stream crossings and dams that currently obstruct aquatic and terrestrial wildlife movement and that offer the greatest opportunity for restoration of landscape connectivity in Massachusetts.

INTRODUCTION

The disruption of landscape connectivity by human land use activities is considered a principal cause of the decline in biodiversity and is increasingly of concern to conservation scientists (Chetkiewicz et al. 2006, Crooks and Sanjayan 2006, Hilty et al. 2006, Beier et al. 2008). In addition, connectivity is considered a vital attribute of a landscape (Taylor et al. 1993) and deemed critical to the adaptive capacity (*sensu* Elmqvist et al. 2003) of a landscape in the face of climate change (Czucz et al. 2011). There is perhaps no more ubiquitous and insidious anthropogenic influence on landscape connectivity than roads. Roads have both direct (e.g., animal mortality) and indirect (loss of landscape permeability resulting in fragmentation) effects on terrestrial and aquatic ecosystems (Forman et al. 2003). To a large degree, the placement and construction of roads in large measure determines how permeable the landscape is to the movement of organisms, energy, and matter.

In light of the above and in the face of continued human development and climate change, minimizing the influence of roadways on landscape connectivity is of paramount concern among

conservationists and planners. Consequently, the aim of this study was to develop a modern methodology to assess and prioritize where to use mitigation techniques to best facilitate wildlife passage and reduce the risk of animal-vehicle collisions along roadways. Our specific objective was to evaluate and prioritize locations for potential wildlife passage structures and culvert upgrades in Massachusetts, although we extended this to include dam removals as well, even though dams are frequently not associated with roadways – dams are otherwise analogous to culverts in impeding movement of aquatic organisms in riverine networks.

In addition, our objective was to employ a "coarse-filter" approach in our assessment of connectivity; i.e., one that did not involve any particular focal species or process but instead holistically considered ecological systems or settings. While there have been many other efforts to develop methods and software tools for similar purposes (e.g., Fuller and Sarkar 2006, Theobald et al. 2006, Roberts et al. 2010) and many proposed measures of connectivity available for use in this context (e.g., Clabrese and Fagan 2004, Fagan and Calabrese 2006, Saura and Pascual-Hortal 2007, Estrada and Bodin 2008, Kindlmann and Burel 2008, Theobald et al. 2011), none of the available approaches make use of resistant kernels (Compton et al. 2007), which we believe provide the most synoptic perspective on landscape connectivity.

Resistant kernels combine two familiar methods: 1) standard kernel density estimation, and 2) least cost path analysis based on resistant surfaces, into a hybrid approach that allows for nonlinear ecological distance relationships and accounts for connectivity between every location to every other location (as opposed to between a single designated source and destination location). Resistant kernels are described in more detail in the methods section. Consequently, we developed a new approach based on resistant kernels and applied it to potential road crossings, culvert upgrades and dam removals across Massachusetts.

The Concept of Landscape Connectivity

The concept of landscape connectivity (Merriam 1984) provides the broad conceptual underpinning for this study and our approach, and thus it is important to clarify and define the concept as we use it here given the diverse and often confusing uses of the concept in the literature. The concept of landscape connectivity has been defined as the “degree to which the landscape facilitates or impedes movement among resource patches” (Taylor et al. 1993) or as “the functional relationship among habitat patches, owing to the spatial contagion of habitat and the movement responses of organisms to landscape structure” (With et al. 1997). Both of these definitions highlight the functional nature of connectivity, by emphasizing the dependence of movement on landscape structure. Furthermore, while these and other definitions emphasize the movement of organisms, the concept of landscape connectivity can be extended to consider more generally the movement of energy, matter, or information (gene flow) across the landscape. Regardless of which currency is used, the greater the degree of movement or flow across the landscape, the greater the overall connectivity of the landscape.

While the above definitions emphasize the functional nature of connectivity, ecologists often distinguish between functional connectivity (or what is generally referred to as simply "connectivity") and structural connectivity (or what is sometimes referred to as "continuity") (Crooks and Sanjayan 2006). *Structural connectivity* measures the spatial arrangement of landscape elements (e.g., habitat types or ecological systems) without reference to the likelihood of movement of particular organisms (or energy, matter or information for that matter) through the landscape. In contrast, *functional connectivity* incorporates at least some aspects of the behavioral response of individuals, species, or ecological processes to the physical structure of the landscape (Crooks and Sanjayan 2006). Thus, functional connectivity reflects the interaction of ecological flows (e.g., movement of organisms) with the physical landscape structure (i.e., the composition and spatial configuration of the landscape).

What constitutes functional connectivity clearly depends on the organism or process of interest; for example, patches that are connected for bird dispersal might not be connected for salamander dispersal. Thus, functional connectivity is affected by the structural connectivity of the landscape, but the magnitude and nature of the effect depends on how the organism or process scales and perceives the landscape. A central question in landscape management for the conservation of biodiversity and ecological integrity is, "as the physical continuity of the landscape is disrupted (through development), at what point does landscape connectivity become impaired and adversely impact ecological processes?" In other words, at what point do structural disconnections impact the functional connectivity of the landscape.

In this study, we evaluate functional connectivity, not just continuity per se, but we do so in a generalized manner because we do not have a single focal organism or process. Instead, we are concerned with how myriad organisms and processes collectively respond to the physical continuity of environments. This approach is implemented in our "resistant kernel estimator" methodology that combines the physical distribution of land cover types and ecological settings (i.e., continuity) with the concept of permeability or ecological resistance, whereby each location confers a varying degree of resistance to ecological flows (i.e., connectivity).

Functional connectivity can be subdivided further into *potential connectivity*, which uses some basic, indirect knowledge of the potential for movement, and *actual connectivity*, which directly quantifies movement rates based on actual observations (Fagan and Calabrese 2006). The primary difference between potential and actual connectivity lies in the amount of information available on the response of the organism or process to landscape structure. Although assessing the actual connectivity of the landscape might be the goal, we usually do not have sufficient empirical information on how landscape structure influences movement behaviour or other ecological flows across the landscape to permit this level of assessment. Thus, most analyses of landscape connectivity are of the potential connectivity of the landscape. In this study, we evaluate potential connectivity, as we do not have empirical data on movement, nor do we have a single species or process on which to focus estimates of movement rates.

There are myriad ways to measure the functional connectivity of a landscape or of a particular landscape unit (e.g., grid cell) within a landscape. In the context of our approach, the functional connectivity of a landscape unit can be assessed from three different perspectives.

We refer to the connectivity of a focal cell to its ecological neighborhood (i.e., its landscape context) when it is viewed as a target as *connectedness*; in other words, to what extent are ecological flows (e.g., dispersal) to that cell impeded or facilitated by the surrounding landscape. Connectedness is a function of both the similarity of the neighboring cells to the focal cell (i.e., the more similar the more connected) and any impediments to movement from the neighboring cells to the focal cell (i.e. the more impediments the less connected).

The outflow from a focal cell, for example when it is viewed as a source, we refer to as *dispersion*. Dispersion is a function solely of impediments to movement from the focal cell outward to all neighboring cells; it does not take into account whether or not the destination cells are similar to the focal cell, only whether stuff can get there.

Lastly, we refer to the rate of flow through a focal cell (i.e. when it is viewed as a conduit) as *conductance*. Conductance refers to how much stuff moves through a focal cell when all neighboring cells are treated as sources, and it is a function of the focal cell's permeability (or resistance) to ecological flows as well as its strategic position in the landscape between other cells. For example, a wildlife passage structure on an expressway may be quite permeable to wildlife crossings, but if it is not located along an important movement route between sites A and B, it will not function to promote the linkage of A and B. Thus, conductance deals with the role of each location in conferring connectivity to the broader landscape.

From a conceptual standpoint, all three components of connectivity (i.e., connectedness, dispersion and conductance) are relevant to this study. However, after preliminary examination of the results we limited our final results to the use of connectedness. Thus, in this study, we are principally concerned with the effect of roads, culverts and dams on the connectedness of the surrounding landscape.

What ultimately influences the functional connectivity of the landscape is the scale and pattern of movement relative to the physical structure of the landscape (With 1999). Thus, functional connectivity is a scale-dependent concept and there is no one right scale for assessing it. In the context of this study, because we are dealing with biodiversity in its broadest sense (i.e. approaching it using a coarse filter), it is impossible to define a single scale for assessing connectivity that will be meaningful for all organisms and processes of concern. Yet at the same time it is impractical to examine connectivity at every relevant scale. As a practical compromise, we distinguish two important scales for assessing connectivity, which we refer to as local and regional scales.

The distinction between these two scales is best illustrated from the perspective of movement of

organisms (rather than energy or matter). In this context, *local connectivity* refers to the spatial scale at which the dominant organisms interact directly with the landscape via demographic processes such as dispersal and home range movements. This is the landscape context that an individual organism might experience during their lifetime.

Regional connectivity refers to the spatial scale exceeding that in which organisms directly interact with the landscape. This is the scale at which long-term ecological processes such as range expansion/contraction and gene flow occur. At this scale, individuals generally do not interact with the landscape, but their offspring or their genes might over multiple generations. Consequently, there is no real upper limit on the regional scale; the longer the time frame, the larger the regional scale at which the landscape context matters.

In the first phase of this study reported in this paper, we are concerned with local connectivity; regional connectivity will be addressed in the next phase of this study. Of course, even this does not constrain the range of suitable scales for assessing connectivity, since even the dominant organisms in a community may have ecological neighborhoods that vary in scale by orders of magnitude. Thus, in choosing the spatial scale(s) for the local connectivity assessment (using the resistant kernel estimator), we incorporated two important considerations. First, we focussed on vertebrates, largely because their life history and habitat use patterns are better understood than many plants and invertebrates and because they are more often the focus of conservation concerns. Second, we focussed on the average maximum movement distances of a suite of organisms; in other words, we did not use the maximum movement distance of a single “indicator” species nor did we choose to bias the result towards the most or least vagile organism.

In summary, connectivity is a complex and multi-faceted concept with many different constructs depending on the application. In this study, we are interested in evaluating and prioritizing locations for potential wildlife passage structures, culvert upgrades and dam removals based on an assessment of how these mitigation measures influence functional, potential, local connectivity as measured from the perspective of connectedness.

The Critical Linkages Project

The University of Massachusetts (UMass) in collaboration with The Nature Conservancy (TNC) integrated data related to landscape connectivity and human development, and developed a comprehensive analysis of areas in Massachusetts where connections must be protected or restored to support biodiversity and minimize vehicle-wildlife collisions. The Critical Linkages project built on the existing Conservation Assessment and Prioritization System (CAPS) through a statewide landscape connectivity study. Phase 1 of the project involved scenario analysis using CAPS to assess the potential for restoring functional connectivity via dam removal, culvert/bridge replacement and use of wildlife passage structures on roads and highways.

METHODS

The Conservation Assessment and Prioritization System (CAPS) is an ecosystem-based (coarse-filter) approach for assessing the ecological integrity of lands and waters and subsequently identifying and prioritizing land for habitat and biodiversity conservation. CAPS is a computer software program and an approach to prioritizing land for conservation based on the assessment of ecological integrity for various ecological communities (e.g., forest, shrub swamp, headwater stream) within an area.

The first step in the CAPS approach is the characterization of both the developed and undeveloped elements of the landscape. Developed land uses are grouped into categories such as various classes of roads and highways, e.g., high-intensity urban, low-density residential, agricultural land, and other elements of the human dominated landscape. Undeveloped (“natural”) land is mapped based on ecological community classification (e.g., swamp, marsh, bog, pond).

With a computer base map depicting various classes of developed and undeveloped land, we then evaluate a variety of landscape-based variables (“metrics”) for every point in the landscape. A metric may, for example, take into account the microclimatic alterations associated with “edge effects,” intensity of road traffic in the vicinity, nutrient loading in aquatic ecosystems, or the effects of human development on landscape connectivity. Two of these metrics measure the connectedness of each undeveloped cell; i.e., the degree to which a focal cell is surrounded by ecologically similar cells and the degree of impedance of ecological flows from similar neighboring cells to the focal cell. One (*connectedness*) applies to both terrestrial and aquatic cells and the other (*aquatic connectedness*) applies only to aquatic cells, as described below.

Because CAPS provides a quantitative assessment for each metric it can be used for comparing various scenarios. In essence, scenario analysis involves running CAPS separately for each scenario, and comparing results to determine the loss (or gain) in specific metric units. This scenario testing capability can be used to evaluate and compare the impacts of development projects on habitat conditions as well as the potential benefits of habitat management or environmental restoration.

In Phase 1 of the Critical Linkages project we used the scenario testing capabilities of CAPS to assess the change in either the *connectedness* or *aquatic connectedness* metrics for three types of ecological restoration to promote connectivity: dam removal, culvert/bridge replacement, and the use of wildlife crossing structures on roads and highways (for technical reasons, railroads have not yet been included in the analysis).

Connectedness

The *connectedness* metric is a measure of the degree to which a focal cell is interconnected with other cells in the landscape that can be a source of individuals or materials that contribute to the long-term ecological integrity of the focal cell. *Connectedness* uses a resistant kernel (Compton et al. 2007) to assess the local connectivity around a focal cell. The resistance of each cell is based on the ecological distance to the focal cell in ecological settings space, defined by a number of ecological settings variables (Table 1) that define ecological community characteristics. It measures the multivariate distance across all ecological setting variables between the focal cell and those of neighboring cells. See Figure 1 for an example of a resistant kernel.

Table 1. Ecological settings variables used to calculate ecological distance among cells in the landscape.

Biophysical attribute	Biophysical variable	Description
Temperature	Growing season degree-days	Degree-days is calculated by taking the sum of daily temperatures above a threshold (10°C). Temperatures above an upper threshold of 30°C are excluded.
	Minimum winter temperature	The minimum temperature (°C) reached in the winter
Solar energy	Incident solar radiation	Solar radiation based on slope, aspect, and topographical shading.
Chemical & physical substrate	Soil pH	Soil pH
	Soil depth	Soil depth (cm)
	Soil texture	Soil texture based on USDA-NRCS classification
	Water salinity	Salinity (ppt) in coastal settings in three broad classes: fresh, brackish, and saltwater
	Substrate mobility	The <i>realized</i> mobility of the physical substrate, due to both substrate composition (i.e., sand) and exposure to forces (wind and water) that transport material
	CaCO ₃ content	Calcium carbonate content based on the composition of the soil and underlying bedrock
Physical disturbance	Wind exposure	Wind exposure based on the mean sustained wind speeds at 30 m above ground level using a 200 m resolution model
	Wave exposure	Direct exposure to ocean waves
	Steep slopes	The propensity for gravity-induced physical disturbance

Biophysical attribute	Biophysical variable	Description
Moisture	Wetness	Soil moisture (in a gradient from xeric to hydric) based on a topographic wetness index
Hydrology	Flow gradient	Gradient (percent slope) of a stream approximated by categories such as step-pool, riffle, run, cascade and flat water
	Flow volume (watershed size)	The absolute size of a stream or river
	Tidal regime	In coastal areas, degree of tidal influence
Vegetation	Vegetative structure	Coarse vegetative structure, from unvegetated through shrubland through closed canopy forest
Development	Developed	Whether a cell can be considered largely developed or undeveloped
	Traffic rate	A scaled measure of traffic volume on roads and highways
	Impervious	Percent of impervious surfaces
	Terrestrial barriers	Degree to which a cell constitutes a barrier to terrestrial organisms
	Aquatic barriers	Degree to which a cell constitutes a barrier to aquatic organisms

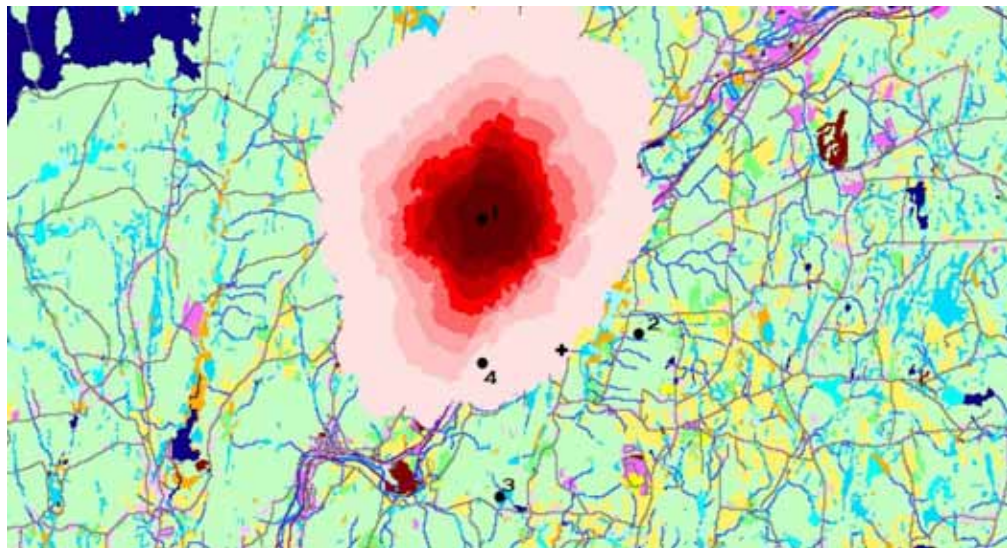


Figure 1. A resistant kernel for a cell of forest in a predominantly forested landscape.

Connectedness is the sum of resistant kernels built for each cell in the neighborhood of the focal cell (fig. 2) weighted by ecological distance to the focal cell. Underlying this metric is the assumption that *dispersion* of ecological flows from similar ecological communities is more

important to long-term integrity than those from dissimilar communities. The *connectedness* metric applies to all ecological communities including aquatic communities (e.g., lakes, rivers, streams). In order to characterize the ecological distances and ultimately the resistant surface for developed land classes we included anthropogenic elements among these gradients. These included aquatic barriers, terrestrial barriers, traffic rate, imperviousness, and developed.

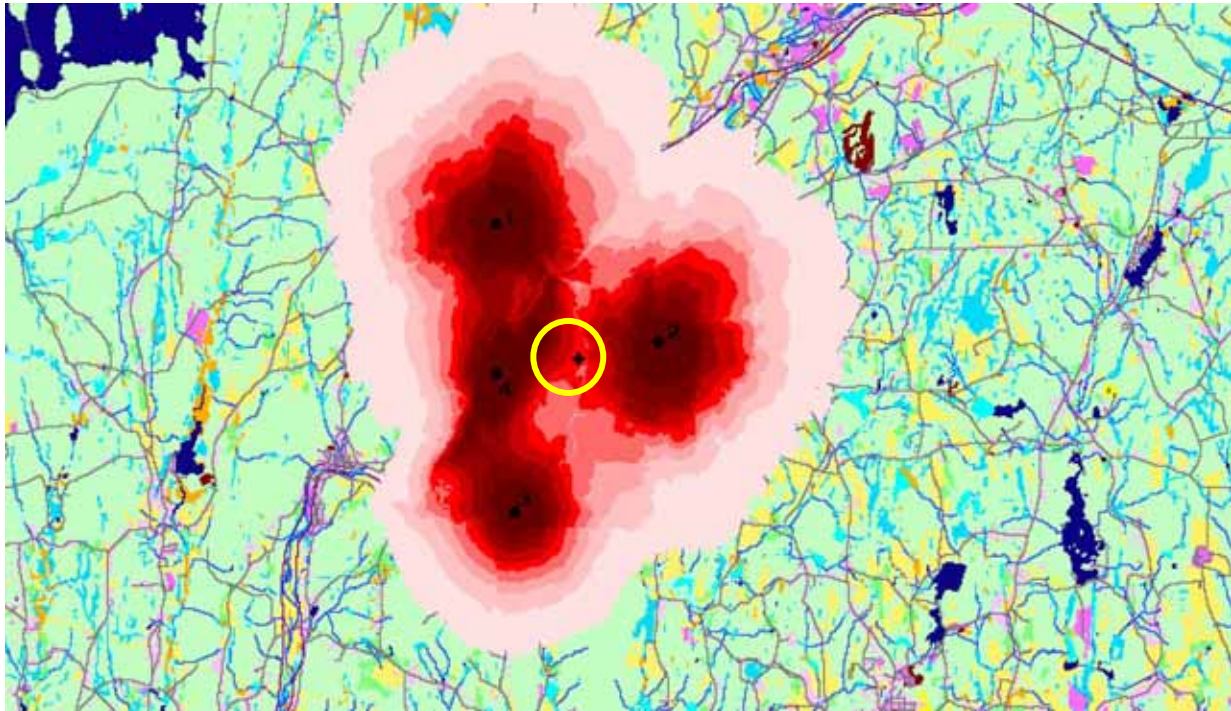


Figure 2. “Connectedness” for the focal cell (circled in yellow) is based on the sum of “dispersion” values from all cells with resistant kernels that overlap the focus cell, weighted by ecological distance. Depicted here are the “dispersion” kernels from four nearby cells prior to weighting by ecological distance.

Dams generally have traffic rates of zero. However, dams that have a road that runs along their surfaces will have non-zero traffic rates. Dams have a terrestrial barrier score of zero unless a road goes over the dam, in which case it gets the road’s terrestrial barrier score. The aquatic barrier scores are a function of dam height.

Aquatic barrier scores for road-stream crossings are based on an assessment protocol and scoring system developed by the River and Stream Continuity Partnership (2010, www.streamcontinuity.org). The protocols were developed for implementation by trained volunteers or technicians and rely on information that can be readily collected in the field without surveying equipment or extensive site work. The Partnership also created an algorithm for scoring crossing structures according to the degree of obstruction they pose to aquatic organisms. Data and crossing scores from over 1,000 crossings were used to create a model to predict aquatic barrier scores for those crossings that had not been assessed in the field.

To assign terrestrial barrier scores for road-stream crossings we created a scoring algorithm using data collected by the River and Stream Continuity protocols. The following variables were included in the scoring algorithm: height, width, openness (cross-sectional area divided by structure length), substrate and span (an approximation of constriction ratio). As with aquatic barriers a model was developed to predict terrestrial barrier scores for crossings that had not been assessed in the field.

The road-stream crossing models for both aquatic barrier and terrestrial barrier produced noisy results ($R^2 \approx 0.4$). Therefore, we calculated 60% confidence intervals for both scores to allow modeling both a “best estimate” scenario (based on the predicted score) and a reasonable “best case” scenario (described below). To calculate 60% confidence intervals on the scores we broke the data into three equal sized strata for predicted scores. For each stratum we then calculated a 60% confidence interval from the distribution of the residuals in the predictions. The lower bound of the confidence interval was the prediction minus the 20th quantile of the residuals for all observations in the stratum while the upper confidence interval was based on the 80th quantile of the residuals in the stratum. We smoothed the transitions between strata to force the confidence intervals to increase monotonically with predicted score (fig. 3).

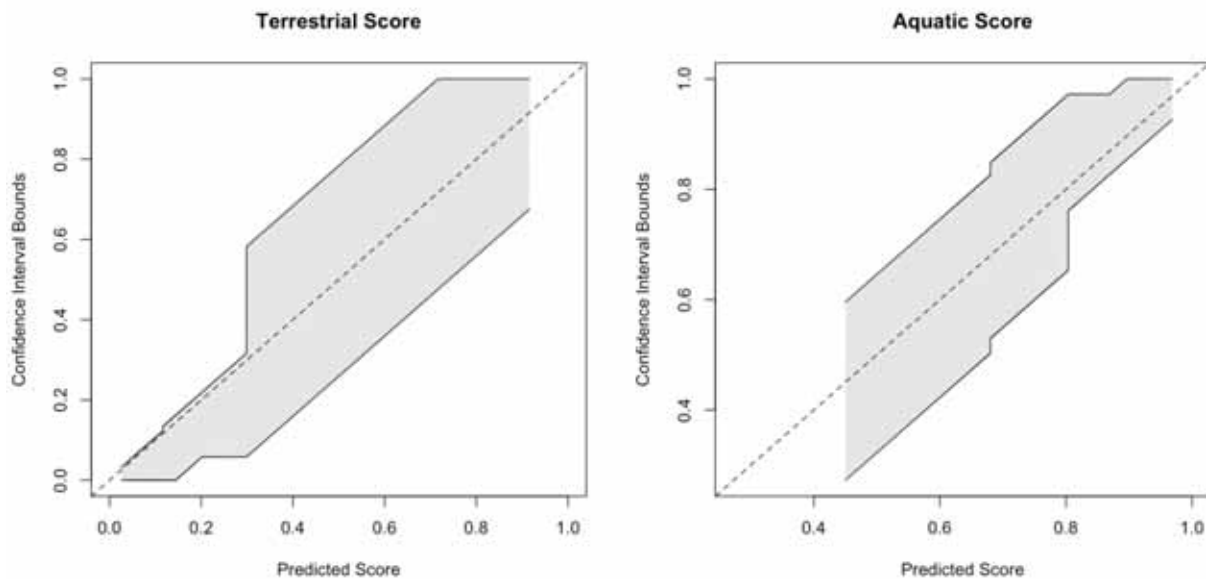


Figure 3. Sixty percent confidence intervals for terrestrial and aquatic barrier scores.

Terrestrial barrier scores for road segments were parameterized based on road class and professional judgment by an expert team. Traffic rates for roads are assigned from MA Department of Transportation (MassDOT) interpolated road traffic data, using the ADT (average daily traffic) field. We modified traffic rates somewhat to correct errors; for example, when traffic rates were zero due to missing data, or where traffic was overestimated for unpaved roads running through state forests. Traffic rates were converted to a probability of roadkill using a

mechanistic model presented by Hels and Buchwald (2001) and Gibbs and Shriver (2002), as illustrated in Figure 4.

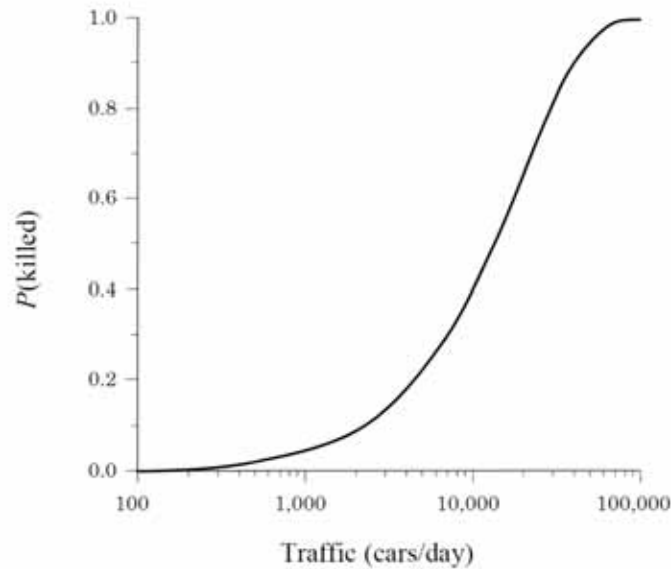


Figure 4. Relationship between traffic rate and probability of mortality.

Aquatic Connectedness

Ecological flows modeled for *connectedness* are allowed to flow overland and diagonally from cell to cell. As a result, resistant kernels can wrap around highly resistant cells or patches of cells. This makes sense for organisms that move terrestrially (flows can easily go around a building, parking lot or subdivision). However, for aquatic organism passage this is a problem because what would otherwise be considered severe barriers (dams, bad culverts) are easily circumvented. We created *aquatic connectedness* to get around this problem. *Aquatic connectedness* functions much like *connectedness* but is constrained to move only along the centerlines of streams, rivers, water bodies and wetlands. *Aquatic connectedness* includes one settings variable not used by *connectedness* (aquatic barriers) and ignores four settings variables used by *connectedness* (terrestrial barriers, traffic, imperviousness, and developed). This allows *aquatic connectedness* to respond to the effects of culverts, bridges, and dams on aquatic passability, rather than the effects of roads that may pass overhead.

Scenario Analysis

Within the framework of CAPS the *connectedness* and *aquatic connectedness* metrics are used to model various scenarios and quantify the differences among them. Using this approach we conducted a comprehensive statewide assessment of restoration potential for 1) dam removals, 2) culvert/bridge replacements and 3) construction of wildlife passage structures on roads and

highways. A baseline assessment of *connectedness* and *aquatic connectedness* provided statewide base scenarios for comparison of restoration options.

In calculating the change in *connectedness* and *aquatic connectedness* we used the modeled aquatic barrier and terrestrial barrier scores for road stream crossings to produce a “best estimate” delta score. In an effort to bracket these results and as a hedge against the uncertainty of the modeled scores we also used values associated with the 60 percent confidence intervals to produce what we called a reasonable “best case” value for the change in either *connectedness* or *aquatic connectedness*. Where terrestrial barrier and aquatic barrier scores based on field assessments were available these were used instead of modeled scores.

When conducting dam removal scenarios the “best estimate” analysis used the modeled aquatic barriers scores for road-stream crossings with potential to affect *aquatic connectedness* in the vicinity of dams. For the “best case” analysis road-stream crossings in the vicinity of dams were scored at the 60% confidence interval above their estimated score.

For culvert/bridge replacement scenarios the “best estimate” analysis was based on the modeled scores for aquatic barriers. “Best case” analyses set the target crossing score at the 60% confidence interval below the estimated score with all other crossings scored at the 60% confidence interval above their estimated score.

When evaluating wildlife passage structures for “best estimate” analyses we used the modeled terrestrial barrier scores for road-stream crossings with potential to affect *connectedness* associated with road/highway segments. For the “best case” analysis road-stream crossings in the vicinity of dams were scored at the 60% confidence interval below their estimated terrestrial barrier score. For wildlife passage structures the scaled traffic rate, impervious, and terrestrial barriers settings variables were reduced by 90 percent.

RESULTS

Dams

A total of 2,467 dams were included in the dam removal scenario analysis. Results from a portion of the state are shown in Figure 5. A cumulative histogram of the dams arranged by change in *aquatic connectedness* (fig. 6) suggests that much improvement in aquatic connectivity could be achieved with the removal of a relatively small number of dams.

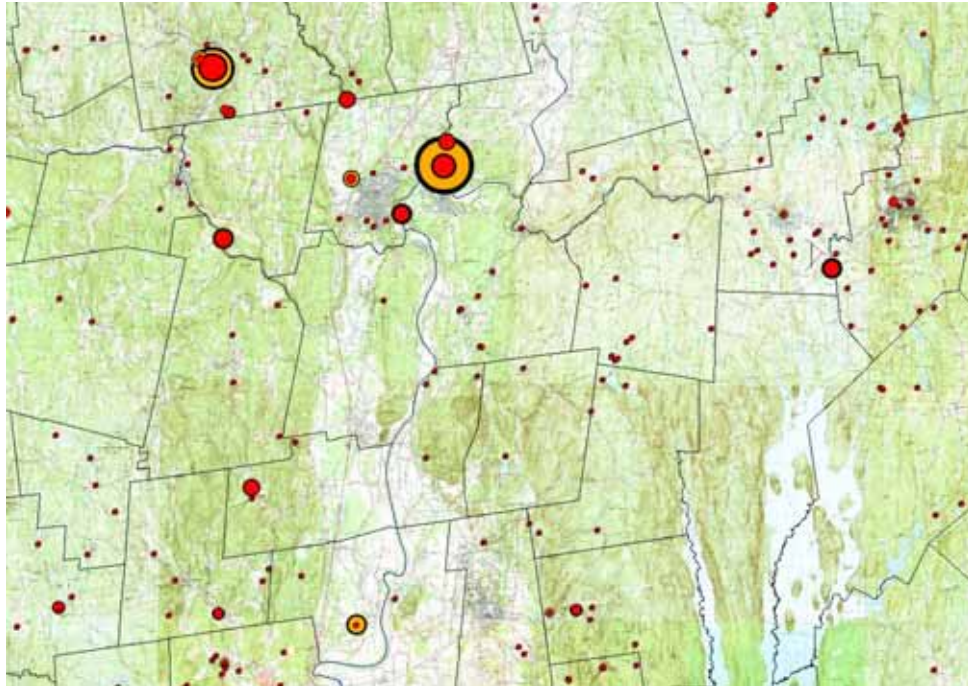


Figure 5. Results of dam removal scenario analyses for a portion of Massachusetts. Size of the circles is proportional to the change in “aquatic connectedness” that would be achieved by dam removal. Red circles are “best estimate” and yellow circles “best case” results.

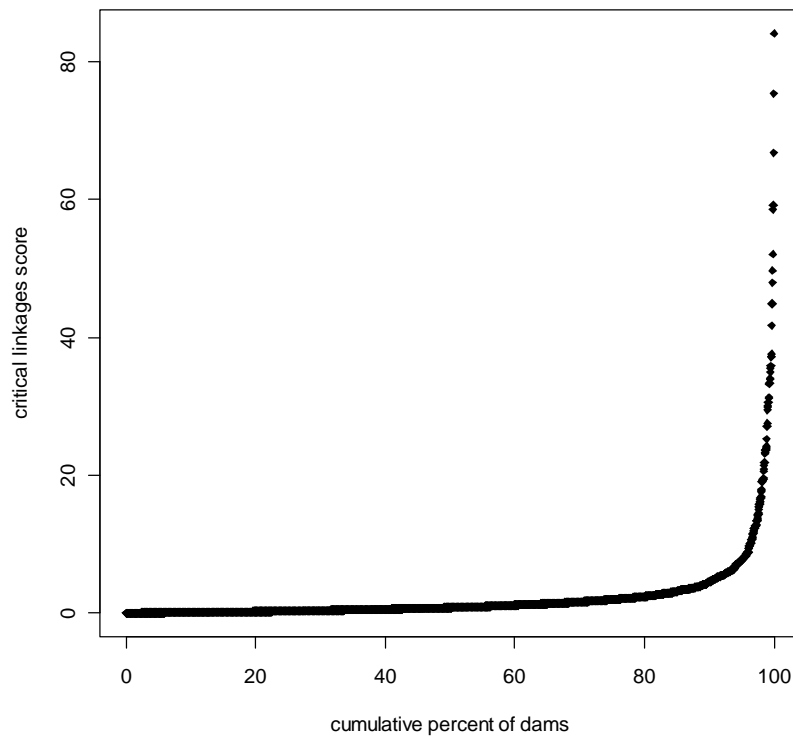


Figure 6. Cumulative histogram of dams arranged by change in “aquatic connectedness.”

Road-Stream Crossings

Culvert/bridge replacement scenarios were conducted for 26,582 road-stream crossings throughout Massachusetts. A sample of the results is shown in Figure 7. Figure 8 is a cumulative histogram of the road-stream crossings arranged by change in *aquatic connectedness*. These results suggest that selective replacement of a small proportion of culverts/bridges would yield disproportionate benefits in terms of aquatic connectivity.

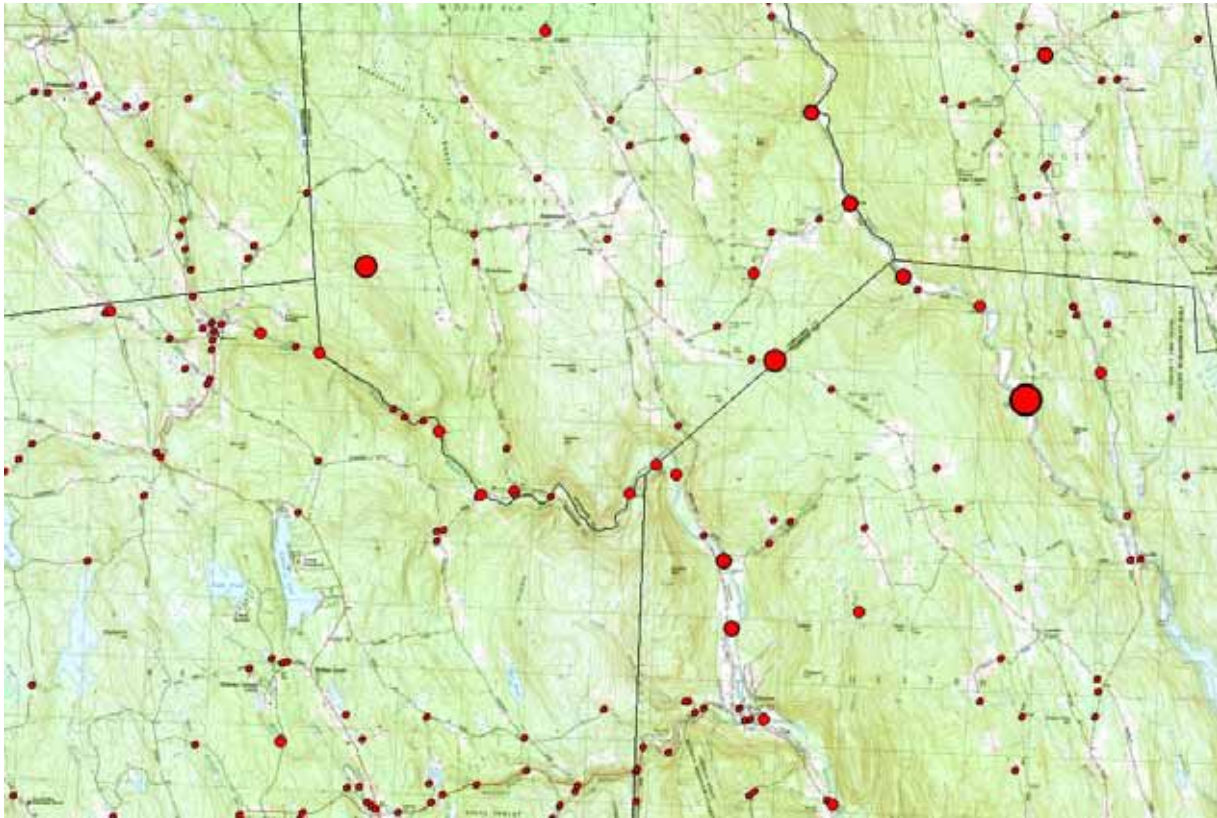


Figure 7. Results of culvert/bridge replacement scenario analyses for a portion of Massachusetts. Size of the circles is proportional to the change in “aquatic connectedness” that would be achieved by crossing replacement. The larger the circles the greater the improvement in “aquatic connectedness.”

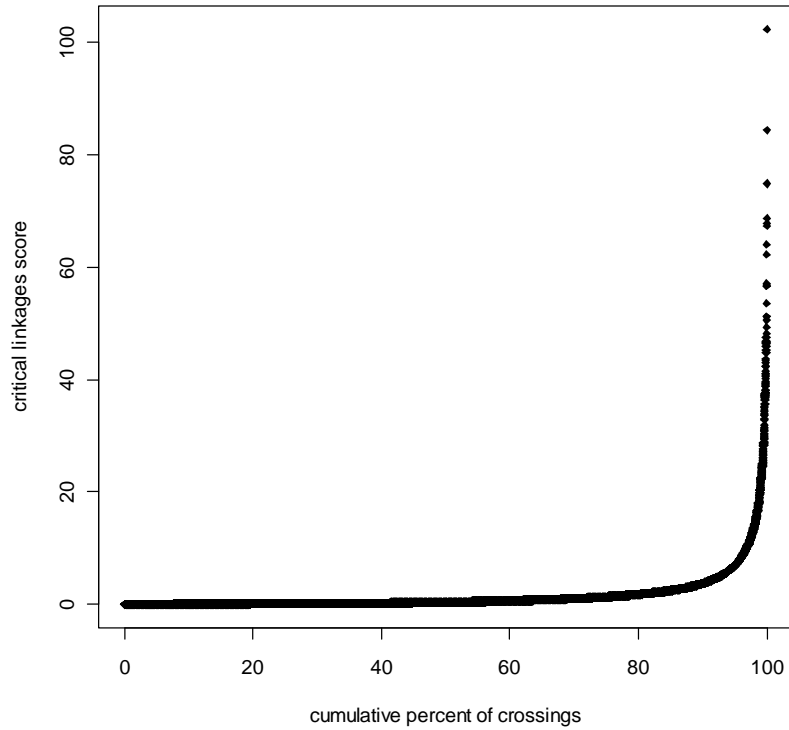


Figure 8. Cumulative histogram of road-stream crossings arranged by change in “aquatic connectedness.”

Road and Highway Segments

A total of 48,859 miles of roads and highways were included in the scenario analysis for wildlife passage structures. Results of this analysis for a portion of the state are shown in Figure 9. For technical reasons railroads have not been included in this analysis.

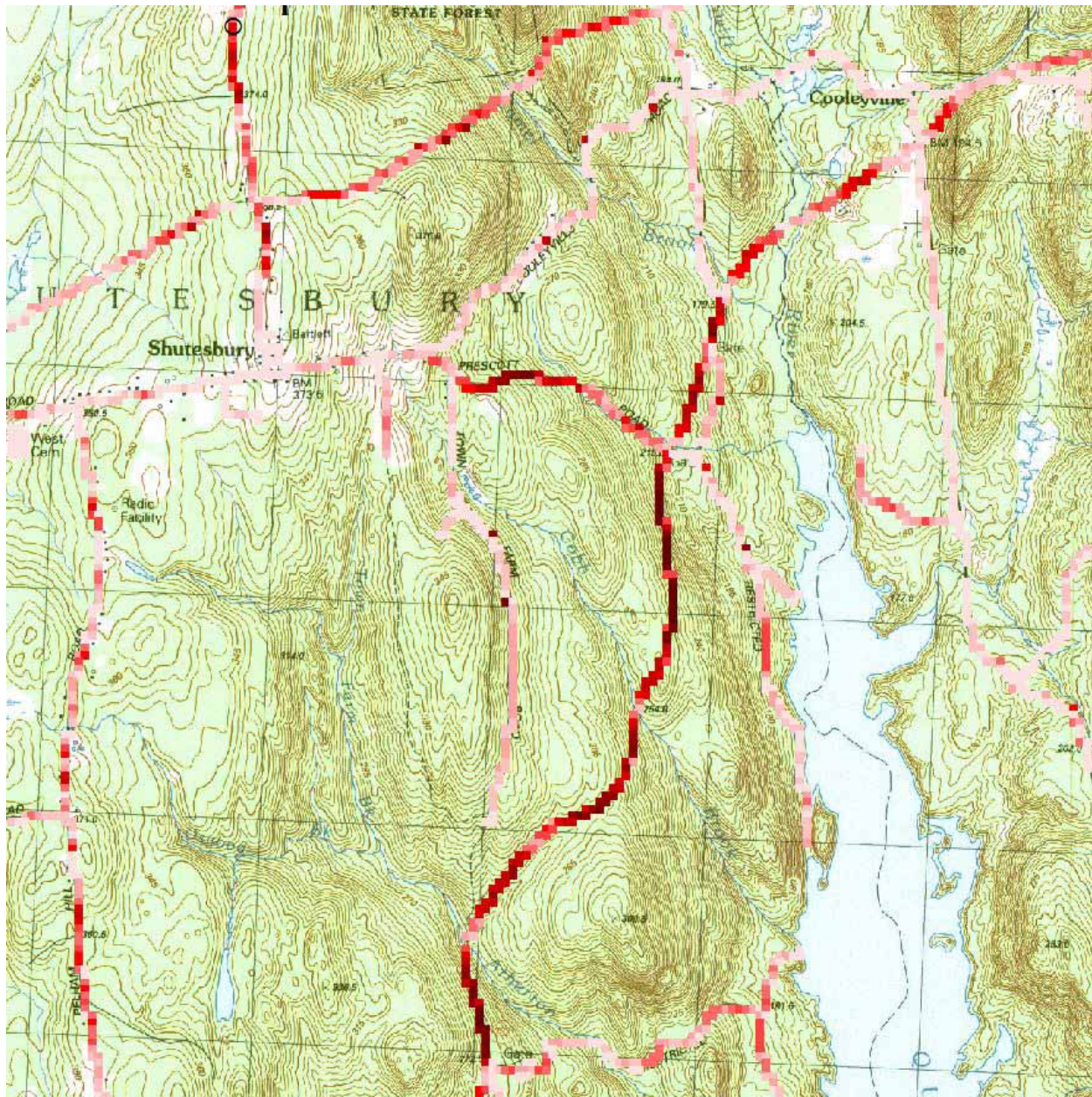


Figure 9. Results of wildlife passage structure scenario analyses for a portion of Massachusetts. The color of the lines is proportional to the change in “connectedness” that would be achieved by the construction of a wildlife passage structure. The darker the color the greater the benefit of using a passage structure.

Availability of Results

Complete results of these analyses are available from our web site: www.masscaps.org.

DISCUSSION

Scenario-testing software was developed to efficiently assess restoration potential for large numbers of possible restoration projects and then applied statewide to identify road segments, road-stream crossings and dams that currently obstruct aquatic and terrestrial wildlife movement and that offer the greatest opportunity for restoration of landscape connectivity in Massachusetts. Cumulative histograms of dams and road-stream crossings arranged by change in *aquatic connectedness* (fig. 5 and 7) indicate that a relatively small proportion of dams and crossings accounts for much of the restoration potential statewide. These histograms suggest that there is much to be gained from prioritizing restoration efforts.

CAPS Scenario analysis provides an efficient method for comprehensive assessment and prioritization of movement barriers. It is, however, important to remember the limitations of a modeling exercise such as the Critical Linkages analysis.

Data gaps and errors inherent in the source data used in CAPS are likely to affect the accuracy and usefulness of the analysis. Examples include:

- Unmapped dams
- Unmapped natural barriers to aquatic organism passage (e.g., waterfalls)
- Phantom road-stream crossings erroneously generated by the intersection of roads and streams data in GIS
- Lack of information on the passability of dams (e.g., fish passage structures)
- Lack of information about passability for most road-stream crossings (only about ten percent had been assessed in the field)
- Lack of information about the location of wildlife movement barriers associated with roads (Jersey barriers, fencing)

Another limitation of this analysis is that it only included single structure (dam, culvert) restoration scenarios. This focus on single structures can mask benefits of restoration potential for multi-structure projects. As part of our comprehensive state-wide analysis it was not feasible to evaluate all possible combinations of structure scenarios. However, we are developing separate software to be used with CAPS allowing users to define custom scenarios that can include multiple structures and combinations of different types of structures (e.g., culverts and dams).

The CAPS coarse filter, community based approach is an efficient means for integrating needs of a variety of organisms as well as ecological processes (flow of energy, materials and information). However, scale is important for community-based analyses. Phase 1 of the Critical Linkages project presented here is based on analyses at the local scale. The results of these

analyses may be less appropriate for highly vagile species such as birds, bats, and some anadromous fish. The next phase of the Critical Linkages project will focus on regional scale assessment of connectivity. Results from this next phase of analysis are likely to be more relevant for these highly vagile species.

ACKNOWLEDGEMENTS

The Critical Linkages project is funded by The Nature Conservancy and the Federal Highway Administration via a grant administered by the Massachusetts Department of Transportation. Additional support for CAPS has been provided by the U.S. Environmental Protection Agency, Massachusetts Department of Environmental Protection, Massachusetts Office of Energy and Environmental Affairs, and the Trustees of Reservations – Highlands Community Initiative. The following people made significant contributions to the development of CAPS and the implementation of the Critical Linkages project: Eduard Ene, Kasey Rolih and Ethan Plunkett (UMass Amherst), Andrew Finton, Mark Anderson, Jessica Dyson, Alison Bowden and Laura Marx (TNC), Lisa Rhodes, Michael McHugh, Lealdon Langley, James Sprague and Michael Stroman (MassDEP), Jan Smith and Marc Carullo (Mass CZM) and James DeNormandie (Massachusetts Audubon Society).

BIOGRAPHICAL SKETCH OF THE AUTHORS

Scott Jackson is Program Director for UMass Extension's Natural Resources and Environmental Conservation program and is in the Department of Environmental Conservation at UMass Amherst. Research interests include: ecology and breeding biology of amphibians, vernal pool ecology, wetland assessment and monitoring, impacts of roads and highways on wildlife, and landscape-based ecological assessment. He has been involved in the use of underpass systems to facilitate wildlife movement across roads and development of methods for evaluating the effectiveness of animal passage structures. He has lead efforts to develop standards for road-stream crossing structures, survey protocols for assessing crossing structures for aquatic organism passage, and approaches for prioritizing structures for replacement.

Bradley Compton is a research associate at the Department of Environmental Conservation at UMass Amherst. Research interests include: landscape ecology, turtle ecology, vernal pool ecology, and the application of ecological modeling to conservation, both for landscapes and individual species. He has been involved in the design and implementation of the CAPS project since 2000.

Kevin McGarigal is a professor of landscape ecology in the Department of Environmental Conservation at UMass Amherst. Research interests include: landscape ecology, including methods for quantifying landscape pattern, identifying agents of pattern formation, assessing the affect of landscape pattern on ecological processes, and modeling changes in pattern and process over time; metapopulation dynamics of vernal pool amphibians; fire ecology and management;

and conservation of biological diversity. He has led efforts to develop decision-support systems for conservation and forest management, and is the principal developer of the FRAGSTATS software for quantifying the structure of landscape mosaics.

REFERENCES CITED

- Beier, P., D.R. Majka, and W.D. Spencer. 2008. Forks in the road: choices in procedures for designing wildland linkages. *Conservation Biology* 22(4): 836-851.
- Calabrese, J.M. and W.F. Fagan. 2004. A comparison-shopper's guide to connectivity metrics. *Frontiers in Ecology and Environment* 2(10): 529-536.
- Chetkiewicz, C.L.B., C.C. St. Clair, and M.S. Boyce. 2006. Corridors for conservation: integrating pattern and process. *Annual Review of Ecology, Evolution, and Systematics*. 37:317-342.
- Compton, B.W., K. McGarigal, S.A. Cushman, and L.R. Gamble. 2007. A resistant-kernel model of connectivity for amphibians that breed in vernal pools. *Conservation Biology* 21(3):788-799.
- Crooks, K.R., and M.A. Sanjayan, editors. 2006. *Connectivity Conservation*. Cambridge University Press, New York.
- Czucz, B., A. Csecserits, Z. Botta-Dukat, G. Kroel-Dulay, R. Szabo, F. Horvath, and Z. Molnar. 2011. An indicator framework for the climatic adaptive capacity of natural ecosystems. *Journal of Vegetation Science* 22:711-725.
- Elmqvist, T., C. Folke, M. Nystrom, G. Peterson, J. Bengtsson, B. Walker, and J. Norberg. 2003. Response diversity, ecosystem change, and resilience. *Frontiers in Ecology and the Environment* 9:488-494.
- Estrada, E. and O. Bodin. 2008. Using network centrality measures to manage landscape connectivity. *Ecological Applications* 18(7): 1810-1825.
- Fagan, W.F. and J.M. Calabrese. 2006. Quantifying connectivity: balancing metric performance with data requirements. In: Crooks, K.R. and M.A. Sanjayan (eds.). *Connectivity conservation: Maintaining connections for nature*. Cambridge University Press. Pgs. 297-317.
- Forman, R. T.T., D. Sperling, J. A. Bissonette, A. P. Clevenger, C. D. Cutshall, V. H. Dale, L. Fahrig, R. France, C. R. Goldman, K. Heanue, J. A. Jones, F. J. Swanson, T. Turrentine, & T. C. Winter. 2003. *Road Ecology; Science and Solutions*. Island Press, Covelo, California.
- Fuller, T., and S. Sarkar. 2006. LQGraph: A software package for optimizing connectivity in conservation planning. *Environmental Modelling & Software* 21(5): 750-755.

- Gibbs, J. P., and W. G. Shriver. 2002. Estimating the effects of road mortality on turtle populations. *Conservation Biology* 16:1647-1652.
- Hels, T., and E. Buchwald. 2001. The effect of road kills on amphibian populations. *Biological Conservation* 99:331-340.
- Hilty, J.A., W.Z. Lidicker, A.M. Merenlender. 2006. *Corridor ecology: The science and practice of linking landscapes for biodiversity conservation*. Island Press, Washington, DC.
- Kindlmann, P. and F. Burel. 2008. Connectivity measures: a review. *Landscape Ecology* 23:879-890.
- Merriam, G. 1984. Connectivity: A fundamental ecological characteristic of landscape pattern. In: Brandt, J. and Agger, P. (eds), *Proceedings First international seminar on methodology in landscape ecological research and planning*. Theme I. International Association for Landscape Ecology. Roskilde Univ., Roskilde, pp. 5-15.
- River and Stream Continuity Partnership, 2010. "Field Data Form: Road-Stream Crossing Inventory" and "Instruction Guide for Field Data Form: Road-Stream Crossing Inventory." May 27, 2010.
- Roberts, J.J., B.D. Best, D.C. Dunn, E.A. Treml, and P.N. Halpin. 2010. Marine Geospatial Ecology Tools: An integrated framework for ecological geoprocessing with ArcGIS, Python, R, MATLAB, and C++. *Environmental Modelling & Software* 25:1197-1207.
- Saura, S., and L. Pascual-Hortal. 2007. A new habitat availability index to integrate connectivity in landscape conservation planning: comparison with existing indices and application to a case study. *Landscape and Urban Planning* 83: 91-103.
- Taylor, P. D., L. Fahrig, K. Henein, and G. Merriam. 1993. Connectivity is a vital element of landscape structure. *Oikos* 68:571-573.
- Theobald, D.M., J.B. Norman, and M.R. Sherburne. 2006. *FunConn v1 User's Manual: ArcGIS tools for Functional Connectivity Modeling*. Natural Resource Ecology Lab, Colorado State University. April 17, 2006. 47 pages. www.nrel.colostate.edu/ftp/theobald.
- Theobald, D.M., K.R. Crooks, and J.B. Norman. (In Press). Assessing effects of land use on landscape connectivity: loss and fragmentation of western US forests. *Ecological Applications*.
- With, K.A., R.H. Gardner, and M.G. Turner. 1997. Landscape connectivity and population distributions in heterogeneous environments. *Oikos* 78:151-169.
- With, K.A. 1999. Is landscape connectivity necessary and sufficient for wildlife management? Pages 97-115 in J. A. Rochelle, L. A. Lehmann, and J. Wisniewski, (eds). *Forest fragmentation: wildlife and management implications*. Brill, The Netherlands.