Conservation Assessment and Prioritization System (CAPS) Western Massachusetts Assessment

Final Report
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Introduction

The Massachusetts Wetlands Protection Act protects those areas within its jurisdiction that provide "important" habitat for wildlife. The statute does not further define "important" but the Massachusetts Department of Environmental Protection (MassDEP) has determined that the state Legislature intended to protect "wildlife habitat which is important to wildlife from a regional or statewide perspective." These regulations are difficult to implement on a case-by-case basis, however, because of the diversity and variability of habitat requirements for over 100 wildlife species that use wetlands, the cumulative nature of habitat impacts over time, and a wide range in opinion as to what constitutes "important" wildlife habitat.

In March 2006, MassDEP issued the "Massachusetts Wildlife Habitat Protection Guidance for Inland Wetlands." MassDEP adopted a new assessment and mapping system, CAPS (the Conservation Assessment and Prioritization System), developed by UMass that would easily allow regulators, applicants and others to identify potentially

important wildlife habitat both regionally and statewide and to increase the level of review required for projects within these areas.

    CAPS is a coarse-filter approach for assessing the ecological integrity of lands and waters and subsequently identifying and prioritizing land for biodiversity conservation. We define ecological integrity as the ability of an area to support biodiversity and the ecosystem processes necessary to sustain biodiversity, over the long term. Our approach assumes that by conserving intact, ecologically-defined communities of high integrity, we can conserve most species and ecological processes. Applications of CAPS include helping towns, land trusts, and other conservation organizations target land for protection, assessing alternatives for development projects (such as highways), and prioritizing infrastructure upgrades (such as wildlife passage and culvert upgrades).

    In the application described here, CAPS results are used to identify important regional or statewide wildlife habitat to support implementation of the Wetlands Protection Act in Massachusetts. CAPS analyses were performed for 112 towns in western Massachusetts (42% of the state). These analyses were used to identify 40% of the land within the study area estimated to have the highest ecological integrity. Important habitat maps will be produced for these 112 towns, and posted on the web at http://masscaps.org/. In addition, maps indicating the variation in modeled ecological integrity, suitable for non-regulatory land protection efforts will be posted on the web. All source data and results in GIS format are available on the enclosed DVD.

    In addition to this modeling work, in 2007 , for the first time, we carried out a season of field work to test and validate CAPS predictions of ecological integrity. We sampled several field-based metrics, including exotic invasive earthworms, exotic invasive plants, macrolichens, and native plant species richness. Nearly 100 plots in forested uplands were sampled in the Deerfield watershed.

Overview of CAPS

    CAPS is an approach to prioritizing land for conservation based on the assessment of ecological integrity of ecological communities within an area. The quantitative nature of CAPS not only facilitates identifying and prioritizing areas for biodiversity conservation (e.g., designating critical natural areas), but it allows for comparisons among alternative scenarios in a wide variety of applications, including evaluating and quantifying direct and indirect impacts of development projects and serve as a basis for mitigation and compensation to prevent loss of habitat and biodiversity value; and prioritizing ecological restoration projects. Also, CAPS is designed to conduct assessments at different scales (e.g., watershed, ecoregion, state) and integrate them into a strategic blueprint for conservation, providing the best opportunity for the development of "nested" conservation strategies at the local, regional, and state scales.

    Integrity metrics - Beginning with a digital base map depicting various classes of developed and undeveloped land and a number of auxiliary layers representing anthropogenic alterations (such as road traffic or imperviousness) and ecological variables (such as wetness or stream gradient), the first step involves computing a

variety of landscape metrics to evaluate ecological integrity for every point in the landscape. A metric may, for example, take into account how well a point in the landscape is connected to similar points, the intensity traffic on nearby roads, or the expected vulnerability to invasions by exotic plants. Various metrics are applied to the landscape and then integrated in weighted linear combinations as models for predicting ecological integrity. This process results in a final Index of Ecological Integrity (IEI) for each point in the landscape based on models constructed separately for each ecological community. Intermediate results are saved to facilitate analysis—thus one can examine not only a map of the final indices of ecological integrity, but maps of road traffic intensity, connectedness, microclimate alterations, and so on. Note that metrics do not apply to developed land—all cells corresponding to developed land cover types are given an ecological integrity index of zero, even though we recognize that even developed land may contribute to the conservation of biodiversity.

Combining Metric Results – Results from the landscape metrics are rescaled, weighted, and then combined into an overall index of ecological integrity. First, the results of each metric are rescaled by percentiles for each community so that, for instance, the best 10% of marshes have values ≥ 0.90, and the best 25% have values ≥ 0.75. This is done to adjust for differences in units of measurement among metrics and to account for differences in the range of metric values for each community. The rescaling by community is done to facilitate identifying the "best" of each community, as opposed to the best overall – which is strongly biased towards the dominant, matrix-forming communities. Next, the rescaled values are weighted (weights assigned by the user), to reflect the relative importance of each metric for each community (Appendix C), and then added together to compute an overall index of ecological integrity. Thus, the final index of ecological integrity for each cell is a weighted combination of the metric outputs for that cell, based on the community the cell falls in.

Identifying and Prioritizing Land for Conservation – Among its many uses, the index of ecological integrity can be used alone or in combination with other approaches to identify and prioritize lands for conservation. The index can be used, for example, to identify the top 10% or 30% of the land (in terms of ecological integrity) in an area that will hopefully provide the greatest ecological value and therefore provide an effective and credible basis for a land conservation strategy. It is especially important to note that the assessed ecological integrity of land in an area (and therefore the lands identified and prioritized for conservation) depends on the geographic extent of the analysis area. This is so because the rescaling of the metrics is done to identify the best of the available lands, but the "available lands" varies with geographic location and extent. Thus, the best example of a particular community within a certain geographic extent might be a relatively poor example when assessed over a much larger extent. For this reason, the index of ecological integrity can be rescaled to reflect the range of conditions within any sub-landscape or geographic extent less than the entire analysis area. For example, the index might be rescaled within each of several logical ecological units such as watersheds or ecoregions.

Objectives

In 2006, we completed initial CAPS analyses and produced important habitat maps for 50 towns in the Highlands and Housatonic regions of western Massachusetts. In this second phase, we have updated the initial maps and completed analysis for an additional 62 towns.

Each map shows polygons representing the 40% of the landscape with the highest wildlife habitat value. These polygons represent "Habitat of Potential Regional or Statewide Importance" as described in MassDEP's document Massachusetts Wildlife Habitat Protection Guidance for Inland Wetlands. Project proposals within the polygons that are also within Wetland Protection Act jurisdiction may trigger a requirement for a detailed Wildlife Habitat Evaluation as part of routine wetlands permitting.

This project had the following objectives:

1. Compile a comprehensive land cover map, including developed land cover classes and natural communities for the assessment area.

2. Update and improve the CAPS software to make analyses more convenient and reliable, and to reflect our evolving vision of how best to capture ecological integrity.

3. Conduct the CAPS analysis to produce maps of the ecological integrity of undeveloped lands throughout the region, specific watersheds, and within individual towns.

4. Carry out field work to sample several biological indicators across ca. 100 plots in the Deerfield watershed as a partial validation of the CAPS index of ecological integrity.

Project Area

Our analysis was done for all of Western Massachusetts west of the Millers, Chicopee, and Connecticut River watersheds, inclusive (Fig. 1). This area includes 112 towns (plus several partial towns for which we did analyses but did not produce maps) covering nearly 9,000 km² (2.2 million acres; about 42% of Massachusetts).

Much of this area is still largely rural, the result of geographic isolation and slow growth rates during many of the last several decades, but it includes the urban area around Springfield, several current and former mill towns such as Pittsfield, Holyoke, and North Adams, and the suburbanizing agricultural areas of the Connecticut and Housatonic valleys.

Methods

Input Data

GIS data from a variety of sources were combined to create a base map depicting natural communities, developed land types, and roads. Appendix B describes the GIS data used. All data are mapped in 30 m grids. The final land cover layer depicts natural communities, development and roads. See Appendix A for the land cover classification. Several other layers depict subsets of this final land cover, including roads, railroads, and streams layers. Finally, several ancillary layers are used by specific metrics. These include the flow and stream flow grids, the flow resistance grid, imperviousness, and point-source pollution.
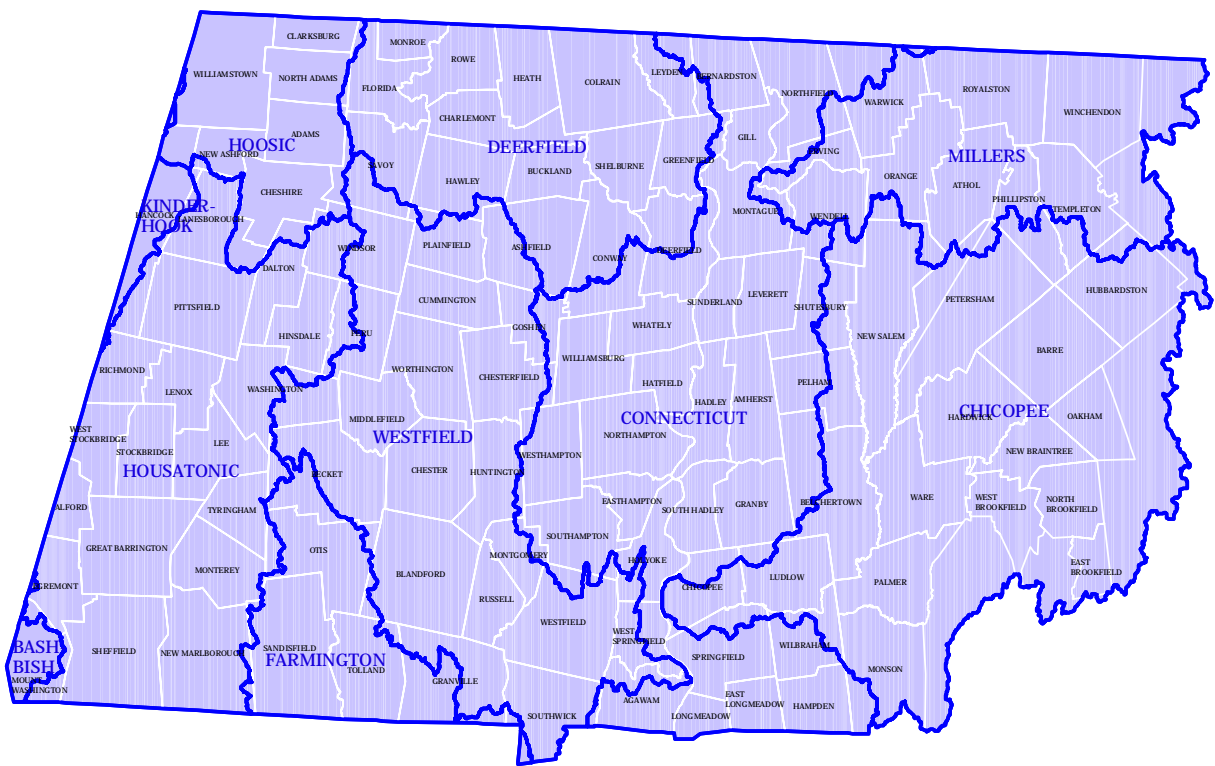

Fig. 1. Project area. The CAPS analysis was done for the Hoosic, Kinderhook, Bash Bish, Housatonic, Deerfield, Westfield, Farmington, Connecticut, Millers, and Chicopee watersheds. Maps were produced for the 112 towns that fall within these watersheds.

Data Accuracy

The CAPS analysis for western Massachusetts was done entirely with available data. These GIS data come from a variety of sources, and the quality of these data are variable. We integrated these data sources into a single land cover map, with several parallel data layers, including a flow grid, watershed resistance, and imperviousness. We put

considerable effort into integrating these input layers in ways that maximized the accuracy of available data, while making sure the final map generally makes sense, both visually and to the CAPS metrics. Because input data came from several different sources, we have no estimate of the accuracy of the final map, nor of the effect errors in the base map may have on final CAPS results. Nobody should have any illusions that the base map presents a "true" depiction of the landscape—a comparison of the landcover with aerial photos or with familiar places will turn up errors in classification and position. Furthermore, the classification is fairly coarse, and distinctions between deciduous and mixed forested wetland, or between marsh and shrub swamp, are necessarily arbitrary. Many of these communities change over time, so our snapshot based on data generated over several years may depict today's beaver pond as yesterday's forested wetland. These issues are important to understand and to communicate clearly to stakeholders and users of the results—nobody should be surprised when they find data errors in their backyards.

Given these caveats, we believe that the effects of many of the data errors will be relatively small. CAPS operates at fairly broad scales, looking at the effects of the surrounding landscape on any particular point. Small errors in classification and placement (small roads and streams omitted, marshes slightly shifted, small forest patches lost because of the grain of the map) will usually have a small but negligible effect on final results. We plan to evaluate the effects of various kinds of errors on CAPS results in the future.

The coarseness of the classification scheme is perhaps a larger issue. Available data necessitated lumping many different forest communities into a single class; likewise, many rare and small-patch-forming communities are omitted. This leaves CAPS unable to compare patches of rich mesic forest to other patches of rich mesic forests, or to evaluate acidic rocky outcrops.

CAPS Analysis

The full details of the CAPS analysis conducted for this project are beyond the scope of this report. Briefly, once the input data layers are created, analysis in CAPS requires a model to be defined for each natural community or broad ecological system. Each community's model entails selecting a number of metrics, parameterizing them for that community, and weighting them by importance for that community. This model parameterization was originally done by three expert teams as part of the Housatonic watershed pilot project. Additional parameterization and some necessary modifications were done for this project by Kevin McGarigal, Scott Jackson, and Brad Compton. The metrics selected for each of the communities and their relative weightings are listed in Appendix C.

The parameterized model is run on the input layers using the CAPS software, written at UMass by Brad Compton and Eduard Ene. This software produces an output grid for each metric. These output grids are then rescaled, weighted, and combined into final index of ecological integrity (IEI) values. The IEI for each cell is a weighted combination of the metric outputs for that cell, based on the community the cell falls in. Results are

rescaled by percentiles, so that, for instance, the best 10% of marshes have values ≥ 0.90, and the best 25% have values ≥ 0.75. A separate analysis allows each cell to be assessed in the context of its watershed or ecoregion. For this analysis, the IEI is rescaled by percentiles within each watershed or ecoregion. For example, if the IEI is rescaled by watershed, a marsh with a value of 0.85 would be interpreted as being in the 85th percentile of marshes for its watershed.

We rescaled results at three extents (full extent, rescaled by major watershed, and rescaled by ecoregion), plus a final integrated rescaling. The integrated rescaling takes the maximum of full and watershed extent for wetland and aquatic communities, and the maximum of full and ecoregion extent for upland communities. The resulting IEI is then rescaled again by community to preserve the interpretation (i.e., the top 10% of IEI values represent 10% of the landscape).

Field Methods

Field work was carried out in the Massachusetts portion of the Deerfield River watershed during the summer of 2007 (Fig. 2). The river flows from the Berkshire Plateau southeast toward its confluence with the Connecticut River, draining about 900 km² within MA, with elevations ranging from about 50 m to 850 m above sea level. The watershed is primarily forested and rural but also encompasses some urban and large tracts of agricultural lands. Roughly 80% of this watershed is privately owned (Deerfield River Watershed Open Space Planning Committee 2004).

We sampled 98 25-meter radius plots in deciduous-dominated forests (Fig. 2) from June to early October) for birds, vascular plants, epiphytic macrolichens, and terrestrial earthworms. Plot locations were randomly stratified across elevation and IEI gradients. Bird count data were not used because not all plots were sampled early enough in the season for data to be meaningful.

Vascular plants were tallied on four 25-meter transects using a point intercept method, followed by a 20-minute walk around the plot to list any species not found along transects.

Percent cover of epiphytic macrolichens was estimated on tree hosts from base to 6 m above the base. Trees greater than 4 inches dbh (10.2 cm) were selected using a 15 BAF prism. A cover class was assigned for each macrolichen on each tree. Tree sampling was followed by a 20 minute walk around the plot to list any additional species found in litterfall.

Exotic earthworms are considered a stressor in this study because of the rapid turnover of the forest floor they may facilitate. Middens of the common nightcrawler, *Lumbricus terrestris*, were counted, and juvenile and adult earthworm species were extracted from the soil using a liquid mustard extraction (Hale et al. 2005) on each of three small subplots. The entire 25 m radius plot was searched for 15 minutes to capture additional earthworm species and note the presence of middens elsewhere on the plot.
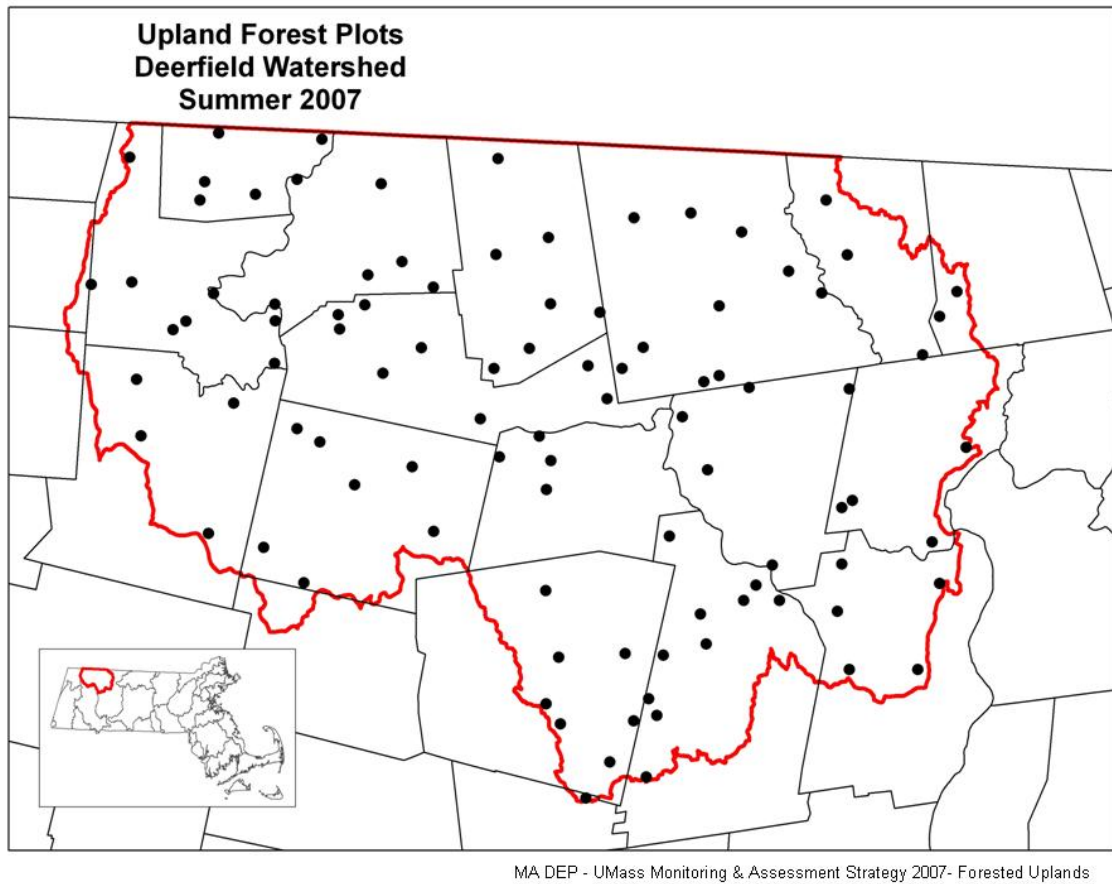
Fig 2. Location of forested upland plots in the Deerfield River Watershed of
Massachusetts.

Results

CAPS results are best explored interactively, using a GIS that can display grids (e.g.,
ArcView or ArcMap). The attached DVD includes input data, raw metric output, scaled
metric output, and the IEI for each extent (full, watershed, ecoregion, and integrated).
The attached CD contains a subset of these data. See Appendix E for details.

The most useful results are the landcover grids and the IEI grids. The landcover grid
(Fig. 3) represents developed land and broad natural communities. Landcover classes
and names are listed in Appendix A, and ArcView legends are provided with the data.
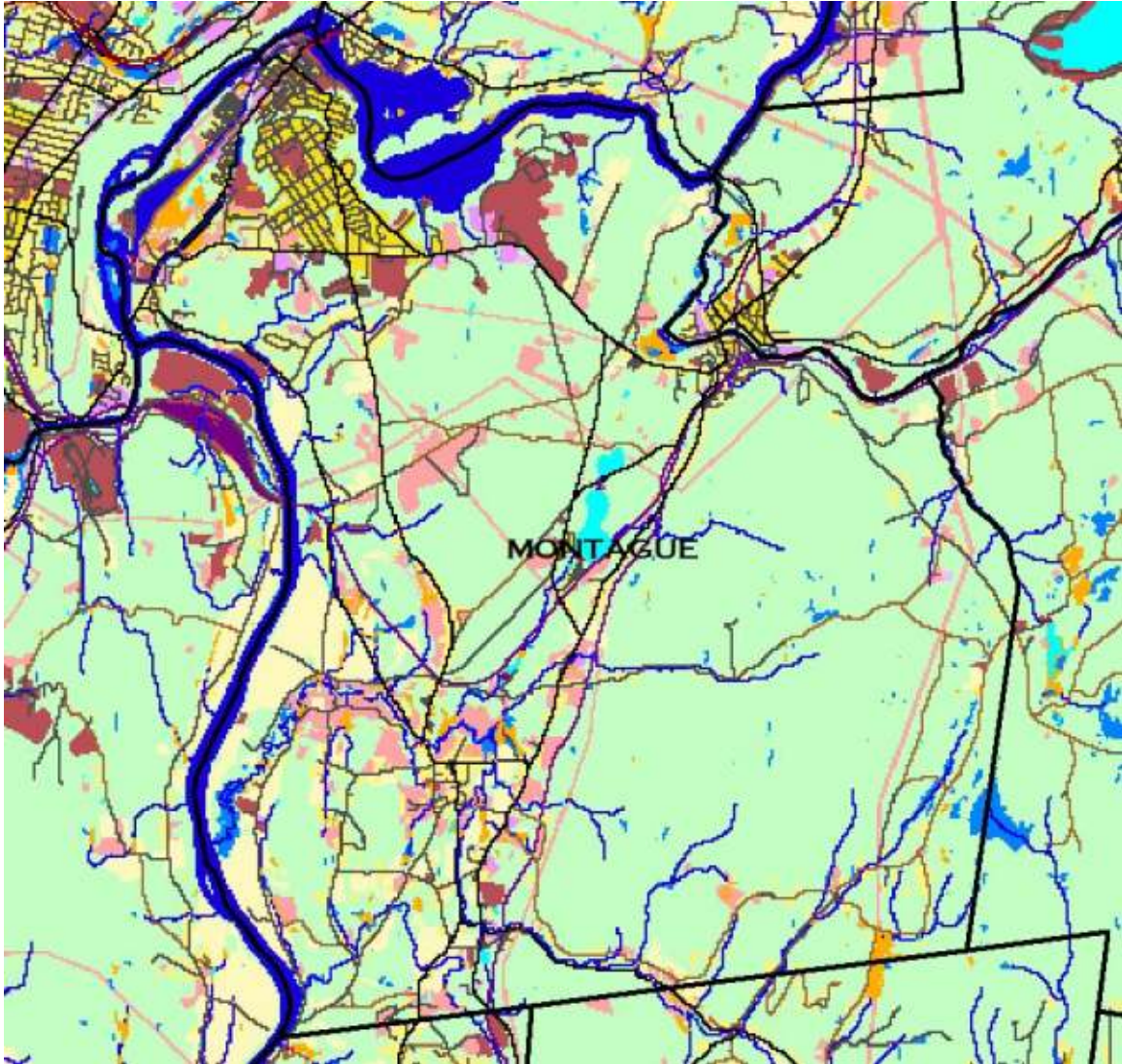
Fig. 3. Landcover for the town of Montague.

The IEI grids give the Index of Ecological Integrity at four scales: the entire project area (Fig. 4), watershed, ecoregion, and integrated (Fig. 5). Because IEIs are scaled from 0 to 1 by percentiles within each community, images such as Figs. 4 and 5 tend to be overwhelmed by values for forest communities, because the landscape of western Massachusetts is mostly forest.

Fig. 4. Index of ecological integrity (IEI) for town of Montague, scaled to the entire project area. Darker areas denote higher IEI values; white areas are developed land.

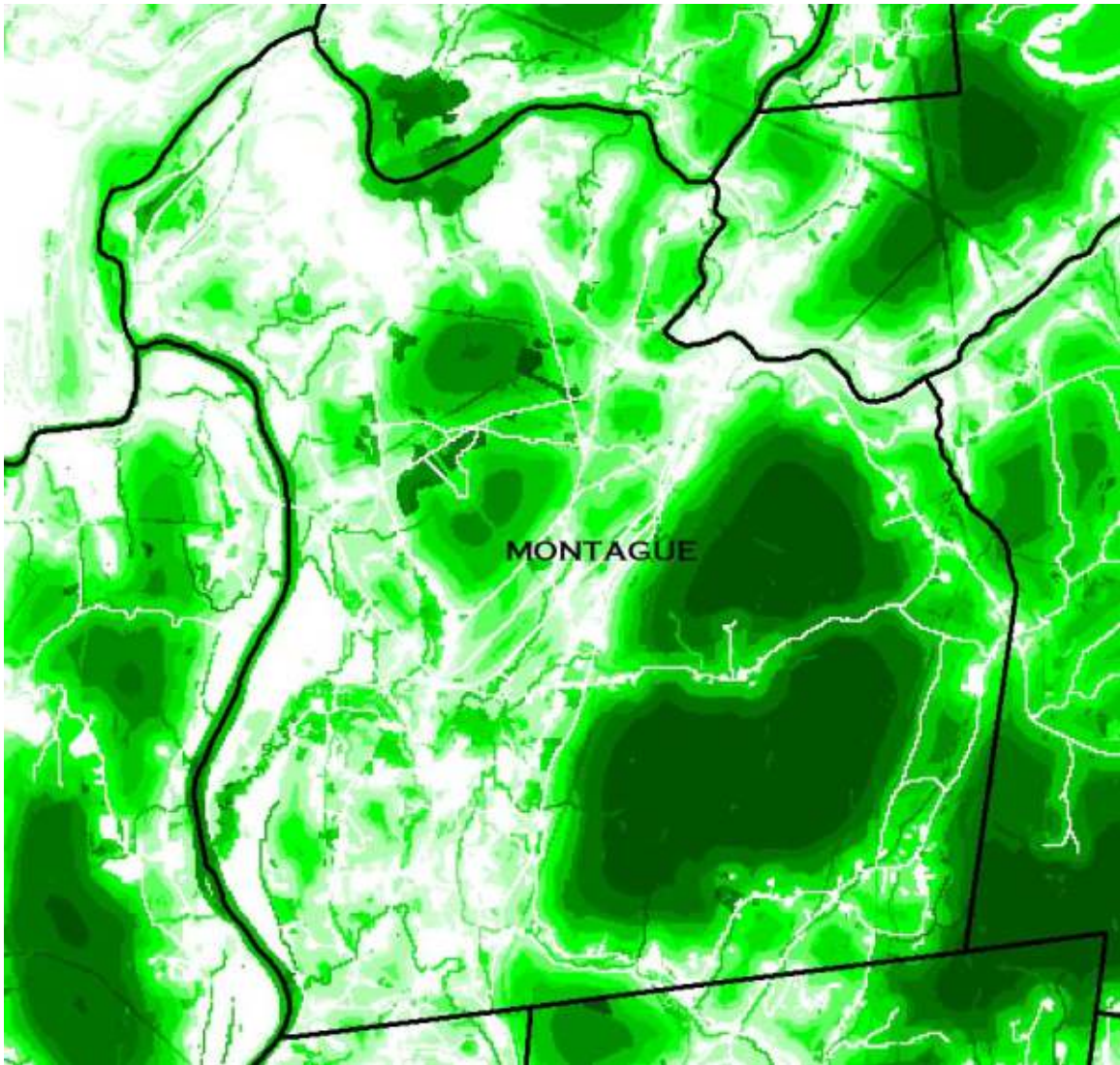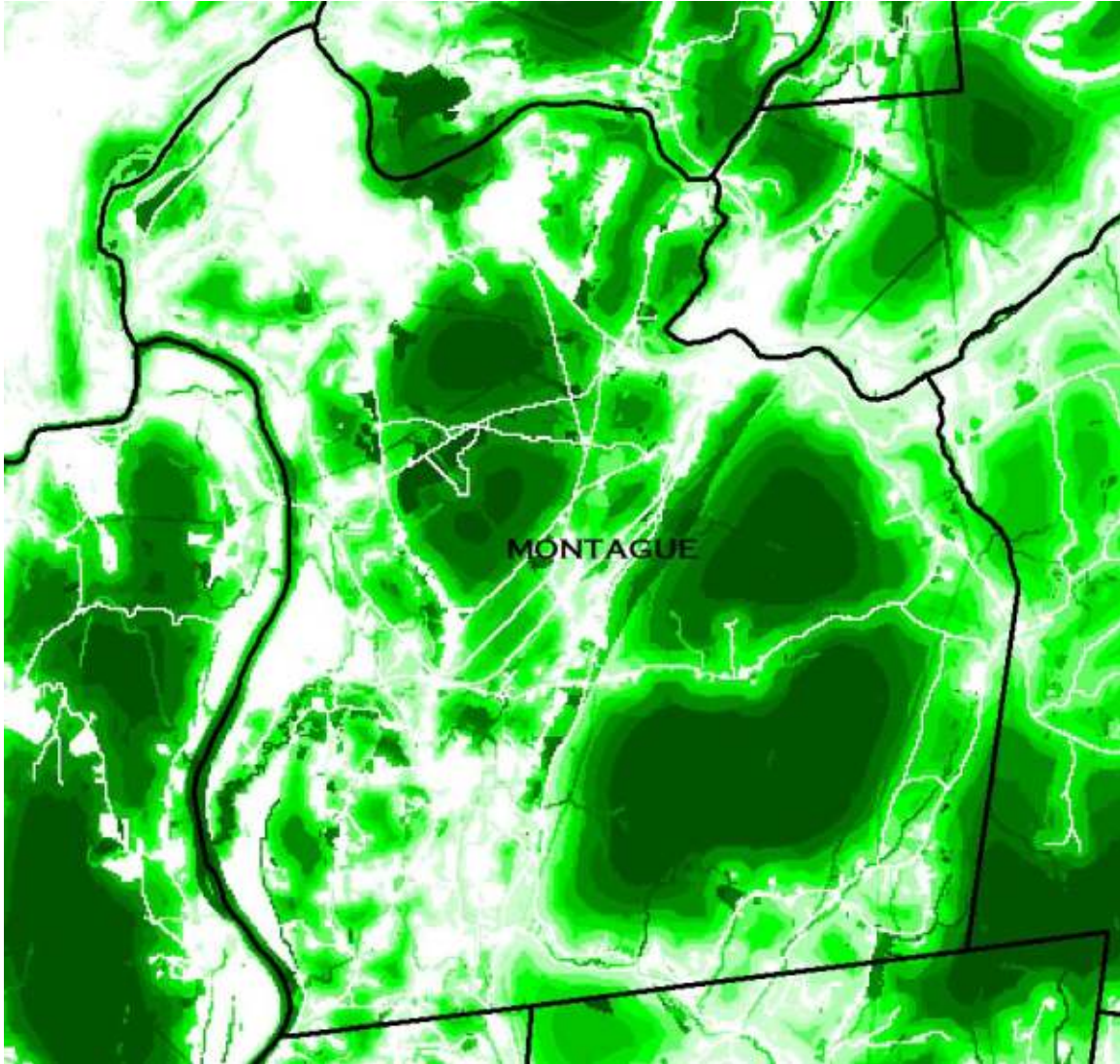Fig. 5 Index of ecological integrity (IEI) for town of Montague, integrated across full extent, watershed, and ecoregion. Note that results are somewhat different from IEI for the full extent (Fig. 4).

Priority areas can be highlighted by showing only the top x%, for instance the top 40% (IEI ≥ 0.60, Fig. 6). Because the IEI is scaled by percentiles within each community, these images show the top 40% in each community. Depictions of the top x% may keep the (still meaningful) gradations, or they can just show polygons of the top x% in each community on top of a reference map, as has been done for the important habitat maps.
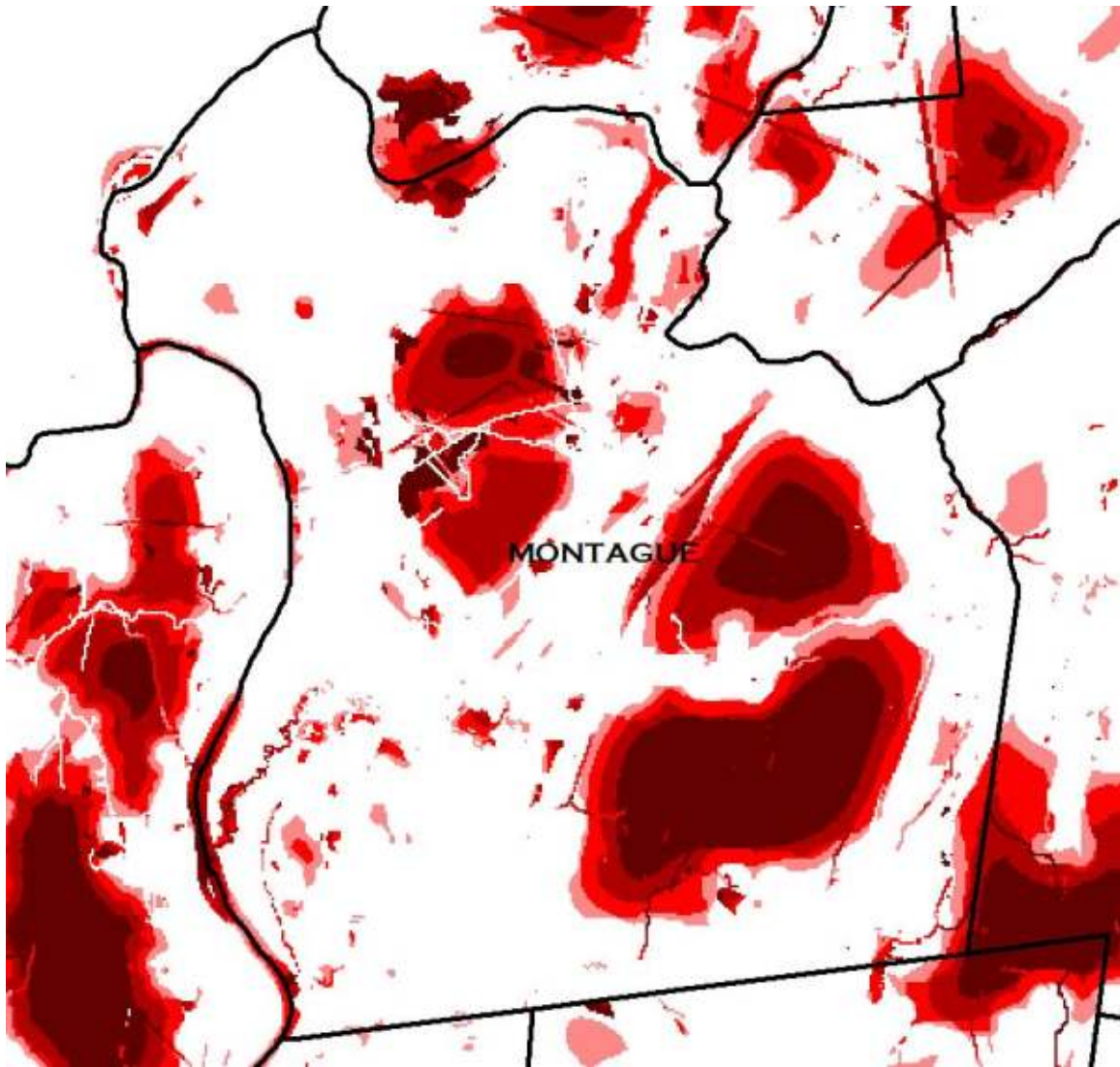
Fig. 6. Index of ecological integrity (IEI), top 40%.

Finally, individual metrics may be examined. Here are examples of connectedness (Fig. 7), microclimate alterations (Fig. 8), and wetland buffer insults (Fig. 9). Examining results of individual metrics can help a user understand why areas were given a high or low IEI, and can be used for specific purposes (e.g., flagging wetlands with high levels of buffer zone intrusion for site visits).
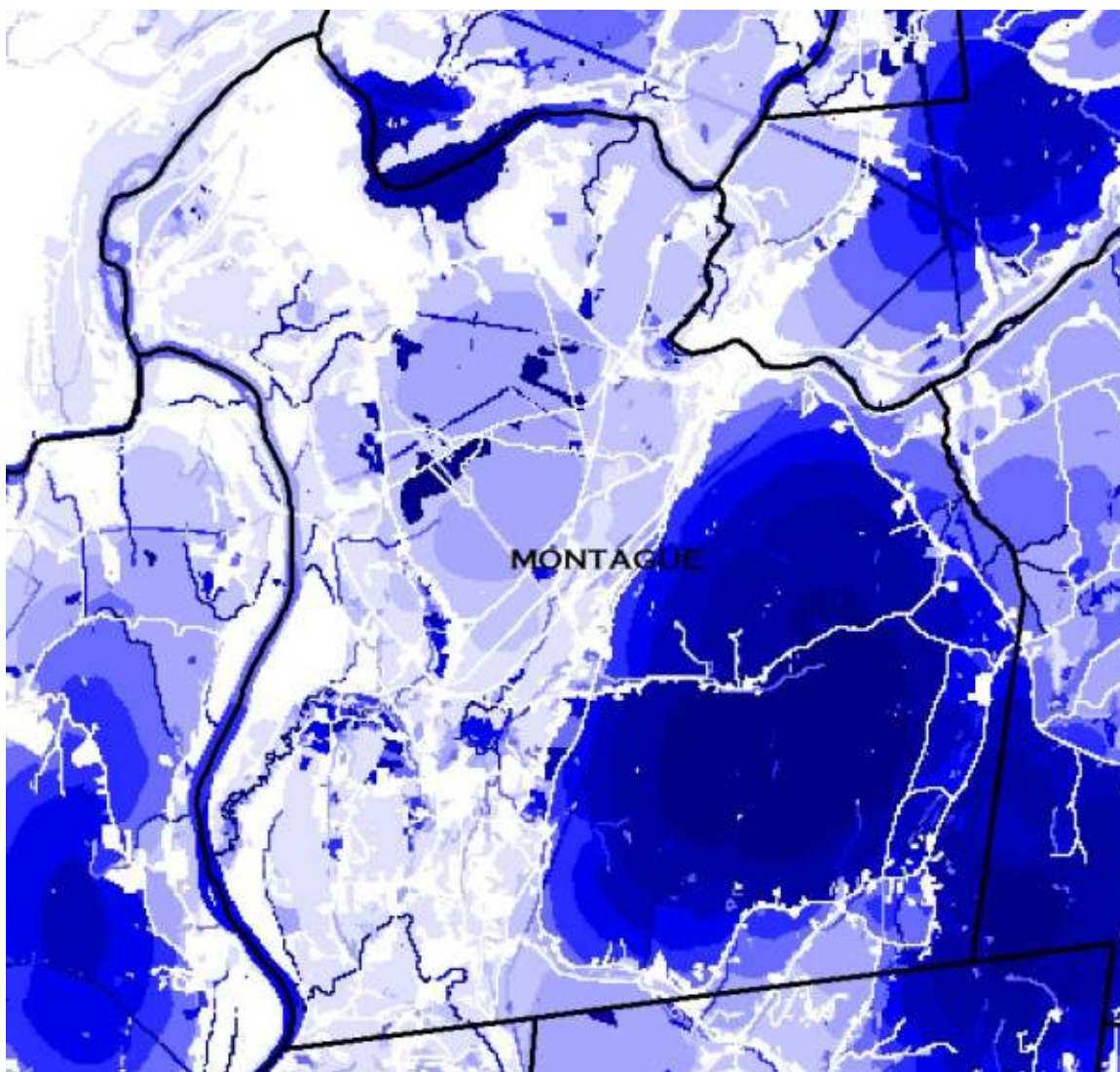
Fig. 7. Connectedness metric for the town of Montague. Darker areas are those more connected to similar areas across the landscape.
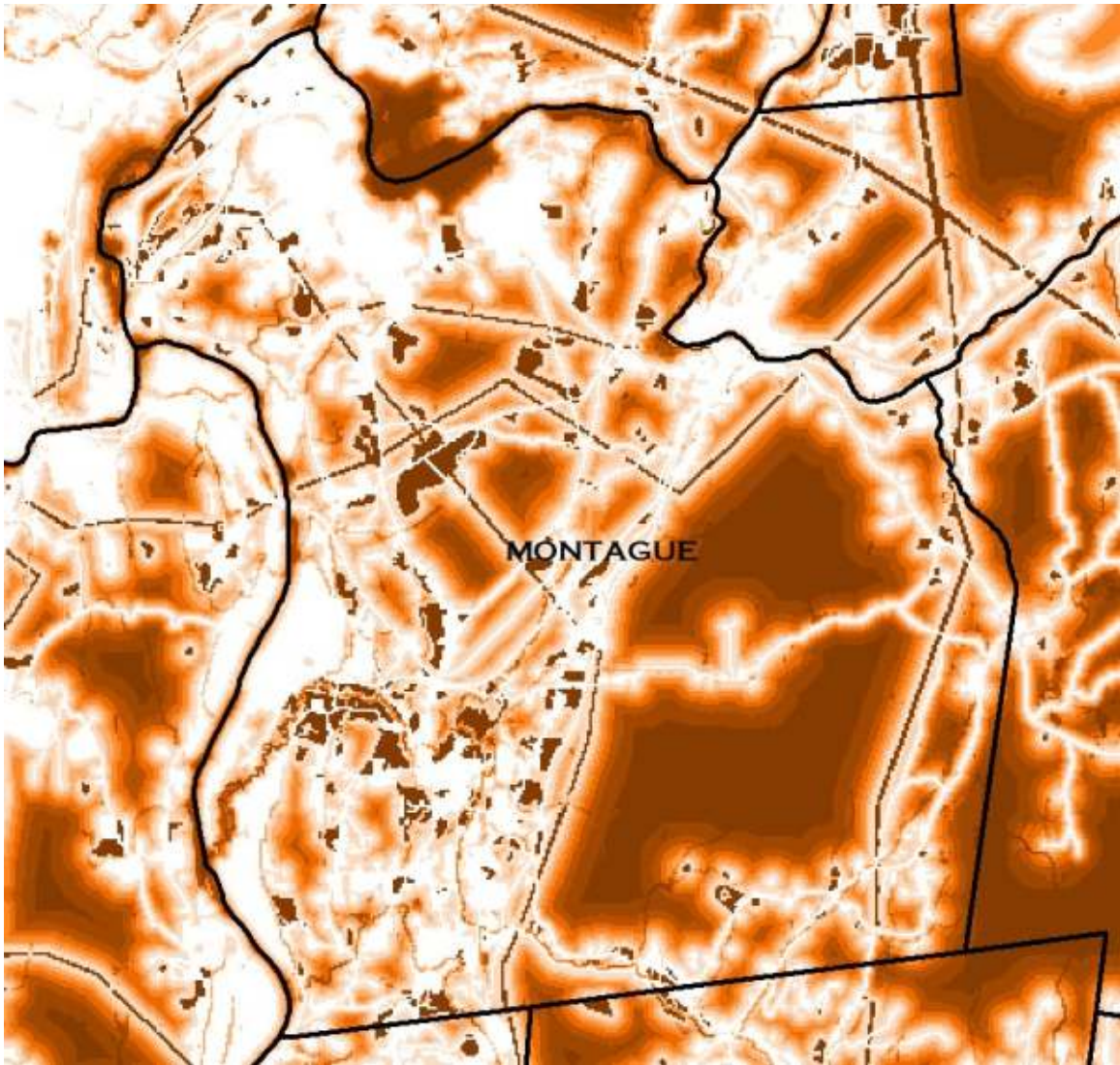
Fig. 8. Microclimate alterations metric for the town of Montague. Light areas, close to anthropogenic edges, are expected to have modified microclimates due to decreased moisture, higher wind, and more extreme temperatures than interior areas.
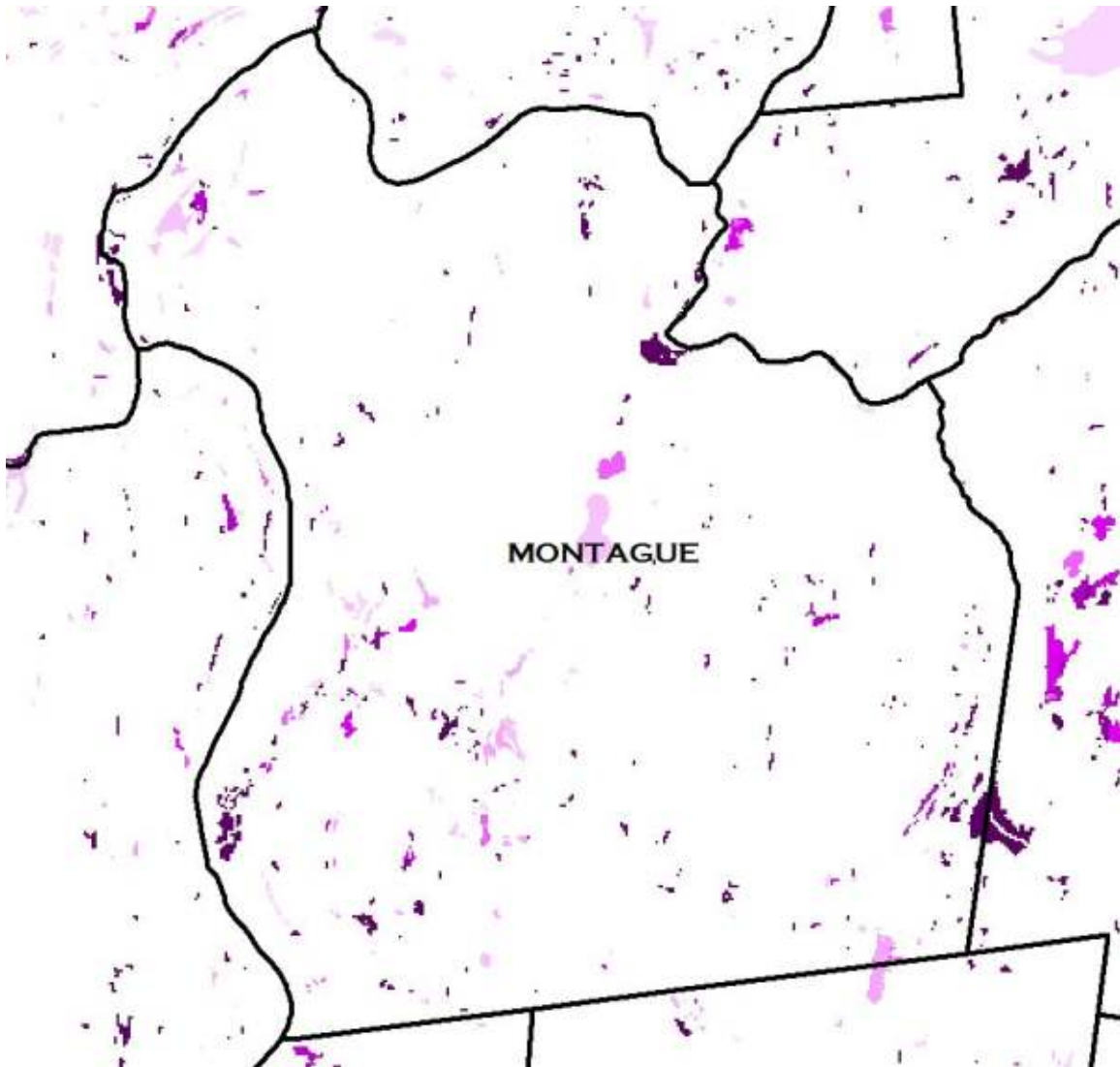
Fig. 9. Wetland buffer insults metric for the town of Montague. This metric is applied only to wetlands. Lighter wetlands have a higher percentage of impervious surface in their 100-ft buffer.

Field Results

We used logistic regressions to explore the relationships between IEI and the field-based condition or stressor metrics. Plant species richness, measured as total number of native species per plot did not correlate significantly with IEI (n=98, r^2=0.10, P=0.28). Epiphytic macrolichens showed a similar pattern as native plant richness. Invasive plants were widespread across the watershed but not abundant, occurring in 26% of plots. As IEI decreased, total cover of invasive plant species increased (n=98, ρ^2=0.06, P=0.009; Fig 10). Although the relationship between IEI and invasive plant cover is rather noisy, it is strong. Although many low-IEI plots were not invaded, nearly all invasive plants found were on low-IEI plots.

15

Until earthworm identifications are completed for this study, we are assuming all are non-native species introduced from Europe and Asia. Fifty-eight percent of all plots had earthworms of any species present. Earthworms were much less likely to be encountered in stands where cover of American beech (*Fagus grandifolia*) was high. As IEI decreased total numbers of earthworms increased (n=98, ρ^2=0.07, P=0.003). Adults of the common nightcrawler and their middens are easily identified in the field (Figs. 11 and 12). Middens were present on 38% of plots. As with total earthworm count, the number of middens increased with decreasing IEI (n=98, ρ^2=0.10, P=0.0003; Fig 13). Much like the data on invasive plants the pattern is noisy but clear—high-IEI plots tended not to be invaded by earthworms. In a study of northern hardwood forests in south-central New York, Suarez et al. (2006) found that forest type and distance to agriculture were the best predictors of earthworm distribution. Similar patterns may emerge in our study upon further analysis.
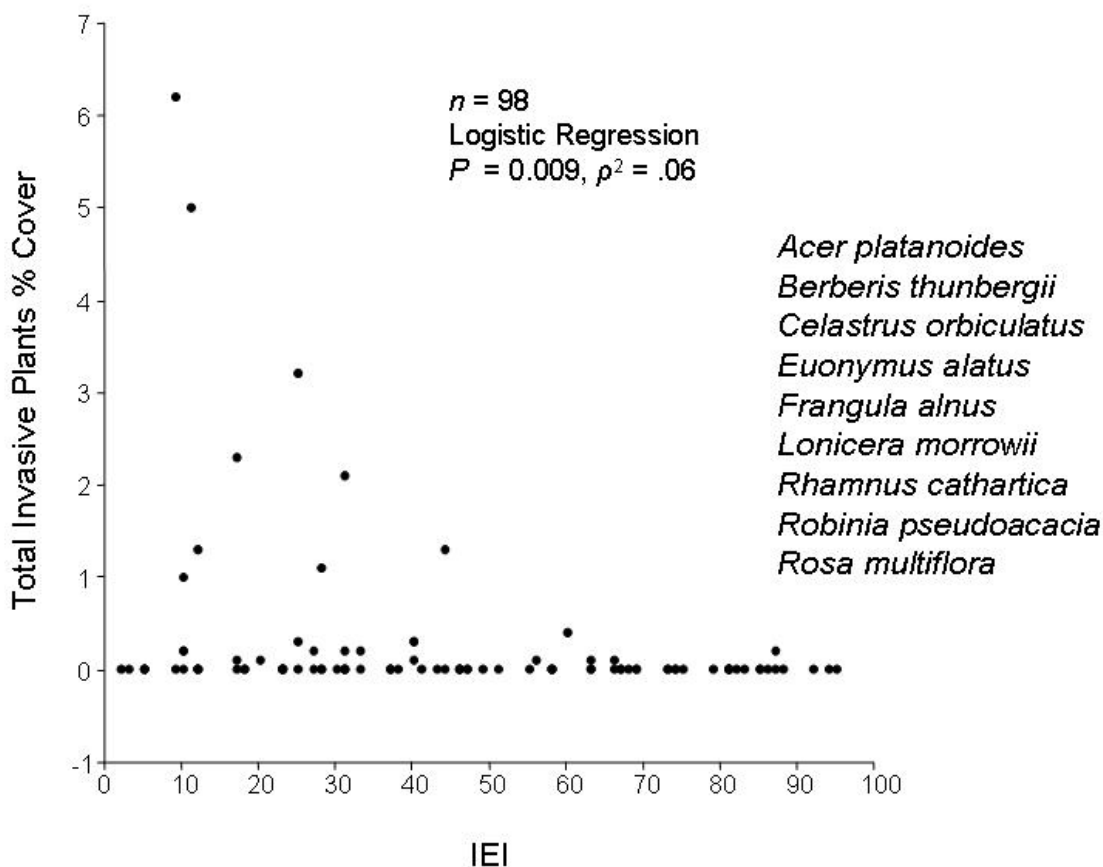
Fig. 10. Percent cover of all invasive plant species by IEI.

Fig. 11. Common nightcrawler, *Lumbricus terrestris*, **adult.**

Fig. 12. Midden of common nightcrawler (*Lumbricus terrestris***).**
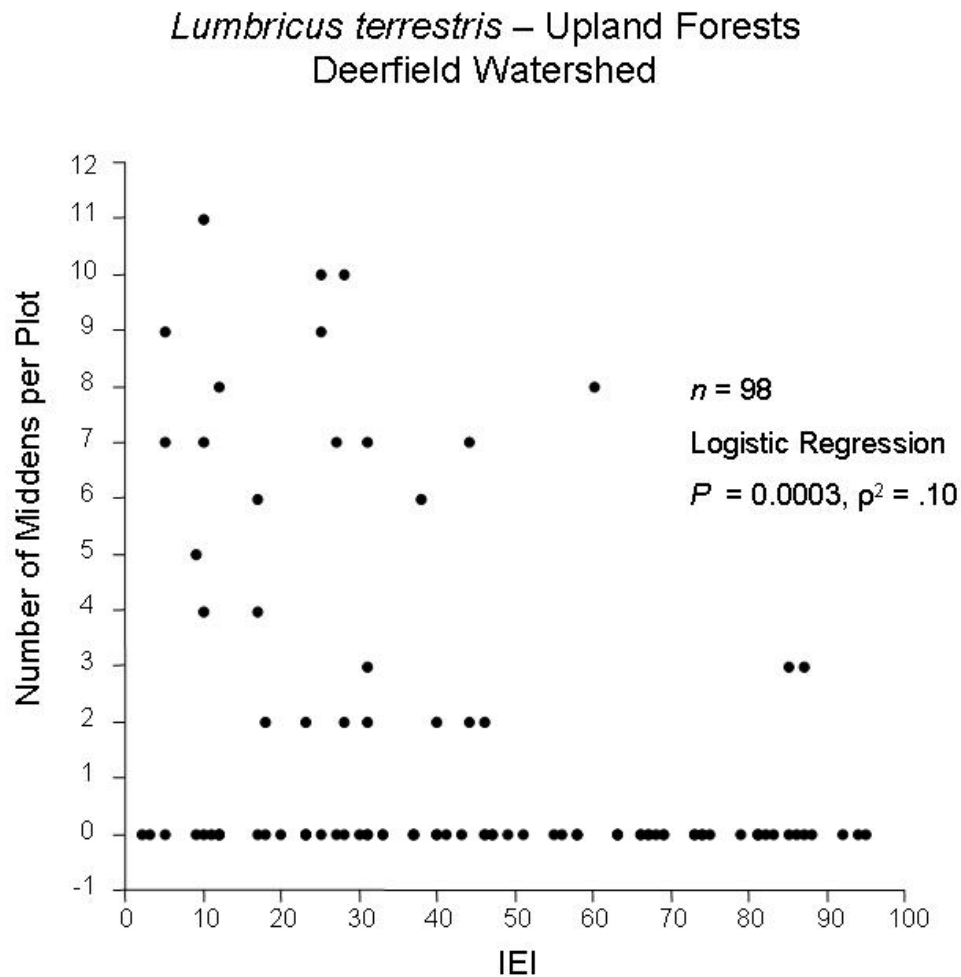
Fig. 13. Number of middens of *Lumbricus terrestris* per plot by IEI.

These results represent a preliminary field-based assessment of the validity of CAPS predictions. CAPS IEI correlated well with field measures of invasiveness (invasive plants, earthworms). Planned fieldwork during 2008 and 2009 will further explore the relationship between CAPS IEI and other metrics and field-sampled indicators of ecological integrity. This research will allow us to calibrate and refine CAPS metrics in the future.

Literature Cited

Deerfield River Watershed Open Space Planning Committee. 2004. Deerfield River Watershed Open Space and Recreation Plan. Unpublished report. Prepared with assistance of the Franklin Regional Council of Governments Planning Department.

Hale, C.M., L.F. Freilich, and P.B. Reich. 2005. Exotic European earthworm invasion dynamics in northern hardwood forests of Minnesota, USA. Ecological Applications 15:848-860.

Suárez, E., G. L. Tierney, T. J. Fahey, and R. Fahey. 2006. Exploring patterns of earthworm distribution in a temperate hardwood forest in south-central New York, USA. Landscape Ecology 21:297-306.

Appendix A: Land cover classes

Land cover classes are listed below, with numeric codes for each class.

Natural Communities

Forests

111	Forests
191	Forested wetland – deciduous
192	Forested wetland – mixed
193	Forested wetland – coniferous

Non-forested uplands

211	Powerline
212	Old field
221	Pasture

Wetlands & aquatic

304	Bog
305	Cranberry Bog
307	Deep marsh
308	Shallow marsh
312	Shrub swamp
351	Pond
352	Lake
353	Vernal pool

Riverine*

411	First order flatwater
412	First order pool-riffle
413	First order plane-bed
414	First order step-pool
415	First order cascade
421	Second order flatwater
422	Second order pool-riffle
423	Second order plane-bed
424	Second order step-pool
425	Second order cascade
431	Third order flatwater
432	Third order pool-riffle
433	Third order plane-bed
434	Third order step-pool
435	Third order cascade
441	Fourth order flatwater
442	Fourth order pool-riffle
443	Fourth order plane-bed
444	Fourth order step-pool
445	Fourth order cascade
451	Fifth order flatwater
452	Fifth order pool-riffle
453	Fifth order plane-bed
454	Fifth order step-pool
455	Fifth order cascade
461	Sixth order flatwater
462	Sixth order pool-riffle
463	Sixth order plane-bed
464	Sixth order step-pool
465	Sixth order cascade

*Encoded as 4og, where o = order (41x – 46x) and g = gradient (4x1 – 4x6).
    Orders: First – Sixth
    Gradients: Flatwater, Pool-riffle, Plane-bed, Step-pool, Cascade

Development & Roads

Developed land

1	Cropland
5	Mining
7	Participatory recreation
8	Spectator recreation
9	Water based recreation
10	Multi-family residential
11	High-density residential
12	Medium-density residential
13	Low-density residential
15	Commercial
16	Industrial
17	Urban open
18	Transportation
19	Waste disposal
26	Golf
29	Marina
31	Urban public
32	Transportation facilities
34	Cemetery
35	Orchard
36	Nursery

Dams

61	Large dam
62	Medium dam
63	Small dam
64	Tiny dam

Roads

71	Expressway
72	Primary highway
73	Secondary highway
74	Light duty road
75	Unpaved road
76	Railroad
81	Culvert
91	Bridge

Appendix B: Input Data Layers

Nonforested Uplands – Three of these communities came from the UMass Resource Mapping Unit's 1999 Land Use: pasture, powerlines, and old fields (from open land).

Wetlands – We used Massachusetts DEP Wetlands. DEP wetlands were photo-interpreted, and are generally of high quality, although beaver pond disturbance/succession has introduced many "errors," most commonly current shrub swamps mapped as forested wetland.

Lakes and Ponds – We used MassGIS 1:25k hydrography to represent lakes and ponds. Ponds were defined as being waterbodies smaller than 5 ha, lakes as those larger than 5 ha. This is based on a logistic regression of sizes of lakes and ponds in areas where NWI falls within the Highlands, because NWI distinguishes between lakes and ponds, whereas DEP wetlands depict all open water as one class.

Vernal Pools – We used Potential Vernal Pools from MassWildlife's Natural Heritage and Endangered Species Program. Potential vernal pools that fell within a larger wetland (up to 0.5 ha) identified the wetland as a vernal pool; others were treated as a single pixel pool (30 m × 30 m).

Streams and Rivers – Streams and rivers are based on our work for Natural Heritage and Endangered Species Projgram's Living Waters project. MassGIS 1:25k stream centerlines were used to define streams. Streams are classified by order and gradient. Order is calculated from the stream centerline data; and gradient is based on the digital elevation model. We identified rivers that flow into the state to correct the order of these stream networks. For rivers wider than 30 m, the open water class from Land Use was used to represent the entire river basin, and the class based on order and gradient was applied to the entire width.

Developed Land – Developed land comes directly UMass Resource Mapping Lab's 1999 Land Use.

Dams – Dams (in four size classes) were developed in collaboration with DEP and Mass Riverways as part of Natural Heritage's Living Waters project. Dams were derived from a MassDEP point shapefile and digitized as lines over stream centerlines overlaid on the MassGIS 1 meter, 1:5000 black and white orthophotos. Dams are treated as a developed type.

Roads and Railroads – Roads are railroads are from MassGIS's 1:25k EOT roads and trains layers. Roads were reclassified into five types based on original road classes as well as surface type (for unpaved roads). We also used interpolated traffic rates from the EOT roads layer.

Elevation – A digital elevation model (DEM) was created by David Goodwin of the UMass Resource Mapping Unit from MassGIS digital terrain model (DTM) elevation contours, elevation points, and topographic breaklines as part of the Living Waters project.

Flow – A flow grid (giving the direction of expected water flow for each cell) based on a digital elevation model was created for all of mainland Massachusetts by our lab as part of the Living Waters project. This flow grid conforms to MassGIS centerline data. We used this flow grid directly.

Aquatic Resistance – We modified the approach of Randhir et al. 2001 (Forest Ecology and Management 143:47-56) to build a time-of-travel grid for each cell in the project area, based on land cover, slope, flow, and stream gradient. This grid was used to define the influence area within the watershed of each point for our watershed metrics.

Point-source Pollution – Point-source pollution was defined by Massachusetts Natural Heritage and Endangered Species Program as part of their Living Waters project. These data are based on an assessment of pollution risk compiled from six DEP and EPA data layers: TRI (Toxic Release Inventory), RCRIS (Resource Conservation and Recovery Information), PCS (Permit Compliance System), MINES (Mineral Industry Locations), IFD (Industrial Facility Discharge Sites), and CERCLIS (Superfund National Priority List Sites) from the EPA Basins 3.0 website (http://www.epa.gov/waterscience/basins/metadata.htm). UST (Underground Storage Tank Locations), GRWTR (Ground Water Discharge Permits), and DEP Solid Waste Facilities point sources are available from MassGIS. See Heritage's Living Waters Technical Report for details.

Imperviousness – Impervious surfaces are from MassGIS. This layer is at 1 m resolution, based on the 2005 orthophotos. Imperviousness is summarized as percent impervious in 30 m cells.

Appendix C: CAPS integrity metrics

These ecological integrity metrics are included in the Conservation Assessment and Prioritization System (CAPS). Integrity metrics include both anthropogenic *stressor* metrics that measure the level of anthropogenic activities exclusively and *resiliency* metrics that measure the combined effect of anthropogenic stressor and landscape context.

Stressor Metrics	
Development & roads	
Habitat loss	Measures the intensity of habitat loss caused by all forms of development in the neighborhood surrounding the focal cell, based on a logistic function of Euclidean distance.
Wetland buffer insults	Measures the adverse effect of impervious surfaces within the 100-foot regulatory buffer around a wetland.
Road traffic intensity	Measures the intensity of road traffic (based on measured road traffic rates) in the neighborhood surrounding the focal cell, based on a logistic function of distance.
Microclimate alterations	Measures the adverse effects of induced (human-created) edges on the microclimate of patch interiors, such as moisture, temperature, and wind. The edge effects metric is based on the "worst" edge effect among all adverse edges in the neighborhood surrounding the focal cell, where each adverse edge is evaluated using a "depth-of-edge" function in which the "effect" is scaled using a logistic function of distance.
Pollution	
Road salt intensity	Measures the intensity of road salt application in the watershed above an aquatic focal cell weighted by road class and the modeled "influence value" for each cell, which is the aquatic distance from the focal cell based on a time-of-flow model. This metric is a surrogate for road salt application rates.
Road sediment intensity	Measures the intensity of road sediment production in the watershed above an aquatic focal cell weighted by road class

	(i.e., size, substrate, gradient) and the modeled "influence value" for each cell, which is the aquatic distance from the focal cell based on a time-of-flow model. This metric is a surrogate for road sediment production rates.
Fertilizer intensity	Measures the intensity of fertilizer application in the neighborhood surrounding the focal cell, based on the aquatic distance from the focal cell based on a time-of-flow model to development classes (primarily agriculture and residential land uses). This metric is a surrogate for fertilizer application rate.
Point-source pollution	Measures the intensity of actual or potential point-sources of pollution (such as permitted discharges into streams, municipal and industrial sewage plants, and underground storage tanks) in the watershed above an aquatic focal cell, weighted by type and size of point source and by the modeled "influence value" for each cell, which is the aquatic distance from the focal cell based on a time-of-flow model.

Biotic alterations

Domestic predators	Measures the intensity of development associated with sources of domestic predators (e.g., cats) in the neighborhood surrounding the focal cell, based on a logistic function of distance to development classes. This metric is a surrogate for domestic predator abundance measured directly in the field.
Edge predators	Measures the intensity of development associated with sources of human commensal mesopredators (e.g., raccoons and skunks) and nest parasites (cowbirds) in the neighborhood surrounding the focal cell, based on a logistic function of distance to development classes. This metric is a surrogate for mesopredator/nest parasite abundance measured directly in the field.
Non-native invasive plants	Measures the intensity of development associated with sources of non-native invasive plants in the neighborhood surrounding the focal cell, based on a logistic function of distance to development classes. This metric is a surrogate for non-native invasive plant abundance measured directly in the field.
Non-native invasive earthworms	Measures the intensity of development associated with sources of non-native invasive earthworms in the

neighborhood surrounding the focal cell, based on a logistic function of distance to development classes. This metric is a surrogate for non-native invasive earthworm abundance measured directly in the field.

Hydrological alterations

Imperviousness	Measures the intensity of impervious surface in the watershed above the focal cell, based on imperviousness and the modeled "influence value" for each cell, which is the aquatic distance from the focal cell based on a time-of-flow model.
Percent impounded	Measures the proportion of the watershed above an aquatic focal cell that is impounded by dams, weighted by the modeled "influence value" for each cell, which is the aquatic distance from the focal cell based on a time-of-flow model.
Upstream road crossings	Measures the number of upstream road crossings per kilometer of stream above an aquatic focal cell weighted by the modeled "influence value" for each cell, which is the aquatic distance from the focal cell based on a time-of-flow model.
Dam intensity	Measures the number of dams in the watershed above an aquatic focal cell weighted by dam size and the modeled "influence value" for each cell, which is the aquatic distance from the focal cell based on a time-of-flow model.

Resiliency Metrics

Connectedness	Measures the disruption of habitat connectivity caused by all forms of development between each focal cell and surrounding cells as well as the "resistance" of the surrounding undeveloped landscape. A hypothetical organism in a highly connected cell can reach a large area with minimal crossing of "hostile" cells. This metric uses a least-cost path algorithm to determine the area that can be reached from each focal cell. The focal cell gets a "bank account," which represents the distance a hypothetical organism could move through the undeveloped landscape. Each cell is assigned a travel cost, based on a resistance matrix, as a function of its ecological similarity to the focal cell. The algorithm then creates a least-cost hull around the focal cell, representing the maximum distance that can be

moved from the cell until the "bank account" is depleted.

Similarity   Measures the amount of similarity between the ecological setting at the focal cell and those of neighboring cells, weighted by a logistic function of distance. Similarity is based on the ecological distance between the focal cell and each neighboring cell, where ecological distance is a multivariate distance across all ecological setting variables.

Appendix D: Metric Parameterizations

This table gives relative weights for each metric by community.

	Development & roads	Habitat loss	Wetland buffer insults	Road traffic intensity	Microclimate alterations	Pollution	Road salt intensity	Sedimentation	Nutrient loading	Point-source pollution	Biotic alterations	Domestic predators	Edge predators	Non-native invasive plants	Non-native invasive earthworms	Hydrological alterations	Imperviousness	Percent impounded	Upstream road crossings	Dam intensity	Resiliency metrics	Connectedness	Similarity
Forest		2		2	1							1	2	2	2							5	3
Forested wetland (deciduous)		2	1	2	1		1	1	1	1			1	2	1							4	2
Forested wetland (mixed)		2	1	2	1		1	1	1	1			1	2	1							4	2
Forested wetland (coniferous)		2	1	2	1		1	1	1	1			1	2	1							4	2
Powerline		4		2								1	2	2	1							5	3
Old field		4		2								1	2	2	1							5	3
Pasture		4		2								1	2	2								5	4
Bog		2	2	1			2	1	2	1			1	1			1					4	2
Deep marsh		2	2	2			1	1	1	1			1	2			1					4	2
Shallow marsh		2	2	2			1	1	1	1			1	2			1					4	2
Shrub swamp		2	2	2			1	1	1	1			1	2			1					4	2
Pond		2	2	2			1	1	2	1			1	1			1					4	2

	Development & roads	Habitat loss	Wetland buffer insults	Road traffic intensity	Microclimate alterations	Pollution	Road salt intensity	Sedimentation	Nutrient loading	Point-source pollution	Biotic alterations	Domestic predators	Edge predators	Non-native invasive plants	Non-native invasive earthworms	Hydrological alterations	Imperviousness	Percent impounded	Upstream road crossings	Dam intensity	Resiliency metrics	Connectedness	Similarity
Vernal pool		2	2	2			2	1	1	1			1	1			1					4	2
Lake		2	2	1			1	1	2	2			1	1			1					4	2
First order streams		2		1	1			1	1	1			1	1			2	1	1	1		6	
Second order streams		2		1	1			1	1	1			1	1			2	1	1	1		6	
Third order streams		2		1	1			1	1	1			1	1			2	1	1	1		6	
Fourth order streams		2		1				1	1	1			1	1			2	1	1	2		6	
Fifth order streams		2		1				1	1	1			1	1			2	1	1	2		6	
Sixth order streams		2		1				1	1	1			1	1			2	1	1	2		6	

Appendix E: GIS Data Directory

This appendix lists all GIS data provided on DVD. The *Landcover grids* and *Final results* are also provided on a CD. All data are Arc/Info grids unless otherwise noted.

Landcover grids
    \landcover\landcover   Landcover map, including roads and streams
    \landcover\landcover.avl   ArcView legend files for the landcover grid

Final results
    \results\final\iei_i   Index of Ecological Integrity, integrated
    \results\final\iei   Index of Ecological Integrity, full extent
    \results\final\iei_w   Index of Ecological Integrity, by watershed
    \results\final\iei_e   Index of Ecological Integrity, by ecoregion

    \results\final\iei.avl   ArcView legend files for CAPS results
    \results\final\watershed   Arc/Info coverage of watersheds
    \results\final\ecoregion   Arc/Info coverage of ecoregions

Auxiliary grids & coverages (source for most: MassGIS)
    \auxil\elevation   Elevation grid, in meters
    \auxil\hillshade   Hillshading grid, for display
    \auxil\slope   Slope grid, in percent slope
    \auxil\slopeln   Logarithm of slope, for prettier viewing
    \auxil\openspace   Protected open space (coverage)
    \auxil\massachusetts   Outline of Massachusetts (coverage)
    \auxil\towns   Massachusetts towns (coverage)

Scaled landscape metric* results
    \results\scaled\...   Rescaled landscape metric results

Raw landscape metric* results
    \results\raw\...   Raw (unscaled) landscape metric results

Input grids
    \caps\roads   Roads
    \caps\rails   Railroads
    \caps\streams   Streams
    \caps\flow   Flow grid
    \caps\strflow   Streamflow grid
    \caps\resist   Watershed resistance grid

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* For a list of landscape metrics and their corresponding grid names, see *CAPS Landscape Metrics*, below.

\caps\point	Point-source pollution
\caps\imperv	Percent impervious

CAPS Landscape Metrics

The following grids are supplied in the \results folder, both in raw and scaled forms. Raw metrics are the original, unscaled results. Scaled metrics are rescaled by percentiles within each community, thus values of "connect" ≥ 0.90 represent the 10% best locations for connectedness for each community. These scaled metrics were combined using the weights listed in Appendix C to create the final Indices of Ecological Integrity.

Grid name	Landscape metric
Development & roads	
habloss	Habitat loss
insults	Wetland buffer insults
traffic	Road traffic intensity
edges	Microclimate alterations
Pollution	
salt	Road salt intensity
sediment	Sedimentation
fertilize	Nutrient loading
point	Point-source pollution
Biotic alterations	
cats	Domestic predators
edgepred	Edge predators
badplants	Non-native invasive plants
worms	Non-native invasive earthworms
Hydrological alterations	
imperv	Imperviousness
impound	Percent impounded
roadx	Upstream road crossings
damint	Dam intensity
Resiliency metrics	
connect	Connectedness
sim	Similarity