Designing Sustainable Landscapes:
Index of Ecological Integrity

A project of the University of Massachusetts Landscape Ecology Lab

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McGarigal K, Compton BW, Plunkett EB, DeLuca WV, and Grand J. 2017. Designing sustainable landscapes: index of ecological integrity. Report to the North Atlantic Conservation Cooperative, US Fish and Wildlife Service, Northeast Region.

General description

The ***index of ecological integrity*** (*IEI*) is a measure of relative intactness (i.e., freedom from adverse human modifications and disturbance) and resiliency to environmental change (i.e., capacity to recover from or adapt to changing environmental conditions driven by human land use and climate change). It is a composite index derived from up to 21 different landscape metrics, each measuring a different aspect of intactness (e.g., road traffic intensity, percent impervious) and/or resiliency (e.g., ecological similarity, connectedness) and applied to each 30 m cell (see technical document on integrity, McGarigal et al 2017). The index is scaled 0-1 by ecological system and geographic area, such that it varies from sites with relatively low integrity (representing highly developed and/or fragmented areas) to relatively high integrity (representing large, undisturbed natural areas) within each ecosystem type and geographic area (e.g., Northeast, state, ecoregion, watershed) (**Fig. 1**). Consequently, boreal forests are compared to boreal forests and emergent marshes are compared to emergent marshes, and so on for each ecosystem type within the specified geographic extent. It doesn't make sense to compare the integrity of an average boreal forest cell to that of an average emergent marsh cell, because the latter have been substantially more impacted by human activities than the former. Scaling 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 within the specified geographic extent.

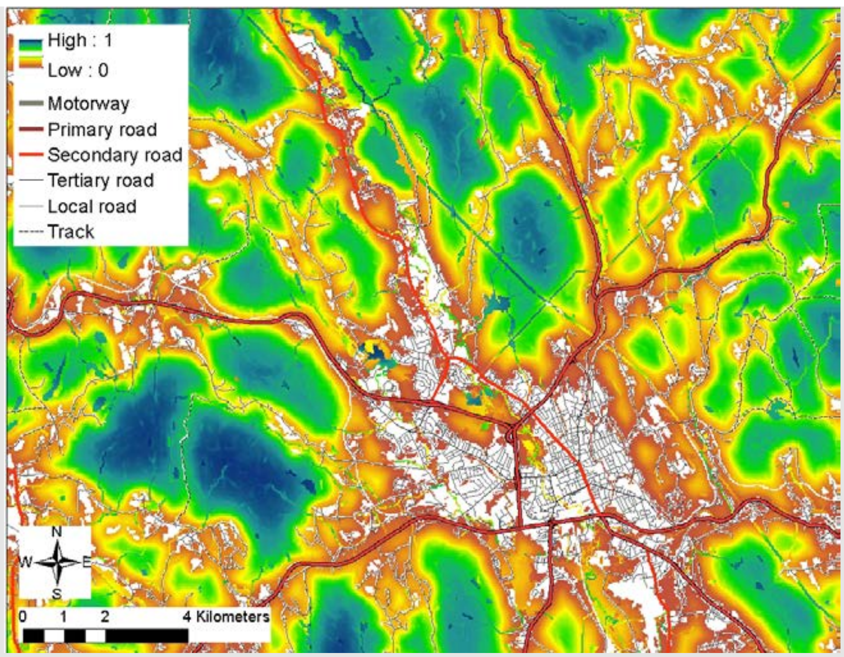

Figure 1. Example of *IEI* in 2010 scaled by ecosystem across the Northeast region. Values for undeveloped cells range from near 0 (minimum integrity) to 1 (maximum integrity) over the full extent of the region, and within each ecological system; developed cells are not assessed and are represented as nodata (shown as white).

Use and interpretation of this layer

As described above, *IEI* is a composite index derived from the individual intactness and resiliency metrics (**Table 1**); it is a synoptic measure of local ecological integrity that combines many different elements of integrity into a single index. The use of *IEI* should be guided by the following considerations:

- *IEI* is quantile-scaled by ecological system within various geographic extents (Northeast region, state, ecoregion and HUC6 watershed). The end result is that within the extent considered, the worst cells within an ecological system get 0.01 and the best cells within that system get a 1. Thus, forests are compared to forests and emergent marshes are compared to emergent marshes, and so on, within the corresponding geographic extent. Rescaling by ecological system means that all the cells within an ecological system are ranked against each other in order to determine the cells with the greatest relative integrity for each ecological system. Similarly, it may not be that meaningful to compare the integrity of the best forest cell in Maine to that of a forest cell in, say, Maryland, if you are responsible for finding the best forest in Maine to conserve. Therefore, *IEI* is scaled not only by ecological system but also by various geographic extents. Consequently, the choice of extent will depend on the intended application of *IEI*.

- It is critically important to recognize the relative nature of *IEI*; a value of 1 does not mean that a site has the maximum <u>absolute</u> ecological integrity (i.e., completely unaltered or unimpaired by human activity), only that it is the best of that ecological system within the corresponding geographic extent. In an absolute sense, the best within any particular geographic extent 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 elsewhere for the index of ecological impact.

- *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 value of 0.8 has a value that is greater than or equal to 80% of all the cells, and all the cells with >0.8 values comprise the best 20% across ecological systems within the corresponding geographic extent. Importantly, these "top 20%" areas are distributed across all ecosystems in proportion to their abundance in the landscape. Thus, if "Laurentian-Acadian Northern Hardwood Forest" comprises 30% of the landscape, then 30% of the top 20% *IEI* is composed of that ecosystem. For these reasons, the *IEI* maps are best interpreted in conjunction with the *dslLand* map, since the latter depicts the landcover classes (ecological systems) by which the quantile-scaling was conducted.

- 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 ecosystem. For example, in the area depicted in **figure 1**, 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 are also swamped by the pattern of the dominant forest ecosystem type. To mitigate this visual bias, it is often useful to mask all but the focal ecological system(s) of interest. For example, in **figure 2**, the *IEI* for only the "Northern Appalachian-Acadian Conifer-Hardwood Acidic Swamp" ecosystem is displayed, revealing the integrity gradient for this particular ecosystem without being overwhelmed by the integrity of the dominant ecosystems.

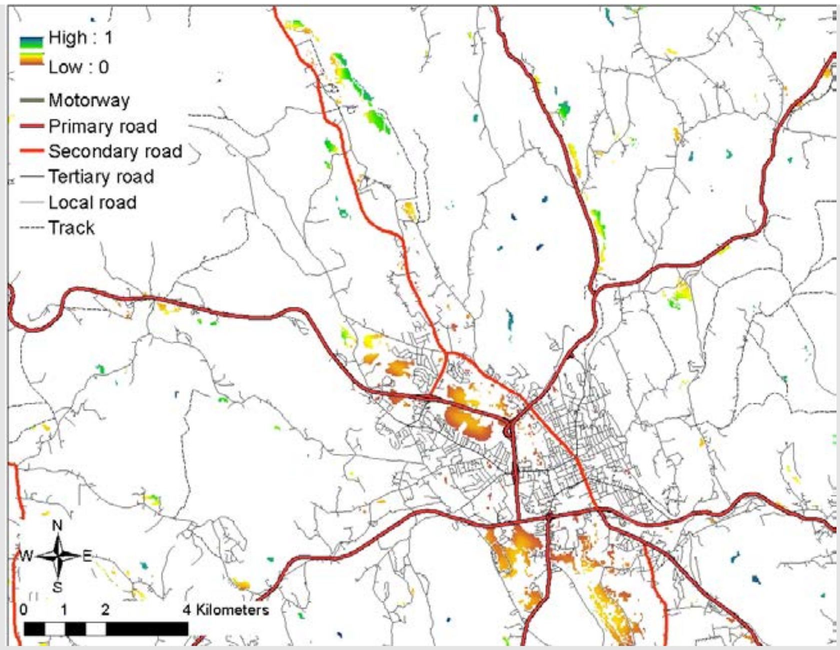

Figure 2. Example of *IEI* in 2010 scaled by ecosystem across the Northeast region, shown here with a mask to reveal only the "Northern Appalachian-Acadian Conifer-Hardwood Acidic Swamp" ecosystem; all other ecosystems and developed lands are shown in white, although road classes are depicted separately.

- Experience has revealed that scaling by ecological system at extents less than the full Northeast region is subject to producing occasional spurious results. For example, when scaling by ecological system and state or HUC6 watershed, *IEI* values can vary abruptly along ecosystem boundaries even within a single forest patch, owing entirely to the relatively arbitrary categorical mapping of closely-related ecosystems and the quantile-scaling by ecosystem (**Fig. 3**). This effect is more pronounced at smaller spatial extents such as HUC6 watersheds, and is the principal reason we don't compute IEI for small extents, unless the ecological system classification is very coarse. Thus, abrupt changes in *IEI* are sometimes an artifact of the landcover map and the scaling procedure and should not be interpreted too literally. It is perhaps best to view the *IEI* map with blurred vision, especially when using the state- or HUC6-scaled version.

- It is important to acknowledge that *IEI* is simply a model, and thus it is subject to the limitations of any model due to incomplete and imperfect data, and a limited understanding of the phenomenon being represented. In particular, the GIS data that serve as inputs to the individual metrics (e.g., ecological systems map, road traffic) are imperfect; they contain errors of both omission and commission. Consequently, at the resolution of 30 m cells there will be many places where the model gets it wrong, not necessarily because the model itself is wrong, but rather the input data are wrong. In addition, while *IEI* incorporates many different components of ecological integrity, namely those associated with intactness (i.e., freedom from human stressors) and short-term resiliency (e.g., similarity and connectedness), it is clearly not comprehensive. There are other aspects of ecological integrity that are not included in this index or represented perfectly by the metrics included. For example, long-term resiliency of a site, and thus its long-term ecological integrity, may be a function of access to a variety of different ecological settings, but this is not currently addressed in *IEI*. Thus, *IEI* in its current form should be viewed as a partial assessment of short-term, local ecological integrity.

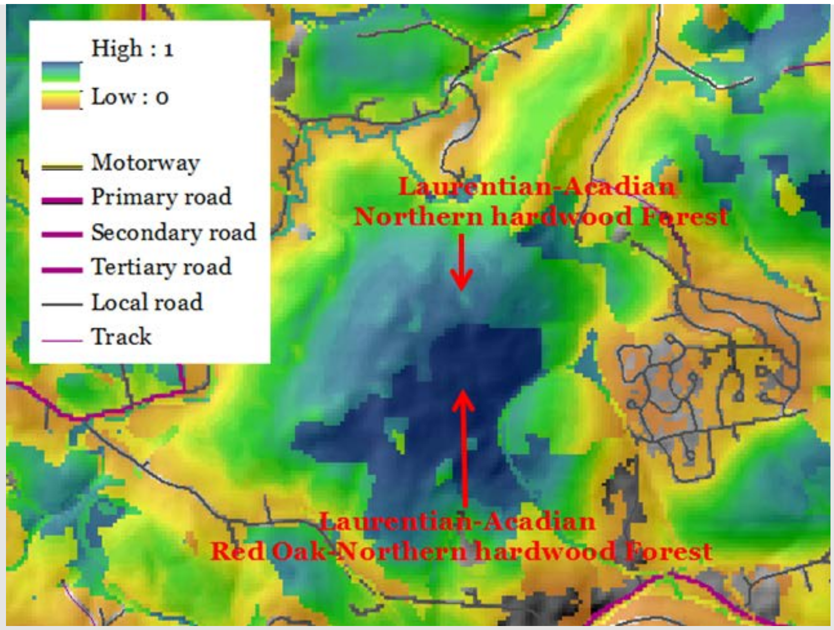

Figure 3. Example of *IEI* depicting abrupt change in IEI due to the relatively arbitrary categorical mapping of two closely-related ecosystems and quantile-scaling by ecosystem.

- While IEI has a wide variety of potential uses, perhaps its most significant application is to facilitate efforts of organizations seeking to conserve biodiversity to identify and prioritize places of high ecological value for conservation action (e.g., land protection). Other uses include, but are not limited to, monitoring changes over time in the ecological condition of the landscape and evaluating the potential impacts of land use/land cover change scenarios on the ecological integrity of the landscape. See the UMassCAPS website (www.umasscaps.org) for examples of these and other applications.

Derivation of this layer

For a detailed description of the derivation of *IEI* and its context in the broader assessment of ecological integrity, see the technical document on integrity (McGarigal et al 2017). Briefly, the derivation of *IEI* consists of the following major steps:

1. Compute individual metrics

The first step involves computing the individual intactness and resiliency metrics listed in **Table 1**. Each metric measures a slightly different aspect of the landscape and corresponds to a distinct mechanism by which the stressor exerts its influence on the ecological integrity of a site. However, these metrics are not statistically independent and can exhibit a moderate to high degree of correlation.

Table 1. Intactness (a.k.a. stressor) and resiliency metrics included in IEI.

Metric group	Metric name	Description
Development and Roads	Habitat loss	Measures the intensity of habitat loss caused by all forms of development in the neighborhood of the focal cell.
	Watershed habitat loss	Measures the intensity of habitat loss caused by all forms of development in the watershed above the focal cell based on a time-of-flow kernel.
	Road traffic	Measures the intensity of road traffic (based on estimated road traffic rates) in the neighborhood of the focal cell.
	Mowing & plowing	Measures the intensity of agriculture (as a surrogate for mowing/plowing rates) in the neighborhood of the focal cell.
	Microclimate alterations	Measures the adverse effects of induced (human-created) edges on the microclimate integrity of patch interiors in the neighborhood of the focal cell.
Pollution	Watershed road salt	Measures the intensity of road salt application in the watershed above an aquatic focal cell based on road class (as a surrogate for road salt application rates) and a time-of-flow kernel.
	Watershed road sediment	Measures the intensity of sediment production in the watershed above an aquatic focal cell based on road class (as a surrogate for road sediment production rates) and a time-of-flow kernel.
	Watershed nutrient	Measures the intensity of nutrient loading from non-point sources in the watershed above an aquatic focal

Metric group	Metric name	Description
	enrichment	cell based on land use class (primarily agriculture and residential land uses associated with fertilizer use, as a surrogate for nutrient loadings) and a time-of-flow kernel.
Biotic Alterations	Domestic predators	Measures the intensity of development associated with sources of domestic predators (e.g., cats) in the neighborhood of the focal cell weighted by development class (as a surrogate for domestic predator abundance).
	Edge predators	Measures the intensity of development associated with sources of edge mesopredators (human commensals such as raccoons, skunks, corvids, and cowbirds) in the neighborhood of the focal cell weighted by development class (as a surrogate for edge predator abundance).
	Non-native invasive plants	Measures the intensity of development and roads associated with sources of non-native invasive plants in the neighborhood of the focal cell weighted by development class (as a surrogate for non-native invasive plant abundance).
	Non-native invasive earthworms	Measures the intensity of land cover associated with sources of non-native invasive earthworms in the neighborhood of the focal cell weighted by development class (as a surrogate for non-native invasive earthworm abundance).
Climate	Climate stress	Measures the magnitude of climate change stress at the focal cell based on the climate niche of the corresponding ecological system and the predicted change in climate (i.e., how much is the climate of the focal cell moving away from the climate niche envelope of the corresponding ecological system). Note, this metric is used only in the calculation of future *IEI*.
Hydrologic Alterations	Watershed imperviousness	Measures the intensity of impervious surface (as a surrogate for hydrological alteration) in the watershed above an aquatic focal cell based on imperviousness

Metric group	Metric name	Description
		and a time-of-flow kernel.
	Dam intensity	Measures the intensity of dams (as a surrogate for hydrological alteration) in the watershed above an aquatic focal cell based on dam size and a time-of-flow kernel.
	Sea level rise inundation	Measures the probability of the focal cell being unable to adapt to predicted inundation by sea level rise (developed by R. Theiler, USGS Woods Hole). Note, this metric is used only in the calculation of future *IEI*.
Coastal Metrics	Salt marsh ditching	Measures the magnitude of temporal loss of open water habitat (i.e., loss of open water habitat during mid to low tides) in the neighborhood of the focal cell due to ditching. Note, this metric is done but only covers about 63% of the mapped salt marsh in the Northeast due to limitations in available 1 m Lidar-derived DEMs; consequently, it is not included in IEI.
	Tidal restrictions	Measures the magnitude of hydrologic alteration due to tidal restrictions below the focal cell.
Resiliency	Similarity	Measures the amount of similarity between the ecological setting at the focal cell and those of neighboring cells based on the ecological settings variables.
	Connectedness	Measures the connectivity of each cell to other similar cells in the neighborhood, emphasizing the disruption of habitat connectivity caused by development between each focal cell and surrounding cells.
	Aquatic connectedness	Aquatic connectedness is identical to connectedness except that it measures connectivity within the aquatic network, and emphasizes impediments to movement of aquatic organisms by culverts and dams.

2. Quantile-rescaling

Each of the raw intactness and resiliency metrics are scaled differently. Some are bounded 0-1 (e.g., similarity), while others have no upper bound. Moreover, each of the metrics will have a unique empirical distribution for any particular landscape. In order to combine the metrics into a composite index, it is therefore necessary to rescale the raw metrics to put them on equal ground. To do this, we use a method called *Quantile-rescaling*, which involves transforming the raw metrics into quantiles, such that the worst cell gets a 0 and the best cell gets a 1. Quantile-rescaling facilitates interpretation and the compositing of metrics by putting them all on the same scale with the same uniform distribution regardless of differences in raw units or distribution. Moreover, quantiles have an 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 0.9 quantile is a cell that has a metric value that is greater than 90% of all the cells, and all the cells with >0.9 quantile values comprise the best 10% within the analysis area. Lastly, for our purposes, we quantile-rescale each metric separately within each ecological system, so that forests are compared to forests and emergent marshes are compared to emergent marshes, and so on. 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.

3. Ecological integrity models

After quantile-rescaling by ecological system, the metrics are all on the same scale (0-1) and have identical uniform distributions within each ecosystem. The next step is to combine the rescaled metrics into a composite index. However, given the range of metrics (**Table 1**), it is reasonable to assume that some metrics are more important than others to the overall ecological integrity of the cell and thus should be assigned more weight. Indeed, the watershed-based stressor metrics and aquatic connectedness were designed specifically for application to aquatic and/or wetland ecosystems and thus don't meaningfully apply to terrestrial ecosystems. Moreover, it is reasonable to assume that the weights applied to the metrics might vary among community types. For example, the stressors with the most impact on an emergent marsh may not be the same as those with the most impact on an upland boreal forest. Consequently, we employ ecosystem-specific ecological integrity models to weight the component metrics in the composite index. An ecological integrity model is simply a weighted linear combination of metrics designated (by expert teams) for each ecological system. For parsimony sake, we designate a unique ecological integrity model for each ecological formation, which is a group of similar ecological systems. Consequently, all the ecological systems within the same formation get the same ecological integrity model. The list of ecological systems and their grouping into formations, along with the corresponding ecological integrity models, is included in the technical document on integrity (McGarigal et al 2017).

4. Rescaling the final index

After combining the rescaled-metrics in a weighted linear combination, to maintain the quantile-scaling by ecosystem, it is necessary to quantile-rescale the composite index by ecosystem again to ensure the proper quantile interpretation.

It is important to recognize that as a consequence of quantile-rescaling, the results are dependent on the extent of the analysis area, because the quantiles rank cells relative to other cells within the analysis area. Therefore, quantile-rescaling must be done separately for each analysis area. The best of the Northeast is not the same as the best of the Connecticut River watershed or the state of Maryland. Therefore, the analysis area used for the quantile-rescaling must be explicit. Note, the analysis area used for the quantile-rescaling may be larger than the focal area of interest. For example, let's say that we wanted to evaluate the integrity of cells within the Connecticut River watershed. We might nonetheless rescale cells based on the entire Northeast, and merely clip the results to the Connecticut River watershed. In this case, the range of values within the Connecticut River watershed may not range from 0-1 because the relatively best or worst locations may fall outside of the watershed.

Thus, in this final step, we also specify a geographic extent for the quantile-rescaling by ecosystem. To facilitate the use of *IEI* by a variety of conservation practitioners, we quantile-rescale *IEI* by ecological system within the entire Northeast, but also by state, ecoregion, and HUC6 watershed, but any geographic unit could be used.

GIS metadata

This data product is distributed as a geotiff raster (30 m cells). The cell value = *IEI* and ranges from 0 (developed) to 1 (maximum ecological value within each ecological system). As described above, this data product is available scaled by various geographic extents, and can be obtained from McGarigal et al (2017):

- IEI scaled by northeast region:
- IEI scaled by state:
- IEI scaled by ecoregion:
- IEI scaled by HUC6 watershed

Literature Cited

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