# Designing Sustainable Landscapes:

# Resiliency metrics: similarity, connectedness, and aquatic connectedness

## *A project of the University of Massachusetts Landscape Ecology Lab*

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- University of Massachusetts, Amherst

*Reference*:

McGarigal K, Compton BW, Plunkett EB, DeLuca WV, and Grand J. 2018. Designing sustainable landscapes: resiliency metrics. Report to the North Atlantic Conservation Cooperative, US Fish and Wildlife Service, Northeast Region.

## General description

This document describes three resiliency metrics that measure a system's ability to recover from disturbance or stress, as opposed to the other metrics, which assess sources of anthropogenic stress. Resiliency is both a function of the local ecological setting, since some settings are naturally more resilient to disturbance and stress (e.g., an isolated wetland is less resilient to species loss than a well-connected wetland because the latter has better opportunities for recolonization of constituent species), and the level of anthropogenic stress, since the greater the stressor the less likely the system will be able to fully recover or maintain ecological functions.

All three of these metrics are based on assessing the distance from the focal cell to cells in its neighborhood in ecological settings space, as defined by a suite of 24 ecological settings variables (**Table 1**). The settings variables are an attempt to capture the geophysical attributes that are primary determinants of ecological systems, e.g., temperature, sunlight, moisture, hydrology, and soils (McGarigal et al 2017). Settings also include several anthropogenic variables, such as development, traffic rates, and impervious surfaces. Ecological distance is low for points that fall nearby in settings space (e.g., two points that are on dry ridgetops with similar soils and climate), and higher for points that are further apart in settings space (e.g., a ridgetop and a valley wetland). Ecological distance is highest between natural and anthropogenic points (e.g., the ecological distance between a forest and a point in the middle of an expressway is extremely high, despite any similarities in landform or climate). Note that ecological distance is unrelated to physical distance (although two points that are nearby are more likely to share similar ecological settings).

These metrics are elements of the ecological integrity analysis of the Designing Sustainable Landscapes (DSL) project (McGarigal et al. 2017). Consisting of a composite of 21 stressor and resiliency metrics, the index of ecological integrity (IEI) assesses the relative intactness and resiliency to environmental change of ecological systems throughout the northeast. For a more detailed description of these metrics, see the technical document on integrity (McGarigal et al 2017).

**Similarity** (**Fig. 1b**). Assesses the similarity of cells (in ecological settings space) in the neighborhood using a logistic kernel, such that nearby cells have more weight than more distant cells. Similarity is most meaningful for species and ecological processes that are not particularly affected by intervening landscape, e.g., birds, bats, flying insects, and wind-dispersed seeds.

**Connectedness** (**Fig. 1c**). Like similarity, connectedness assesses the ecological distance between the focal cell and cells in the neighborhood, but it defines the neighborhood using a resistant kernel (Compton et al. 2007), which measures the functional distance between any two cells based on their ecological distance. This yields a metric that is most meaningful for species and processes that are affected by the intervening landscape, such as terrestrial animals, plants that depend on animals for seed dispersal, and wildfires.

**Aquatic connectedness** (**Fig. 1d**). Aquatic connectedness is a modified version of connectedness that uses a resistant kernel to access connectedness through the stream network, focusing on the anthropogenic variables that affect aquatic species: culverts and dams, as well as natural settings variables such as flow gradient and volume, salinity, and stream temperature.

## Use and interpretation of these layers

These metrics rely on several assumptions:

- Ecological settings variables are complete and correct.
- Weights used for each ecological settings variable are reasonable.
- Scaling used for each metric is reasonable. Obviously, scaling is species- or process-dependent. For each of these metrics, we use a single scale that gives useful results.

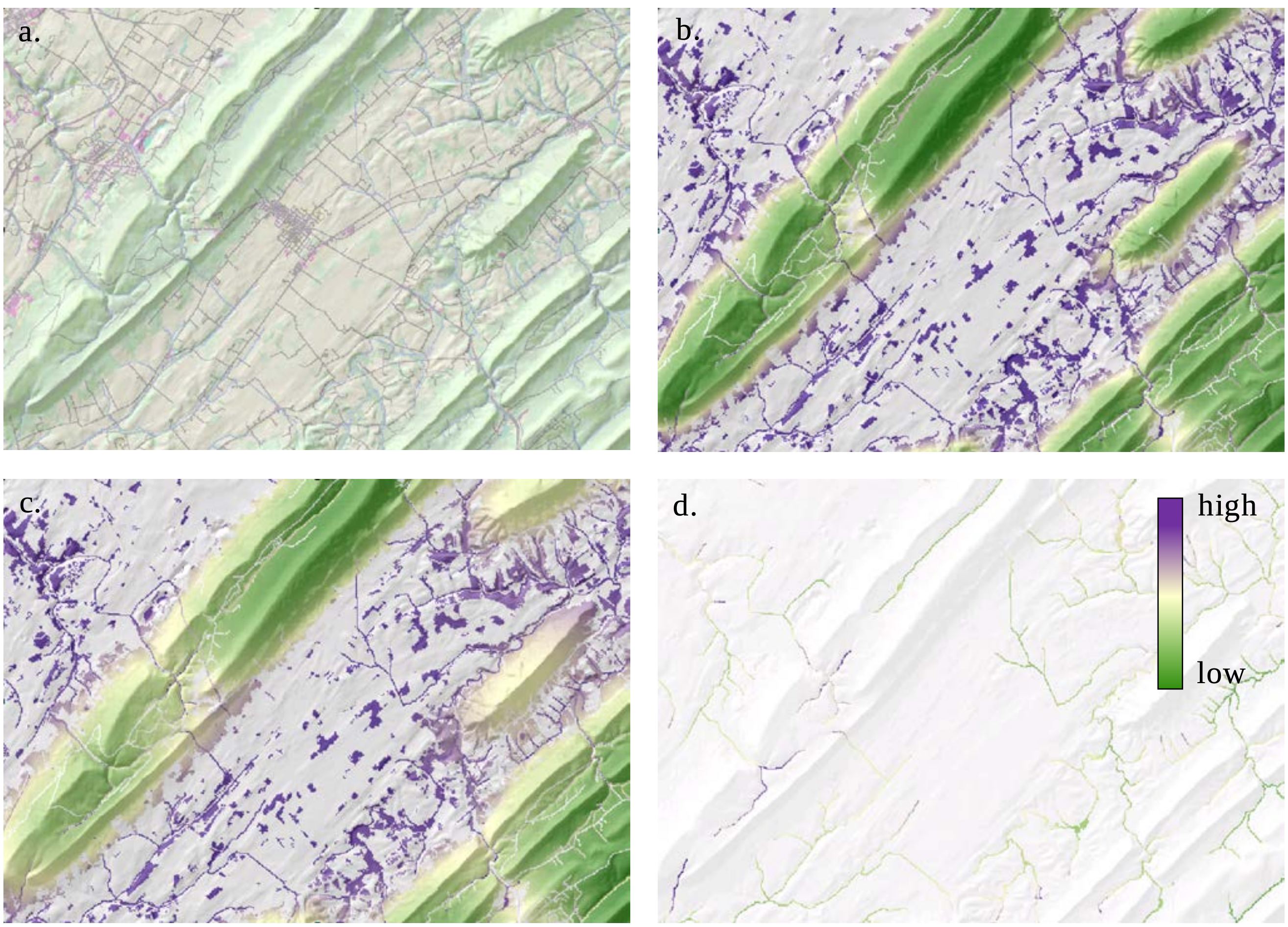


**Figure 1**. Examples of each metric to the northeast of State College, Pennsylvania: (a) landcover, and each metric: (b) Similarity, (c) Connectedness, (d) Aquatic connectedness, all with hillshading. Gray areas correspond to development and roads, where the metrics are not applied.

# Derivation of these layers

## *Data sources*

- These metrics are based on the 24 ecolocial settings variables (**Table 1**). For details, see the individual abstracts for each one at McGarigal et al (2017).

## *Algorithm*

***Ecological distance***. All three resiliency metrics are based on ecological distance in settings space. For each focal cell, the ecological distance to any target cell is a weighted Euclidean distance, as follows:

Each ecological settings variable is first rescaled from 0-1. Weights are assigned for each ecological settings variable by an expert team to represent the importance of that settings variable (Table 1). Note that some anthropogenic variables (imperviousness, traffic, terrestrial barriers, and aquatic barriers) are excluded from ecological distance. Weights are rescaled such that the maximum possible distance among non-anthropogenic settings variables is 1.0:

$$w'_j = \frac{w_j}{\sqrt{\sum {w_{N_k}}^2}}$$

where

$w'_j$ = weight of $j$th settings variable, rescaled
$w_j$ = weight of $j$th settings variable
$w_{Nk}$ = weight of $k$th natural (non-anthropogenic) settings variable

Ecological distance is than the weighted Euclidean distance in multi-dimensional settings space:

$$d_{f,i} = \sqrt{\sum \mathbf{min}\left(\left(w'_j\left(x_{j,f} - x_{j,i}\right)\right)^2, 1\right)}$$

where

$d_{f,i}$ = ecological distance between focal cell $f$ and cell $i$
$w'_j$ = weight of $j$th settings variable (rescaled, as above)
$x_{j,f}$ = value of $j$th settings variable at the focal cell
$x_{j,i}$ = value of $j$th settings variable at cell $i$

Ecological distances range from 0 for pairs of cells with identical settings variables to 1 for cells with maximum differences in all non-anthropogenic settings variables, with distances of >1 possible for when one of the cells falls on roads or development. Note that ecological distance is never allowed to be more than 1, despite the presence of anthropogenic settings variables.

***Similarity*** is calculated as the logistic kernel-weighted mean contrast between the focal cell and all cells in the neighborhood. Similarity uses a logistic function cell (inflection point = 700, scaling factor = 140; **Fig. 2**) for the kernel. Contrast is calculated as

$$c_f = \frac{\sum d_{f,i} K_i}{\sum K_i}$$

where

$c_f$ = contrast for focal cell $f$
$d_{f,i}$ = ecological distance between focal cell $f$ and cell $i$
$K_i$ = kernel weight for cell $i$

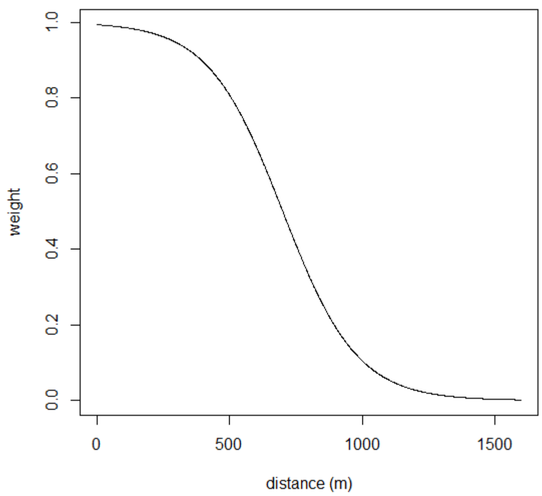


**Figure 2**. The logistic kernel used for the similarity metric.

***Resistance***. Resistant kernels, used for the connectedness and aquatic connectedness metrics, use a unique resistant surface for each focal cell. Resistance is calculated similarly to ecological distance, but it uses a different set of weights, and different anthropogenic variables are used for connectedness and aquatic connectedness (**Table 1**). Resistance also allows anthropogenic cells to have distances much greater than 1, especially those representing high-traffic highways and dams. Finally, resistance is multiplied by a the resistance multiple, and 1 is added, such that resistance always ranges between 1 (minimal resistance), and an upper value that can represent a complete barrier.

$$r_i = m\sqrt{\sum \left(w'_i\left(x_{j,f} - x_{j,i}\right)\right)^2} + 1$$

where

$r$ = resistance of cell $i$
$m$ = resistance multiplier (50 for connectedness, 300 for aquatic connectedness)
$w'_j$ = weight of $i$th settings variable (rescaled, as above)
$x_{j,f}$ = value of $j$th settings variable at the focal cell
$x_{j,i}$ = value of $j$th settings variable at cell $i$

***Resistant kernel***. The resistant kernel (Compton et al. 2007) is calculated by spreading from a focal cell, subtracting the resistance of each target cell from an initial “bank account” until the account is depleted. The result is a kernel that spreads farther through areas with low resistance, and spreads less (or not at all) where resistance is high (**Figure 3**). The resistant kernel is equivalent to calculating the least cost path from the focal cell to all other cells in the neighborhood, and recording the cost-distance in each cell. For a detailed description of this algorithm, see Appendix C in the technical document on integrity (McGarigal et al 2017).

***Connectedness*** uses resistant surface for each focal cell to build a resistant kernel for the given bandwidth. The kernel is rescaled using the normal density function, and scaled by a kernel built with minimal resistance. The result is multiplied by the ecological distance between the focal cell and each cell in the kernel.

$$c_i = (1 - d_i)\frac{\mathbf{z}\left(\mathbf{max}\left(s - \frac{\mathbf{rk}(r_i, h)}{h}, 0\right)\right)}{\mathbf{z}\left(\mathbf{max}\left(s - \frac{\mathbf{rk}(1, h)}{h}, 0\right)\right)}$$

where

$d_{f,i}$ = ecological distance between focal cell $f$ and cell $i$
$r$ = resistance of cell $i$
$h$ = bandwidth (2 km for connectedness, and 5 km for aquatic connectedness)
$s$ = maximum s.d. (generally 3)
rk = resistant kernel function
z = normal density function, mean = 0, s.d. = 1

The connectedness kernel built for each focal cell $f$ is added across all cells in the kernel as each focal cell is processed, as with a standard kernel estimator.

***Aquatic connectedness*** is calculated identically to connectedness, but uses different weights (**Table 1**), and runs only for stream centerline cells (which run through lentic and wetland systems, as well as lotic systems). In particular, aquatic connectedness omits all of the anthropogenic settings variables used for connectedness, but includes aquatic barriers, which has values for road-stream crossings (culverts and bridges) and dams. In general, bridges have fairly low values (thus low resistant), culverts have much higher values, and dams have the highest values. The results of aquatic connectedness for off-centerline lotic cells are set to the nearest centerline values, and values are mixed assigned the mean centerline value for lentic waterbodies and wetlands.

# GIS metadata

These data products are distributed as geoTIFF rasters (30 m cells). The cell values are continuous, representing the resiliency of each cell. Similarity is calculated as contrast, with values ranging from 0 (low contrast/high similarity) to 1 (high contrast/low similarity). Connectedness and aquatic connectedness range from 0 (low connectedness) to an arbitrary maximum (high connectedness). These data products can be found at McGarigal et al (2017):

- **Similarity**
- **Connectedness**
- **Aquatic connectedness**

## Literature cited

Compton, BW, K McGarigal, SA Cushman, and LR Gamble. 2007. A resistant-kernel model of connectivity for amphibians that breed in vernal pools. Conservation Biology 21(3):788-799.

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/

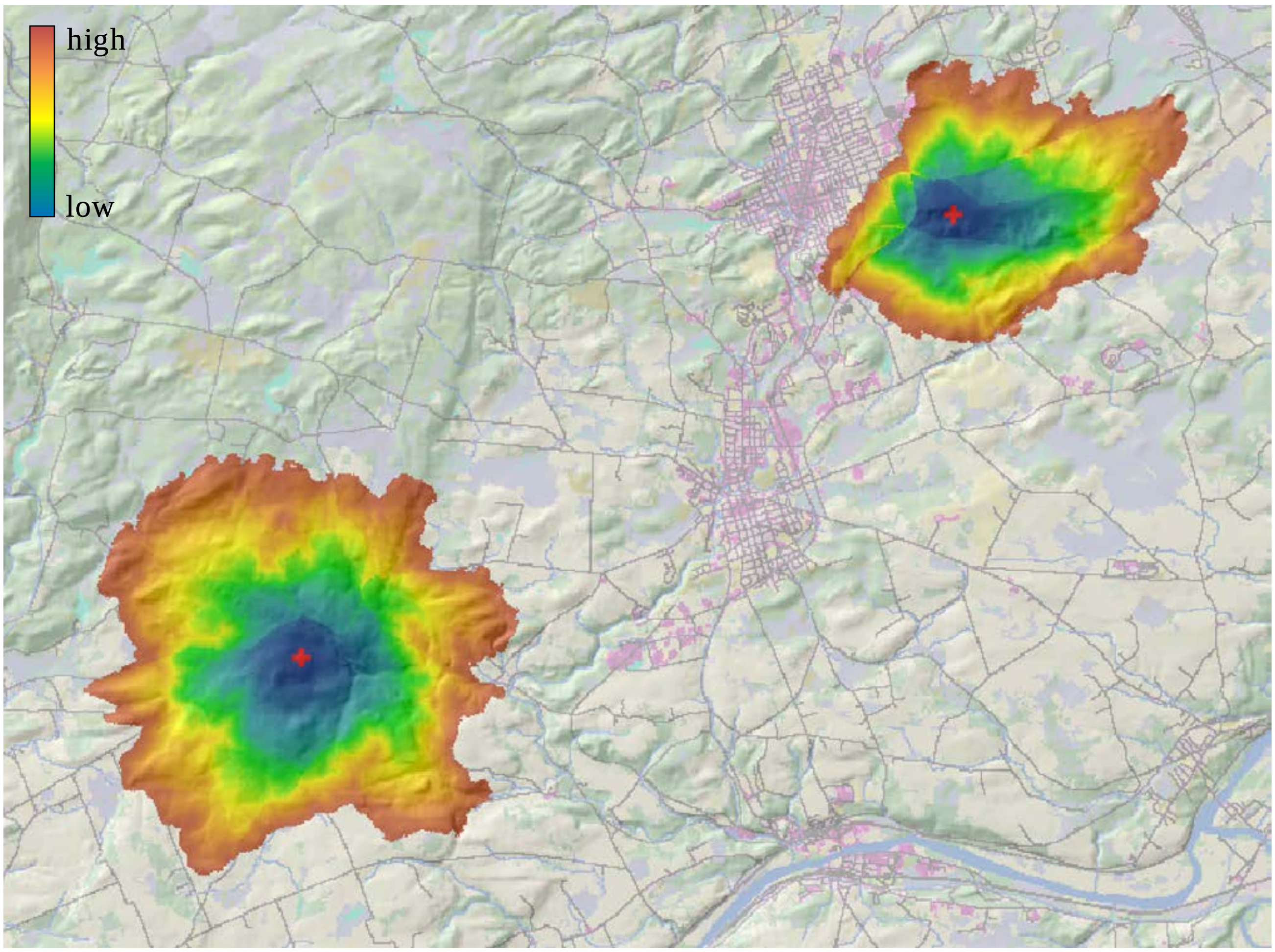


**Figure 3**. Examples of resistant kernels for two focal cells (✚) based in the vicinity of Johnstown, New York. Hillshading helps provide context.

**Table 1**. Ecological settings variables and information on how each is used by the resiliency metrics. Ecological settings variables are used to determine resistance ("R" in the metric columns) for Connectedness and Aquatic connectedness metrics, and to determine ecological distance ("D" in the metric columns) for all three metrics. Settings variables are combined using the weights listed below for resistance and distance. Weights for both resistance and distance were determined by expert teams. Settings variables are mixed for water bodies according to the Mixing column.

| Ecological settings variable | Resistance | Distance | Similarity | Connectedness | Aquatic Connectedness | Mixing* |
|---|---|---|---|---|---|---|
| *Temperature* | | | | | | |
| Growing season degree-days | 0.3 | 1 | D | RD | RD | |
| Minimum winter temperature | 0.1 | 1 | D | RD | RD | |
| Heat index | 0.1 | 1 | D | RD | RD | |
| Stream temperature | 0.1 | 1 | D | RD | RD | |
| *Solar energy* | | | | | | |
| Incident solar radiation | 0.1 | 1 | D | RD | RD | |
| *Chemical & physical substrate* | | | | | | |
| Water salinity | 4 | 3 | D | RD | RD | |
| Substrate mobility | 2 | 2 | D | RD | RD | |
| CaCO3 content | 0.1 | 1 | D | RD | RD | inflows |
| Soil available water supply | 0.05 | 0.5 | D | RD | RD | |
| Soil depth | 0.05 | 0.5 | D | RD | RD | |
| Soil pH | 0.05 | 0.5 | D | RD | RD | |
| *Physical disturbance* | | | | | | |
| Wind exposure | 0.1 | 1 | D | RD | RD | |
| Slope | 1 | 1 | D | RD | RD | |
| *Moisture* | | | | | | |
| Wetness | 4 | 8 | D | RD | RD | |
| *Hydrology* | | | | | | |
| Flow gradient | 1 | 2 | D | RD | RD | pond |
| Flow volume | 5 | 5 | D | RD | RD | sumlogs |
| Tidal regime | 2 | 2 | D | RD | RD | |

| **Ecological settings variable** | **Resistance** | **Distance** | **Similarity** | **Connectedness** | **Aquatic Connectedness** | **Mixing*** |
|---|---|---|---|---|---|---|
| *Vegetation* | | | | | | |
| Dominant life form | 3 | 8 | D | RD | RD | |
| *Development* | | | | | | |
| Developed | 1 | 20 | D | RD | –– | |
| Hard development | 2 | 1000 | D | RD | –– | |
| Gibbs traffic rate | 40 | 0 | D | RD | –– | |
| Impervious | 5 | 0 | D | RD | –– | |
| Terrestrial barriers | 15 | 0 | D | RD | –– | |
| Aquatic barriers | 100 | 0 | – | –– | R– | |

*Settings variables may be mixed for water bodies and wetlands in several different ways:
inflows: all cells in a water body or wetland get the sum of inflowing values
sumlogs: the same as inflows for log-scaled variables
pond: all cells in a waterbody or wetland get the mean of all non-missing values