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Authors	McGarigal, Kevin;Compton, Brad;Plunkett, Ethan;DeLuca, Bill;Grand, Joanna
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Designing Sustainable Landscapes:
Index of Ecological Impact

A project of the University of Massachusetts Landscape Ecology Lab

Principals:

- Kevin McGarigal, Professor
- Brad Compton, Research Associate
- Ethan Plunkett, Research Associate
- Bill DeLuca, Research Associate
- Joanna Grand, Research Associate

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

General description

The ***index of ecological impact*** (*ecoImpact*) is a measure of the relative change in ecological integrity over time under a specific landscape change scenario. This document provides a description of ecoImpact as computed and used to compare different landscape change scenarios associated with various applications. See McGarigal et al (2018a,b) for details on two of the completed applications to date. For a detailed description of *ecoImpact* and the associated *index of ecological integrity* (*IEI*) in the context of the broader ecological integrity assessment of the Designing Sustainable Landscapes (DSL) project, see the technical document on integrity (McGarigal et al 2017).

Briefly, *ecoImpact* is derived from *IEI*, which is a composite index derived from several individual metrics measuring the intactness (i.e., freedom from anthropogenic disturbance or stress) and/or resiliency (i.e., ability to recover from anthropogenic disturbance or stress) of a site as applied to each unique ecosystem. *IEI* characterizes the integrity of sites relative to other sites in a similar ecological setting or ecosystem. Thus, it is a static measure of ecological integrity based on a snapshot of the landscape. *IEI* can be equally useful to assess the change in ecological integrity over time under a specific landscape change scenario. For this purpose, we developed *ecoImpact* to measure the change in *IEI* between the current and future time steps relative to the current *IEI*; i.e., effectively delta *IEI* times current *IEI*. A site that experiences a major loss of *IEI* has a high predicted ecological impact; for example, a loss of 0.5 *IEI* units reflects a greater relative impact than a loss of

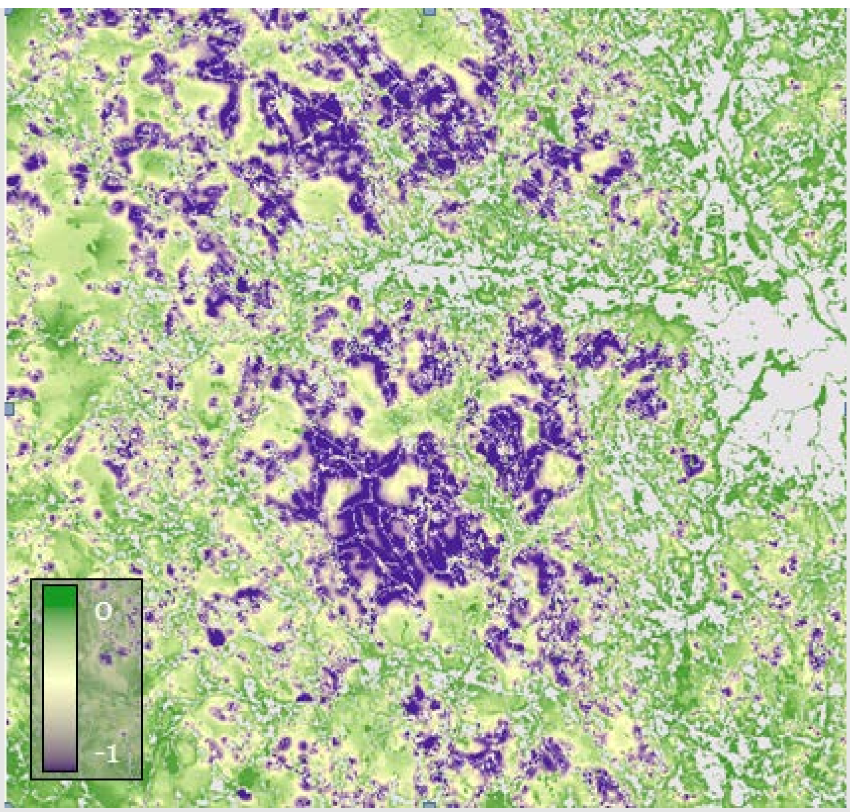

Figure 1. *ecoImpact* metric under a baseline 70-year urban growth scenario for a single stochastic simulation, shown here for an area east of Nashua, New Hampshire. Large negative values indicate areas of high predicted ecological impact of the forecasted landscape changes and represent places with high current ecological integrity (i.e., high IEI in 2010) and relatively large predicted loss of ecological integrity over time. Development, roads, and other non-forested areas are shown in gray.

0.2 units. Moreover, the loss of 0.2 units from a site that has a current *IEI* of 0.9 is more consequential than the same absolute loss from a site that has a current *IEI* of 0.5. Thus, *ecoImpact* reflects not only the magnitude of *IEI* loss, but also where it matters most—sites with high initial ecological integrity.

ecoImpact has a theoretical range of -1 (when a cell with initial *IEI* =1 gets developed) to +0.25 (when a cell with initial *IEI* =0.5 gets restored to the maximum *IEI*), but in practice it will rarely approach the upper limit and only infrequently will it even be > 0 (denoting an improvement in *IEI*). In addition, because *IEI* is scaled by ecological setting or ecosystem and geographic extent, as described below, *ecoImpact* also varies depending on the geographic extent used to scale *IEI* for the baseline condition.

Use and interpretation of this layer

As described above, *ecoImpact* is a composite index that measures the change in *IEI* over time where it matters most (i.e., sites with high initial *IEI*) under a specific landscape change scenario; thus, it is a synoptic measure of impacts to local ecological integrity that combines many different elements of integrity into a single index. The use of *ecoImpact* should be guided by the following considerations:

- As described above, *ecoImpact* is a composite index derived from the individual intactness and resiliency metrics; it is a synoptic measure of the predicted local ecological impact of landscape change and represents the principal result of our coarse-filter assessment of the ecological impact of the forecasted landscape changes. In contrast to *IEI*, *ecoImpact* is delta-scaled (see below) to reflect the percentage loss of *IEI* from cells of high baseline *IEI* largely independent of their ecological setting or ecosystem, and is only modestly affect by the geographic extent of the analysis. Briefly, as described in the following section, the individual raw metrics are first delta-rescaled, then combined in a weighted linear function specific to each ecological setting or ecosystem, and then multiplied by the baseline *IEI* to produce the final *ecoImpact* index for each landscape comparison. The end result is that a cell with maximum baseline *IEI* (1) that loses all of its *IEI* (1→0) in the alternative landscape (e.g., projected future landscape) gets a value of -1, indicating the maximum possible ecological impact. Conversely, a cell that experienced no change in *IEI* would get would get a value of 0, indicating no ecological impact. Lastly, a cell that experienced a gain in *IEI* would get a positive value that has an upper limit of 0.25, although in practice positive values are rare and typically very small.
- It is important to recognize the relative nature of *ecoImpact* and how it differs from *IEI*. Whereas *IEI* is always relative to the ecological system of a cell and the geographic extent of the scaling, the *ecoImpact* of a cell is always relative to itself (regardless of ecosystem or landscape extent) under the baseline condition. The *ecoImpact* of a cell reflects how much the integrity of the cell (as measured by *IEI*) decreases as a result of the forecasted landscape changes relative to the initial or baseline *IEI* of the cell. Thus, ecoImpact compares a cell to itself — e.g., the change in integrity over time — whereas *IEI* compares a cell to other cells of the same ecological setting or ecosystem within the specified geographic extent. While this interpretation is roughly correct, it is not

entirely so. *ecoImpact* involves multiplying the weighted linear combination of delta-rescaled metrics by the baseline *IEI*. Therefore, technically speaking the ecological setting or ecosystem of the cell and the geographic extent of the analysis have an effect on the final computed value, but the role of ecosystem membership and geographic extent is relatively minor compared to *IEI*. Because of the relative nature of *ecoImpact*, it can be used as a comparative index to compare one site to another or to compare the same site to itself under different landscape change scenarios.

- While *ecoImpact* 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) that are highly vulnerable to predicted landscape changes (e.g., urban growth). 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, as in the SPRAWL and INTEGRITY papers referenced below.

Derivation of this layer

The derivation of *ecoImpact* consists of rescaling the individual raw ecological integrity metrics, but using a different rescaling procedure than used with *IEI*, then combining the metrics into the composite index, and then computing the final index. Each of these steps are described in the following sections.

Delta-rescaling.—The embedded use of quantile-rescaling in *IEI* suffers from what we refer to as the "Bill Gates" effect when used for scenario comparison. Note, quantile rescaling involves transforming the raw *IEI* values into their corresponding quantiles by ecosystem, so that the x^{th} quantile represents the top x% of the cells in each ecosystem. The "Bill Gates" effect occurs when the value of the raw metric is decreased in a cell but it remains the highest valued cell -- the quantile is unchanged. This is analogous to taking millions of dollars away from Bill Gates and yet he remains one of the richest persons around. Likewise, a small absolute change in a raw metric can under certain circumstances result in a large change in its quantile, even though the ecological difference is trivial. Therefore, the use of quantile-rescaling is not appropriate if we want to be sensitive to any absolute change in the integrity metrics. To address these issues, we developed *delta-rescaling* as an alternative to quantile-rescaling that is more meaningful when comparing among scenarios (or timesteps of a single scenario).

Delta-rescaling is rather complicated in detail. Briefly, delta-rescaling involves computing the difference in the metric from its baseline value at timestep 0. Thus, delta-rescaling does not involve comparing the condition of a cell to ecologically similar cells of the same ecological system, but rather comparing the condition of a cell to itself under the baseline (e.g., timestep 0) condition. These delta-rescaled metrics can then be combined in a weighted linear combination to form a composite delta ecological integrity index, and this composite index can be multiplied by the ecological integrity index (*IEI*) of the cell under the baseline scenario to derive an "impact" index (*ecoImpact*), as described below.

Unfortunately, since the raw metrics are on different scales, we can't simply compute the delta between the current and future timesteps, as the raw deltas would also be on different scales. But in order to combine the metrics into a composite index they must be placed on the same or similar scale. A simple solution would be to range rescale each raw metric so that it ranges 0-1. However, range rescaling is very sensitive to extreme values and most of the raw metrics have positively or right-skewed distributions containing relatively few very large values. To address this issue we instead use a rather complicated rescaling procedure, as follows:

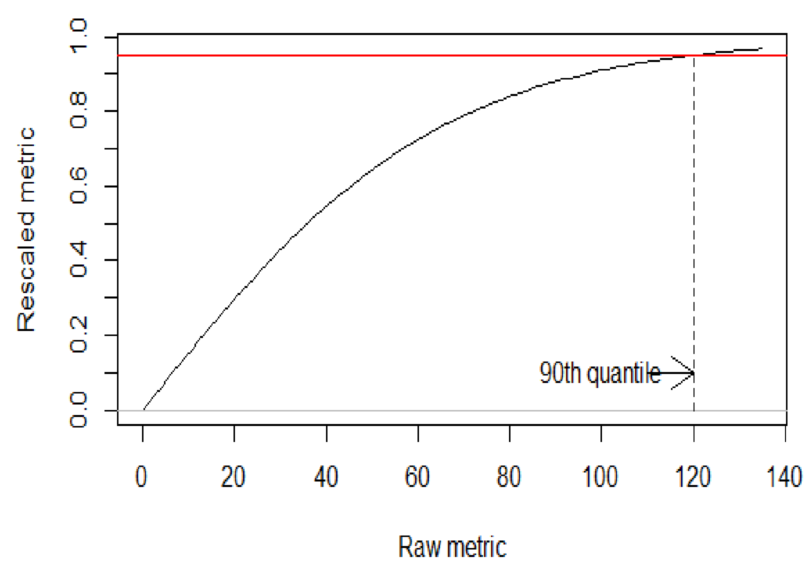

Figure G1. Logistic transformation of a raw metric scaled 0-135 with a 90th quantile of 120 as used in delta-rescaling. The rescaled metric ranges from 0~1 with a value of 0.95 (red line) for the 90th quantile.

1) For each raw stressor metric at the fullest geographic extent, we find its 90th quantile benchmark and apply a logistic transformation such that this benchmark ends up with a score of 0.95, as follows:

$$rescaled.metric = \left(\frac{1}{e^{\left(-raw.metric/s\right)} + 1}\right) * 2 - 1$$

$$s = \frac{-benchmark}{ln\left(2/_{1.95} - 1\right)}$$

The end result is that each rescaled stressor metric ranges from 0~1.

2) For the aquatic connectedness (aqconnect) metric, we compute the maximum value of aqconnect (aqcmax) for each cell by running it without the anthropogenic settings variables (i.e., as if there were no road-stream crossings and dams), find the 95th quantile of aqcmax, and rescale the metric as follows:

$$rescaled.aqconnect = \frac{0.95}{quantile(aqcmax, 0.95)}$$

The end result is that rescaled aqconnect ranges from 0 ~ 1.

3) For the connectedness and similarity metrics, which scale naturally from 0~1 (for a highly similar and connected neighborhood), we keep them in their raw scale form.

After rescaling each of the integrity metrics, we compute the difference (or delta) between the baseline (e.g., timestep 0) value and the alternative (e.g., future landscape) value. These delta-rescaled metrics have a theoretical range of -1 to 1. A value of -1 indicates the maximum potential loss of *IEI* (e.g., a cell with the maximum *IEI* gets developed), whereas a value of 1 indicates the maximum potential increase in IEI (e.g., a developed cell is restored to the maximum *IEI*). These delta-rescaled metrics are combined into a composite index as described next.

Ecological integrity models.—After delta-rescaling, the metrics are all on approximately the same scale. The next step is to combine the delta-rescaled metrics into a composite index. To do this we apply the ecological integrity models described in the text for *IEI*.

Computing the final index.—After combining the delta-rescaled metrics in a weighted linear combination, we multiply the value by the baseline value of *IEI* (e.g., the value in timestep 0). In this manner, roughly speaking the index is designed to reflect the percentage change in *IEI* (as estimated via delta-rescaling) where it matters most — areas with high initial *IEI*. For example, the ecological impact is relatively greater (and thus more important) for a cell with a delta score of -0.4 and an initial *IEI* of 1 compared to a cell with the same delta score but an initial *IEI* of 0.5. The final index has a theoretical range of -1 (when a cell with initial *IEI*=1 gets developed) to +0.25 (when a cell with initial *IEI*=0.5 gets restored to the maximum *IEI*), but in practice it will rarely approach the upper limit and only infrequently will it even be > 0 (denoting an improvement in *IEI*). In addition, because *IEI* is scaled by ecological setting or ecosystem and geographic extent, as described in the text for *IEI*, *ecoImpact* also varies depending on the geographic extent used to scale *IEI* for the baseline condition.

GIS metadata

This data product is distributed as a geotiff raster (30 m cells). The cell value = *ecoImpact* and ranges from -1 (maximum impact) to +0.25 (maximum improvement in ecological value). As described above, this data product can be scaled by any geographic extent and for any landscape change scenario, but the products distributed here are scaled by the Northeast region and for the landscape change scenarios reported in the SPRAWL and INTEGRITY papers (McGarigal et al 2018a,b), as follows:

- DSL_ecoImpact_baseline_v3.0.tif = ecoImpact under the baseline urban growth scenario
- DSL_ecoImpact_plusDemand_v3.0.tif = ecoImpact under the 25% increased demand scenario
- DSL_ecoImpact_plusSprawl_v3.0.tif =- ecoImpact under the increased sprawl scenario
- DSL_ecoImpact_plusBoth_v3.0.tif = ecoImpact under the 25% increased demand plus increased sprawl scenario

- DSL_ecoImpact_NaturesNetwork_v3.0.tif = ecoImpact under the Nature's Network landscape conservation design scenario (www.naturesnetwork.org) in which 25% of the landscape was protected from future development in reserve area

Literature Cited

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McGarigal K; Plunkett EB; Willey LL; Compton BW; DeLuca WV; Grand J. 2018a. Modeling non-stationary urban growth: the SPRAWL model and the ecological impacts of development. Landscape and Urban Planning [in press].

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