Designing Sustainable Landscapes:
HUC6 Terrestrial Core-Connector Network

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

With support from:

- North Atlantic Landscape Conservation Cooperative (US Fish and Wildlife Service, Northeast Region)
- Northeast Climate Science Center (USGS)
- University of Massachusetts, Amherst

Report date: 20 April 2018

Reference:

McGarigal K, Compton BW, Plunkett EB, DeLuca WV, and Grand J. 2017. Designing sustainable landscapes: HUC6 terrestrial core-connector network. Report to the North Atlantic Conservation Cooperative, US Fish and Wildlife Service, Northeast Region.

General description

The HUC6 terrestrial core-connector network is one of the principal Designing Sustainable Landscapes (DSL) landscape conservation design (LCD) products, and it is best understood in the context of the full LCD process described in detail in the technical document on landscape design (McGarigal et al 2017). This particular product was initially developed for the Connecticut River watershed as part of the Connect the Connecticut project (www.connecttheconnecticut.org) — a collaborative partnership under the auspices of the North Atlantic Landscape Conservation Cooperative (NALCC), and subsequently developed for the entire Northeast region as part of the Nature's Network project (www.naturesnetwork.org).

The HUC6 terrestrial core-connector network represents a set of terrestrial **core areas** and the **connectors** between them (**Fig. 1**). In combination with the aquatic core areas, they spatially represent the ecological network designed to provide strategic guidance for conserving natural areas, and the fish, wildlife, and other components of biodiversity that they support within the Northeast.

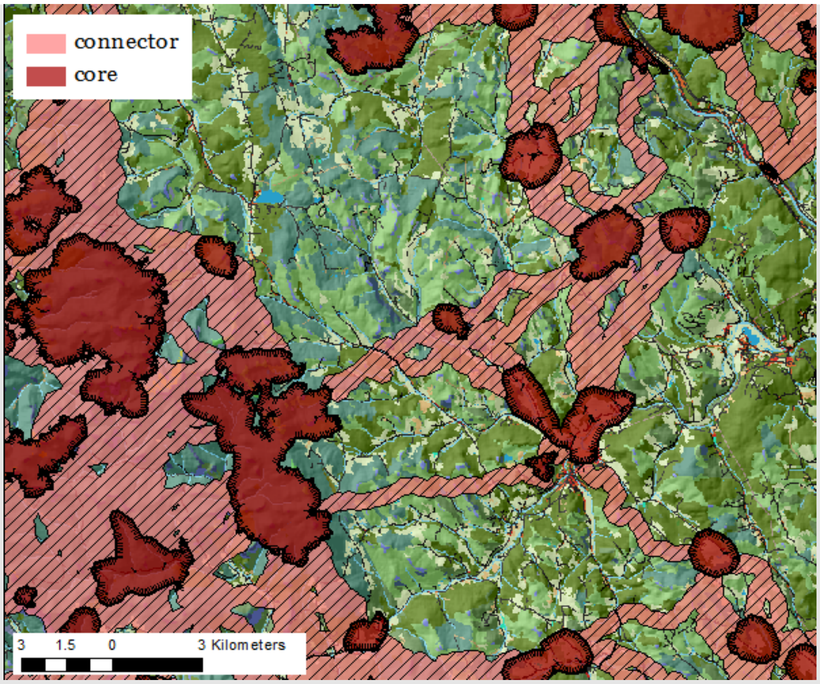

Figure 1. Terrestrial core areas and connectors on a background of the ecological systems map (without a legend).

Core areas serve as the foundation of the LCD. They reflect decisions by the LCD planning team about the highest priority areas for sustaining the long-term ecological values of the landscape, based on currently available, regional-scale information. In this product the terrestrial core areas represent the following:

1) areas of relatively high **ecological integrity** across all terrestrial and wetland ecosystem types and geophysical settings, emphasizing areas that are relatively intact (i.e., free from human modifications and disturbance) and resilient to environmental changes (e.g., climate change). Integrity has the potential to remain high in these areas, both in the short-term due to connectivity to similar natural environments, and in the long-term due to proximity to diverse landforms and other geophysical settings;
2) areas of relatively high current **landscape capability** for a suite of representative (a.k.a. surrogate species) terrestrial wildlife species, emphasizing areas that provide the best habitat and climate conditions today; and

3) areas of **rare terrestrial natural communities** that support unique biodiversity, regardless of their landscape context; inclusive of communities listed by state heritage programs as S1 (extremely rare), S2 (rare), and S3 (uncommon), with definitions of S1-S3 varying slightly among states.

Core areas were built from focal areas ("seeds") within each HUC6 watershed that have high value based on one or more of the attributes listed above. These "seeds" were expanded to encompass surrounding areas that provide additional ecological value and resilience to both short- and long-term change. The surrounding areas were typically of high to moderate ecological value. In some cases the final core areas contained low-intensity development and minor roads, but high-intensity development and major roads were excluded. Collectively, the terrestrial core areas identified in this product encompass ~25% of the Northeast, as decided by the LCD planning team, including a total of 20,358 disjunct core areas encompassing a total of 16,160,371 ha and ranging in size from 3.6 to 107,996 ha, with an average size of 794 ha.

Connectors represent "corridors" that could facilitate the movement of plants and animals (i.e., ecological flow) between terrestrial core areas. These connectors increase the resiliency of the core area network to uncertain land use and climate changes. They are wider where more movement between cores is expected because of larger, higher-quality, and closer core areas and where a more favorable natural environment exists between them. Connectors primarily link adjoining core areas along routes that possess the greatest ecological similarity to the ecosystems in the adjoining cores; they do not necessarily represent travel corridors for any individual species. Connectors may traverse through areas of low-density development and cross roads of all classes, but they do not include high-intensity development. Connectors are not identified between core areas that are greater than 10 km apart. Collectively, connectors encompass an additional ~17% of the Northeast.

Use and interpretation of this layer

The HUC6 terrestrial core-connector network is intended to serve as a starting point for a regional conservation network that can be used in combination with other sources of information to direct and prioritize conservation action. The use of this product should be guided by the following considerations:

- It is important to acknowledge that the HUC6 terrestrial core-connector network was derived from a model, and thus 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 upon which this product was built are imperfect; they contain errors of both omission and commission. Consequently, there will be places where the model gets it wrong, not necessarily because the model itself is wrong, but rather because the input data are wrong. Thus, the terrestrial core-connector network should be used and interpreted with caution and an appreciation for the limits of the available data and models. However, getting it wrong in some places should not undermine the utility of the product as a whole. As long as the model gets it right most of the time, it still should have great utility. Moreover, the model should lead to new insights that might at first seem counter-intuitive or inconsistent with limited observations. This is so because the model is able to integrate a large amount of data over broad spatial scales in a consistent manner and thus provide a perspective not easily obtained via direct and limited observation.

- The HUC6 terrestrial core-connector network represents a synthesis of many data products and decisions. As such, it does not explicitly reveal why any particular area was selected as a core or connector (although the attributes of the core polygons do indicate the ecosystems and species for which the core is relatively important; see below), and therefore it is perhaps best used in combination with the principal supporting data layers that we are permitted to distribute, including: 1) DSL index of ecological integrity (see IEI document, McGarigal et al 2017), 2) The Nature Conservancy's (TNC) terrestrial resiliency index (see resiliency page at TNC's Conservation Gateway), 3) individual species landscape capability indices (see technical document on species, McGarigal et al 2017), and 3) regional conductance index (see conductance document, McGarigal et al 2017).
- HUC6 terrestrial cores were selected to represent the most ecologically important areas within each HUC6 watershed; i.e., the best examples of each ecosystem, geophysical setting, and representative species habitat within each HUC6 watershed. The HUC6 scaling means that in some cases the “best” condition of an ecosystem, geophysical setting or species habitat within a particular HUC6 watershed is not very good in an absolute sense but it still gets selected as a core because it is the best there is within the watershed. Likewise, there may be areas within a particular HUC6 watershed that are not captured in a core but are nonetheless in better condition than areas within cores in other HUC6 watersheds. The HUC6 scaling involves a tradeoff between capturing the highest ecological value and creating a well-distributed ecological network of core areas.
- HUC6 terrestrial cores represent ~25% of the landscape and are deemed the highest priority for conservation along with the connectors between them. However, it is important to recognize that the cores alone (and the connectors between them) are not believed to be sufficient for the long-term conservation of biodiversity in the landscape. Rather, the cores (and the connectors between them) merely represent a possible starting point for landscape conservation; a place to get started given the need to prioritize conservation actions due to limited resources. The terrestrial natural blocks containing the cores (i.e., the undeveloped terrestrial area surrounding the cores extending out to major roads and development; see terrestrial core area tiers document, McGarigal et al 2017), for example, are probably also essential to prevent the future degradation of the cores (**Fig. 2**).
- This core-connector network was derived from regionally consistent data. As such, it may not capture all resource priorities identified at the state or local level made possible with local data. Consequently, this ecological network should not be viewed as “the” conservation network, but rather as a regional complement to state and locally identified conservation priorities.
- After extensive consideration, we opted to define and delineate core areas as places of particularly high ecological value that met certain criteria without regard to existing protected lands (a.k.a., secured lands). In other words, we sought to identify an “ideal”

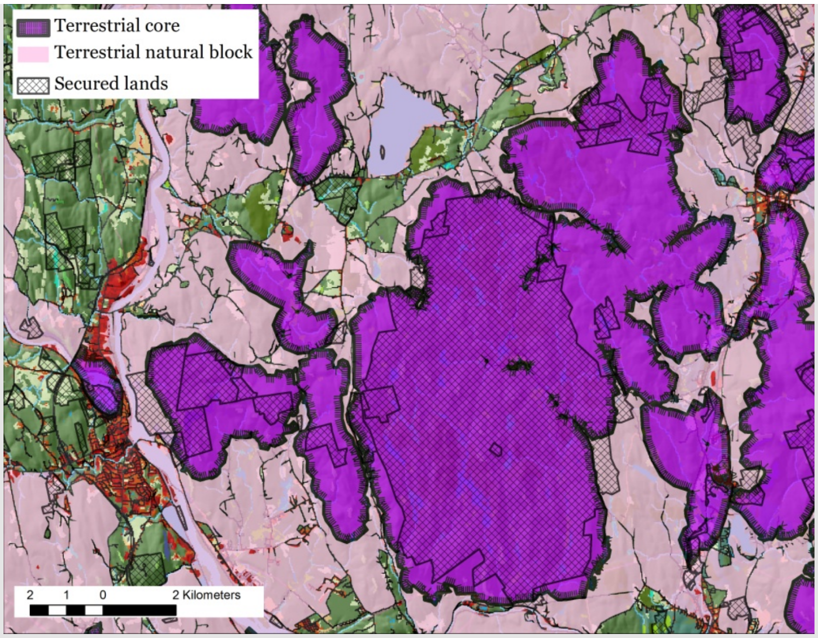

Figure 2. Terrestrial core areas and their supporting landscape (terrestrial natural blocks) overlaid by secured lands on a background of the ecological systems map (no legend).

core area network without bias towards existing protected lands. Existing protected lands may not represent places of particularly high ecological value based on our criteria and thus we did not want to confound the meaning of "core" with "protected." Existing protected lands can serve as an overlay to the "ideal" solution to determine where additional conservation action is needed (**Fig. 2**). Indeed, much of the designated core-connector network is in fact already protected from development; these areas merely need to be managed to ensure their ecological value to the network. The unsecured portion of the terrestrial core-connector network could represent priorities for additional land protection.

- This product can be used in combination with the probability of development layer (see probability of development document, McGarigal et al 2017) and local and regional vulnerability layers (see vulnerability document, McGarigal et al 2017) to identify places in the terrestrial core-connector network that are relatively vulnerable to future development, which could represent priorities for land protection (**Fig. 3**).
- HUC6 terrestrial core areas and connectors, as delineated, may not always represent logical or practical conservation units, since they do not correspond to parcel boundaries or any other practical scheme such as road-bounded blocks. Core areas are places of particularly high ecological value that meet certain criteria using the highest possible resolution of the data (i.e., 30 m cells). As such, rarely will a core area boundary correspond exactly to a parcel boundary. The delineation of core areas on a map should be treated as "fuzzy" boundaries and should not prevent or deter conservation in practice based on other real-world considerations. In practice, conservation actions can (and will necessarily) be directed towards more practical geographic units. Terrestrial cores and connectors are best interpreted as general places to focus attention.
- HUC6 terrestrial cores and connectors can and do include some low-intensity development, minor roads and agriculture. For the core areas, this is the result of growing out the cores from the highest-valued seed areas in which we elected to allow only major roads and medium-to-high intensity development to serve as barriers to

spread. For the connectors, this is the result of the necessity of traversing developed areas when moving between cores embedded in a developed landscape. The inclusion of such developed areas in the cores and connectors should not be interpreted as indicating their intrinsic ecological value, although agriculture has assigned value for some of the representative species, but rather that they represent places with high influence on the target ecological values in the undeveloped areas of the associated cores and connectors. These developed areas could be considered high priorities for restoration or sustainable urban redevelopment.

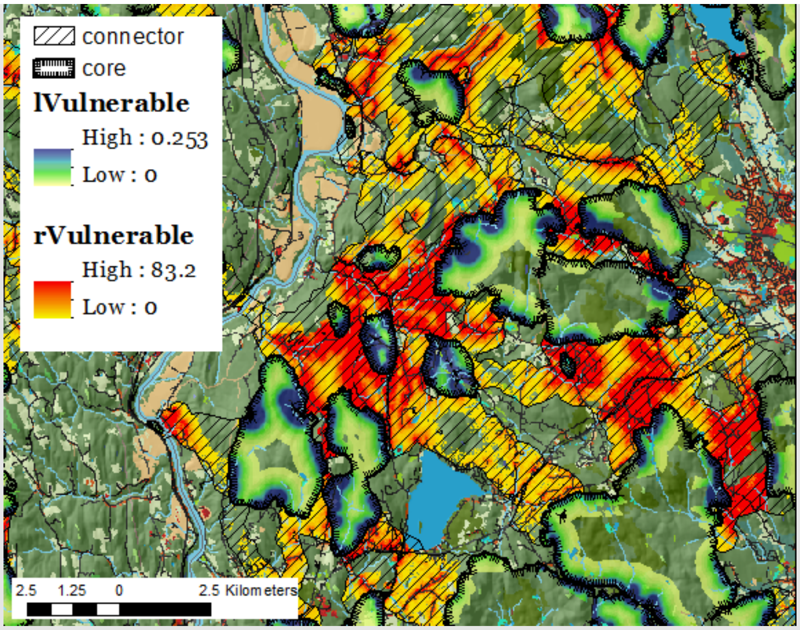

Figure 3. Vulnerability of conductance to future development depicted by a combination of the local vulnerability index (lVulnerable) within terrestrial core areas and the regional vulnerability index (rVulnerable) within connectors. Areas in dark blue within cores and dark red within connectors have a high risk of future development.

- Lastly, while the HUC6 terrestrial core areas and connectors logically represent high priorities for land protection, they also represent opportunities for land management and restoration. In particular, some of the ecological values targeted in some cores (and connectors) may require active management to maintain those values. For example, some ecosystems are fire-dependent and may require the use of prescribed fire to maintain the system in its more natural state. Similarly, some species require grassland or shrubland habitat and may require active habitat management (e.g., mowing) to maintain those habitats. Of course, the management needs of each core area (and connector) will vary with the composition of the cores (and connectors). The GIS metadata provided with this layer (see below) include a list of the top three ecosystems and species targeted in each core area, in addition to links to detailed composition statistics that quantify how important each core area is for each ecosystem and species. This information can help inform the management needs for each core area.

Derivation of this layer

The derivation of the HUC6 terrestrial core-connector network was quite complex, as described in detail in the technical document on landscape design (McGarigal et al 2017).

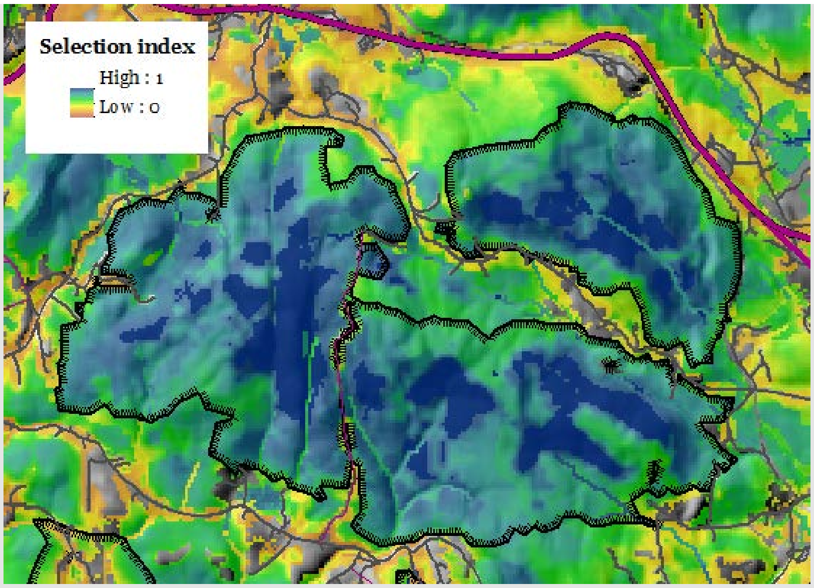

Figure 4. Terrestrial ecosystem-based core areas (depicted by the bold polygons with feathered outlines) showing the initial “seeds” (dark blue) and the underlying terrestrial ecosystem-based core area selection index (depicted as a gradient).

Here, we describe a highly abbreviated version of the process that is sufficient for the use and interpretation of this product.

1. Establish the core areas

We established the HUC6 terrestrial core area network to meet several general criteria based on a two-stage strategy. In the first stage we selected core areas based solely on ecosystem-based considerations, without explicit consideration of individual representative species needs, but recognizing that ecosystem-derived cores contribute substantially towards meeting representative species needs. In the second stage we expanded the stage 1 core areas based solely on meeting representative species needs to ensure that collectively the core areas captured a minimum amount of habitat for each representative species, as follows:

1) *Create the ecosystem-based core area selection index* — The first step was to create a “selection index” that integrated the different ecosystem-based values that core areas were intended to represent within each HUC6 watershed (to ensure distribution across the region), which involved combining: 1) the index of ecological integrity scaled by HUC6 (see IEI document, McGarigal et al 2017), 2) TNC's terrestrial resiliency scaled by HUC6 (see resiliency page at TNC's Conservation Gateway), and 3) mapped rare natural communities listed by state heritage programs as S1 (extremely rare), S2 (rare), and S3 (uncommon)(**Fig. 4**).

2) *Build initial ecosystem-based cores* — The next step was to build the cores based on the selection index, essentially by selecting the very best places by “slicing” the selection index above a threshold level and then “growing” out these “seed” areas through surrounding lower-valued areas (including undeveloped land as well as agriculture, low-intensity development and minor roads) to create larger, contiguous cores in which the highest-value places (i.e., the “seeds") are now buffered by moderately-valued places (**Fig. 4**). Note, by scaling the selection index by HUC6 watersheds we ensured that the “seeds” were well distributed across the region. We grew out the “seed” areas until we captured ~20% of the landscape. **Importantly**, the 20% represents an arbitrary threshold. There is no scientific basis or scientific consensus on “how much is enough” to conserve biodiversity. Indeed, if our goal were to maintain biodiversity at its current level, then it is reasonable to conclude that there

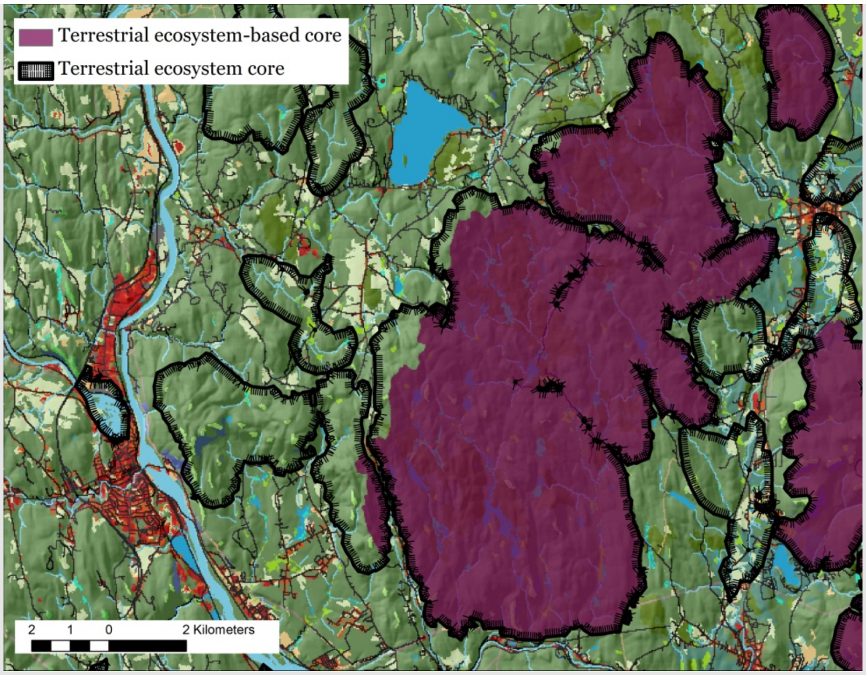

Figure 5. Terrestrial cores, depicting the portion of the cores derived from ecosystem-based considerations (purple) and the final cores in which the additional area was based on meeting representative species habitat needs.

should be no loss of natural areas. However, this is not practical, nor can we affirm that even this would be sufficient to sustain biodiversity as there are other drivers of landscape change affecting biodiversity besides human development. Therefore, rather than try to construct a core area network that captures "enough" to conserve biodiversity, which is an unknown and unknowable quantity, we instead chose an arbitrary constraint on how much to include in cores that emphasizes finding the very best places or the highest priorities for conservation action.

3) *Build final species-complemented cores* — The next step was to supplement the ecosystem-based (stage 1) cores with additional core areas to partially meet the habitat needs of 28 representative terrestrial wildlife species (**Table 1**). The basic idea behind this stage of the core building algorithm was to first determine how much of each species' targeted landscape capability (an index of habitat and climate suitability for each species) was already included in the ecosystem-based cores, and then build additional cores to ensure that a minimum proportion of each species' landscape capability target was included in the final set of cores. Note, for this version of the terrestrial cores we set the targets to be the same for all species, and thus they received equal weight in building the cores. However, in the Connect the Connecticut project, species-specific landscape capability targets were defined by the partnership based on multiple criteria pertaining to anthropogenic threats to the species, CTR responsibility for the species, and rarity of the species. The species-based (stage 2) cores were built sequentially, one at a time, by focusing on the species that were furthest from meeting their targets with each new core. In many cases this involved adding to the existing ecosystem-based (stage 1) cores, but in other cases it involved creating new disjunct cores (**Fig. 5**). This process of building new species-based cores continued until roughly 25% of the landscape was included in the final set of cores. Note, the LCD planning team decided to build separate cores (from the process described above) for the eastern meadowlark as a representative of grasslands.

Table 1. List of 28 terrestrial representative species used in the creation of the terrestrial cores for the Northeast region. B=breeding season; NB=nonbreeding season; A=all year; M=migratory.

Species	Species
American black duck (B)	Moose (A)
American black duck (NB)	Northern Waterthrush (B)
American oystercatcher (B)	Ovenbird (B)
American woodcock (B)	Prairie warbler (B)
Bicknell's thrush (B)	Red-shouldered hawk (B)
Black bear (A)	Ruffed grouse (B)
Blackburnian warbler (B)	Saltmarsh sparrow (B)
Blackpoll warbler (B)	Sanderling (M)
Box turtle (A)	Snowshoe hare (A)
Brown-headed nuthatch (B)	Snowy egret (B)
Cerulean warbler (B)	Virginia rail (B)
Diamondback terrapin (A)	Wood duck (B)
Louisiana Waterthrush (B)	Wood thrush (B)
Marsh wren (B)	Wood turtle (A)

2. Build connectors between cores

After establishing the terrestrial cores, we built connectors among them to facilitate ecological flows (e.g., movement of plants and animals) across the core area network to ensure landscape connectivity. The basic idea was to build conservation corridors between core areas by identifying likely pathways of concentrated ecological flows (i.e., high conductance of plants and animals) between the cores. The connectors were built as part of the process of creating random low-cost paths (RLCPs) between pairs of cores, which is described in detail in the technical document on connectivity (McGarigal et al 2017). Briefly, we modeled thousands of RLCPs between each pair of cores, in which each path started from a randomly selected location in the source core and tried to find a low-cost path to the same ecological system in the destination core (up to a maximum specified distance), where resistance (or cost) was based on ecological similarity to the cell of origin. RLCPs were created in both directions. Thus, the final set of paths reflected likely routes of movement of plants and animals associated with the ecosystem composition of the two cores. For each pair of cores, we selected a subset of the best (highest probability of connectivity) paths, such that the larger, higher-quality, more connected cores got more paths between them. Lastly, we buffered each of the selected paths by 250 m and combined the buffers to form the final connectors (**Fig. 1**).

GIS metadata

HUC6 terrestrial cores and connectors includes two separate data products that can be found at McGarigal et al (2017):

- **geoTIFF raster** (30 m cells) — with the cell values listed below:

  1 = terrestrial core

  2 = connector

- **ESRI ArcGIS shapefile** (polygons) – including the attributes listed below for each polygon. Note, the connector polygons contain values for only the first four attributes listed below.
  - FID = ESRI assigned unique number (which we do not use) for each polygon.
  - Shape = ESRI assigned feature type = "polygon."
  - type = indicator designating the polygon as: "t1core" or "connector."
  - coreID = connectors all have an ID of 1, each core has a unique ID > 1.
  - areaCount = size of the core area in number of cells (30 × 30 m); this includes any developed cells.
  - areaHa = size of the core area in hectares; this includes any developed area.
  - rareCom = percentage of the core comprised of S1-S3 rare communities as defined and mapped by the state Heritage Programs.
  - system1, system2, system3 = The top one to three terrestrial or wetland ecological systems for which the core is particularly important based on index1 described below. For these systems the cumulative ecological integrity of the system within the core is greater than expected (from a statistical perspective) given its distribution across the entire core area network (i.e., index1>1). A blank indicates that no additional ecosystem had an index1>1. Note, the systems listed here reflect the systems for which the core is especially important, but are not necessarily the most abundant systems in the core. A complete listing of the relative importance of the core for all ecological systems, including the relative abundance of systems within the core, is available separately in the Ecosystem table described below.
  - species1, species2, species3 = The top one to three representative species for which the core is particularly important based on index1 described below. For these species the cumulative landscape capability index within the core is greater than expected (from a statistical perspective) given its distribution across the entire core area network (i.e., index1>1). A blank indicates that no additional species had an index1>1. Note, the species listed here reflect the species for which the core is especially important, but are not necessarily the species with the highest total landscape capability in the core. A complete listing of the relative importance of the core for all species, including the total landscape capability in the core attributed to each species (index2, see below), is available in the Species table described below.

Detailed core area composition statistics

Detailed composition statistics are available for each individual core and are divided into ecosystems and species tables (see files in the tCoreStats folder corresponding to the coreID field in the shapefile). In these tables, there are four different indices computed (and their corresponding ranks) that represent different ways of understanding the relative importance of the individual cores to specific ecosystems or species. In all cases, larger values indicate greater importance.

Ecosystem table:

- coreID = unique number assigned to each core.
- systemName = name of the ecosystem as given in the dslLand map (developed classes are not included).
- areaCount = number of cells of the corresponding system in the core. Note, because developed classes were excluded, the sum of areaCount across systems in the core as listed in this table may be less than the core area size as given in the layer attributes.
- areaHa = hectares of the corresponding system in the core.
- index1 = index of importance of the core for the corresponding system, based on deviation of the observed sum of the selection index for the system from its expected value, which is based on the size of the core and the system's average selection index and proportional representation across all cores. The index ranges from 0 to unbounded on the upper end; <1 indicates observed value less than expected, whereas >1 indicates the opposite.
- index1Rank = rank of index1 (1 = max index1).
- index2 = index of importance of the core for the corresponding system, defined as the percentage of the core's total selection index comprised of the corresponding system. The index ranges from 0-100.
- index2Rank = rank of index2 (1 = max index2).
- index3 = index of importance of the core for the corresponding system, defined as the percentage of the system's total selection index across all cores found in the focal core. The index ranges from 0-100.
- index3Rank = rank of index3 (1 = max index3).
- index4 = index of importance of the core for the corresponding system, defined as the difference between the system's average selection index in the focal core and its average selection index across all cores. The index ranges from -1 to 1; negative values indicate an average selection index in the focal core less than its average across all cores, whereas positive values indicate the opposite.
- index4Rank = rank of index4 (1 = max index4).

Species table:

- coreID = unique number assigned to each core.
- speciesName = name of the representative species.

- sumLC = sum of the current landscape capability (LC) index for corresponding species.
- index1 = index of importance of the core for the corresponding species, based on deviation of the observed sum of the LC index for the species from its expected value, which is based on the size of the core and the species' average LC index across all cores. The index ranges from 0 to unbounded on the upper end; <1 indicates observed value less than expected, whereas >1 indicates the opposite.
- index1Rank = rank of index1 (1 = max index1).
- index2 = index of importance of the core for the corresponding species, defined as the percentage of the core's total LC index comprised of the corresponding species. The index ranges from 0-100.
- index2Rank = rank of index2 (1 = max index2).
- index3 = index of importance of the core for the corresponding species, defined as the percentage of the species' total LC index across all cores found in the focal core. The index ranges from 0-100.
- index3Rank = rank of index3 (1 = max index3).
- index4 = index of importance of the core for the corresponding species, defined as the difference between the species' average LC index in the focal core and its average LC index across all cores. The index ranges from -1 to 1; negative values indicate an average LC index in the focal core less than its average across all cores, whereas positive values indicate the opposite.
- index4Rank = rank of index4 (1 = max index4).

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/