Habitat Condition for Imperiled Species: Technical Documentation

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Introduction

In response to the broadly recognized global biodiversity crises, conservationists are urgently attempting to document and conserve thousands of imperiled species in North America. In practice, the number of species and true level of risk faced by each is not measurable, and attempting to evaluate and conserve them one at a time is not practical. Conservation resources are finite and must be allocated to achieve maximum benefits for the most species, yet conservation practitioners are faced with daunting lists of species with uncertain needs. In the Northeast, state wildlife agencies designated almost 3,000 Species of Greatest Conservation Need (SGCN) in their 2016 Wildlife Action Plans, while the U.S. Fish and Wildlife Service is mandated to evaluate hundreds of species that have been petitioned for listing by outside entities. Under such pressures, there is growing interest in the consideration of multiple species benefits and conflicts within shared habitats targeted for conservation. We developed a multi-species mapping approach that leverages the best available species data to identify patterns of concurrent habitat dependence for large numbers of species. Our mapped results represent locations expected to be the most efficient conservation solution protecting the highest concentrations of imperiled species in the Northeast region.

The prioritization and mapping of habitats for imperiled species is a fundamental step in the assessment of species status and for guiding subsequent conservation action. For example, in endangered species listing decisions, explicit spatial estimates of habitat requirements serve as a basis to prescribe effective levels of conservation activity, and during recovery, similar measurements may serve to demonstrate increments of implemented conservation. Beyond regulatory approaches, spatially explicit assessments of species' status are essential to the development of conservation strategies and useful throughout the implementation process, from the prescription and delegation of actions to achieve conservation goals, to tracking progress and response. Instead of evaluating intersecting habitat priorities across separate strategies for individual species, our approach addresses multiple species from the inception, recognizing that many imperiled species depend concurrently on interconnected ecological systems and landscape features.

It is widely acknowledged that location data describing species distribution and corresponding environmental data describing species unique habitat requirements are limited and often unreliable for modelling habitat suitability. Broad land classifications mapping ecological systems or other vegetation-based land units may be used to approximate species habitat requirements, and further augmented by evaluating location data for species with similar habitat requirements (habitat associates). Where data are available for individual species, assessing those species in the context of broader habitats and their habitat associates fortifies the available data, enhances understanding of habitat ecological needs, and more fully illuminates multi-species opportunities for conservation.

In response to the growing demand for spatially explicit assessment of species *en masse*, including the States' charge to map Conservation Opportunity Areas for SGCN, we developed and implemented an approach to leverage existing species tracking systems and current habitat classifications to identify areas of critical habitat importance. The approach is designed to be integrated with institutional species occurrence data management systems for state and federal wildlife agencies, using the best available data. Natural Heritage programs and NatureServe operate together at state and continental scales, serving as the premier quality controlled species occurrence data archive for North America. Integration of our approach with their system could allow assessment and mapping for any specified list of species tracked by NatureServe.

By integrating our multi-species habitat mapping approach with institutional NatureServe data formats and management systems, our work represents an updatable and nationally transferable multispecies status assessment and mapping framework. National implementation of the framework is a feasible vision, since the network of state and federal programs contributing to the NatureServe systems already exists. All data inputs were specified in concert with NatureServe to be executable from their centralized database, and were generated there for our analysis. Our first iteration of results provides a region-wide assessment of habitat condition for the aggregated list of SGCN named by Northeast states (Maine, New Hampshire, Vermont, New York, Massachusetts, Rhode Island, Connecticut, New Jersey, Delaware, Maryland, Virginia, West Virginia, and District of Columbia), but the approach could be adopted in other regions.

At the outset of our effort to devise a data-driven, multi-species mapping mechanism for at-risk species, it was widely recognized that species occurrence data are fraught with challenging inconsistencies. Some of the data quality issues include:

- Absence of data for some species for whole states;
- Inclusion of historic and aging data for many species;
- Incomplete or unstructured methodology yielding uneven survey effort and spotty data;
- Geographic bias toward public land and population centers;
- Inconsistent spatial representation and accuracy.

Acknowledging the known data quality issues, NatureServe data are the only comprehensive data available for most of our species of interest. To manage data quality issues, we applied rigorous quality controls at multiple levels: NatureServe flagged species of generally poor data quality; we analyzed data age, range-wide completeness, and sample size for each species and excluded hundreds of species; we screened individual records for age and accuracy; and we devised a likelihood analysis to minimize the influence of locational and habitat mapping error. In practice, the available data indicate locations of known significance for species at risk. The results generated in this first iteration will improve as conservation action, including more directed surveys, feeds new information to the analytical framework.

Methods Overview

The Habitat Condition for Imperiled Species analysis integrates species occurrence data with a combined version (McGarigal et al. 2016) of the Northeast Terrestrial and Aquatic Habitat Classifications (Gawler 2008; Olivero and Anderson 2008; Ferree and Anderson 2013) and the Index of Ecological Integrity (McGarigal et al. 2016) to map the places that are most important for the conservation of Species of Greatest Conservation Need. The analysis generated the following products:

- a table of species-habitat associations (not disseminated due to large size) and a refined habitat classification;
- a derived table of habitat importance scores and a matching habitat importance map;
- a final map showing the relative condition of the most important habitats.

In brief, we first created a refined classification based on the Northeast Terrestrial Habitat Classification by combining information from ecological systems, distance from aquatic features, and hydrologic units. Next, all records of Northeast plant and animal species tracked by NatureServe were spatially joined to the refined habitat classification to create tabular attributes. In the third step, the tabular attributes recording the co-occurrence of species and habitats were summarized and processed to derive a single importance score for each habitat; the resulting table has a classification structure identical to the refined habitat classification. The importance scores are intended to measure the diversity of species and their collective dependence on each habitat class. The importance scores were weighted by an index of the level of imperilment of species to focus effort on the most at-risk groups of species. Fourth, the habitat importance scores were joined to the refined habitat classification, resulting in a raster map of habitat importance. Fifth, habitat importance was combined with the Index of Ecological Integrity (McGarigal et al. 2016) to measure the combined importance and condition of habitats for imperiled species in the Northeast Region.

Estimation of species-habitat associations

1. The estimation of species-habitat associations is based on the Northeast Terrestrial and Aquatic Habitat Classifications (Gawler 2008; Olivero and Anderson 2008; Ferree and Anderson 2013). In practice, we used a data layer combining the habitat classifications, referred to as DSLland, which was

developed by the University of Massachusetts (UMass) for the Designing Sustainable Landscapes (DSL) project (McGarigal et al. 2016). Preliminary analyses revealed that while some species were strongly associated with ecological systems mapped in the Northeast classifications, species often had a strong relationship to aquatic features or were limited geographically. To account for such patterns in the habitat importance analysis, we refined the Northeast habitat classification by intersecting 3 layers: 1) combined ecological systems, streams, and lake classes (DSLland); 2) distance from aquatic features; and 3) hydrologic watershed units (basin level, HUC06). The layer describing distance to water was created by combining GIS layers for streams (Olivero and Anderson 2008), lakes (Olivero and Anderson 2008), wetlands (National Wetlands Inventory), and oceans. These layers were combined into one feature class, and the Euclidean distance to water was calculated. Data were then reclassified into four distance bands (<100m, 100-300m, 300-1000m, and >1000m). The combination of these three layers creates 9,040 unique classes across the landscape. The DSLland, distance to water, and HUC6 GIS layers were combined using the 'Combine' command in ArcGIS Spatial Analyst to create a layer that creates a unique value for each combination. It is important to note that since the layer defining aquatic classes does not always map aquatic features in the same location as DSLland, the combined layer contains counterintuitive classes where discrepancies exist, such as streams >100 meters from aquatic features. In practice, many aquatic features shift on the landscape, and the classification detects transitional or ambiguous zones relevant to wildlife, regardless of the true location of aquatic features. Hereafter, we will refer to the combined layer as HABITAT9040. HABITAT9040 served 3 purposes: 1) as the input for a spatial join with occurrence data representing species locations, where overlapping raster cells were used to quantify observed species-habitat relationships; 2) the number of raster cells populating each unique class in HABITAT9040 was used as an estimate of the expected values for unique species-habitat associations; and 3) final derived importance weights were applied to each unique class in HABITAT9040, resulting in a map of the relative importance of habitats. **Figure 1** shows HABITAT9040 displayed with different levels of classification.

2. As a pre-cursor to quantifying observed species-habitat relationships, NatureServe processed the records for all Northeast plant and animal species they track to create tabular spatial attributes for each record, although only a subset of animals (SGCN) were used to complete the analysis. A series of spatial joins linked tracked species occurrence data across the 13 Northeast states to HABITAT9040. Unique species-by-habitat intersections were identified, with each record containing a count of species occurrence cells over-lapping a single habitat class. The preliminary data analysis performed by NatureServe provided a tabular dataset which served as the input for estimating the strength of

association between each species and the classes mapped in HABITAT9040. In keeping with our vision to develop methods that can be eventually be employed within the existing NaturServe and Natural Heritage Program network it is relevant to note that that this step was completed by NatureServe and a Natural Heritage program. **Figure 1** demonstrates species data (not actual) overlaid with HABITAT9040.

3. We employed a series of data screening steps on the tabular species occurrence dataset, prior to processing in GIS, beginning with species flagged by NatureServe, and progressing through analysis of the dataset quality for each species, then for each record, then for individual raster cells documented in the tabular data for each occurrence record. First, NatureServe removed species with documented data deficiencies. Next, we analyzed data age, range-wide completeness, and sample size for each species and excluded hundreds of species for related deficiencies. At the level of individual records, we removed low-precision records (G- and M-precision, Very-low and Low RA, etc.). Next we removed Extirpated and Historical Records (EORANKS of "X" and "H"). Records older than 30 years (last seen before 1986) were removed from the database. Additional screens were done to remove other minor issues and to minimize differences between heritage program methodologies. Finally, we removed raster cells that overlapped with anthropogenic habitats (i.e. Dam, Culvert/bridge, Track, Local road, Active train, Motorway, Primary road, Secondary road, Tertiary road, Developed- high intensity, Developed- medium intensity, Developed- low intensity, and Cultivated Crops and Pasture) to minimize the influence of locational and mapping errors manifest in the co-occurrence of species records with mapped habitats.

4. **Table 1** shows an excerpt from the list of 664 SGCN that passed data screening, derived from the full list of nearly 3,000 species compiled from all Northeast state lists presented in 2016. Table 1 also reports values for the Total Species Screen, a metric used to weight each species according an estimated level of imperilment (Fuller 2016, Fuller and Crisfield 2016), referenced below in the context of the weighting procedure. The analysis of species-habitat associations described below was specifically applied to the subset of SGCN passing data screens. However, as previously stated, data were processed for all plants and animals tracked by NatureServe, and while the full suite of species is not of primary interest here, the full dataset was used throughout the development of the analysis as a source of validation for biodiversity patterns observed in the target group of SGCN. In the future, habitat importance and condition mapping may be completed for any designated list of species included in the full dataset of plants and animals. As the primary group of interest here, SGCN were extracted after testing and calculating associations and used in the final analysis to estimate and map habitat importance and condition exclusively for that group.

5. The method used to calculate the strength of association between species and habitat classes is as follows. Observed counts of species occurrences overlapping each habitat class were tallied for all species in the NatureServe tabular dataset and each of the habitat classes in HABITAT9040. The counts of cells in each class were then divided by the total number of observations of the species, resulting in a table of the relative frequency of species-habitat intersections with a sum of 1 across all habitat classes—a matrix of 664 SGCN by approximately 9040 habitat classes. Not all of the theoretically possible 9040 combinations of DSLland, distance to water, and HUC6 watersheds exist on the landscape, therefore only a subset are real, natural habitat classes—as previously stated, developed classes were not allowed as intersections of interest. Further, of all the possible intersections of species records with real and allowed habitat classes, only 5% accounted for the actual associations, indicating that all the records were collectively associated with a finite group of habitat classes. To estimate expected frequencies, the number of raster cells populating each of the unique classes in HABITAT9040 was tallied and set to a relative scale by dividing by the total number of habitat cells. The expected frequencies were constant across all species. To calculate the strength of association of each species with each class of habitat, we measured deviations of the observed relative frequencies from the expected—much like the chi-square statistic. Here, the relative frequency of each species co-occurrence is related to the relative frequency of over-lapping classes. Many cells must intersect one of the habitat classes to register a high observed relative frequency, and where few cells intersect a habitat class, a low relative frequency is registered. The “chi-square” measurement was intended to account for the rarity of habitat classes and improbable intersections with those classes—is it unlikely for species to co-occur with rare classes, and therefore such observations are more likely to indicate a non-spurious positive association. In simple terms, each intersection is scaled to the likelihood of the event. The “chi-square” measurement does not completely remove spurious events from the analysis, instead, it limits their influence by muting coincidental intersections and amplifying ones that represent a majority of species habitats. Further, improbable coincidences must be replicated across hundreds of species to register significantly in the final aggregated assessment of each habitat class. Taken across a large number of species, this approach reduces the noise created by misclassified habitats and the inevitable observation of species in atypical habitats. The formula for calculating the chi-square adjusted habitat association follows:

$$W = ((F_o - F_e) / F_e) + 1$$

where W represents a single cell in the matrix of over 663 SGCN and 9040 fine-scale habitat classes, where F_o is the observed relative frequency of raster cells representing the co-occurrence of species X with each unique fine-scale habitat class, and finally, where F_e is the expected relative frequency of co-occurring cells for species X based on the total count of cells for each class in the fine-scale habitat classification. Recognizing that the value W may approach infinity for species that are frequently found on uncommon habitats, or when species are coincidentally (spuriously) observed on extremely rare habitats, we applied a log transformation to limit the influence of rarity and scale on W:

$$W_{log} = 75 / (1 + e^{-0.1(W-48)})$$

where again W_{log} represents a single transformed cell in the matrix of species and habitats, and each row of W_{log} represents a model of the association of species X with the habitat classes. Using the log transformation, intersections with the rarest classes tended toward the ceiling value of 75, but their influence was limited in the final result by the simple rarity of such classes, and constrained in practice to cases where many species realized a similar unusual association.

The matrix of W_{log} was calculated using two alternative levels of stratification inherent to HABITAT9040, intended to balance local and regionally observed effects. In the first matrix (MATRIX1), emphasizing localized observations, DSLland, distance to water, and HUC6 levels were included, where the inclusion of HUC6 units constrains the extrapolation of observed species-habitat associations to patterns observed within individual HUC6 watersheds. In MATRIX1, of the 9040 hypothetical classes, only 2965 of those that were allowed and real on the landscape were positively associated with a species record. Inclusion of this matrix in the final estimation of habitat importance takes advantage of more localized observations of species, but may include values that are inflated where species coincidentally intersect with classes that are rare within individual HUC6 watersheds. In the second matrix (MATRIX2), emphasizing regional extrapolation of observed species-habitat associations, only the ecological classes (DSLland) and distance from aquatic features were considered, totaling 486 hypothetical classes and representing a maximum extrapolation of species-habitat associations to the Northeast region. In MATRIX2, of the hypothetical 486 classes, only 328 of those that were allowed and real on the landscape were positively associated with a species record. Inclusion of this matrix in the final calculation of habitat importance takes advantage of observed regional patterns to overcome gaps in data resulting from incomplete survey efforts. The classes in MATRIX2 are larger because they are not subdivided by HUC6 watersheds, and serve to reinforce the regional context of local observations—or not if local observations are atypical. Combined, the two terms balance the strength of local observations with observed larger scale patterns and limit the influence of spurious or coincidental associations. **Table 2** provides a conceptual representation of a portion of MATRIX1, which is too large to view.

Estimating and mapping Habitat Importance for Imperiled Species

1. The overall importance of each of the habitat classes represented in HABITAT9040 was estimated by summing each column (habitat class) in the species-habitat matrices (MATRIX1 and MATRIX2). Prior to summation, each matrix was multiplied by a vector of species imperilment scores:

   $$W_{sum} = \sum_{Wlog*TSS}$$

   where W_{sum} is the habitat importance score for a single habitat class in the string of 9040 habitat classes for MATRIX1 and 486 classes for MATRIX2. W_{sum} is equal to the sum of all $W_{log*TSS}$ where TSS is an imperilment score calculated for each species, otherwise known as Total Species Screen (Fuller 2016, Fuller and Crisfield 2016). TSS gives the greatest weight to species of the highest level of imperilment. Table 2 shows how W_{sum} was calculated using the habitat association matrices. In the final step, each of the strings of importance scores values for the two matrices were set to a quantile scale (0-100), then the two were joined in a many-to-one table, and summed, yielding a final value of 0-200 for each of the real and allowed classes. **Table 3** shows an example of nested classes and the resulting habitat importance scores for the Allegheny-Cumberland Dry Oak Forest and Woodland type. **Table 4** shows the highest scoring most important classes of habitat for SGCN.

   In summary, the habitat importance scores have the following properties:
   - If a very large number of species are weakly to moderately associated with a habitat class, it can score highly;
   - if fewer species have a very strong (obligate) association with a habitat class, it can score highly;
   - if associated species are highly imperiled, the importance of a habitat will be higher;
   - habitat importance scores equal to zero indicate that no species were observed for a class level.

2. Habitat Importance for Imperiled Species was mapped by joining the table of habitat importance scores to HABITAT9040, yielding the HABITAT_IMPORTANCE raster. **Figure 2** shows HABITAT_IMPORTANCE displayed in a map.

3. Sensitivity of importance scores to data gaps was iteratively tested by omitting

species occurrence data for groups of species and whole geographies. Detailed sensitivity results are not reported here since large omissions had little impact on the net pattern of important habitats across species and states. Geographic gaps in data availability for individual species may have significant effects on individual species-habitat associations, but these effects were insignificant on the collective pattern across hundreds of species.

Estimating and mapping Habitat Condition for Imperiled Species

1. Habitat Condition for Imperiled Species provides an assessment of the relative condition of important habitats for SGCN. The analysis is built on two key components, HABITAT_IMPORTANCE and the Index of Ecological Integrity (McGarigal et al. 2016), hereafter, IEI. IEI is based on a series of metrics for intactness (freedom from human impairment such as impervious surfaces) and resiliency (capacity to recover from disturbance and stress, enhanced by connections to neighboring natural areas). **Figure 2** shows both input layers and the resulting HABITAT_CONDITION data displayed in a map.

2. A unique stratification for IEI was developed to approximate the unique 3-level habitat classification structure used to create HABITAT9040 and to calculate habitat importance scores, where classes were derived from the 3-way interaction of ecological systems classes, aquatic feature distance classes, and HUC6 watersheds. The application of three-way interaction of the same classes to stratify IEI was not feasible because it produced unreliable Index values in "rare" subclasses. Instead, we applied a mixed model comprised of a pair of equally weighted two-way classifications:

   $$I = 0.5 * E + 0.5 * D$$

   where I is the final mixed version of IEI, E is IEI stratified by ecological system and watershed (quantile scale 0-1), and D is IEI stratified by ecological system and distance class (quantile scale 0-1), with a combined range of values 0-1.

3. The SGCN Habitat Condition score was calculated as follows:

   HABITAT_CONDITION = H * I

   where H is the raster data layer extracted from Important Habitat for Imperiled Species where habitat importance >77 and I is a uniquely stratified version of the Index of Ecological Integrity, as described above. The value 77 marks the upper third of the distribution of habitat importance values--the most important places for SGCN. After values >77 were extracted, we used one pass of the ArcGIS "boundary clean" function to remove stray and isolated pixels. We intended this step to increase continuity of the most important habitats, accepting a minor loss of cells. The regions extracted represent riparian zones and other critically important habitats because these are the habitats upon which the largest numbers of SGCN depend.

4. The final HABITAT_CONDITION result contains a possible range of values from 0-200, where 200 represents the product of the maximum HABITAT_IMPORTANCE score (200) and the maximum Index of Ecological Integrity Score (1). The results do not include Important Habitat scores below 77. All habitats shown in the Habitat Condition for Imperiled Species layer are "important", but only the locations scoring highly in the data layer can be considered both "important" *and* "intact." We cautiously *recommend* interpreting the top ⅓ of Habitat Condition as intact, the middle ⅓ as being moderately intact and the bottom ⅓ as being severely degraded and probably in need of restoration. The top, middle, and bottom third of the Habitat Condition layer are labelled "Protect", "Buffer", and "Restore" in the included layer file. The labels are not a formal prescription for action, they are only meant help interpret the condition of the habitats.

5. The dataset Core Habitat for Imperiled Species (CORE_HABITAT) was created as follows. The top ⅓ of HABITAT_CONDITION was extracted and converted to polygons. Small, isolated "patches" of habitat of one or two cells (30m × 30m cells) were then removed. Finally, the polygon outlines were smoothed to remove the sharp angles. Core Habitat for Imperiled Species is intended to represent the most intact habitats for imperiled species, and it includes places that are likely to contain high species diversity.

Known Limitations, Clarifications, and Alternatives

- The mapping of habitats (i.e. ecological systems) is known to be imperfect, which consequently affects the mapped values for ecosystem integrity and species habitat. While the habitat mapping is anticipated to correctly reflect broad patterns of ecosystem occurrence, errors in classification and placement do occur. Additionally, some specialized, small patch habitats may be missed entirely.
- When the Northeast region boundaries are combined with HUC6 boundaries, it results in some small watershed pieces at the boundaries; a few HUC6s (as defined by USGS) are inherently small to begin with, artificially inflating the rarity and expected frequency of classes in the border region. To avoid problems in

calculating IEI on small regions, UMass created a custom HUC6 version that combines some of the small HUC6 pieces, reducing the USGS set to 40, resulting in a minor discrepancy in the calculation of condition scores in small watersheds. In the future, this discrepancy will be resolved, but is currently viewed as inconsequential since the local contribution of habitat importance is only half the total importance score.

- State Natural Heritage Programs may not track the same suite of species within each jurisdiction. Additionally, there are gaps in geographic coverage both within and among states with variation in survey effort. The current versions of Habitat Importance and Habitat Condition for Imperiled Species do not reflect rare species data from Rhode Island. We attempted to compensate for this and other data gaps by allowing a both regional and more localized (HUC6) effects to be included in the model.
- Sensitivity of importance scores to data gaps was iteratively tested by omitting species occurrence data for groups of species and whole geographies. Detailed sensitivity results are not reported here since large omissions had little impact on the net pattern of important habitats across species and states. Geographic gaps in data availability for individual species may have significant effects on individual species-habitat associations, but these effects were insignificant on the collective Habitat Importance pattern across hundreds of species.
- Certain species have been identified that were excluded from the source dataset or the analysis, including Delmarva fox squirrel, New England cottontail, Appalachian cottontail, and Allegheny woodrat, for no apparent reason. We are working to correct such omissions.
- The identification of Habitat Condition for Imperiled Species is predicated on the assumption that biodiversity is best supported by intact, well connected landscapes. While this assumption is soundly grounded in conservation biology theory and findings, it is recognized that many species of conservation concern may depend on habitat currently existing in a less intact state or otherwise missed by core areas. The Habitat Condition for Imperiled Species product is intended to complement the terrestrial core areas by focusing on such areas.
- The obvious ecological distinction between aquatic and terrestrial species and ecosystems was considered early in the development of the analysis—we questioned the validity of species data intersecting the wrong category of habitat. We recognized that few, if any, aquatic species are free from interaction with surrounding uplands, and the same for terrestrial species interacting with aquatic features. Aquatic species were removed from the dataset and separately intersected with stream reaches depicted as watershed catchments. The resulting habitat importance scores were applied to appropriately classified stream reaches and mapped. In parallel, habitat importance was calculated for all species using the combined terrestrial and aquatic map (HABITAT9040). We compared the results of both approaches and found that aquatic features mapped using the second approach matched those mapped using the

segregated aquatic analysis. We concluded that the combined analysis was a superior result because it includes the relevance of the aquatic-terrestrial interface for both groups of species, a zone which is ambiguous when mapped as discrete features on the landscape.

- The identification of areas as providing habitat for imperiled species does not necessarily mean that imperiled species are actually present in those areas. Users are encouraged to verify, with field visits and local knowledge, the value of any areas identified as habitat for imperiled species before planning conservation action.

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Tables and Figures

Figure 1. HABITAT9040 combines habitat classification, distance to aquatic features, and HUC6 watersheds. The map on the upper left shows an aerial photograph for reference. The map on the upper right displays HABITAT9040 by DSLland classification; bottom left shows the distance to aquatic features; and bottom right shows the combination of the preceding classes with HUC6 watersheds. The combined classification shown in the bottom right was used to create species-habitat associations as indicated by the species data (not actual).

Table 1. Example of Species of Greatest Conservation included in Habitat Importance for Imperiled Species. The full list is over 600 species. Listed species were designated by one or more states and passed multiple data quality screens. The column labelled TSS contains imperilment scores used to weight species-habitat associations.

Scientific Name	Common Name	TSS
Acipenser brevirostrum	Shortnose sturgeon	1
Noturus flavipinnis	Yellowfin Madtom	1
Sterna dougallii	Roseate tern	1
Cicindela puritana	Puritan tiger beetle	1
Cicindela dorsalis dorsalis	Northeastern Beach Tiger Beetle	1
Callophrys hesseli	Hessel's Hairstreak	1
Lasmigona subviridis	Green Floater	1
Alasmidonta heterodon	Dwarf wedge mussel	1
Crystallaria cincotta	Diamond Darter	1
Percina bimaculata	Chesapeake Logperch	1
Alasmidonta varicosa	Brook Floater	1
Glyptemys muhlenbergii	Bog Turtle	1
Williamsonia lintneri	Banded bog skimmer	1
Speyeria idalia	Regal Fritillary	0.8
Cicindela patruela	Northern Barrens Tiger Beetle	0.8
Erynnis martialis	Mottled Duskywing	0.8
Callophrys irus	Frosted Elfin	0.8
Cicindela marginipennis	Cobblestone Tiger Beetle	0.8
Catharus bicknelli	Bicknell's Thrush	0.8
Plebejus melissa samuelis	Karner Blue	0.8
Acipenser oxyrinchus	Atlantic Sturgeon	0.8
Glyptemys insculpta	Wood Turtle	0.6
Bartramia longicauda	Upland Sandpiper	0.6
Hemileuca maia maia	The Buckmoth	0.6
Picoides borealis	Red-cockaded Woodpecker	0.6
Acipenser fulvescens	Lake Sturgeon	0.6
Scaphiopus holbrookii	Eastern Spadefoot	0.6
Rana virgatipes	Carpenter Frog	0.6
Emydoidea blandingii	Blanding's Turtle	0.6
Dendroica castanea	Bay-breasted Warbler	0.6
Botaurus lentiginosus	American Bittern	0.6
Hyla andersonii	Pine Barrens Treefrog	0.4
Enallagma recurvatum	Pine Barrens Bluet	0.4
Quadrula pustulosa	Pimpleback	0.4
Podilymbus podiceps	Pied-billed Grebe	0.4
Euphyes pilatka	Palatka Skipper	0.4
Polyodon spathula	Paddlefish	0.4
Pandion haliaetus	Osprey	0.4
Asio flammeus	Short-eared owl	0.4
Aquila chrysaetos	Golden Eagle	0.4
Clemmys guttata	Spotted Turtle	0.2
Sorex palustris albibarbis	Northern Water Shrew	0.2
Ambystoma opacum	Marbled Salamander	0.2
Sterna hirundo	Common tern	0.2
Chordeiles minor	Common nighthawk	0.2
Gavia immer	Common Loon	0.2
Dolichonyx oryzivorus	Bobolink	0.2
Ambystoma laterale	Blue-spotted Salamander	0.2
Rallus limicola	Virginia Rail	0.2
Pooecetes gramineus	Vesper sparrow	0.2

Table 2. Conceptual representation of species-habitat matrices used to estimate strength of association and overall Habitat Importance. The first two columns contain species information, and each of the remaining columns contain data about the intersection of each species with each of 9040 habitat classes. Each row maps a habitat association for a single species. Prior to summation of the columns to derive Habitat Importance scores for each habitat class, the matrix of log-transformed weights (W_{log}) is multiplied by the TSS vector, giving the habitats of imperiled species a higher contribution to overall importance.

	DSLand code	11000	11000	11000	11000	11000	11000	11000	11000	11000	11000	...
	Distance class	100	100	100	100	100	300	300	300	300	300	...
	HUC6 code	50701	50200	50500	50302	60102	50702	50500	50200	50302	50901	...
	Habitat class code (total=9040)	11000_100_050701	11000_100_050200	11000_100_050500	11000_100_050302	11000_100_060102	11000_300_050702	11000_300_050500	11000_300_050200	11000_300_050302	11000_300_050901	...
Species Code	**TSS Score (0-1)**											
1	X1	$W_{log1.1}$	$W_{log1.2}$	$W_{log1.3}$	$W_{log1.4}$	$W_{log1.5}$	$W_{log1.6}$	$W_{log1.7}$	$W_{log1.8}$	$W_{log1.9}$	$W_{log1.10}$	...
2	X2	$W_{log2.1}$	$W_{log2.2}$	$W_{log2.3}$	$W_{log2.4}$	$W_{log2.5}$	$W_{log2.6}$	$W_{log2.7}$	$W_{log2.8}$	$W_{log2.9}$	$W_{log2.10}$	...
3	X3	$W_{log3.1}$	$W_{log3.2}$	$W_{log3.3}$	$W_{log3.4}$	$W_{log3.5}$	$W_{log3.6}$	$W_{log3.7}$	$W_{log3.8}$	$W_{log3.9}$	$W_{log3.10}$	...
4	X4	$W_{log4.1}$	$W_{log4.2}$	$W_{log4.3}$	$W_{log4.4}$	$W_{log4.5}$	$W_{log4.6}$	$W_{log4.7}$	$W_{log4.8}$	$W_{log4.9}$	$W_{log4.10}$	...
5	X5	$W_{log5.1}$	$W_{log5.2}$	$W_{log5.3}$	$W_{log5.4}$	$W_{log5.5}$	$W_{log5.6}$	$W_{log5.7}$	$W_{log5.8}$	$W_{log5.9}$	$W_{log5.10}$	...
6	X6	$W_{log6.1}$	$W_{log6.2}$	$W_{log6.3}$	$W_{log6.4}$	$W_{log6.5}$	$W_{log6.6}$	$W_{log6.7}$	$W_{log6.8}$	$W_{log6.9}$	$W_{log6.10}$	...
7	X7	$W_{log7.1}$	$W_{log7.2}$	$W_{log7.3}$	$W_{log7.4}$	$W_{log7.5}$	$W_{log7.6}$	$W_{log7.7}$	$W_{log7.8}$	$W_{log7.9}$	$W_{log7.10}$	...
8	X8	$W_{log8.1}$	$W_{log8.2}$	$W_{log8.3}$	$W_{log8.4}$	$W_{log8.5}$	$W_{log8.6}$	$W_{log8.7}$	$W_{log8.8}$	$W_{log8.9}$	$W_{log8.10}$	...
9	X9	$W_{log9.1}$	$W_{log9.2}$	$W_{log9.3}$	$W_{log9.4}$	$W_{log9.5}$	$W_{log9.6}$	$W_{log9.7}$	$W_{log9.8}$	$W_{log9.9}$	$W_{log9.10}$	...
10	X10	$W_{log10.1}$	$W_{log10.2}$	$W_{log10.3}$	$W_{log10.4}$	$W_{log10.5}$	$W_{log10.6}$	$W_{log10.7}$	$W_{log10.8}$	$W_{log10.9}$	$W_{log10.10}$	...
...	...	...∑	...∑	...∑	...∑	...∑	...∑	...∑	...∑	...∑	...∑	...
Habitat Importance Score		W_{sum1}	W_{sum2}	W_{sum3}	W_{sum4}	W_{sum5}	W_{sum6}	W_{sum7}	W_{sum8}	W_{sum9}	W_{sum10}	...

Table 3. Allegheny-Cumberland Dry Oak Forest and Woodland example: two levels of stratification contribute to the final Habitat Importance Score. The example shows how the nested classification structure combines Habitat Importance scores for the local (DSLland x Distance x HUC) and regional (DSLland x Distance) effects within the Allegheny-Cumberland Dry Oak Forest and Woodland type. The two different levels of Habitat Importance scores were derived from species-habitat matrices (MATRIX1 and MATRIX2).

Habitat Class Name	Distance	HUC6	DSLland x Distance x HUC6 Importance Score	DSLland x Distance Importance Score	Final Importance Score
Allegheny-Cumberland Dry Oak Forest and Woodland	100	50701	100	92	192
Allegheny-Cumberland Dry Oak Forest and Woodland	100	50200	90	92	182
Allegheny-Cumberland Dry Oak Forest and Woodland	100	50500	87	92	179
Allegheny-Cumberland Dry Oak Forest and Woodland	100	50702	85	92	177
Allegheny-Cumberland Dry Oak Forest and Woodland	100	50901	80	92	172
Allegheny-Cumberland Dry Oak Forest and Woodland	100	50301	78	92	170
Allegheny-Cumberland Dry Oak Forest and Woodland	100	50302	76	92	168
Allegheny-Cumberland Dry Oak Forest and Woodland	100	60102	63	92	155
Allegheny-Cumberland Dry Oak Forest and Woodland	100	60101	58	92	150
Allegheny-Cumberland Dry Oak Forest and Woodland	1000	60102	57	59	116
Allegheny-Cumberland Dry Oak Forest and Woodland	1000	50702	43	59	102
Allegheny-Cumberland Dry Oak Forest and Woodland	1000	50500	43	59	102
Allegheny-Cumberland Dry Oak Forest and Woodland	300	50701	78	20	98
Allegheny-Cumberland Dry Oak Forest and Woodland	1000	60101	34	59	93
Allegheny-Cumberland Dry Oak Forest and Woodland	1000	50200	33	59	92
Allegheny-Cumberland Dry Oak Forest and Woodland	300	50702	61	20	81
Allegheny-Cumberland Dry Oak Forest and Woodland	1000	50302	12	59	71
Allegheny-Cumberland Dry Oak Forest and Woodland	1000	50701	5	59	64
Allegheny-Cumberland Dry Oak Forest and Woodland	1000	50901	1	59	60
Allegheny-Cumberland Dry Oak Forest and Woodland	1000	30101	1	59	60
Allegheny-Cumberland Dry Oak Forest and Woodland	1001	50500	26	32	58
Allegheny-Cumberland Dry Oak Forest and Woodland	300	50500	30	20	50
Allegheny-Cumberland Dry Oak Forest and Woodland	300	50200	28	20	48
Allegheny-Cumberland Dry Oak Forest and Woodland	300	50302	16	20	36
Allegheny-Cumberland Dry Oak Forest and Woodland	300	50901	11	20	31
Allegheny-Cumberland Dry Oak Forest and Woodland	300	50301	6	20	26
Allegheny-Cumberland Dry Oak Forest and Woodland	300	60102	3	20	23

Table 4. Highest scoring classes by Habitat Importance. The table shows the top 25 habitats scored by Habitat Importance.

Habitat Class Name	Distance	HUC6	DSLland x Distance x HUC6 Importance Score	DSLland x Distance Importance Score	Final Importance Score
Stream (small) cool low	100	50100	100	100	200
Stream (small) warm low	100	20503	100	100	200
Stream (small) cool moderate	100	20401	100	99	199
Southern Ridge and Valley / Cumberland Dry Calcareous Forest	100	60102	100	99	199
Stream (headwater/creek) warm low	100	30102	100	98	198
Stream (headwater/creek) warm low	100	30101	100	98	198
Stream (small) cool low	100	20501	98	100	198
Stream (small) cool moderate	100	20802	99	99	198
Stream (small) warm low	100	50302	98	100	198
Stream (small) warm moderate	100	30102	98	100	198
Stream (medium) warm	100	50701	98	100	198
North-Central Appalachian Large River Floodplain	100	41201	100	98	198
Southern Ridge and Valley / Cumberland Dry Calcareous Forest	100	60101	99	99	198
Stream (headwater/creek) warm low	100	20801	99	98	197
Stream (small) cool low	100	20200	97	100	197
Stream (small) warm moderate	100	30101	97	100	197
Stream (medium) warm	100	60101	97	100	197
Stream (medium) warm	100	50500	97	100	197
North Atlantic Coastal Plain Heathland and Grassland	100	20302	100	97	197
Ruderal Shrub Swamp	100	20501	100	97	197
Stream (small) cool low	100	41300	96	100	196
Stream (small) cool low	100	20802	96	100	196
Stream (small) cool moderate	100	11000	97	99	196
Stream (small) warm low	100	30101	96	100	196
Stream (small) warm moderate	100	20503	96	100	196
Stream (large) warm	100	20401	99	97	196
Ruderal Shrub Swamp	100	20200	99	97	196
North Atlantic Coastal Plain Pitch Pine Barrens	100	10900	100	96	196
Stream (headwater/creek) cool moderate	300	20700	98	97	195
Stream (headwater/creek) warm low	100	20403	97	98	195
Stream (small) cool low	100	11000	95	100	195
Atlantic Coastal Plain Beach and Dune	100	20302	96	99	195
Stream (large) warm	100	50500	98	97	195
Small Pond	100	41402	100	95	195
Small Pond	100	41501	100	95	195
Small Pond	100	10802	100	95	195
Small Pond	100	20801	100	95	195
Small Pond	100	20802	100	95	195
Small Pond	100	20403	100	95	195
Small Pond	100	10600	100	95	195
Small Pond	100	20301	100	95	195
Small Pond	100	10500	100	95	195
Small Pond	100	20700	100	95	195
Stream (headwater/creek) cool low	100	41503	100	94	194
Stream (headwater/creek) cool low	100	50500	100	94	194
Stream (headwater/creek) cool low	100	20200	100	94	194
Stream (headwater/creek) cool low	100	41504	100	94	194
Stream (headwater/creek) warm low	100	20600	96	98	194
Stream (headwater/creek) warm low	100	20402	96	98	194

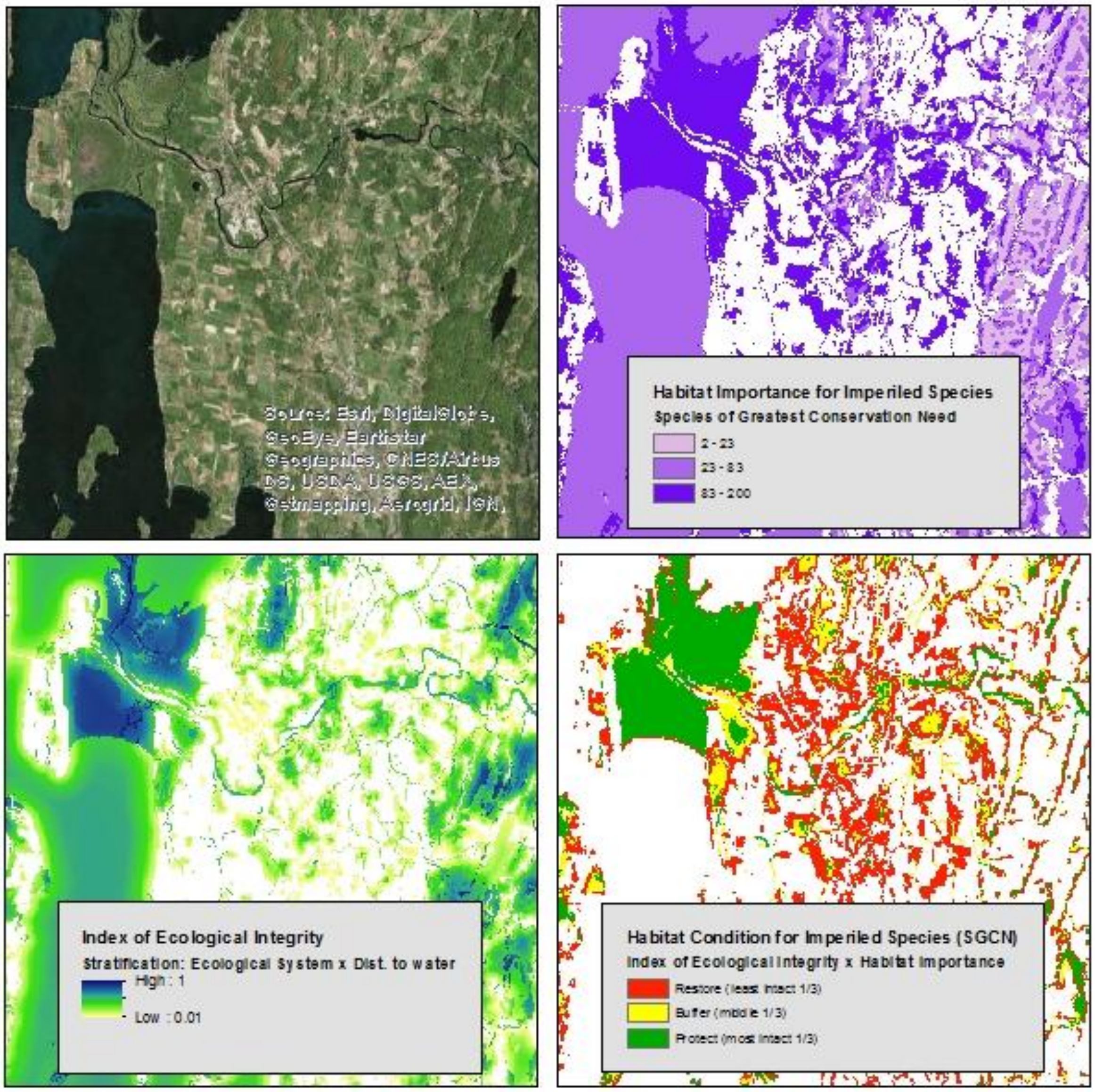

Figure 2. Mapping Habitat Condition for imperiled species (SGCN). The map on the upper left shows an aerial photograph for reference. The map on the upper right shows HABITAT_IMPORTANCE for Species of Greatest Conservation Need; the map at bottom left shows the Index of Ecological Integrity (McGarigal et al. 2016) stratified by ecological systems (Gawler, 2008; Ferree and Anderson 2013); and the map at bottom right shows HABITAT_CONDITION for Species of Greatest Conservation Need, which is the product of the preceding two raster datasets.

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