SECTION 1. ADMINISTRATIVE INFORMATION

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Institution of the recipient: University of Massachusetts-Amherst
Project title: Refugia are important but are they connected? Mapping well-connected climate refugia for species of conservation concern in the northeastern U.S.
Agreement number: G20AC00070
Date of this report: July 15, 2021
Period of time covered by this report: April 15, 2020 - April 14, 2021
Actual total cost of the project: $73,747

SECTION 2. PLAIN LANGUAGE PUBLIC SUMMARY

As the climate continues to change, vulnerable wildlife species will need specific management strategies to help them adapt. One strategy is based on the idea that some locations that species inhabit today will remain suitable over time. These locations are called climate refugia. However, other locations may become too hot, dry or wet for a species to continue to inhabit, and may eventually become unsuitable for the species. When wildlife managers are considering protecting land for vulnerable species, they sometimes prioritize locations that are predicted to be climate refugia. Rarely can those managers consider how *accessible* refugia locations are to these species. Some species are often unable to move through particular features on the landscape, for example, development, wetlands, or steep slopes. What good is it to protect climate refugia if they are not connected to the broader landscape? We focused on 10 vulnerable species identified by conservation practitioners, identifying a set of cores for each species that include areas of high relative value to the species either in the present, the future, or both. We assessed and mapped the connections between each nearby pair of cores (both in the present and future) and used the pairwise connectivities to score each core's connectivity in the present and future. Finally, we created an overall score that combines landscape capability, climate refugia, and the connectivity of each core which we consider a good starting point for conservation of each species. In general we found that the highest habitat values, connectivites, and scores were concentrated both towards the center of each species range and towards the center of clusters of cores. This information will help conservation practitioners prioritize land that will not only remain suitable for species given climate change but will also be accessible and thus habitable by those species.

SECTION 3. PROJECT SUMMARY

Managing for climate refugia is an important strategy for biodiversity conservation. The premise of refugia as an effective climate adaptation management strategy relies on the assumption that animals are able to access specific locations on the landscape which will retain suitable biotic and abiotic conditions required to fulfill their life history requirements. Most refugia management tools simply identify geographic locations where current conditions are most likely to persist and ignore how connected those locations are to ex-situ refugia or how accessible they are to current species distributions. How effective can a management strategy based on a refugia network be if it is disconnected from the current best habitat within a species distribution or other refugia, particularly in the context of metapopulation dynamics? We mapped 2080 refugia networks for each of 10 SGCN species in the northeastern US. Species were selected based on stakeholder feedback and modeling feasibility. We used connectivity metrics developed during previously funded efforts of the Designing Sustainable Landscapes (DSL) project to model connections among 2080 refugia and among 2020 cores for each species. The newly developed species cores and refugia connectivity maps and metrics enable us to prioritize refugia for SGCN species based on how well they may provide current habitat, refugia, and current and future connectivity. The delineated cores themselves highlight areas that are locally of high value while the scores allow comparison among them. Not surprisingly for most species the quality of the habitat, refugia, and connectivity tended to be concentrated in the same areas, although depending on the spatial structure of the cores some aspects of connectivity are high in areas that may not otherwise score high. To our knowledge, connectivity has not been explicitly included on a species-specific basis in refugia prioritization tools for SGCN species in the northeastern US. Our findings offer an initial step to incorporate landscape connectivity among refugia networks in landscape conservation design.

SECTION 4. REPORT BODY

Purpose and Objectives

The Biden administration and major conservation organizations support the newly proposed Global Deal for Nature (GDN) to protect 30% of terrestrial areas by 2030 (i.e., “30 by 30”) and 50% by 2050 (Dinerstein et al. 2020). These ambitious goals must account for climate change, as < 10% of North America’s existing protected area network will host climates that represent analogs of current conditions (Batllori et al. 2017, Hoffman et al. 2019). Subsequently, identification of climate change refugia – locations that are relatively buffered from climate change and therefore likely to facilitate the persistence of current physical, ecological (e.g., species), and/or sociocultural resources (Morelli et al. 2016) – has become a major focus of conservation planning (Michalak et al. 2020, Stralberg et al. 2020). Recent research supports the hypothesis that as the climate warms, refugia will be important for population persistence, genetic diversity, and evolutionary potential of climate-sensitive species, and that habitat connectivity among refugia is a key element of functional refugial networks (Carroll et al. 2018, Morelli et al. 2017). However, most refugia management tools simply identify geographic locations where current conditions are most likely to persist and ignore how connected those locations are to other refugia or how accessible they are to current species distributions.

Our initial goals for this project were to (1) identify well-connected sets of core areas for 2020 for each of 10 stakeholder-selected species in the northeastern U.S., (2) identify 2080 refugia networks for each of the selected species, (3) independently for each species, assess connectivity among the 2020 cores, between 2020 cores and 2080 refugia, and among 2080 refugia, (4) apply a relatively new approach to assessing landscape connectivity by using random low cost paths to assess connectivity at finer spatial scales in conjunction with using graph theory to assess connectivity at broader, regional spatial scales. However, these objectives were modified as follows:

- Our original plan was to use an objective process to identify species cores (e.g., capture top 25% of total Landscape Capability). It turned out that the distributions of Landscape Capability (LC) scores varied considerably among species, making this an unrealistic approach. Instead, we subjectively adjusted core selection parameters to give a reasonable distribution of cores across the geographic range for each species. This new approach ensured that important core areas were selected throughout a species range.
- We dropped the original plan to model connectivity from lost 2020 cores to refugia cores, as several species had few refugia cores (see below for further discussion regarding this change). We revised our approach to modeling connectivity for the present (2020) and future (2080) separately, in order to bracket uncertainty in projections of species response to climate change.

Organization and Approach

Species models. Analyses were based on species Landscape Capability models from the Designing Sustainable Landscapes project (McGarigal et al. 2017b). These expert-based models, which have been validated to some extent (McGarigal et al. 2017b, Loman et al. 2017, 2018) assess LC in the present (2020), as well as Climate Refugia (CRefugia) in the future (2080) based on climate change (McGarigal et al. 2021) under RCP 8.5 but holding habitat constant (i.e., no urban growth, as conservation action now will shape where future urban growth occurs). Both LC and CRefugia provide a quantitative index of expected habitat capability. Working with stakeholders (see Stakeholder Engagement, below), we selected 10 wildlife species for this project: American woodcock (AMWO), Bicknell's thrush (BITH), Blackburnian warbler (BLBW), Box turtle (TECA), Cerulean warbler (CERW), Moose (MOOSE), Piping plover (PIPL), Saltmarsh sparrow (SALS), Spotted turtle (CLGU), and Wood turtle (GLIN).

Identifying cores. We built current (2020) and future (2080) conservation cores for each species using the following process separately for each timestep, using the same parameters for both timesteps (see Appendix A for parameters used for each species). First, we sliced the species index (LC for 2020, Fig. 1a, and CRefugia for 2080) at a specified value to capture "seeds" of the highest-scoring habitat for each species (Fig. 1b). Although we'd originally planned to do this objectively, capturing a fixed top percent of the species index for each species, the distributions of the species index scores for each species varied considerably, with much of the total species index for several species consisting of large areas of low values that are unlikely to provide habitat. Instead, we adjusted core selection parameters individually for each species to try to capture a good representation of cores across the species range.

Taking a rangewide slice for each species typically results in seeds only in the heart of the range but not the periphery. As range peripheries are typically sites of greater genetic variation, acting as loci of potential future evolution, range peripheries are important to conservation. This is, of course, particularly true given climate change: range peripheries are likely sources of dispersal. We addressed this issue by building large-scale kernels (with a bandwidth of 25 km) on LC for each species, and varying core selection parameters between two set values based on the kernel at each location. This process allowed selecting the highest-valued species index in the heart of a species range, and progressively lower-valued species indices in peripheral areas. This allowed us to meet the goal of identifying conservation cores in the best habitat at the core of the range, and the best available habitat all the way to range edges.

After slicing to obtain seeds for each species (Fig. 1b), we built resistant kernels (Compton et. al 2007) on each seed (Fig. 1c), with resistance based on the species index (within habitat) or each species' movement resistance (where the species index was 0). This buffered and coalesced seeds, preferentially including higher-valued habitat, and avoiding areas each species was less likely to traverse, including both natural systems a species is unlikely to cross (e.g., lakes for box turtles) and anthropogenic classes such as roads and development. We sliced these kernels at a specified point to create preliminary cores (Fig 1d and 1e), and dropped cores that were smaller than a specified threshold size.

Once cores were built for each species, we identified overlapping cores and assigned each core to one of three types: (1) refugia, present in both 2020 and 2080 (Fig. 1f); (2) lost, present in 2020 but not in 2080; and (3) new, present in 2080 but not in 2020. As the cores typically have different sizes and values in each of the time steps, we used the footprint of 2080 core for refugia cores.

Assessing connectivity among cores. Connectivity was assessed using random low-cost paths (McGarigal et al. 2013 and McGarigal et al. 2017a, under Regional Conductance). Random low-cost paths are an approach to estimating how individuals of a species may move across the landscape during long-distance dispersal. The landscape is represented as a resistant surface specific to the species. Large numbers of paths between two points (here, between points in each of two species cores) are created by including a random component in least-cost paths, resulting in a probabilistic assessment of movement paths of individuals. We used the species movement parameters for each landcover class from the original species LC models for landscape resistance, and built 400 paths between each pair of cores, including both current (2020) and future (2080) cores. The result is a raster representation of the paths, known as conductance, for each time step, where higher values represent higher ecological connections (Fig. 2). Core selection and connectivity modeling used custom code written in APL+Win 11.1.03, APLNow LLC.

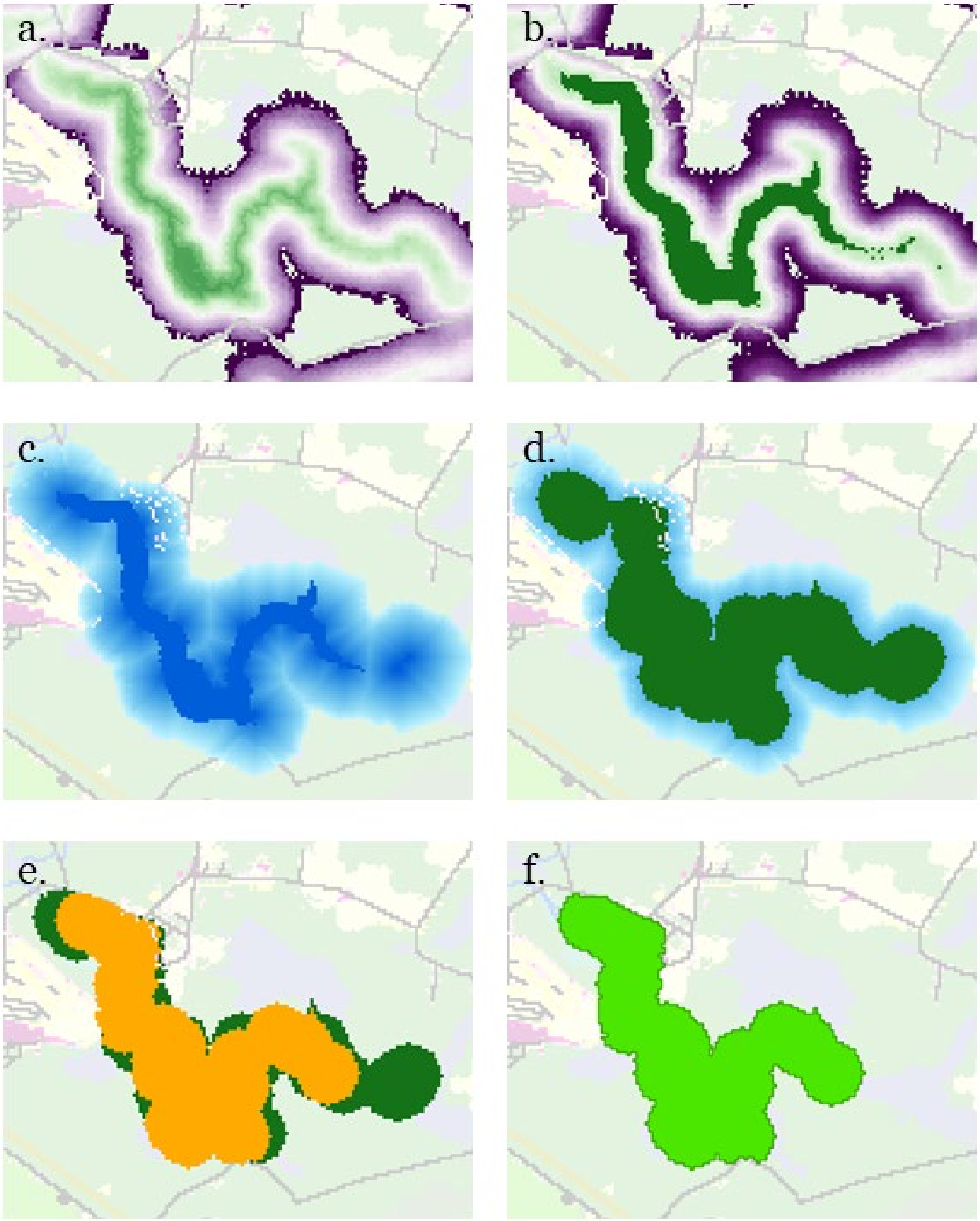

Fig. 1. Example core building for wood turtle in eastern Pennsylvania. a) 2020 Landscape Capability (LC; green = high, purple = low); b) sliced LC to create a core seed, dark green; c) kernel based on the seed; d) preliminary 2020 core, dark green; e) preliminary 2080 core, orange; and f) final core.

Graph analysis of connectivity. Graph theory, increasingly used in landscape ecology (Urban and Keitt 2001), offers several methods of efficiently assessing connectivity for large datasets. The basic data structure is the graph: a collection of nodes (here, species cores), connected by edges with an associated distance or cost (we used connection strength between pairs of cores). We calculated connection strength as the complement of mean functional distance from the random low-cost path analysis divided by the maximum distance in the graph.

We quantified each node's connectivity within the graph with 3 metrics (Fig. 3): (1) *strength* is the sum of the connection strength for all edges that connect to that node—it quantifies the direct connections to the node; (2) *closeness* is the sum of the inverted distance between the focal node and all other nodes in the graph (Latora and Marchiori, 2001); and (3) *betweenness* assesses how often a node is on the shortest path between all possible pairs of nodes (Freeman 1979). All graph analysis was done in R 4.0.4 (R Core Team, 2021) using the igraph (Csardi and Nepusz 2006) and centiserve (Jalili et al. 2015) packages. We calculated the three metrics using two sets of edges (connections): those between cores that were present in 2020 (refugia, and lost) and those that were present in the future, 2080 (refugia and new). We rescaled the betweenness metric by taking its logarithm and then dividing by the maximum value realized for the species in both the current and future graphs. Similarly, we rescaled closeness and strength by dividing by the maximum value realized for each metric in either the current or future graphs. The resulting metrics all range from 0 to 1 with higher values indicating greater connectedness. We calculated an overall *connectivity* by averaging the three graph metrics of connectivity.

We calculated a composite metric *score* for each core based on logarithm-transformed and range rescaled total squared LC and total squared climate refugia. This forced each to be distributed from 0 to 1 on the same scale as the average current *connectivity*. The score is a weighted average of the three with weights of 0.5, 0.3, and 0.2 on the LC, connectivity, and climate refugia components respectively. We chose these weights as we suggest conservation should focus on well-connected cores that have high value in the present and future. We weighted the present higher than the future as we have greater confidence in the present modeled distribution, and we weighted connectivity lower than LC as it is likely that connectivity complements but does not supersede LC. This score is a rough indicator of sites we hypothesize are most likely to persist.

By using a hybrid approach to assessing connectivity—random low-cost paths for a detailed fine-scale assessment of movement between nearby cores, and a graph analysis of regional connectivity, we were able to assess connectivity across a wide range of scales with finite computing resources.

Project Results, Analysis and Findings

The core-building process resulted in 177-1844 cores for each species (Table 1 and Appendix B). The only species that retained all cores in 2080 is the box turtle (TECA), which occurs at the southern edge of our region, and will expand to the north according to the climate niche model. Four species lost more than 90% of their 2020 cores by 2080. Of these, three species had very few refugia cores. Some of these losses were expected, such as for Bicknell's Thrush (BITH) which, in the Northeast, breeds only at high elevations in the Adirondacks and New England. Others were unexpected, such as American woodcock (AMWO), which currently breeds all the way south to Florida, and the spotted turtle (CLGU), which also is found in Florida.

Table 1. Number of cores of each type built for each species, sorted by percent lost. Refugia cores were present in both current (2020) and future (2080) timesteps, lost cores were present only in 2020, and new cores were present only in 2080.

Species	Refugia	Lost	New	Total
Box turtle (TECA)	1165 (95.7%)	0 (0%)	52 (4.3%)	1217
Moose (MOOSE)	441 (84.2%)	82 (15.7%)	1 (0.2%)	524
Wood turtle (GLIN)	1118 (60.6%)	430 (23.3%)	296 (16.1%)	1844
Spotted turtle (CLGU)	889 (49.8%)	872 (48.9%)	24 (1.3%)	1785
Piping plover (PIPL)	254 (41.8%)	354 (58.2%)	0 (0%)	608
Saltmarsh sparrow (SALS)	49 (22.5%)	169 (77.5%)	0 (0%)	218
Cerulean warbler (CERW)	124 (7.0%)	1647 (92.9%)	2 (0.1%)	1773
Bicknell's thrush (BITH)	4 (2.3%)	173 (97.7%)	0 (0%)	177
Blackburnian warbler (BLBW)	2 (0.2%)	885 (99.8%)	0 (0%)	887
American woodcock (AMWO)	1 (0.2%)	604 (99.8%)	0 (0%)	605

Connectivity among cores was assessed separately for current cores (refugia and lost cores) and future cores (refugia and new cores). This analysis yields a pair (current and future) of conductance grids for each species (Fig. 2 and Appendix B). Cores, core value (sum of LC or CRefugia for each core), and the mean functional distance between each pair of cores were saved in a graph representation for graph connectivity analysis.

Each core was scored based on its total Landscape Capability, its total Climate Refugia, and the connectivity metrics in the present and future. These attributes are all included with the core shapefiles (Appendix B).

The basis of innovative approaches used in this study, including cores based on resistant kernels and connectivity derived from random low-cost paths, were previously developed in our lab, funded by both USFWS and NECASC. We modified and extended these approaches for this study. The kernel-based variable scaling for selecting cores was developed for this study, as was our particular approach to the graph analysis and scoring of species cores.

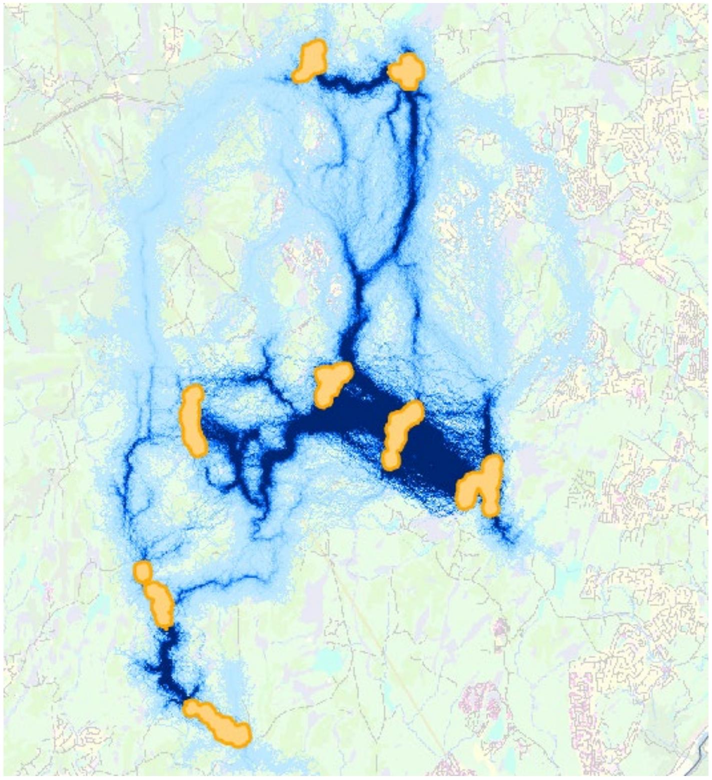

Fig. 2. Conductance for several wood turtle refugia cores in eastern Pennsylvania. Cores are orange, and conductance is in shades of blue, with darker blues indicating higher conductance.

Conclusions and Recommendations

We encountered two major unexpected problems during this study. Originally, we had planned to use an objective approach to building cores for each species, capturing a specified percent of total Landscape Capability for all species. This worked poorly, as the distribution of LC varies wildly across species. We modified our approach to subjectively adjust core-selection parameters for each species. We developed an innovative approach, using large-scale kernels of LC for each species to allow parameters to vary from the heart of a species range to the periphery. We think this approach shows promise, as the goal for natural resource managers in the heart of a species range is likely to conserve large connected areas of the best habitat for a species, while the goal near the edge of the range is to conserve the best available habitat, although these areas are likely to be of far lower quality than those in the core of the range. Delineating species cores with a single cutoff will either result in delineating absurdly large areas in the core of the range (e.g., one third of northern Maine for moose) in order to delineate cores in the periphery, or restricting cores to the core of the range, neglecting peripheral areas that are vitally important for genetic diversity, future evolution, and dispersal to new areas in response to climate change.

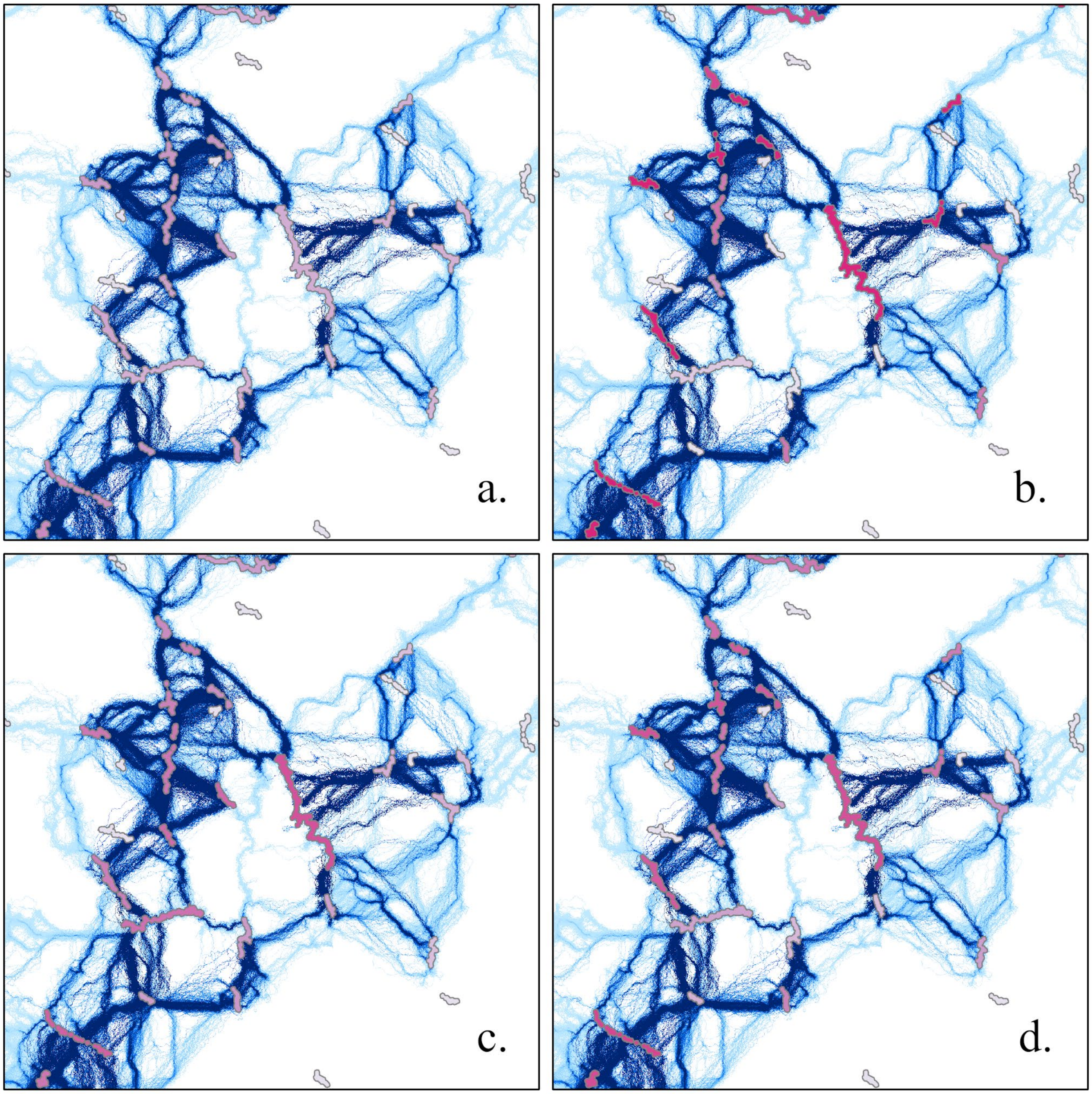

Fig. 3. Conductance between cores (shades of blue) and graph-based connectivity scores (fuschia) within each core for a collection of wood turtle cores: a) closeness, b) betweenness, c) strength, and d) the average of the three connectivity scores. In each light pink indicates lower graph-based connectivity while dark pink indicates higher connectivity.

The second unexpected problem was with the future cores based on climate niche models. We're skeptical of climate niche models, given the extreme shifts in some species but not others. Climate niche envelope models have always been conceptually problematic, as factors other than climate contribute to biogeography (e.g., land use history, inter-species interactions), and climate-driven ranges may be the result of second and higher order effects (e.g., climate drives vegetation structure which drives species range). As a result, there may be significant time lags, and although we expect climate change to drive species north and uphill in general, making predictions for any individual species is difficult or impossible. Although we've been aware of these issues, some of the findings of this study (e.g., projected severe climate-driven American Woodcock decline in Maine) are unexpected and seem unlikely in the next 60 years. We modified the study design to identify a range of expected future connectivity for species refugia, producing connectivity networks for each species for both the present and future, to bracket expected effects given uncertainty.

Our final scoring of species cores weights factors based on our confidence in the results, with the current Landscape Capability and connectivity given the greatest weights. GIS results with these scores will help inform natural resource managers focused on conserving habitat for the selected species. Some species were more successful candidates for this approach than others. Species with relatively limited mobility (moose and the three turtles) are far more reliant on landscape connectivity at a fine scale when dispersing than birds, especially migratory species. On the other hand, the two coastal species, piping plover and salt marsh sparrow, are more reliant on habitat management and subject to sea level rise. Although sea level rise was included in the CRefugia models for these two species, the conservation issues these species face are more specific than the general climate change/sea level rise models we used. Piping plovers, in particular, are entirely reliant on what has become a human-dominated landform—coastal beaches, thus are dependent upon intensive management of beach recreation near nests.

Our primary findings are as follows:

- Based on the conservative premise that species will persist at locations only if the climate remains suitable as defined by their current distributions, about half of the species we considered for this project will either not have or will have very little refugia remaining in the northeast in 2080 under RCP 8.5 (Table 1).
- As a result, it will be imperative to prioritize locations on the landscape that will facilitate ecological flow over time to ensure that generational movements and metapopulation dynamics are preserved as species distributions shift due to climate change.
- The multi-scaled approach of assessing local connectivity with conductance and assessing regional connectivity with graph theory analyses offers a promising path for assessing the connectivity of refugia and current species distributions.
- Graph connectivity metrics are useful for assessing both how well-connected individual cores are and how important they are to the connectivity of other cores within the network.
- Species varied substantially in how connected their networks were in the present, and in how much species connectivity changed in the future (Figure 4). Some species remained largely connected (e.g. moose), others were disconnected in the present and future (e.g. saltmarsh sparrow), and some species had a connected core network in the present but not in the future (e.g. American woodcock).

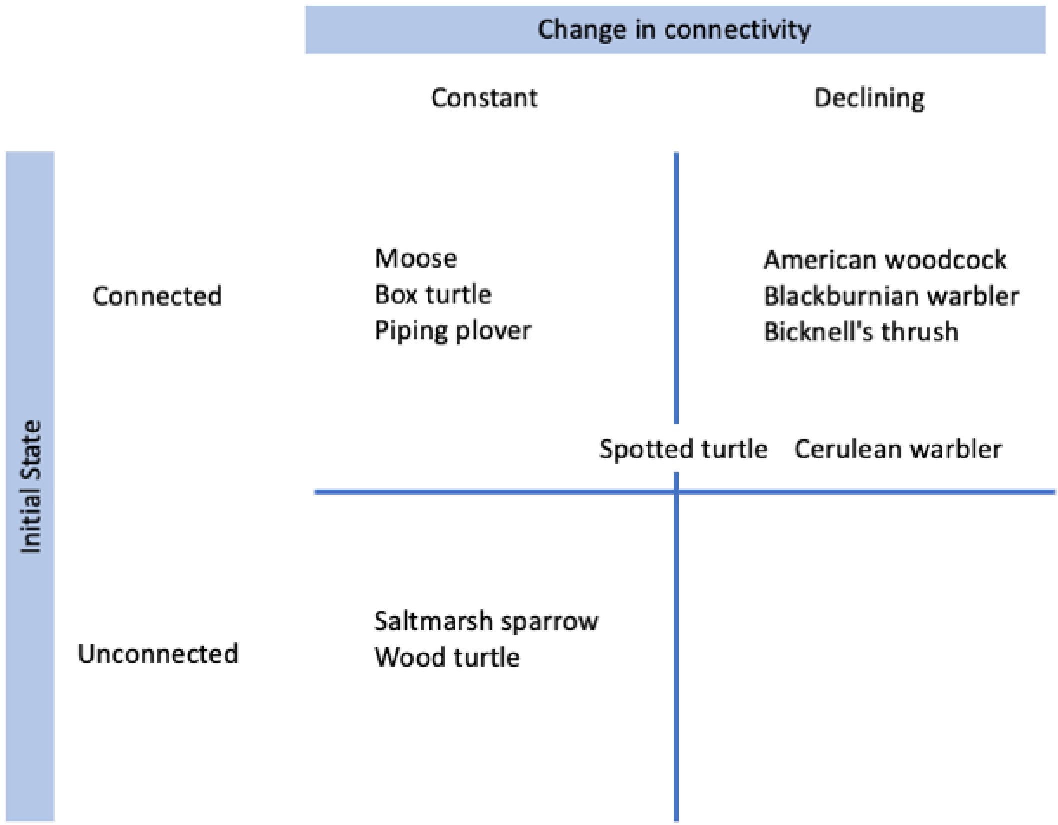

Fig. 4. Rough categorization of species based on degree of initial connectivity and change in connectivity. Constant was used for species that didn't change much - some change was tolerated. Spotted turtle and cerulean warbler both started with moderate connectivity, and spotted turtle connectivity declined moderately.

This study highlights the complexities of species-specific conservation actions in the face of climate change: not only is it extremely inefficient to practice conservation one species at a time, but uncertainty for each individual species is high. While fine-filter approaches (Hunter et al. 1988) focused on individual at-risk species (particularly those with unusual habitat associations or life history patterns and endangered species) will always be necessary, we believe conservation efforts should include coarse-filter multi-species approaches as major components, especially as uncertainty increases. Climate refugia are a prime example: modeling future refugia for large numbers of species would be a huge undertaking; doing so accurately is likely impossible. We suggest that approaches based on ecological integrity (McGarigal et al. 2018) and landform diversity (Anderson et al. 2012) should be the first step. As the climate changes (and continues to do so beyond any benchmark year, such as 2080), regional ecosystem connectivity will become increasingly important. Our proposed project (Ecosystem-based regional connectivity to inform climate refugia networks) is a promising step in this direction. The difficulties and inconsistencies in identifying species refugia highlight the importance of locating and prioritizing areas that will facilitate landscape connectivity as ecosystems reconfigure with climate change.

Outreach and Products

All spatial products for each species are available on the DSL website (Appendix B). These data can be easily downloaded and used by the resource management community. As the DSL project continues its collaboration with the NE CASC and USFWS Region 1 community, we will share the outcomes and products to ensure that interested stakeholders, including those that provided feedback on the species list, are aware of our findings. Moving forward, we will continue to support the use of these products for any resource managers that require it. PI DeLuca will be giving a NE CASC seminar and we will use this as an opportunity to invite all interested stakeholders as a means to make them aware of our findings. We will include a highlight and summary of this project on the DSL website (www.umassdsl.org).

Stakeholder Engagement

Stakeholder feedback drove the selection of species used for this project. We gave a brief presentation outlining our intended approach to modeling refugia and connectivity to a meeting of the Forests Climate Adaptation Work Group coordinated by Maria Janowiak of the US Forest Service (USFS) on Jun 24, 2020 and solicited feedback via a web survey (Appendix C). We reached out directly to Northeast Climate Adaptation Science Center (NECASC), the U.S. Fish and Wildlife Service (USFWS), and Massachusetts Ecosystem Climate Adaptation Network (MASS ECAN) via email and phone. We received species selections or rankings from the following people: Kevin Barnes, USFWS; Toni Lyn Morelli, NECASC; Michelle Staudinger, NECASC; Jeff Horan, USFWS; Christopher Riley, University of Rhode Island/Sweet Birch Consulting; and Gene Albanese, Mass Audubon. Additionally, we incorporated feedback facilitated by Michelle Staudinger, NECASC and collected from a survey sent to the Northeast State Wildlife Action Plan Coordinators. Responses were received from the New York State Department of Environmental Conservation, Massachusetts Division of Fisheries and Wildlife, West Virginia Department of Natural Resources, Connecticut Department of Energy and Environmental Protection, and the Pennsylvania Fish & Boat Commission. We used this feedback to select species with broad appeal to stakeholders while also considering the feasibility of the species and the similarity of the species climate or habitat niches to other selected species. We also heard from our survey respondents that there is interest in ecosystem level refugia and adaptation planning, which we intend to incorporate in future NE CASC projects. The selection of a variable scaling approach to core development, which ensures that cores were selected throughout a species range, anticipated the needs of stakeholders to have identified the best cores in their local area of interest. For instance, stakeholders in NY would likely be interested in understanding where moose cores were located in their state, rather than having moose cores be solely located in ME.

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Appendix A. Parameters used for core selection for each species

We used the following parameters for each species (see Table 1 for full species names).

Species	Seedslice	Bandwidth	Kernslice	Drop
AMWO	0.15, 0.45	1000	0.5	200
BITH	0.02	1000	0.5	40
BLBW	0.1, 0.33	5000	0.7	200
CERW	0.35, 0.65	5000	0.9	40
CLGU	0.25, 0.4	2000	0.7	40
GLIN	0.05, 0.15	3000	0.5	100
MOOSE	0.15, 0.58	3000	0.5, 0.9	40
PIPL	0.05, 0.1	5000	0.5	1
SALS	0.08, 0.55	5000	0.5	5
TECA	0.3, 0.96	5000	0.5, 0.9	40

Species – four-letter species code.
Seedslice – value of LC/CRefugia to slice when building seeds. Paired numbers indicate the values to use when the large-scale (25 km) kernel on LC is at its minimum and maximum. Values are interpolated linearly at each cell in the landscape.
Bandwidth – the bandwidth (m) for resistant kernels used to buffer and coalesce seeds.
Kernslice – the kernel value to slice to create cores. Paired values give the values to interpolate between for the minimum and maximum large-scale kernels.
Drop – minimum size for cores (ha)—all cores smaller than this minimum are dropped.

Appendix B. GIS data

GIS result data are available in a package for each species. Each package includes

1. **LC** and **CRefugia** for each species (source data from the Designing Sustainable Landscapes project, geoTIFF rasters)
2. Cores for each species (**allcores**, polygon shapefiles, with attributes that include scoring from the graph analysis)
3. Conductance for 2020 (**conduct**) and 2080 (**conduct_futr**)for each species (additive paths between each pair of nearby cores (geoTIFF rasters)

Packages are available here:

Species (abbreviation)	**Link to GIS data**
American woodcock (AMWO)	http://landeco.umass.edu/web/lcc/dsl/refugia/species_refugia_amwo.zip
Bicknell's thrush (BITH)	http://landeco.umass.edu/web/lcc/dsl/refugia/species_refugia_bith.zip
Blackburnian warbler (BLBW)	http://landeco.umass.edu/web/lcc/dsl/refugia/species_refugia_blbw.zip
Box turtle (TECA)	http://landeco.umass.edu/web/lcc/dsl/refugia/species_refugia_teca.zip
Cerulean warbler (CERW)	http://landeco.umass.edu/web/lcc/dsl/refugia/species_refugia_cerw.zip
Moose (MOOSE)	http://landeco.umass.edu/web/lcc/dsl/refugia/species_refugia_moose.zip
Piping plover (PIPL)	[sensitive data not distributed]
Saltmarsh sparrow (SALS)	http://landeco.umass.edu/web/lcc/dsl/refugia/species_refugia_sals.zip
Spotted turtle (CLGU)	[sensitive data not distributed]
Wood turtle (GLIN)	[sensitive data not distributed]

Allcores shapefile attributes:

Column	Description
coreid	The value used for the core in the associated grid (not distributed)
id	An integer ID assigned from north to south to each core
lc	The sum of LC (landscape capability) for 2020 in the core across 30 m cells
lc_sq	The sum of squared 2020 LC for the core. As LC ranges from 0 to 1 squaring puts more emphasis on the best values.
cref	The sum of Climate Refugia 2080 for the core. This represents the ability of the landscape to support the species in 2080 if it is constrained by its climate niche and is unable to expand its range into new territory.
cref_sq	The sum of squared Climate Refugia 2080 for the core. As in squared LC the squaring puts more emphasis on high value cells.
area	The area of the core in hectares.
type	Type indicates whether the core was present in the current (2020) and future (2080): 1 = refugia , 2 = lost, 3 = new.
x_ctr, y_ctr	The x and y coordinators of the centroid of each core.
between, f_between	The current (2020) and future (2080) betweenness metric for the core. Higher values indicate that the core is on the shortest path between other pairs of cores more often.
close, f_close	The current (2020) and future (2080) closeness metric. Higher values indicate that the core is relatively closer in the graph which encodes the functional distance to other cores.
strength, f_strength	The current (2020) and future (2080) strength metric. Higher values indicate more and stronger (shorter) direct connections to other cores.
conn, f_conn	The current (2020) and future (2080) average of the three connectivity metrics.
score	A composite score that combines (1) log transformed total squared LC, weight = 0.5; (2) log transformed squared climate refugia, weight = 0.2; and (3) conn (the average connectivity score), weight = 0.3 into a single weighted average. Higher LC (2020), Climate Refugia (2080) and connectivity will all result in higher scores.

Appendix C.

Survey prompts used to solicit feedback from the Forests Climate Adaptation Work Group.

- Which of the following species - listed with their habitat association - would you most like to see refugia mapped for? Select as many as you would like.
  - American black duck breeding; marshes, ponds and bogs
  - American black duck nonbreeding; estuarine and freshwater coastal marsh and open water
  - American oystercatcher; marine intertidal rocky coasts, mudflats and sand
  - American woodcock; northern fens, bogs, peatlands, and floodplain forests
  - Bicknell's thrush; montane boreal forests
  - Blackburnian warbler; mature mixed deciduous-coniferous forests
  - Blackpoll warbler; boreal coniferous forests and montane boreal forests
  - Box turtle; mesic hardwood and mixed forests including southern and central hardwood
  - Brown-headed nuthatch; mature pine forests and pine plantations
  - Cerulean warbler; mature deciduous forests along riparian bottomlands or dry mountain slopes and ridges
  - Common loon; northern New England lakes
  - Diamondback terrapin; coastal estuaries and islands, tidal rivers, salt marshes, and Northern Atlantic sandy
  - Eastern meadowlark; grasslands
  - Louisiana waterthrush; riparian deciduous forests
  - Red-shouldered hawk; moist hardwood and mixed forests
  - Marsh wren; fresh, brackish and salt emergent marshes
  - Moose; early successional forests, coniferous forests and wetlands
  - Northern waterthrush; northern forest wetlands
  - Ovenbird; moist hardwood and mixed forests, including northern hardwood forests, pine-hemlock-hardwood forest, and piedmont mesic forest.
  - Piping plover; marine and estuarine beaches
  - Prairie warbler; xeric early successional forests and shrublands
  - Ruffed grouse; mixed-aged forests within close proximity to open habitat
  - Saltmarsh sparrow; estuarine emergent marshes
  - Snowshoe hare; boreal and mixed forests of northern New England and at the highest elevations of the Appalachian mountain range
  - Snowy egret; shallow estuarine habitats
  - Spotted turtle; shallow marshes, shrub swamps, and forested wetlands especially on the coastal plain
  - Virginia rail; freshwater marshes and oligohaline tidal marshes
  - Wood duck; floodplain forests, forested wetlands and other forested riparian areas
  - Wood thrush; moist hardwood forests
  - Wood turtle; slow-moving moderately sized streams and nearby forest and wetland systems
- If there are other species you would like to see refugia mapped for please list them below.
- In a future phase of this project we may map refugia for ecosystems. How useful would this be to you?
- If you are interested in ecosystem refugia please list any particular ecosystems or forest types that you would like to see modeled.
- Any other feedback for our team?
- Optionally include your name and organization.
- Optionally provide your email.