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Utilizing Climate Change Refugia For Climate Change Adaptation And Management In The Northeast

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UTILIZING CLIMATE CHANGE REFUGIA FOR CLIMATE CHANGE ADAPTATION AND MANAGEMENT IN THE NORTHEAST

A Thesis Presented

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ABSTRACT

UTILIZING CLIMATE CHANGE REFUGIA FOR CLIMATE CHANGE ADAPTATION AND MANAGEMENT IN THE NORTHEAST

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To account for the effects of climate change, management plans in the northeast need to incorporate climate adaptation. Conserving climate change refugia is one adaptation strategy. Climate change refugia are areas buffered by climate change that enable the persistence of valued physical, ecological, and cultural resources; preserving these areas could be a potential adaptation strategy. Using a translational ecology approach where researchers and managers from the National Park Service, US Geological Survey, the University of Massachusetts, and elsewhere worked together, we focused on identifying refugia for tree, herbaceous plant, mammal, and bird species in order to prioritize them for conservation action. Results predict shifts in distribution of habitats and species due to climate change, identifying areas to prioritize for invasive species treatment and other management actions. This study highlights priorities for future monitoring and data analysis, providing a model that can be replicated in other regions and motivate future research.

Key words: climate change, refugia, management, translational ecology, National Park Service, northeastern US

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CHAPTER 1

USING A TRANSLATIONAL ECOLOGY APPROACH TO CREATE CLIMATE CHANGE REFUGIA MAPS AND MANAGEMENT STRATEGIES IN THE NORTHEASTERN U.S.

1.1 Introduction

Climate change will have significant impacts on the Northeastern United States and its biodiversity. Future projections show an increase in frequency of heat waves, droughts, winter temperatures, severe precipitation events, and sea levels (Horton et al. 2014, Meehl & Tebaldi 2004, Alexander et al. 2006, Sillmann et al. 2013). Changes in climate will have devastating ecological effects, including mismatches in phenology, changes in survival, growth, and reproduction rates, and, ultimately, loss of ecosystem services (Staudinger et al. 2015, Weiskopf et al. 2020). Direct climate change impacts will be compounded by increases invasive species and disease (Weiskopf et al. 2021, Allen & Bradley 2016). It is predicted that there will be an increased rate of species decline and extinction across the globe (Good et al. 2010, Maclean and Wilson 2011, Bellard et al. 2012).

Management plans need to adapt to changing environments to preserve and protect climate-vulnerable species. Climate change poses a threat to the principles under which many natural resource management agencies function. For example, the mission of the National Park Service (NPS) is to "preserve unimpaired the natural and cultural resources and values of the national park system for the enjoyment, education, and inspiration of this and future generations". NPS is now attempting to integrate adaptation strategies into their fundamental approach. The four fundamental components which were developed to guide NPS response efforts to address climate change are: Science, Communication, Adaptation and Mitigation (National Park Service. 2010; Table 1).

The NPS has identified using climate models to forecast changes in distributions of species and habitats as a priority for guiding management plans (Roman and Babson 2013). Accurate forecasts of future conditions will allow management plans to be focused and allow funding to be used more efficiently. Identifying and mapping climate change refugia can help resource managers and stakeholders inform this process. One primary focus of climate change adaptation for NPS and other management agencies could be protecting and managing climate change refugia, areas buffered by climate change that enable persistence of valued physical, ecological, and cultural resources (Morelli et al. 2016). Because they are unlikely to remain refugial in perpetuity (Morelli et al. 2020), climate change refugia conservation is often seen as a short (decades) to medium (century) term management strategy (Brown, Wigley, Otto-Bliesner, Rahbek, & Fordham, 2020, Hylander, Ehrlén, Luoto, & Meineri, 2015, Morelli et al., 2016). However, climate change refugia also have a role in transition strategies as they can remain buffered from climate change for range-shifting species, even if they do not remain within the climate niche of their original residents (Morelli et al. 2020). For example, refugia preservation could be enacted in a “stepping-stone” tactic, enabling species to move into more suitable habitats (Hannah et al. 2014).

Table 1.1: National Park Service Climate Change Response Strategy (2010), *Science, Mitigation, Adaptation, Communication* strategy

Science	Conduct scientific research and vulnerability assessments necessary to support NPS adaptation, mitigation, and communication efforts. Collaborate with scientific agencies and institutions to meet the specific needs of management as it confronts the challenges of climate change. Learn from and apply the best available climate change science.
Mitigation	Reduce the carbon footprint of the NPS. Promote energy efficient practices, such as alternative transportation. Enhance carbon sequestration as one of many ecosystem services. Integrate mitigation into all business practices, planning, and the NPS culture.
Adaptation	Develop the adaptive capacity for managing natural and cultural resources and infrastructure under a changing climate. Inventory resources at risk and conduct vulnerability assessments. Prioritize and implement actions and monitor the results. Explore scenarios, associated risks, and possible management options. Integrate climate change impacts into facilities management.
Communication	Provide effective communication about climate change and impacts to the public. Train park staff and managers in the science of climate change and decision tools for coping with change. Lead by example.

In this study, I brought together the best available science, as well as elicited expertise from NPS staff and other natural resource managers, to identify and map climate change refugia for NPS-prioritized species. Key partners during this study were Aaron Weed: Ecologist, NPS I&M division; Toni Lyn Morelli: Research Ecologist, USGS and University of Massachusetts Department of Environmental Conservation (UMass ECo); Amanda Babson: Coastal Adaptation Coordinator, NPS Northeast Region. Collaborators were Ethan Plunkett: Research Associate, UMass ECo; Matthew Duveneck: Research Associate, Harvard University, Harvard Forest; and Benjamin Letcher: Ecologist, USGS Conte Anadromous Fish Lab and UMass ECo.

I accomplished the research by 1) hosting workshops for NPS Northeast Region (NER) staff and their partners to identify priority species and habitats for NPS NER; 2) gathering and synthesizing existing data and models from collaborators; 3) modeling 9 species to fill gaps, using climate change projections and species distribution modeling; and 4) sharing syntheses and model results with stakeholders and discussing potential management actions. This process is based on the climate change refugia conservation cycle paradigm (Figure 1.1) developed by Morelli and colleagues (2016), and the Refugia Research Coalition (RRC) network that they developed (climaterefugia.org).

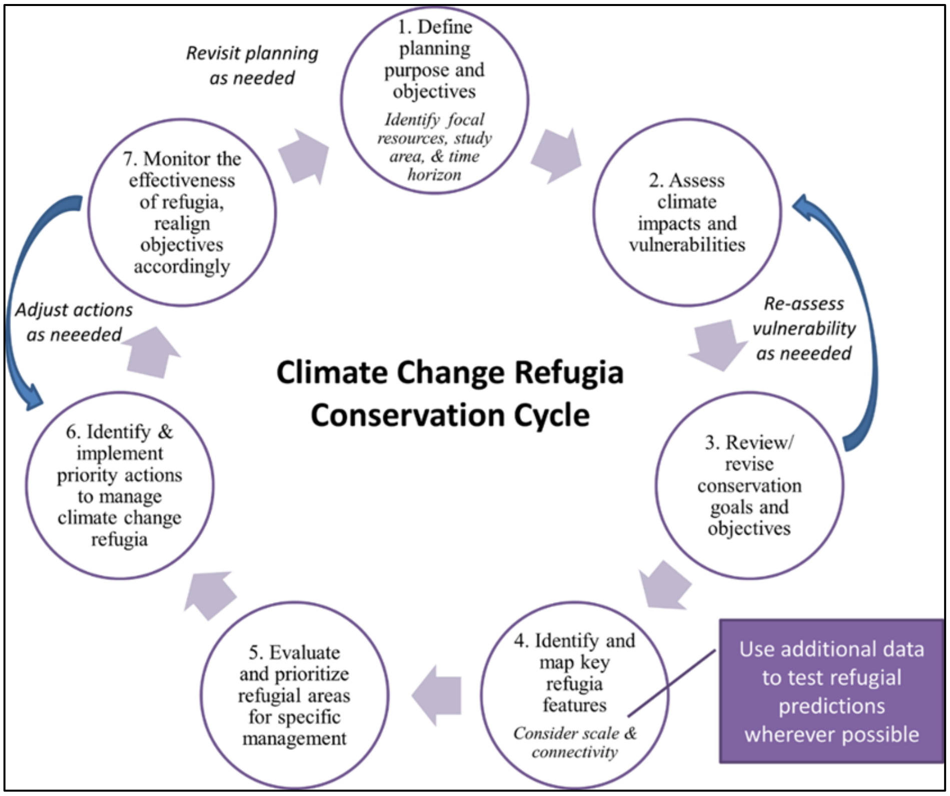

Figure 1.1: Climate change refugia conservation cycle (Morelli et al. 2016)

1.2 Translational Ecology

This research uses a translational ecology (TE; Enquist et al. 2017) approach. "TE is an approach in which ecologists, stakeholders, and decision makers work together to develop research that addresses the sociological, ecological, and political contexts of an environmental problem" (Enquist et al. 2017). TE origins are rooted in translational medicine and evolved from cooperation between clinicians, patients, and biomedical researchers. This cooperation ensured that research was being conducted and used appropriately in diagnosis and treatment of patients (Enquist et al. 2017). There are six principles of TE (Figure 1.2; Enquist et al. 2017): *Collaboration*- between ecologists, managers, stakeholders, and other scientists, where all parties have a stake in science relevant to the decision context. Which results in knowledge developed and shared amongst all parties involved; *Engagement*- meaning to support meaningful collaboration, and frequent engagement between scientists, managers, and other stakeholders. There is a cross-cultural immersion, where managers participate in scientific research and the scientists experience the relevant management culture. This allows for trust building and promoting mutual understanding; *Commitment*- the parties involved must be prepared to devote more time and effort to working with stakeholders than in a typical research project. A translational approach requires long-term commitments to build trust, accountability, and openness to learn; *Communication*- allowing regular and clear communication. Which requires respect for the differing point of views. Actively listening to diverse perspectives; *Process*- enacting the creation of science and policy does not happen spontaneously and requires the participation of the collaborators and communication to achieve this, along with transparency. It involves utilization of varying disciplines and perspectives and builds a sense of ownership for the project (Lemos and Morehouse 2005); *Decision-framing*- is understanding the context of the natural resource management – the beneficiary needs, values, the time frame. While taking into consideration the broader social context of how cultures, economics, laws, policies, and politics are influencing factors of how we build group dynamics and trust (Thompson et al. 2013).

Figure 1.2: The six principles of TE: Collaboration, Engagement, *Commitment, Communication, Process*, and *Decision-framing* (From Enquist et al. 2017).

One critique of TE is that individuals worry that stakeholder participation in research conception and development can lead to bias, or even corruption, of the research results (Enquist et al. 2017). In addition, there is no guarantee that TE will ensure that science will be used to inform decision making, nor that it will link to new science. However, TE can help improve the way that ecologists and stakeholders communicate about a project. It allows stakeholders to gain insight on the whole process and the caliber of the research created (Hallett et al. 2017). This is key in ensuring the development of science and ensuring the effective formulation of policy and decision making (Enquist et al. 2017). Moreover, since stakeholders are involved in the decision-making process, this allows transparency in how things are developed. They can understand how management practices are developed from start to finish, and oftentimes this builds trust in the resulting outcomes.

A related approach, coproduction of knowledge, is the process of producing actionable science through collaboration between the producers and the users of the science (Meadow et al. 2014, Wall et al., 2017). Knowledge coproduction involves scientists and decision makers framing research questions, deciding on how to answer the questions, and together working through the findings. Research developed from knowledge coproduction is more likely to be accepted and used by decision makers; its transparent production is perceived as more legitimate to the end users (Meadow et al. 2014, Wall et al., 2017). Furthermore, the coproduced knowledge is easier to integrate into already existing information because it fits into the organization's decision framework and its spatial and temporal scale (Meadow et al. 2014, Wall et al., 2017).

The origins of coproduction of knowledge can be traced back to Vannevar Bush's report titled "Science, the Endless Frontier" (Bush 1960). Bush articulated a vision for the contribution of scientific knowledge to society, wherein "basic" research generated new knowledge and "applied" research found practical applications for that knowledge (Meadow et al. 2014). Through his vision, a linear model of science policy was created where knowledge was generated in one domain (science) and then handed off to a recipient domain (society). However, to ensure that science was not altered by the values of the world, these two domains were isolated. This linear model of science was critiqued during the 1970s as being insufficient for dealing with complex problems that are based in scientific knowledge and required political judgement for its resolution (Meadow et al. 2014). Knowledge coproduction bridges these concepts and creates a dialogue between scientific expertise and interested parties to find resolution.

Resource managers can benefit from using TE or coproduction of knowledge in their management. Involving a variety of stakeholders can generate new ideas and help create actionable science (Hallett et al. 2017). In addition, research is more likely to result in legitimate solutions when managers advise scientists on real-world constraints (Cook et al. 2013). Using either knowledge coproduction or translational ecology approaches can increase efficiency in creating actionable science that can be trusted by both stakeholders and scientists.

With these paradigms in mind, the goal of this project was to identify priority areas for management to increase species climate change adaptation. My project had these steps:

1. Identify species within the Northeast NPS Region that are conservation priorities.
2. Map climate change refugia for those priority NPS species.
3. Map transition areas for species moving outside their ranges.
4. Communicate these results in a way that was relevant for managers at NPS units and Inventory and Monitoring in the Northeast Region.

1.3 Methods

1.3.1 Study Area

My research was focused on focal resources that were prioritized by the National Park Service staff in the Northeast Region (NER). The NER is composed of four Inventory and Monitoring networks (I&M): Mid-Atlantic, Northeast Temperate, Eastern Rivers and Mountains, Northeast Coastal and Barrier.

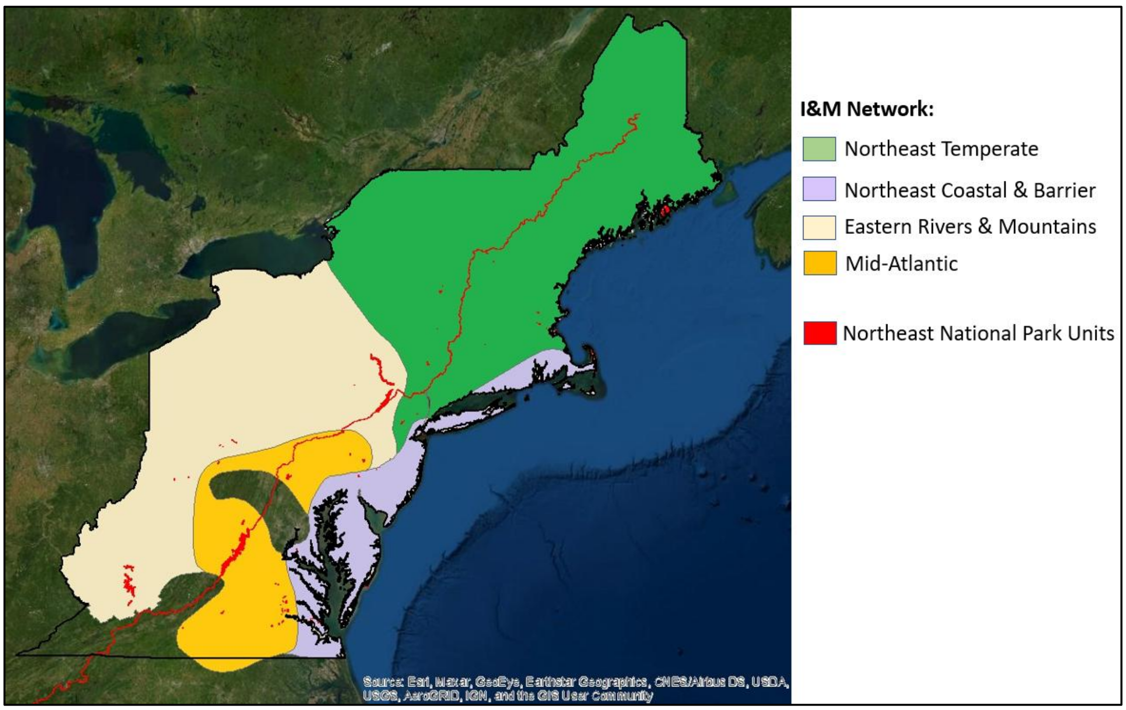

Figure 1.3: The Northeast Region (black border), the four I&M regions: the Mid-Atlantic, Northeast Temperate, Eastern rivers and mountains, Northeast coastal and barrier with the NPS park units in red.

1.3.2 Eliciting Stakeholder Feedback

Figure 1.4: View of the March 19, 2020, Zoom meeting. Source: Toni Lyn Morelli.

I used workshops to elicit information from stakeholders throughout the project. The original intent was to hold workshops in the geographic south and north of the NPS Northeast Region (NER) to maximize accessibility for NPS staff. However, due to the COVID-19 pandemic, both workshops were held entirely via Zoom videoconferencing. The invitees were selected in collaboration with Aaron Weed of the NPS, to get stakeholders with varying expertise that represented management agencies and NPS units throughout the NER.

Following the CCRCC (Fig. 1.1; step 1), Morelli and I met with NPS staff and other relevant stakeholders on March 16 and March 19, 2020, to refine the planning and objectives for the project, and to work with the group to identify a list of focal species to best support the park's management needs. We initiated the meeting by starting with brief introductions of all parties present, followed by presentations by researchers and resource managers that have been working on climate change refugia in the Northeast.

At the workshops, each group discussed *What should we map refugia for?*. After discussions, each group entered their top three priorities for refugia mapping and conservation via Mentimeter (http://www.mentimeter.com/), which formed a world cloud. During each workshop, we discussed the entry results, and each participant then again entered their chosen top 3 priorities (Figure 1.5 and 1.6).

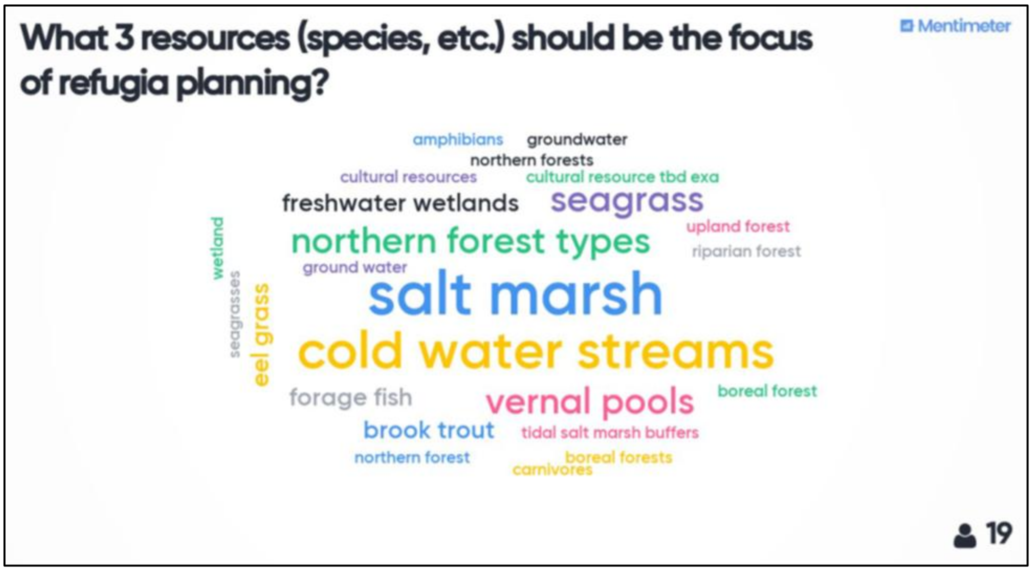

Figure 1.5: Mentimeter word cloud of the priority focal resources highlighted for climate change refugia mapping and conservation identified during the March 16 Zoom meeting. Source: Mentimeter.

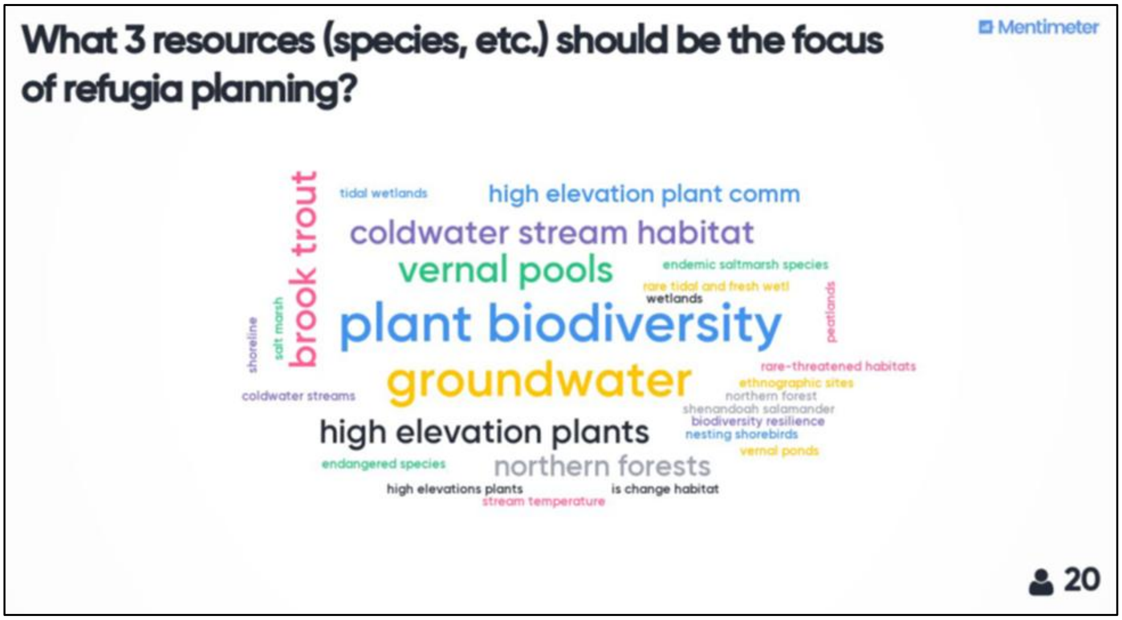

Figure 1.6: Mentimeter word cloud of the priority focal resources highlighted for climate change refugia mapping and conservation identified during the March 19 Zoom meeting. Source: Mentimeter.

The focal resources that received the highest Mentimeter votes were discussed, resulting in some consolidation, and renaming. The final list from the March 16 workshop was: Estuarine Marsh, Submerged Marine (including Seagrasses), coldwater streams, northern forest types, cultural resources, and freshwater wetlands. The final list from the March 19 workshop was: coldwater streams, high elevation plants, salt marsh / intertidal, boreal communities, and plant diversity (this topic was agreed to be considered under the other categories).

Workshop participants self-distributed into breakout groups based on one of these focal resource topics and had to answer the following questions: *What is the specific focus? How to apply climate change refugia results to ongoing or future management actions? And What data and partnerships are available?*.

Participants in each group described data and important researchers, partners, and potential management actions related to a climate change refugia conservation strategy for that focal species/system. Summarized notes can be found in the Preliminary Report on the Refugia Research Coalition (RRC) network website (climaterefugia.org). During these breakout groups, they also discussed what species climate change refugia should be modeled for.

Table 1.2: March 16, 2020 Workshop Focal Resources, listed by group and research focus. The * denotes primary dependents vs intermittent dependents.

Group	Research focus
Seagrasses (Submerged Marine Resources)	seagrasses, rocky intertidal, mudflats, oyster reefs, mussel beds, green crabs.
Coldwater streams	brook trout, riparian forest, forage fish, amphibians, loons
Cultural resources	cultural landscape (pre-contact plus cultural landscape post-contact – include intangible heritage that goes with that), shell-middens, sweetgrass.
Northern forest types	interior forest obligate species, red/black spruce, American black bear, sugar maple and eastern hemlock, boreal forest, high elevation habitat, Bicknell's Thrush, balsam fir, forested wetlands, fringe habitats, pitcher plants, calcareous bogs, vernal pools, northern hardwood, lynx, moose, interior forest obligate songbirds.
Saltwater marsh group	Habitats: Areas that provide protection for species, inland habitats, human communities; serve as nursery habitats; species foraging

(Estuarine marsh system)	and nesting areas; human recreation: tidal salt marsh (low, transitional uplands, high, buffer areas), channels within marshes, salt marsh pannes and pools, transitional areas, open coastal waters. Species: forage fish, mummichogs* and killifish*, menhanden, silversides, herring/clupeids, sandlance, salt marsh* and seaside sparrows*, shore birds (piping plovers), marsh birds (clapper and black rail, clapper rail*, willet*, terns), American black duck, endemic salt, marsh dragonfly*, horseshoe crabs, diamondback terrapins*, crabs*, shellfish*. Cultural resources: recreationally and commercially important species such as flounders (winter flounder* and summer flounder), striped bass, bluefish, shellfish (oysters, mussels, quahog), marine worms (bait), harvest - salt hay, water control, archaeological sites

Table 1.3: March 19, 2020 Workshop Focal Resources, by group and research focus.

Group	Research focus
Coldwater streams	brook trout, eastern hemlock
Coastal	Tidal wetlands (including brackish), fresh & salt marsh, rare tidal (erosion as key stressor), primary and secondary dunes (including over wash areas), bees, bay shorelines (includes salt marsh, beaches, forest), nesting shorebirds – nesting roofs buildings as refugia, piping plover, terns, oyster catchers, state & federally listed.
Boreal communities	Rock outcrop, spruce-fir, arctic alpine, paper birch and northern white cedar.

Other species and habitat/community types that were brought up after the workshops were *Arctostaphylos uva-ursi, Bromus ciliatus, Carex bebbii, Conionselinum chinense, Juncus trifidus, Menyanthes trifoliata* and *Sibaldia tridentata*, black spruce tamarack bog, northern white cedar swamp, sedge meadow, rich sloping fen, rich graminoid fen, rich shrub fen, medium fen, inland poor fen, alpine sliding fen, perched bog, patterned peatland, dwarf shrub bog, spruce-fir swamp, floodplain forest, shrub swamp, marsh-headwater stream, open alpine community, boreal heath barrens, alpine krummholz, sandstone pavement barrens, spruce-flats, balsam-flats, mountain spruce-fir forest, mountain fir forest, boreal community types in NY.

Species that were highlighted as priorities for refugia mapping by the stakeholders are listed in Table 1.4. Some of these species were already modeled through the Designing Sustainable Landscapes (DSL) project and retrofitted to this project (McGarigal et al. 2017). Although some coastal species such as the American oystercatcher, piping plover, and saltmarsh sparrow were already modeled by the DSL project, most identified estuarine marsh, submerged marine, and salt marsh / intertidal focal resources were not chosen for refugia modeling. Although these coastal ecosystems are vitally important, the data needed to predict coastal changes are not yet available. There was an initial working group meeting and a discussion of regular meetings to identify steps toward developing and obtaining the data needed. In addition, bats were highlighted as priority species, but they were ruled out due to white-nosed syndrome (Lorch et al. 2011); refugia maps not incorporating disease would not accurately portray how northeastern bat species would be affected by climate change. Another focal resource we did not synthesize refugia maps for was “cultural resources"; this remains an interesting area that deserves more attention.

Table 1.4: List of all the species including species from the DSL project (McGarigal et al. 2017) that were retrofitted to this NPS project .

Taxa Type	Species
Herps	Blue-spotted salamander (Ambystoma laterale) Jefferson salamander (Ambystoma jeffersonianum) Marbled salamander (Ambystoma opacum) Wood turtle (Glyptemys insculpta)
Plants	Balsam fir (Abies balsamea) Bebb’s sedge (Carex bebbii) Black spruce (Picea mariana) Common bearberry (Arctostaphylos uva-ursi) Eastern hemlock (Tsuga canadensis) Highland rush (Juncus trifidus) Northern white cedar (Thuja occidentalis) Paper birch (Betula papyrifera) Red spruce (Picea rubens) Shrubby five-fingers (Sibbaldiopsis tridentata) Sugar maple (Acer saccharum) White spruce (Picea glauca)
Mammals	Moose (Alces alces) Snowshoe hare (Lepus americanus)
Birds	American black duck breeding and nonbreeding (Anas rubripes) American oystercatcher (Haematopus palliatus) American woodcock (Scolopax minor) Bicknell's thrush (Catharus bicknelli) Blackburnian warbler (Setophaga fusca) Blackpoll warbler (Setophaga striata) Black-throated green warbler (Setophaga virens) Cerulean warbler (Setophaga cerulea) Common loon (Gavia immer) Grasshopper Sparrow (Ammodramus savannarum) Marsh wren (Cistothorus palustris) Northern waterthrush (Parkesia noveboracensis) Ovenbird (Seiurus aurocapilla) Piping plover (Charadrius melodus) Prairie warbler (Setophaga discolor) Ruffed grouse (Bonasa umbellus) Saltmarsh sparrow (Ammodramus caudacutus) Sanderling - migratory (Calidris alba) Snowy egret (Egretta thula) Virginia rail (Rallus limicola) Wood thrush (Hylocichla mustelina)

1.3.3 Data Products

The data producers (Letcher, Walker, Duveneck, Plunkett, and myself) focused on creating climate change refugia data products for the NPS NER based on the species and concerns identified during the stakeholder workshops.

1.3.3.1 Northeast Coldwater Refugia

Letcher and Walker created an interactive data visualization tool to explore coldwater refugia within the Northeast and among NPS park units (http://ice.ecosheds.org/nps-ner/). This interactive data visualization tool was derived from the Interactive Catchment Explorer (ICE) framework, part of the Spatial Hydro-Ecological Decision System (SHEDS) (Walker et al., 2020). SHEDS uses predictions in stream temperature and brook trout occupancy models in the Northeast U.S. and elevation, climate, and land-cover variables. The models use high resolution catchment delineation, 400,000 catchments with an average area of 2 km2 in their predictions. The models use two metrics: mean summer (June-August) stream temperatures, and average number of days per year when temperatures exceed 22 °C. This tool incorporates brook trout occupancy as well and generates predictions for the probability of occurrence in each catchment. A catchment is considered a coldwater refugium if daily mean stream temperature never exceeds 22 °C. The brook trout occupancy model utilizes the same metrics as the stream temperature models: three climate change scenarios: air temperature increase increments of 2, 4 and 6 °C and the same historical conditions. Additionally, the brook trout occupancy model calculates the maximum air temperature increase to achieve 30, 50, and 70% occupancy. This is a measure of the resiliency of each catchment to future air temperatures.

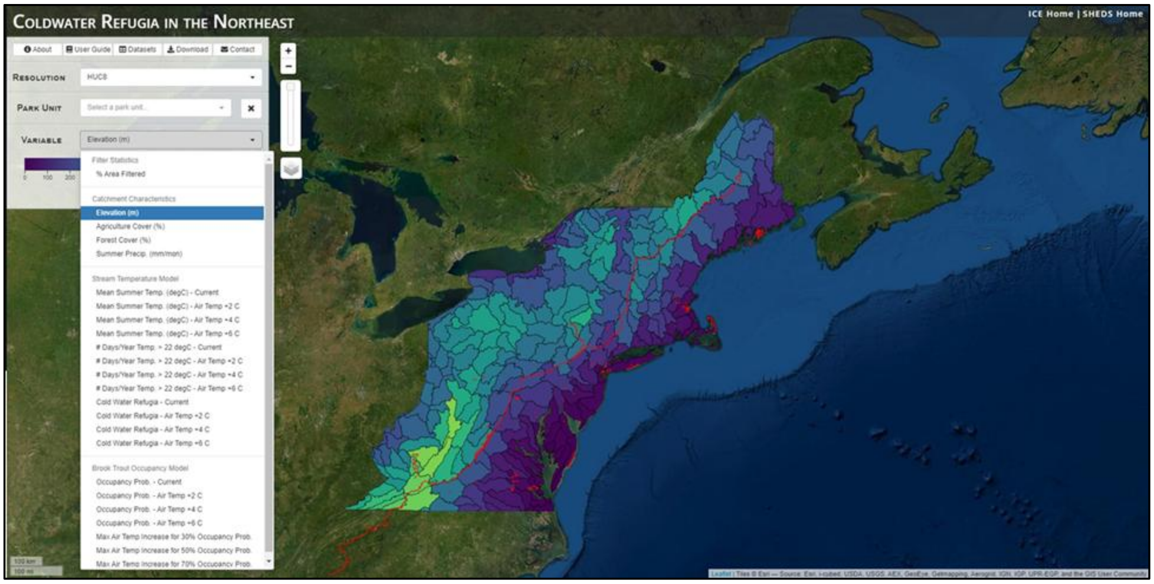

Figure 1.7: Screenshot of the SHEDs interactive tool showing percent of each HUC8 containing catchments that contain coldwater refugia and the available variables users can choose from (Walker et al., 2020).

The SHEDS ICE tool allows the user to explore coldwater refugia within the NPS park units and the region. In addition, one can zoom to each park unit and get a summary of all the metrics of that park unit based on the catchments that intersect it. Individual catchments within each HUC in and around the park unit can also be viewed, allowing the user to determine whether the park or areas can provide coldwater refugia. ICE also allows the user to download the underlying datasets in CSV and GeoJSON formats.

1.3.3.2 Northeast Forest Refugia

Duveneck developed climate change refugia maps for balsam fir (*Abies balsamea*), black spruce (*Picea mariana*), northern white cedar (*Thuja occidentalis*), paper birch (*Betula papyrifera*), red spruce (*Picea rubens*), eastern hemlock (Tsuga canadensis), sugar maple (*Acer saccharum*), and white spruce (*Picea glauca*) were based on forest simulations described in Duveneck & Thompson (2017). The maps were created with simulated current conditions for the year 2010 and simulated future conditions for 2050 and 2080 using climate change projections based on Representative Concentration Pathways (RCP) emission scenario 8.5. Around each park unit, a buffer was added based on a 20% increase in the maximum distance across the NPS park units. This was to account for the varied shape and size of each NPS park unit. The refugia maps for each species were made for the area assuming: sustained sites are sites where species-specific simulated biomass was present in 2010 and during 2080. New sites represent transition areas, areas where species that were not present in 2010 but transitioned to new areas in 2080. Lost sites are sites where species-specific simulated biomass was present in 2010 but did not occur in 2080. The complete set of NPS forest refugia maps can be accessed at https://github.com/mduveneck/New_England_NPS_forest_tree_species_refugia

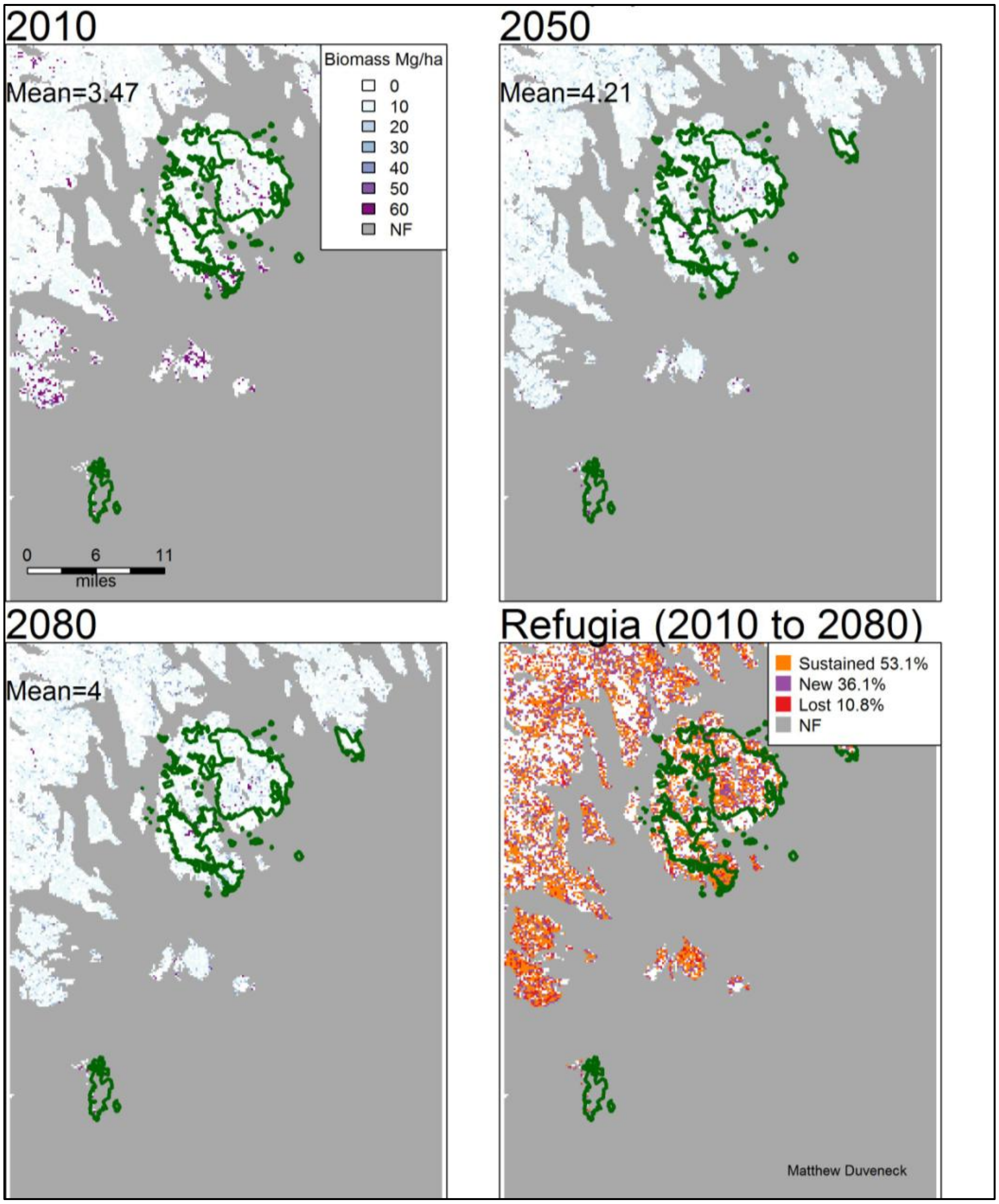

Figure 1.8: Paper birch biomass maps which represent simulated current conditions 2010 (upper left) simulated conditions at year 2050 (upper right), and 2080 (lower left) under climate change. Lower right is all maps combined showing areas of climate change refugia ("sustained"), transition ("New"), and loss of Paper birch between 2010 and 2080 ("Lost"). Areas in gray are where the species is no forest.

1.3.3.3 Northeast Wildlife Refugia

Plunkett utilized species models from the Designing Sustainable Landscapes (DSL) (McGarigal et al. 2017) project to produce climate change refugia models for the NPS NER. The DSL project assesses the capability of current and predicted future landscapes to provide wildlife habitat within the Northeast United States. Moreover, assesses suitable habitat and integral ecosystems for focal species to provide guidance on habitat conservation (McGarigal et al. 2017). For this project, Plunkett modeled 23 herp, bird, and mammal species (Table 1.4). He generated detailed summaries for how the species are predicted to utilize the NPS park units and the region for the present and under future climate change. Plunkett calculated statistics for the ability of the landscape and climate to support these species based on the DSL models of 2010 landscape capability (LC) and 2080 climate refugia. The LC is derived from three components: *climate niche (CN)*, *habitat capability (HC)* and *prevalence* for each cell and then multiplied.

Plunkett added a 5-km buffer around each park unit, except for the Appalachian Trail, and calculated the statistics on the park plus the buffer. The buffer was added because of the small size of many of the park units. The Appalachian trail is not buffered like the rest of the NPS units because NPS Inventory and Monitoring staff uses a 10-digit National Hydrologic Units (HUC10) that intersect the trail in the way they manage and make any analyses. The HUC10 buffers the trail so it not needed when calculating statistical summaries on the Appalachian trail. The DSL project uses current and future climatic conditions derived from six climatic variables: annual precipitation, average annual temperature, growing season precipitation, mean minimum winter temperature and mean maximum summer temperature (Chapter 2, Table 2.6). For each variable, DSL utilized 30-year PRISM normals combined with 30-year mean from the General Circulation Models (GCMs), average across Representative Concentration Pathways (RCPs) 4.5 and 8.5 (McGarigal et al. 2017b). A detailed description for the DSL modeling and variables can be found at https://umassdsl.org/ and the refugia maps created for each park unit can be accessed on: https://umassdsl.org/NPS_refugia.htm

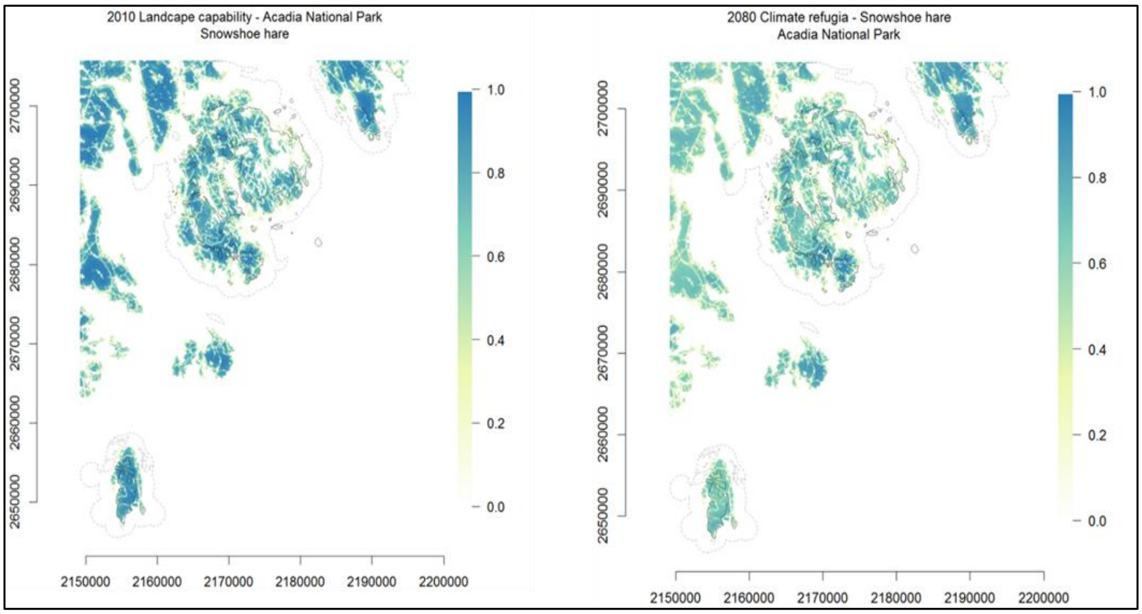

Figure 1.9: Left map is landscape capability of Snowshoe hare in Acadia National Park. The right map is 2080 Climate change refugia for Snowshoe hare in Acadia National Park. Maps produced by Ethan Plunkett (McGarigal et al. 2017).

In addition to the species modeled by Plunkett in collaboration with the DSL project, I modeled 9 priority species that were highlighted in the stakeholder workshops. I created species distribution models (SDMs) for these species and used them to develop refugia maps. I utilized the same climate data from the DSL project (McGarigal et al. 2017) and included a 5-km buffer around my park units. However, I also included USGS 2016 National Land Cover Database (NLCD; Homer et al. 2015), tree canopy, and aspect, which were all compiled for the coterminous United States by the Landfire program (https://www.landfire.gov). In addition, I looked at soil data from SSURGO for my shrub species. My synthesis and results can be found in Chapter 2.

1.3.4 Preliminary Results Workshop

On September 25, 2020, we met with a group of stakeholders to present and discuss data products that were created based on the outcomes of the March 16 and 19 workshops. The objective of this meeting was to elicit feedback on the climate change refugia maps that had been produced since those workshops. The workshop began with presentations from the data producers to showcase what they had preliminarily accomplished. Presentations by researchers and managers on Northeast refugia maps and data were as followed: Northeast Wildlife Refugia – Ethan Plunkett; Northeast Forest Refugia – Matthew Duveneck; and Northeast Coldwater Refugia – Ben Letcher and Jeff Walker. Afterwards, participants separated into topical breakout group where facilitators asked a series of questions: *How would you like the data served/displayed to you? With / without buffers? Do you know of data that could be used for validation? Do you have examples of management decisions that could incorporate these data? Other comments/feedback?*. The aim was to elicit perspectives and insight into the results, as well as potential applications, through moderated discussion, as typically occurs with a focus group (Nyumba et al. 2017). We asked participants to share their ideas after each question and had note takers record all the responses. After the breakout groups, we reconvened, and project leaders Weed (NPS) and Morelli gave a short overview of how their breakout groups went.

Generally, the feedback to the data products the collaborators presented was positive. These breakout groups allowed the participants to get valuable insight from the presenters and get any questions or concerns addressed. Participants could see the potential of using these data products into their own management actions. A potential management application someone highlighted during the workshop was to use these data products to determine what species should be planted in the future. In addition, this would provide a platform to discuss these options to managers and allow them to investigate the caveats that go with such management actions. In addition, some participants wanted to know if there was any modeling done in the south; they wanted to see what would be transitioning up north from below the NER. This would allow them to prepare for species that are transiting north to the NER that had never been previously seen before.

1.3.5 Management Plans Workshop

On September 22, 2021, we met with stakeholders from the previous workshops to present the data products I created and recap the data products made by the collaborators. The objective of this workshop was to formulate management plans from all the products we had created and to get the stakeholders thinking how to apply climate change refugia to their respective project(s). To help with this process we asked attendees to come to the meeting with information that would help in implementing climate change refugia conservation for the NPS NER. They were given access to the data products before the workshop, so they could explore the results and think how they could utilize them.

In addition, Abraham Miller-Rushing presented his work with mapping climate change refugia in Acadia National Park as a case study. Miller-Rushing took the results from the maps created by Jenny Smetzer (USFWS) and implemented management plans best suited to that park (Smetzer and Morelli, 2019), in part following RAD or "Resist, Accept, Direct" approach that has been developed by the National Park Service (Schuurman et al. 2020). With this approach, management teams can *resist* change by intervening to reduce vulnerability or restore conditions where change has occurred, they can *accept* the change, allowing the ecosystems to move into unprecedented new conditions but without knowing the consequences, or they can *direct* change, to transform ecosystems into new states, that are predicted to change (Schuurman et al. 2020).

In the case of Acadia National Park, they used *direct* by relocating species where their ranges are expected to move northward, they restored degraded areas that had succumbed to trampling and they removed invasive species. Acadia National Park also implemented *resist* by using Smetzer's climate change refugia maps and providing restoration and preservation techniques to areas predicted to remain as good or improved habitat. While they implemented these RAD options, they were always researching into the effects of these actions and allowing open communication with stakeholders and the public for transparency.

After the presentations we asked the attendees: *Do you have examples of projects or actions in the upcoming year(s) where these data can be incorporated into decisions (e.g., to identify places to act/manage/restore/monitor)? What opportunities are there to work across organizations? What do you see as some of the main barriers to using these kinds of results to inform your work? What could make the results more useful or easier* *to understand?*. Participants highlighted research opportunities that could derive from these climate change refugia research, such as: experiments on genetic management as a part of eelgrass restorations in Acadia and other national parks; researching Boston Harbor Islands to look at storm surge threats; prioritizing refugia for Fire Island National Park and investigating living shorelines, such as eelgrass beds and marsh other species to stem erosion; expanding their inventory monitoring on certain species to obtain more data, such with diamond-back terrapins; and using refugia modeling for shellfish and diadromous fish. The participants appreciated the case study presentation because it allowed them to see how they can implement these refugia maps in their own park units.

Overall, the participants were very positive in their feedback. They could see the potential in using them to retrofit their already existing management plans and actions. They wanted to continue the discussion about climate change refugia to learn more and to teach others about it. They expressed interest in continuing to communicate with each other and other stakeholders to engage in future partnerships, to share knowledge and work across park units. For example, if a park unit has been battling an invasive species for years and the invasive is projected to move into a new park that has never had that it before, it would be beneficial to share management experience in combating it rather than reinventing the wheel. Likewise, they saw utility in working across agencies and stakeholders to relocate species that are predicted to shift out of their current ranges.

1.4 Discussion

The aim of this project was to produce actionable science and improve management plans by utilizing a translational ecology approach where researchers and stakeholders work together, from start to finish. Due to the COVID-19 pandemic, the planned in-person activities could not be conducted. Nevertheless, the project outcomes were still accomplished. Much of the 6 principles of TE (Figure 1.2) were still met. Moreover, the remote meetings likely increased participation both in numbers and in geographic spread. Although it was challenging, we team adapted to these new conditions, just as we need to adapt management plans to climate change. This project shows that translational ecology can be successful and productive even on a remote platform.

Discussing climate change refugia products with stakeholders allows them to consider the application of climate change refugia within their organizations and with their colleagues, and what additional materials, information, or spatial layers would be needed for their projects. Refugia maps can help stakeholders figure out where suitable habitat could remain into the future, and where to prioritize habitat management. Stakeholders highlighted that they could prioritize restoration along streams that were highlighted as coldwater refugia, e.g., planting vegetation or protecting areas where hemlock are dying off due to hemlock wooly adelgid (Ellison et al. 2005). Several workshop participants decided to organize a subsequent meeting, maybe a monthly working group, to discuss opportunities to collaborate on coastal habitats management and conservation.

Participants proposed that communication between park units should be more prevalent. With species ranges changing and invasives establishing new territories, communicating with parks that already had these invasives would be tremendously helpful. This would allow a transfer of knowledge between parks, to be able to integrate what certain parks have years of experience in rather than starting fresh. Resources are available, for example through Northeast Regional Invasive Species and Climate Change (RISCC) Management (www.risccnetwork.org).

The attendees felt the smaller parks were underrepresented, not for a lack of data but because of a lack of staff. These smaller park units do not have the funding for natural resource staff and cannot allocate the time or resources necessary to analyze the data created or to implement some of the management plans that could potentially result from it. Moving the workshops remotely likely increased the attendance of these small parks. Participants also mentioned working with outside partners to prioritize landscape acquisitions, especially regarding small parks. In addition, they could utilize project results to allocate funding within the NPS system and with outside partners.

Outreach and communication were important themes in workshop discussions. Participants were interested in learning how to accurately interpret climate change refugia in their outreach with the public and potential partnerships. In addition, climate change refugia conservation provides a hopeful focus on climate change, in that it provides potential effective conservation actions in areas that might not be as affected.

This project is just the beginning for climate change refugia conservation in the NPS NER. The CCRC paradigm (Figure 1.1) is a cycle that encourages revision to the science and management. As with TE, there should be a continued line of communication between all parties involved. Packaging of the climate change refugia data products by each park unit is underway. All the climate change refugia data products will be available to NPS and stakeholders so that they can utilize them. These will be made available online as GIS files and in pdf form. This part allows transparency and accessibility to those all were involved and who could benefit from this science. The next step is the delivery of a final report that will be shared with NER NPS partners, which will include management and conservation recommendations for the prioritized species highlighted as a priority and climate change.

An additional next step would be to create an infographic that NPS staff can use when informing stakeholders what climate change refugia is and how you can manage it. The infographic could also include a case study and how the NPS can formulate and implement refugia strategies to manage and protect species and resources in the face of climate change.

CHAPTER 2

MAPPING CLIMATE CHANGE REFUGIA AND TRANSITION AREAS FOR PRIORITY SPECIES IN THE NORTHEAST

2.1 Introduction

Climate change is occurring 20 times faster today than during any other historical period over the past 2 million years (Princé and Zuckerberg 2015, Mann et al. 2008). This rapid change poses a potential threat to birds and a variety of other species, including humans. The effects of climate change will be heavily felt in the Northeastern United States. That region is projected to see the largest increases in temperatures in the continental US (Karmalkar and Bradley 2017), along with an increase in heatwaves, sea levels, droughts, severe precipitation events, and temperatures (Horton et al. 2014, Meehl & Tebaldi 2004, Alexander et al. 2006, Sillmann et al. 2013). Ecological impacts of anthropogenic climate change are already being felt. For both terrestrial and aquatic species, shifts have been documented (including poleward, upslope, and to deeper depths) because of climate change (Chen, et al. 2011, Wiens 2016, Pinksky et al. 2013). According to Wiens (2016), approximately 55% of temperate North American animal species and terrestrial, marine plant species have experienced range shifts.

Natural resource managers are looking to climate adaptation to buffer these impacts (Lenoir and Svenning 2014, Weiskopf et al. 2020). Effective adaptation strategies need to anticipate and ideally ameliorate impacts of climate change to maintain sustainable, functioning communities and ecosystems. One adaptation strategy could be conserving climate change refugia. These areas are defined as “areas relatively buffered from contemporary climate change over time that enable persistence of valued physical, ecological, and socio-cultural resources" (Morelli et al., 2016). Despite changes at a regional and global scale, climate change refugia remain relatively stable and persist for local climatic conditions over time (Morelli et al. 2016). Refugia can be transient and buffer temporarily from changes, i.e., how freshwater springs have served as refugia through eco-climatic changes during periods where the landscape has changed from a wetland ecosystem to a desert (Cartwright et al. 2020). Even though refugia can be considered 'slow lanes' for protecting resident species and ecosystems in the short- and medium-term, refugia can be temporary, they can still be used to provide a buffer in which species can transition in the face of climate change. Moreover, they can provide long-term havens for ecosystem function and biodiversity (Morelli et al. 2020).

Refugia mapping is a relatively new tool for resource management and conservation. It requires identifying resource priorities and their climate change vulnerability, ideally through a translational ecology process among researchers and practitioners (Enquist et al. 2017, Morelli et al. 2016). These identified resources are then mapped out on the landscape, usually through species distribution modeling (Dobrowski 2011, Morelli et al. 2017). Climate change refugia will become increasingly important for future management regarding climate change. Climate change refugia maps can then be incorporated into management prioritization.

The National Park Service (NPS) is one of the natural resource agencies that wants to incorporate climate adaptation into their management. To aid the Northeast Region (NER) of the NPS, I used a translational ecology approach to identify and map climate change refugia for priority animal and plant species (see Chapter 1). Of the 40 species identified (Chapter 1, Table 1.1), 31 were already partially modeled by collaborators, who then produce species- and park-specific maps designed for NPS NER. I mapped climate change refugia for the remaining priority species, along with mapping "transition areas" to which species are predicted to move outside their current ranges.

2.2 Species' Background

I used species distribution modeling to map climate change refugia for 9 focal species: black-throated green warbler (*Setophaga virens*), grasshopper sparrow (*Ammodramus savannarum*), shrubby five-fingers (*Sibbaldiopsis tridentata*), common bearberry (*Arctostaphylos uva-ursi*), highland rush (*Juncus trifidus*), Bebb's sedge (*Carex bebbii*), and Ambystoma salamanders including: blue-spotted salamander (*Ambystoma laterale*), marbled salamander (*Ambystoma opacum*), and Jefferson salamander (*Ambystoma jeffersonianum*).

The focal species experience climate change differently. Shrub species are showing shifts in phenology, such as earlier flowering under warmer spring temperatures, earlier snowmelt (Fremlin, et al. 2011). Bebb's sedge (Carex bebbii) requires consistent moisture and cooler temperatures and is likely to decline with warmer and drier conditions (CCVA Draft Report. 2020). Plant communities in rock outcrops like highland rush, shrubby five-fingers, and common bearberry may be impacted by climate change due to reduced water availability, greater evaporation, higher cloud ceiling, and reduced cloud immersion (Horton & Culatta 2016). Staff at Acadia National Park have witnessed earlier spring leaf-out for Shrubby five- fingers in warmer microclimates (MacKenzie et al. 2018).

Plant species are also at risk from a variety of non-climate stressors. Increases in invasive species and deer herbivory could add to the decline in certain species and decreased resiliency to climate change (Heffernan 1999). With increases in CO_2 levels in the atmosphere, some invasive plant species will become even more problematic as they thrive with elevated CO_2 levels (Ziska 2003, Belote et al. 2004, Northeast Regional Invasive Species and Climate Change (RISCC) Management). Highland rush and Shrubby five-fingers are highly vulnerable to human disturbance, such as trampling, due to their limited distribution (Southern Appalachian Species Viability Project 2002).

Shrubby five-fingers are a shrub typically found in Greenland, Providences of Canada and in the northern United States from Wisconsin to Maine. In addition, there are disjunct populations in the southern Appalachian region. Its habitat includes high elevation rock outcrops and rocky coastal headlands, such as can be found in Maine (Bresowar & Walker 2011). Shrubby five-fingers are considered to grow in a variety of rock substrates and soils, including soils with relatively high pH (Horton & Culatta 2016, Wiser 1998). The potential impacts of climate change on shrubby five-fingers are not well known. However, earlier spring leaf-out associated with the warming microclimate (MacKenzie et al. 2018) has been witnessed in Acadia National Park. In general, plants that live in rock outcrop communities are more susceptible to reduced water availability due to reduced cloud immersion, higher cloud ceiling and greater evaporation rates due to increase in temperature from climate change (Horton & Culatta 2016).

Another plant species, the Bebb's sedge is a perennial sedge that prefers moist to wet open places. Areas such as stream banks, along rivers and streams, margins of swamps and moist meadows. It can also be found in sandy or gravelly shores. It requires moist soils to thrive. Similar to shrubby five-fingers it favors calcareous soils (high pH) (Horton & Culatta 2016, Wiser 1998, Lichvar 2013). The Bebb's sedge is found from

Maine to Washington, including north in many parts of Canada, Wisconsin, south to New Jersey, northern Illinois and in Nevada.

Common bearberry range is distributed across circumboreal regions of the subarctic northern hemisphere (Klinkenberg 2020). Its range comprising of Canada, Greenland, California, the Rocky Mountains and in the Northeast in the Appalachian Mountains. Like its name suggest it is a common plant species of the genus Arctostaphylos, however it is endangered in several states primarily in the Midwest due to low occurrence and habitat destruction from urban sprawl (USDA NRCS Northeast Plant Materials Program. 2002).

The highland rush has a limited range, it is found in the eastern edge of Canada, Newfoundland and in New England. Its habitat includes boreal and alpine cliffs, ridges, and high elevation rock outcrops (Schori 2004). Since it is another plant species that lives in rock outcrops it is potentially susceptible to the same climate change effects as shrubby five-fingers. In addition, highland rush has been seen to be limited by high summer temperatures in Newfoundland (Damman 1965).

Amphibians are considered highly vulnerable to climate change. Global amphibian declines have been suggested to be the result of either changing abiotic conditions, shifting phenology, modifying species interactions, hydrological shifts in key breeding habitats, or increasing pathogens (Miller et al., 2018). Moreover, over evolutionary time, climate niche conservatism has driven a mid-elevation peak in amphibian species richness which makes them particularly vulnerable to rapid climate change (Farallo et al. 2020; Kozak & Weins, 2010). Although temperature affects distributions of amphibians, precipitation is also a large climate driver (Gillings et al.

2015; Reich et al. 2014; Rockwall et al. 2017). Amphibians require environmental moisture for respiration, prevention of desiccation, and for their larval stage. Amphibian distribution and abundance is strongly affected by habitat conditions. Deep leaf litter is associated with higher amphibian abundance due to invertebrate food availability (Coleman et al. 2004, Petranka 1998), and a decrease in desiccation due to the cool, moist microhabitats (Crawford & Semiltsch 2008, Peterman & Semiltsch 2013, Peterman & Semiltsch 2014, Rittenhouse et al., 2008).

Marbled salamanders are endemic to the eastern half of the United States, west through southeastern New England, including southern New Hampshire and Pennsylvania and reaching the Lake Michigan region. They also range south to the eastern parts of Texas and northern Florida (Klemens 1993, DeGraaf and Yamasaki 2001, NatureServe 2004). Marbled salamanders spend most of their lives in forested uplands but breed in the surrounding seasonal flooded palustrine wetlands (Noble and Brady 1933, Bishop 1941, Petranka 1989, Klemens 1993). Marbled salamanders can inhabit drier areas more than most *Ambystoma* species (Bishop 1941) and prefer soils that are dry and friable, including gravel deposits, rocky slopes, and sand (Bishop 1941, Klemens 1993). The marbled salamander was observed at elevations ranging from 30 to 355m in the state of Connecticut (Klemens 1993). Marbled salamander's populations are likely threatened by intensive timber harvesting practices. Timber harvesting practices deplete canopy closure, understory vegetation, and coarse woody debris used as breeding sites (deMaynadier and Hunter 1999). Destruction and degradation to habitat, causing habitat fragmentation, could result in deleterious levels of inbreeding (Petranka 1998).

Conversion of habitat to intensive human uses has resulted in many losses of breeding sites (Petranka 1998).

Figure 2.1: Illustration of marbled salamander by Sara Wisner.

Blue-spotted salamanders range from the provinces of Canada to northern Illinois, eastern New York and north along the Atlantic coast of New England (Klemens 1993, DeGraaf and Yamasaki 2001). For breeding, blue-spotted salamander utilizes a variety of wetland types including semi-permanent and ephemeral pools such as marshes, ditches, flooded sections of logging roads, swamps, ponds (Downs 1989, Klemens 1993, Knox 1999) and only require a depth of less than 40 cm of water (Knox 1999). Blue-spotted salamanders and Jefferson salamanders have close ranges that often overlap, but blue-spotted salamander prefer lowland swamps, damp, deciduous, or mixed woodlands with moderate shade (Downs 1989, Knox 1999), whereas Jefferson salamanders prefer ridge-top vernal pools (Klemens 1993). It is unknown what size of upland habitat is needed to sustain blue-spotted, Jefferson or their hybrid populations, however it is thought that connected, undisturbed upland forests could be helpful in maintaining metapopulations (Semlitsch 1998, USFS 2002). One of the biggest threats to Blue-spotted salamanders is the loss and degradation of habitat due to conversion to agricultural and urban land. Roads are seen to impact natal dispersal or migratory movements and could cause isolated subpopulations (deMaynadier and Hunter 2000). In addition, road runoff is shown to be a potential threat due to a rise in acid deposition (deMaynadier and Hunter 2000).

Figure 2.2: Illustration of blue-spotted salamander by Sara Wisner.

The Jefferson salamander range is limited to the eastern United States -western New England to eastern Illinois, south to central Kentucky, Virginia and Maryland and Canada -north to Ontario (Klemens 1993, DeGraaf and Yamasaki 2001). They prefer deciduous forests and mixed deciduous-hemlock forests (Klemens 1993). In addition, they prefer areas with steep rocky terrain with heavy duff layers and rotten logs (Klemens 1993) and have even been observed at elevations ranging up to 1,700 feet (Klemens 1993, USFS 2002). Like the marbled salamander, Jefferson salamanders spend most of their lives in uplands forests near palustrine wetlands to breed in (Klemens 1993, Faccio 2003). They breed in small seasonal stream filled impoundments, grassy pasture ponds, vernal shrub swamps but prefer vernal pools (Klemens 1993). Jefferson and blue-spotted salamanders have been known to form hybrids; it is thought that most individuals across the ranges are likely hybrids (Klemens 1993). In central Maine, hybrids were found carrying more blue-spotted than Jefferson chromosome sets (Knox 1999).

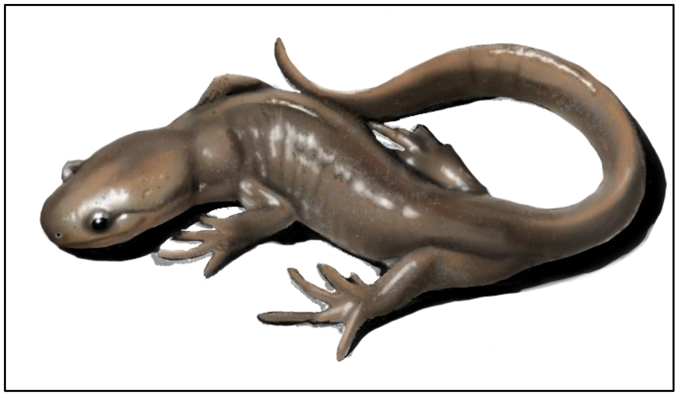

Figure 2.3: Illustration of Jefferson salamander by Sara Wisner.

About 37% of birds in North America are already at high risk of extinction (North American Bird Conservation Initiative (NABCI) 2016). The National Audubon Society found that 64% of bird species (389 of 604) in North America are moderately or highly vulnerable to climate change (Wilsey et al. 2019). Over the past century, birds have been seen tracking their climatic niche (Tingley et al., 2009).

Black-throated green warblers (*Setophaga virens*) range is in the mid-Atlantic and into the southern Appalachians of the NER. They utilize a wide variety of forest habitat, they nest in conifer forests, cypress swamps, and mixed hardwood forests. Although populations are thought to be stable (Partners in Flight 2019), one of the main threats to black-throated warblers is loss of wintering habitats (Morse and Poole 2005) and habitat degradation. They are susceptible to habitat fragmentation because even though they are considered to have an expansive breeding range, they are more commonly found in forest interiors rather than the edges of forests (Hobson and Bayne 2000). Some local populations, such as in southern New England, have been affected due to invasive insects like the wooly adelgid, causing widespread death of Eastern Hemlock (*Tsuga canadensis*), in the black-throated green warbler's range (Morgan et al. 2002). There is a similar trend in southern Appalachian spruce-fir forests with the loss of trees to the Balsam Woolly Adelgid (Rabenold et al. 2008). With declines in balsam fir, yellow birch and striped maple due to climate change it is predicted that abundance in black-throated green warbler in the eastern US will decline as well (Matthews et al. 2004).

Figure 2.4: Illustration of black-throated green warbler by Sara Wisner.

Grasshopper sparrows winter in Mexico and southeastern United States. They breed across southern Canada and the United States, west of the Great Plains (Vickery 1996). Habitat for the grasshopper sparrow in the eastern part of the United States is primarily dry fields with sparse grasses, few shrubs (areas with more than 35% shrub cover are rarely used), weeds and patches of bare ground. Areas such as blueberry barrens, airports, sandplain grasslands, abandoned agricultural fields, capped landfills are often suitable habitats for grasshopper sparrows (Vickery 1996). In areas of southeastern Canada and eastern U.S., there has been a decline in grasshopper sparrow populations due to loss of habitat from cultivation, reforestation, urban sprawl, and losses from increased predation and mowing of habitat (Ehrlich et al. 1992). In the Northeast, grasshopper sparrow populations have declined 4.26% annually since 1966 (Sauer et al.

2014). Breeding Bird Atlases in the northeast have also found declines to be 15-75% (Cadman et al. 2007, McGowan and Corwin 2008, Renfrew 2013, MassAudubon 2014).

Figure 2.5: Illustration of grasshopper sparrow by Sara Wisner.

Under the effects of climate both the black-throated green warbler and grasshopper sparrow could be forced into marginal habitats where they will experience decreases in reproduction and survival rates (Crick 2004). In addition, with suitable habitat changing to higher elevations there is a decrease in the amount of area for species to colonize (Sekercioglu et al, 2008).

2.3 Methods

2.3.1 Study Area

The project study area covered the77 National Park Units of the NPS Northeast Region (Appendix A, Table 12), which consists of the states of Maine, New Hampshire, Massachusetts, Connecticut, Rhode Island, Maryland, Vermont, New York, New Jersey, Delaware, Pennsylvania, and parts of West Virginia and Virginia. During modeling, a 5-km buffer was added to each park unit.

For the Appalachian Trail, I used management units provided by NPS Inventory and Monitoring based on the 10-digit National Hydrologic Units (HUC10) that intersect with it (Appendix A, Table 13). The HUC10 were sufficiently large to be representative and already effectively buffered the trail so I did not buffer the Appalachian Trail management units.

2.3.2 Species occurrence data

Occurrence data were gathered for black-throated green warbler, grasshopper sparrow, shrubby five-fingers, common bearberry, highland rush, Bebb's sedge, blue-spotted salamander, marbled salamander, and Jefferson salamander from iNaturalist and GBIF within the NER. I only included iNaturalist Research Grade observations with a spatial accuracy of up to 800m and that were collected from 2000 until 2020. For my bird species I only included observations between the months of May-September, to omit winter migration. For all species, occurrence records were processed in R to remove any duplicate longitude and latitude records and any missing values (NAs). In addition, occurrence points were checked to make sure there were no outliers outside the extent of the NER. The number of occurrence records retrieved from each source and the final number of records kept after processing can be found in Table 2.1. In order to remove spatial bias, occurrence points were weighed and thinned by using the geothin function of the enmSdm R package. This function removes points within 1000m of the greatest number of neighbors first and then to points that are the closest to the geographic center.

Figure 2.6 shows the resulting removal of these points after using geothin and how many occurrence points were left.

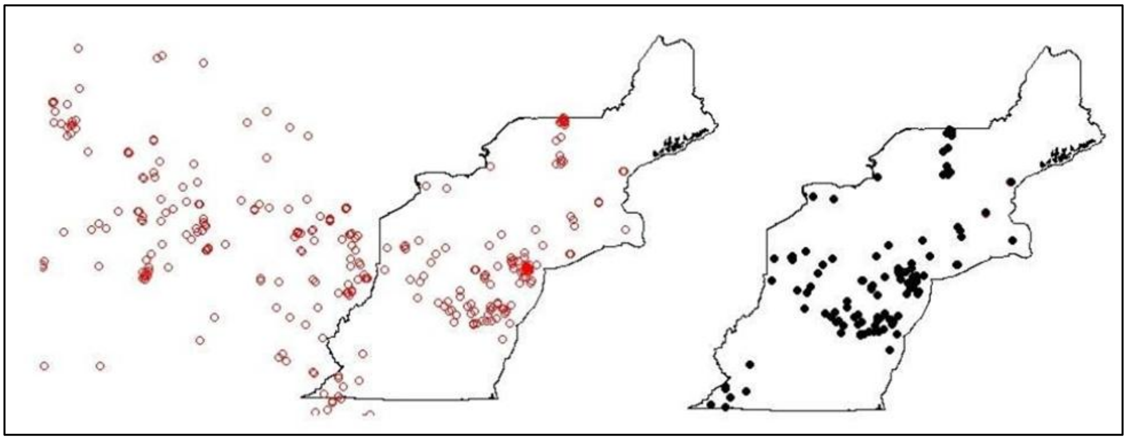

Figure 2.6: Before and after geothin of grasshopper sparrow occurrence points. The outlier occurrence points were also cropped out to just the extent of the Northeast region.

To also deal with spatial bias, I generated pseudo-absences for each one of my species from the sdm R package when creating my species distribution models (Naimi and Araujo 2016). Pseudo-absences are either spatially stratified or randomly drawn from a region (Barbet-Massin et al. 2012).

Table 2.1: List of occurrence data. The number of occurrence records collected from each source, and the number of final records after removing duplicated longitude and latitude, NAs, positional accuracy > 800m and after geothin.

Species	GBIF	iNaturalist	All Records	Final	After geothin
Common bearberry	89	622	711	583	269
Shrubby five-fingers	71	833	904	746	239
Highland rush	67	33	100	49	21
Bebb's sedge	49	1	50	11	11
Grasshopper Sparrow	16	551	567	198	129
Black-throated green	203	1833	2036	610	406

warbler					
Jefferson salamander	711	363	1074	364	234
Marbled salamander	911	944	1855	885	552
Blue-spotted salamander	53	318	371	268	190

2.3.3 Predictor Variables: Climate data

The current (2010) and future (2080) climatic conditions were represented by six climate variables (Table 2.2), modeled by the Designing Sustainable Landscapes (DSL) project at 800m resolution. These variables use 30-year Parameter-elevation Relationships on Independent Slopes Model (PRISM) normals combined with 30-year mean from the Global Climate Models (GCMs) and averaged across 14 separate model runs. Lastly, they are averaged across Representative Concentration Pathways (RCPs) 4.5 and 8.5 (McGarigal et al. 2017b).

Table 2.2: List of all the Climatic variables, their abbreviations, and the calculation details (McGarigal et al. 2017b)

Climate Variable	Calculation Details	
Annual Precipitation	Total precipitation for the year. The sum of the daily values across all days. mm/year * 100. Note the "delta" in this case is actually a ratio.	precip
Growing Season Precipitation	Sum of daily precipitation for days in May through September mm/year * 100. The "delta" is a ratio.	precipgs
Average annual temperature	Mean of daily min and max for every day of the year.	temp
Mean Minimum Winter Temperature	Mean of the daily minimum temperatures for everyday in December, January, and February.	tmin
Mean Maximum Summer Temperature	The mean of the daily maximum temperature for June, July and August.	tmax
Growing Degree Days	The sum across days of the number of degrees by which the mean daily temperature exceeds a threshold of 10 deg C. Where mean temperature is the mean of the min and max temp for the day. For prism data this is calculated from the 30 year mean temperature for each month by multiplying the	gdd

	exceedance by the number of days in the month.	

2.3.4 Predictor variables: Non-Climate Environmental Data

I used USGS 2016 National Land Cover Database (NLCD; Homer et al. 2015), tree canopy, and aspect which were all compiled for the coterminous United States by the Landfire program (https://www.landfire.gov) all of which were at 30m resolution. For plant species, I used soil survey data from the Natural Resources Conservation Service, including depth to resistant layer (bedrock), depth to water table, soil pH, soil drainage, soil organic matter, and available water supply (total volume of water at field capacity) also at 30m resolution. However, not all these data layers were used in the final model outputs. The layers used were on a species-to-species basis to get the most accurate predictions with the least amount of collinearity. Upon correlation analysis I decided to omit elevation in my analysis because it had too much collinearity with tmean (Figure 2.7).

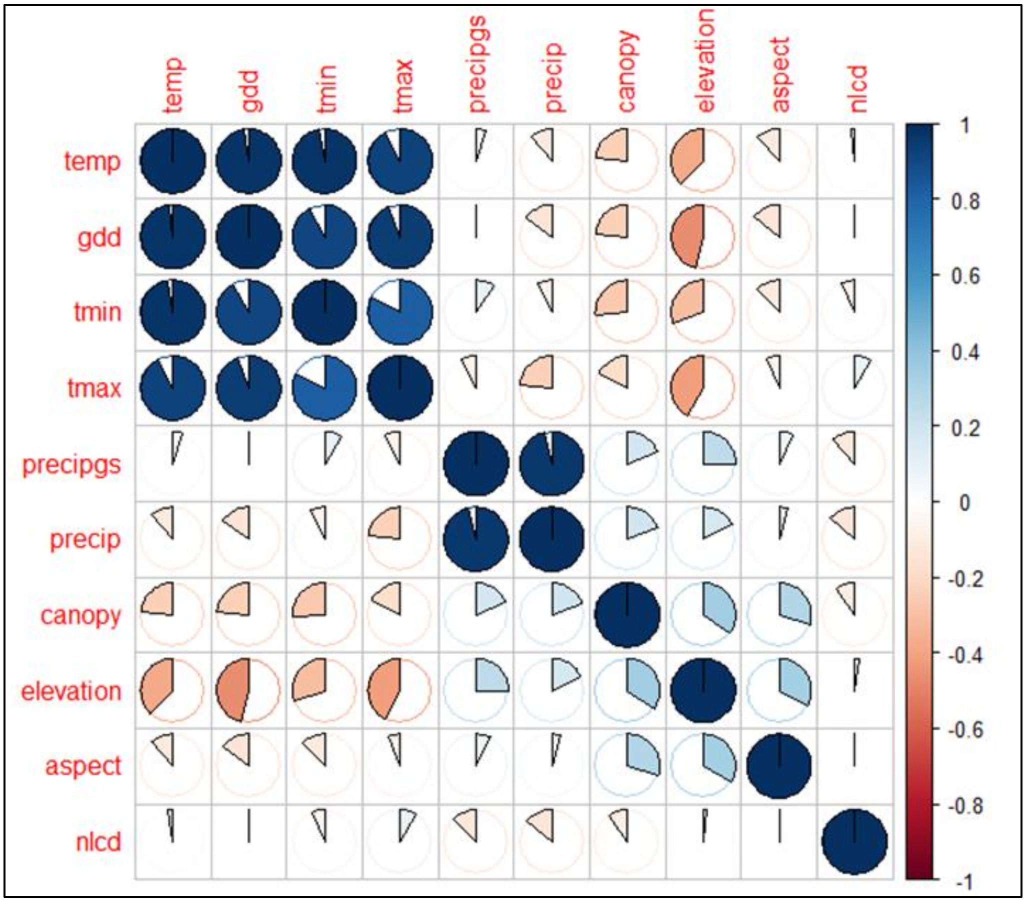

Figure 2.7: Corrplot of the environmental and climatic predictors.

2.3.5 Pseudo-absences / background points

I generated pseudo-absences from the R package sdm when creating my species distribution models (Naimi and Araujo 2016). Pseudo-absences are either spatially stratified or randomly drawn from a region (Barbet-Massin et al. 2012). Franklin and Miller (2010) have hypothesized that background "pseudo-absence" data to pair with presence data can come from anywhere in the study extent. Modeling that includes background observations that are beyond the species range to project species invasion or range changes under climate exchange scenarios yield more plausible and accurate SDMs (Chefaoui & Lobo, 2008; Le Maitre et al. 2008).

2.3.6 Pre-processing

To model the relationship between occupancy and the predictor variables, I used generalized linear models (glm) with a logit link. Generalized linear models are considered particularly apt for presence-only data because model accuracy is less influenced by the choice of pseudo-absence points than machine learning approaches, even at low sample sizes (Massin-Barbet et al. 2012). The models were run on two to three level subsets of climate variables to identify any possible combinations that could be considered together without the problem of collinearity (Table 2.3). To check and detect collinearity, I calculated the variance inflation factor (VIF) with the vif r package on each model run for every one of my species. In addition, a correlation matrix was also used and compared to VIF. From there, I used forward and backwards stepwise selection, step() R function, on a variety of global models with different combinations of climate variables and relevant environmental predictors to each species (Appendix A, Table 3). Predictor variables with high collinearity were removed and 'vif' and 'cor' were used again to compare the results. If multicollinearity was still detected, the next variable with high collinearity was removed. There was high collinearity between precip (vif 25.20) and precipgs (vif 24.65) and between tmax (12.60) and temp (vif 12.60) variables. It is important to note that when including NLCD into my glm model runs it was evaluated as a categorical layer rather than a continuous layer by using the as.factor() function in R. For the resulting models, I used Akaike's Information Criteria (AIC) to find the best models (Lawson et al. 2014; Galante et al. 2018). In Table 2.4, it lists all the predictors that were designated for the best models.

Table 2.3: Example of glms conducted on the climatic variables to check variance inflation factor (vif) to see the possibility of collinearity within the variables.

TT1<- glm(presBg~ gdd + tmax, data = environ, family = "binomial")		
vif(TT1)		
gdd	tmax	
1.04723	1.04723	
TT2<- glm(presBg~ gdd + tmax + temp, data = environ, family = "binomial")		
vif(TT2)		
gdd	tmax	temp
1.053311	7.397507	7.446364
TP1 <- glm(presBg~ gdd + tmax + precip, data = environ, family = "binomial")		
vif(TP1)		
gdd	tmax	precip
1.050892	1.049143	1.005774
TP2 <- glm(presBg~ gdd + tmax + precipgs, data = environ, family = "binomial")		
vif(TP2)		
gdd	tmax	precipgs
1.059021	1.051525	1.013458
TT3 <- glm(presBg~ gdd + tmax + tmin, data = environ, family = "binomial")		
vif(TT3)		
gdd	tmax	tmin
1.059870	1.110485	1.091186

Table 2.4: Environmental and climate predictors included in statistical models, marked with an X for each corresponding species. Species are Bearberry (BEAR), Bebb's sedge (BEBB), black-throated green warbler (BTNW), blue-spotted salamander (BLUE), grasshopper sparrow (GHSP), highland rush (RUSH), Jefferson salamander (JEFF), marbled salamander (MRBLE), shrubby five-fingers (FIVE).

Predictors	Species								
	BEAR	BEBB	BTGW	BLUE	GHSP	RUSH	JEFF	MRBLE	FIVE
temp	X								
tmin		X		X	X	X	X	X	
tmax	X		X		X			X	X
precip	X	X	X			X	X	X	X
precipgs				X	X				
gdd							X		
aws									X
ph		X							
aspect				X		X			

canopy					X				

In addition, I evaluated the performance metrics for the best pre-processing predictor models for each species, which included: mean squared error (MSE), sensitivity or true positive rate (TP), specificity or true negative rate (TN), area under the receiver-operator curve (AUC), Cohen’s Kappa (Kappa), overall accuracy (OA), and the true skill statistic (TSS). These performance metrics are listed in Table 2.6.

2.3.7 Processing (model fitting)

To predict the distribution of the priority species, I used the R package sdm, which uses the 15 modeling methods most implemented through other packages to fit the models based on methods that are selected by the user (Naimi and Araujo 2016). I chose generalized linear model 'glm', support vector machine 'svm', 'maxent', boosted regression trees 'brt', multivariate adaptive regression spline 'mars', 'bioclim', random forest 'rf', and 'maxlike' models with bootstrapping. I compared the AUC values to see which was the best model for each. In order to evaluate the AUC values I followed Araujo et al. (2005a) refine scale: Excellent: AUC > 0.90; Good: 0.80 < AUC < 0.90; 0.70 < AUC < 0.80: fair; 0.60 < AUC < 0.70: poor; 0.50 < AUC < 0.60: fail; AUC < 0.5: counter-predictions. The models with the highest AUC were ‘rf’, followed by ‘brt’, for all species. For my final models, I chose random forest ‘rf’ because it had the highest AUC scores.

Table 2.5: An example of Common bearberry initial model runs of 'glm', 'svm', 'maxent', 'brt', 'mars', 'bioclim', 'rf', and 'maxlike' with bootstrapping n=1000, showing 'rf' has the highest AUC score.

Method	AUC	COR	TSS	Deviance
glm	0.76	0.45	0.48	1.18
svm	0.80	0.54	0.56	1.48
brt	0.81	0.55	0.56	1.13
maxent	0.80	0.53	0.55	1.1
mars	0.80	0.53	0.55	1.42
bioclim	0.73	0.42	0.46	2.24
rf	**0.91**	**0.72**	**0.73**	**0.81**
Maxlike	0.71	0.42	0.41	6.75

I used the MaxSens+Spec method as part of the sdm package (Naimi and Araujo 2016) to identify a threshold for each species, which gives the highest total value of Specificity and Sensitivity, and thus is the equivalent of finding the point on the ROC curve whose tangent is 1 (Franklin and Miller 2010).

To determine if my models had the capability to accurately predict the probability of occurrence I evaluated the ROC-AUCs of all the species. The ROC, or "Receiver Operating Characteristics", curve recalls sensitivity on the y-axis against specificity on the x-axis. AUC-ROC is used as a performance measurement for the classification problems at various thresholds (Bruce and Bruce 2018., Franklin and Miller 2011). The AUC represents the degree of measure of separability, whereas the ROC is probability curve (Bruce and Bruce 2018., Franklin and Miller 2011). These metrics determine if the model is capable of distinguishing between classes (Bruce and Bruce 2018., Franklin and

Miller 2011). The higher the AUC the better the performance of the model at distinguishing between the positive and negative classes (Bruce and Bruce 2018., Franklin and Miller 2011.). The classifier can perfectly distinguish between all the positive and negative class points if AUC = 1. If the adverse is shown, and the AUC = 0, then the classifier would be predicting all negatives as positives and vice versa (Bruce and Bruce 2018., Franklin and Miller 2011).

I calculated the relative variable importance from the sdm R package. The variable importance often refers to how much the model utilizes the given variables to make an accurate prediction. The higher the amount used of a variable, the more important the variable is for the prediction. Predictions are driven by the variable with high importance and their values have a significant impact on the outcome values. In addition, to show how each species responds to the predictor variables, I created response curve plots. Response curve and variable importance plots are useful in determining the role of predictor variables in species distribution models and can be helpful when interpreting outputs of the models to researchers and stakeholders (Naimi and Araujo 2016).

To produce climate change refugia maps, I set conditions for the present habitat suitability map (2010) and future maps (2080 RCP 4.5 and 8.5) to give any cell less than the set threshold (determined in the 2.3.7 Processing (model fitting)) an NA value. Then I subtracted the present habitat suitability from projected future suitability for conditional change in habitat suitability map. Lastly, I found refugia by setting the conditional change in habitat suitability map to 10 where change in the species falls between -0.1 and NA for all other values.

To calculate refugia in the NPS park units I had to trim the climate change refugia maps to the NPS park units. I included a 5 km buffer to make the statistical summaries more meaningful for smaller parks. The HUC 10 shapefile was considered large enough and already buffered the Appalachian trail, so it did not require a 5km buffer like the other NPS units. I calculated the percentage of climate change refugia in each park unit by using extract from the raster R package to find the refugia cells in each park unit, then dividing the refugia in each park by the total number of refugia cells to get the percentage. In addition, I calculated the percentage of refugia within each HUC10 unit of the Appalachian trail. However, it is important to note that not all the Appalachian Trail was mapped, nor percentages synthesized since the Appalachian Trail extends outside the NER.

In addition, I calculated areas of transition, where each species was expected to move under the effects of climate change. Areas of transition were identified by assigning any habitat that is not suitable in 2010 a -1 value and assigning null to all the other areas not deemed suitable. From there everything that was deemed suitable habitat in 2080 was assigned a +1 value and all remaining values were assigned null. Once this is accomplished, I added both 2080 maps with the 2010 maps, with the set conditions, allowing transition zones to appear with a zero value.

2.4 Results

Habitat suitability maps modeled for my 9 priority species are in Figures 2.8 to 2.16. The green 1.0 value on the scale is climate change refugia. The values decreasing from 1.0 to 0.6 are suitable habitat. The yellow 0.5 value on the scale is stable habitat.

The values 0 to 0.4 are habitat decreasing in suitability and the 0 is no longer suitable habitat.

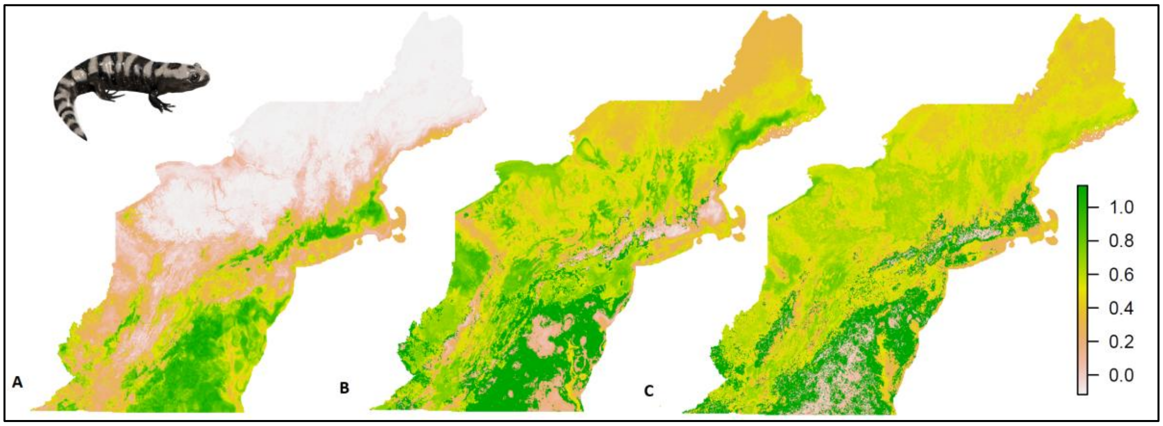

Figure 2.8: Habitat suitability for marbled salamander: A) habitat suitability 2010, B) habitat suitability for 2080 RCP 4.5. C) habitat suitability for 2080 RCP. Illustration by Sara Wisner.

The marbled salamander's habitat suitability has increase from its current range in 2010. There is more suitable habitat reaching into the northern portion of the NER, with dark green regions of refugia in the south. However, within the predicted refugium there are areas that are starting to lose stability (the peach coloration). In RCP 4.5 the refugia going into Maine is more heavily saturated than in RCP 8.5.

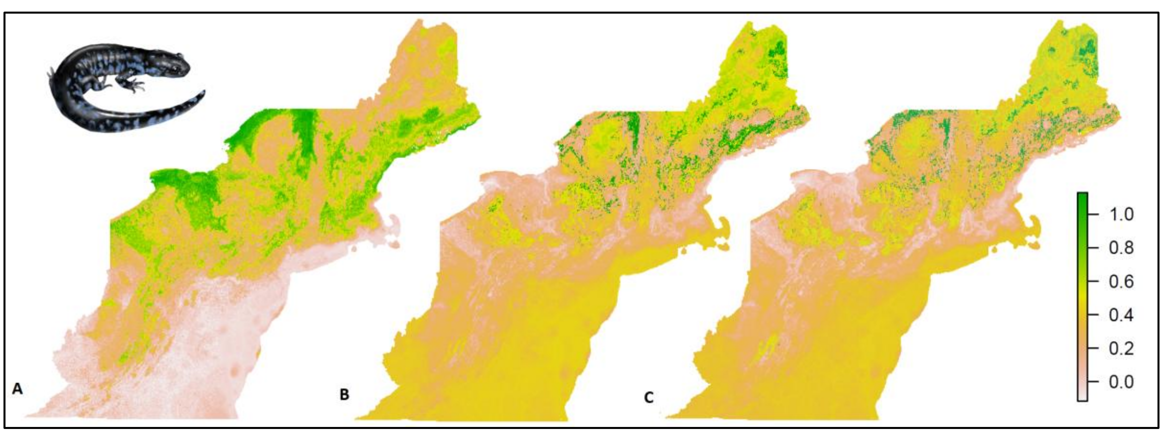

Figure 2.9: Habitat suitability for blue-spotted salamander: A) habitat suitability 2010, B) habitat suitability for 2080 RCP 4.5. C) habitat suitability for 2080 RCP. Illustration by Sara Wisner.

The blue-spotted salamander has lost suitable habitat under the constraints of climate change. There is some refugia and suitable habitat in the north, but it has lost a lot of its original suitably from 2010. Furthermore, there are areas going across the region that are not unsuitable in 2080 in both climatic scenarios. There is more predicted suitable habitat in RCP 4.5 than in 8.5. Lastly, the unsuitable habitat in 2010 in the south has become stable but not good, the orange/yellow value.

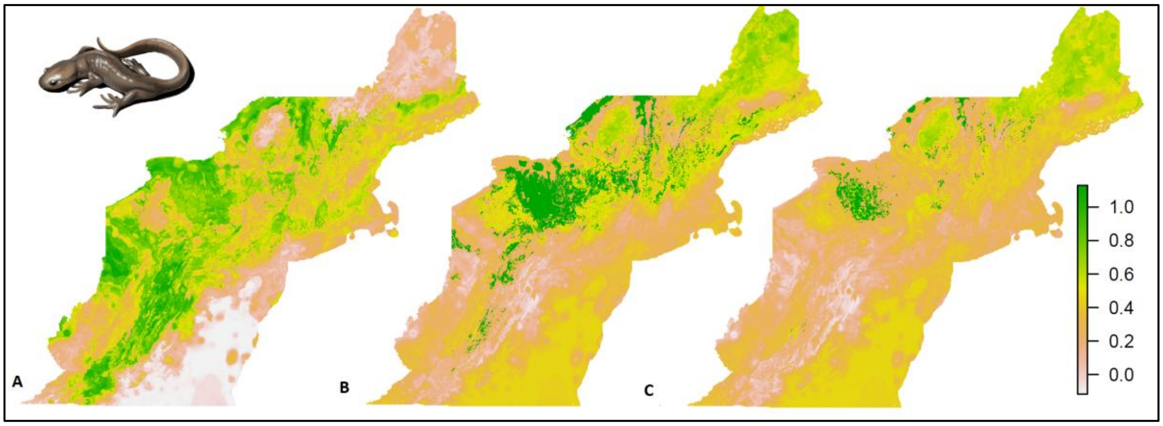

Figure 2.10: Habitat suitability for Jefferson salamander: A) habitat suitability 2010, B) habitat suitability for 2080 RCP 4.5. C) habitat suitability for 2080 RCP. Illustration by Sara Wisner.

The maps show that between RCP scenario 4.5 and 8.5, Jefferson salamander loses refugia in 8.5 (Figure 2.10). There is clearer and more defined refugia in 2080 RCP 4.5. Whereas, in RCP 8.5 there are significantly less refugia and suitable habitat areas. A pocket of refugia / suitable habitat can be seen in the western portion of the map. Along with areas of suitable habitat in the northernmost region of Maine. There is also an area of unsuitable habitat in the south, as marked by the white, in both RCP scenarios.

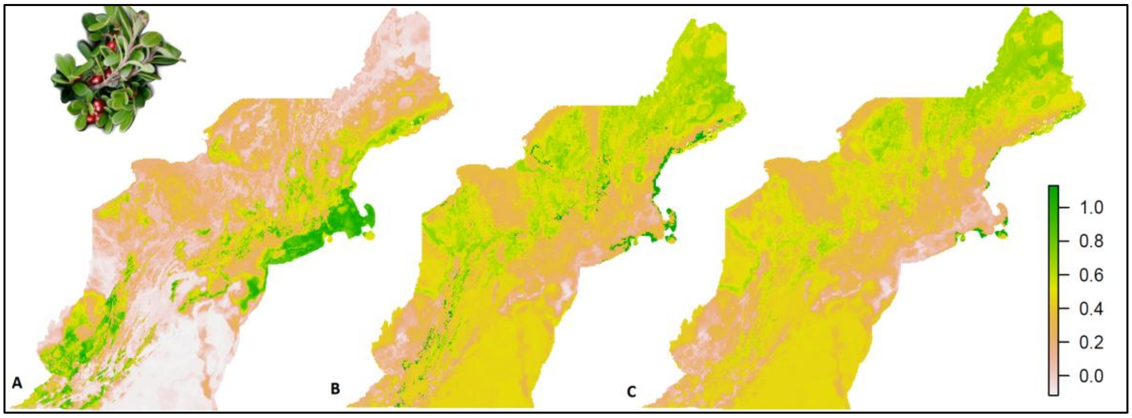

Figure 2.11: Habitat suitability for common bearberry: A) habitat suitability 2010, B) habitat suitability for 2080 RCP 4.5. C) habitat suitability for 2080 RCP. Illustration by Sara Wisner.

Common bearberry has refugia along the coasts and in some regions more inland for RCP 4.5. This area of refugia is smaller in RCP 8.5 than in 4.5. However, in both scenarios suitable habitat has started to be apparent in the north, especially in Maine. Areas in the south have gained stability as highlighted by the yellow, but they have not become highly suitable.

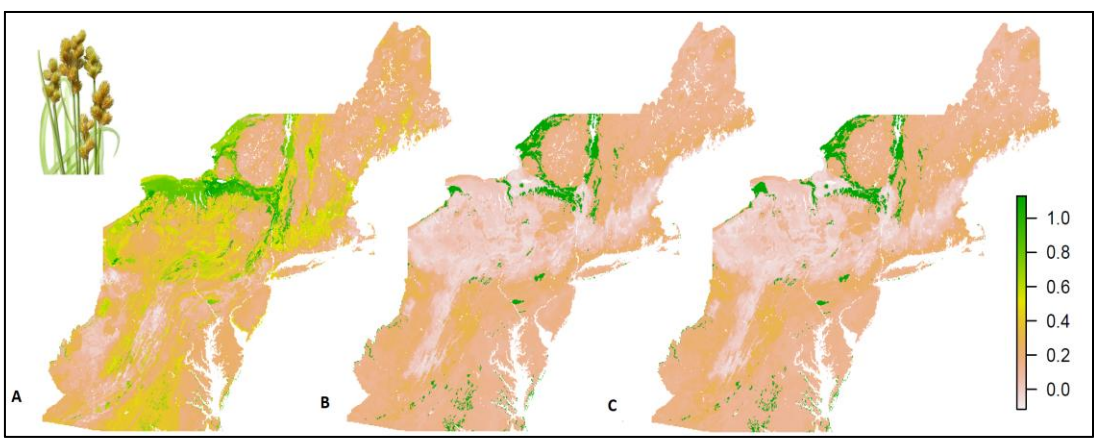

Figure 102: Habitat suitability for Bebb's sedge: A) habitat suitability 2010, B) habitat suitability for 2080 RCP 4.5. C) habitat suitability for 2080 RCP. Illustration by Sara Wisner.

Bebb's sedge almost had no discernible difference between RCP scenarios (Figure 2.12). They look almost identical, however there are a few differing pixels. The habitat suitability maps reveal that cross section of the northeast region will become unsuitable in the future projections, which is distinguished by the white shading. In addition, the areas of suitable habitat in 2010 will remain into the future and become refugia.

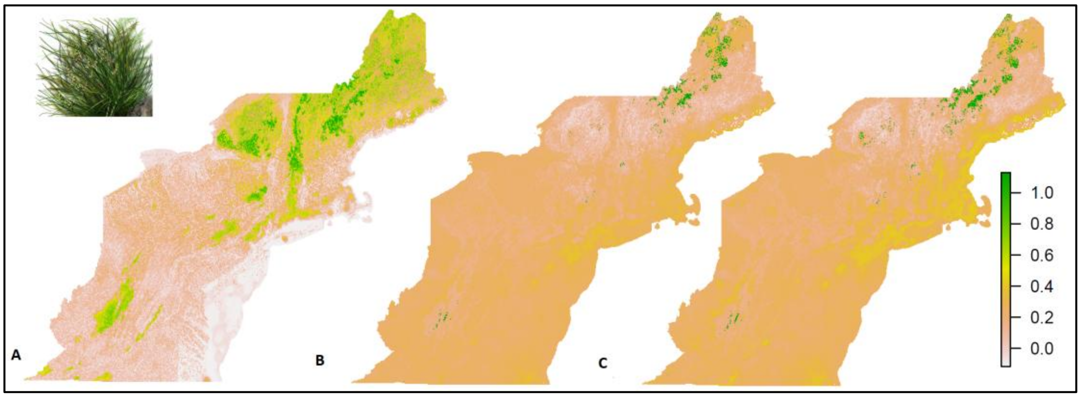

Figure 2.13: Habitat suitability for highland rush: A) habitat suitability 2010, B) habitat suitability for 2080 RCP 4.5. C) habitat suitability for 2080 RCP. Illustration by Sara Wisner.

As for highland rush, there is only slightly more suitable habitat in RCP scenario 8.5 than in RCP 4.5 (Figure 2.13). In RCP 8.5 there is stable habitat (yellow value) along the coast, where there is none in 4.5. There is small amount of refugia in the south for both RCP scenarios where there use to be suitable habitat in 2010. A considerable loss of suitable habitat can be seen going from 2010 to 2080 in the northern region, however there is some refugia.

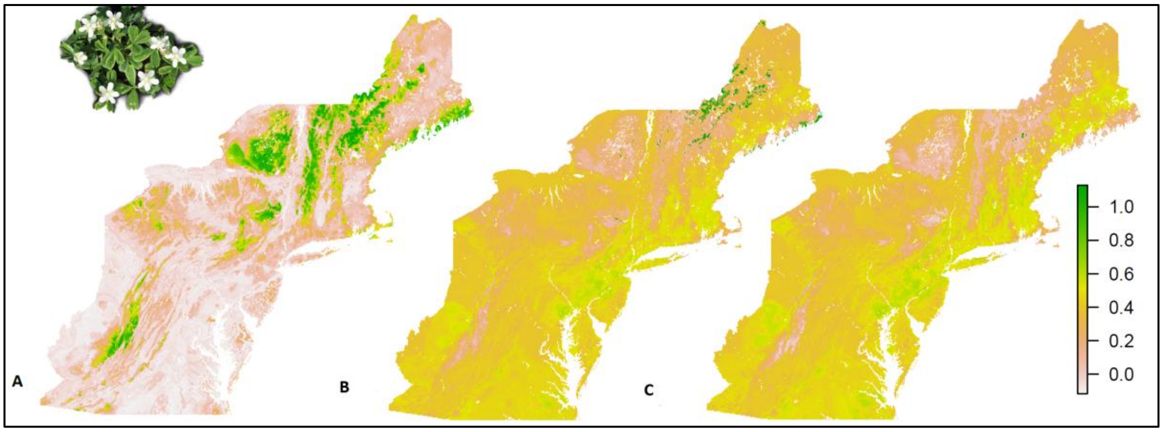

Figure 2.14: Habitat suitability for shrubby five-fingers: A) habitat suitability 2010, B) habitat suitability for 2080 RCP 4.5. C) habitat suitability for 2080 RCP. Illustration by Sara Wisner.

In the case of shrubby five-fingers, the species had a very small range within the Northeast of the United States, specifically northward towards Maine and Canada, so it wouldn't be found in park units in the south. Such can be seen in Figure 2.14, where it shows the refugia areas for shrubby five-fingers range is very northward. Going from map A to B and C, you can see there is a significant loss of highly suitable habitat. Most of the habitat in both future RCP scenarios are stable to declining habitat. There was some suitability in the south for only map A.

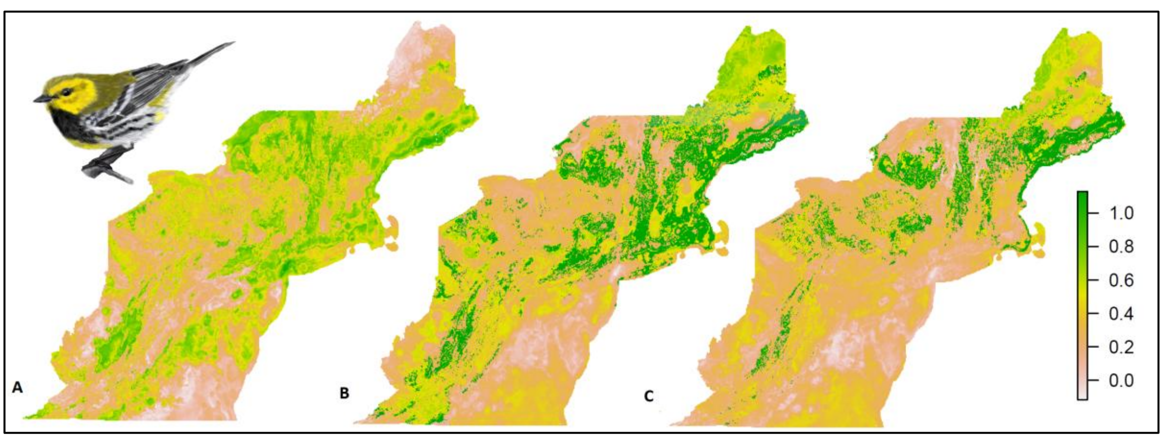

Figure 2.15: Habitat suitability for black-throated green warbler: A) habitat suitability 2010, B) habitat suitability for 2080 RCP 4.5. C) habitat suitability for 2080 RCP. Illustration by Sara Wisner.

The black-throated green warbler has a large amount of refugia and suitable habitat in RCP 4.5, especially gravitating towards the northeast portion. However, in RCP 8.5 the southern region has lost more suitable habitat than in RCP 4.5. The only refugia found the southern region has been suitable habitat since 2010. In 4.5 it has lost some of the suitable habitat in the northwest region that was suitable habitat in 2010.

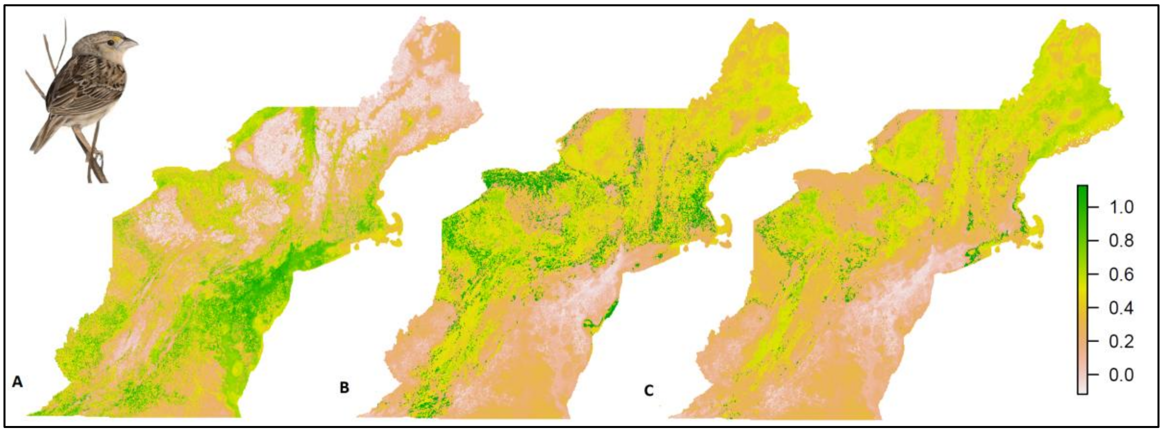

Figure 2.16: Habitat suitability for grasshopper sparrow: A) habitat suitability 2010, B) habitat suitability for 2080 RCP 4.5. C) habitat suitability for 2080 RCP. Illustration by Sara Wisner.

The grasshopper sparrow is predicted to lose suitable habitat and refugia between RCP scenario 4.5 and 8.5 (Figure 2.16). In the northern region of the NER, unsuitable habitat in 2010 has started to gain suitability in the future. However, there is a great loss of suitability in the southeastern coast of the NER (shaded in the white color).

I mapped areas predicted to be refugia (green) and transition (blue) under 2080 RCP scenario 4.5 and RCP scenario 8.5 for each species (Figures 2.17 to 2.25).

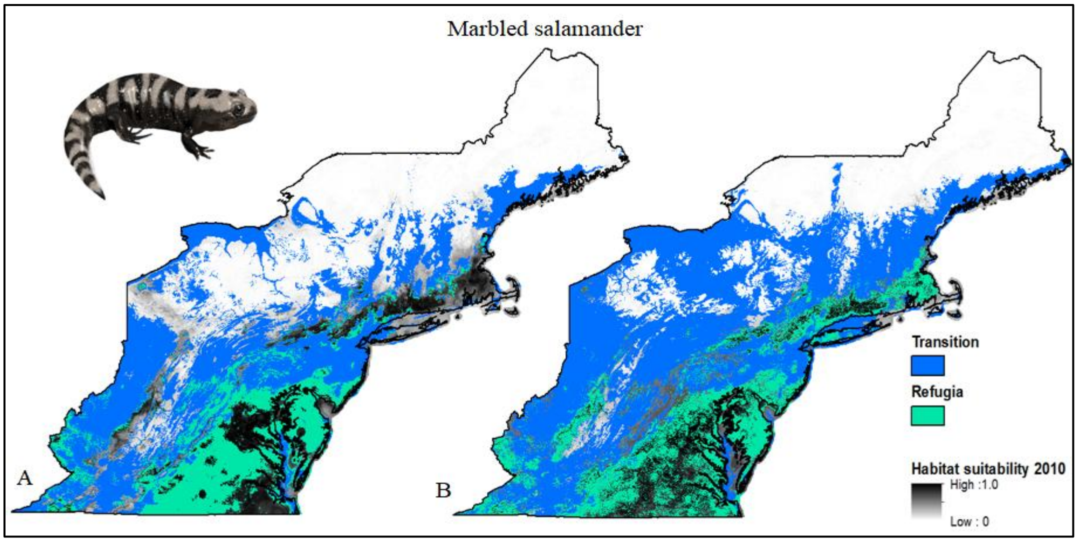

Figure 2.17: Map A 2080 RCP scenario 4.5 and Map B RCP scenario 8.5 displaying the areas predicted to be transition (blue) and refugia (green) for marbled salamander. Base map of habitat suitability in 2010, black is suitable habitat with a gradient going to unsuitable habitat in white. Illustration by Sara Wisner.

The marbled salamander has a considerable amount of refugia and transition areas. Areas that were deemed unsuitable in 2010 have now become suitable habitat, as seen by the blue transition. This area of transition reaches further north, with refugia remaining in the south. Map B has more refugia and transition than in map A.

In addition to mapping climate change refugia and transition area, I calculated the percentage of refugia in each park unit. A full table of all the calculated percentages of refugia in each park unit for each species can be found in Appendix A, Table 4, in addition the full names of the park units can be found in Appendix A, Table 1. For marbled salamander, the park unit with the highest percentage of refugia in 2080 RCP 4.5, was RICH and SHEN both with 11%. Under RCP scenario 8.5, the highest percentage of refugia for marbled salamander was in SHEN 9%. The marbled salamander gained refugia going into RCP scenario 8.5 in FIIS, BOAF, ADAM, SAMA, MIMA, NEBE, LONG, SAIR, ROWI and FRLA. For the Appalachian trail refugia was highest in

APPA: Great Valley of Virginia for RCP scenarios with 18% (RCP 4.5), and under RCP 8.5 it was 15%.

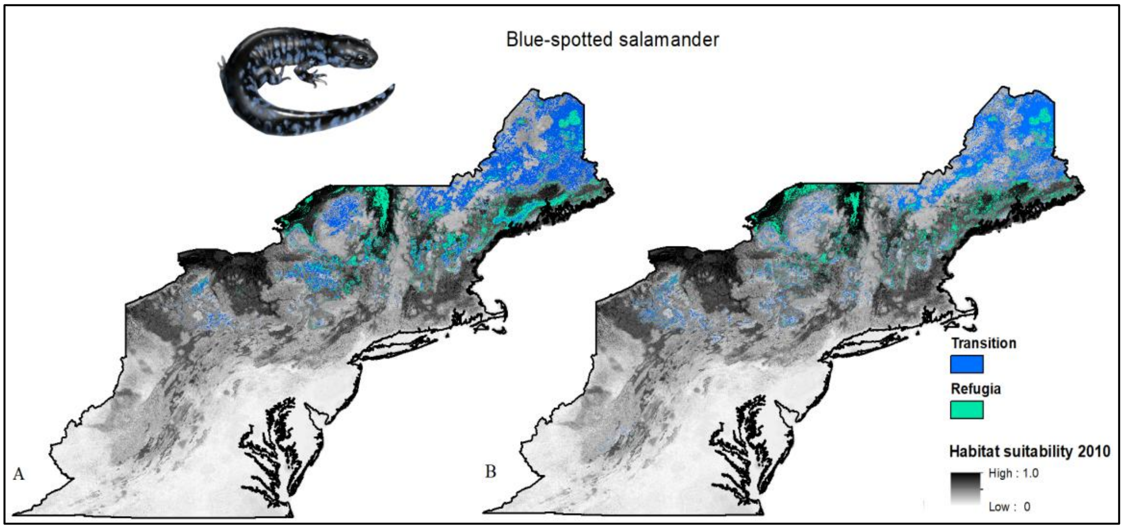

Figure 2.18: Map A 2080 RCP scenario 4.5 and Map B RCP scenario 8.5 displaying the areas predicted to be transition (blue) and refugia (green) for blue-spotted salamander. Base map of habitat suitability in 2010, black is suitable habitat with a gradient going to unsuitable habitat in white. Illustration by Sara Wisner.

The blue-spotted salamander showed a lot of transition into the north. However, there is very little refugia in both RCP scenarios. In addition, the areas that were once suitable are no longer, especially in the areas of the coast of Maine and New York. RCP scenario 4.5 has slightly more transition than in 8.5.

In the park units specifically the blue-spotted salamander gained refugia in RCP 8.5 in FOST with a 0.44% and APPA: Eastern Allegheny Plateau, there was no refugia under RCP 4.5 in those units. Refugia was high in SARA: 5.10% (RCP 4.5), MABI 7.51% (RCP 4.5) and ACAD: 6.20% (RCP 8.5). However, there was tie in the highest with APPA: Maine Central Mountains and Mahoosic Rangely Lakes both having a refugia percentage of 16% in RCP 8.5. The highest for RCP scenario 4.5 was in Maine Central Mountains with 13.1%.

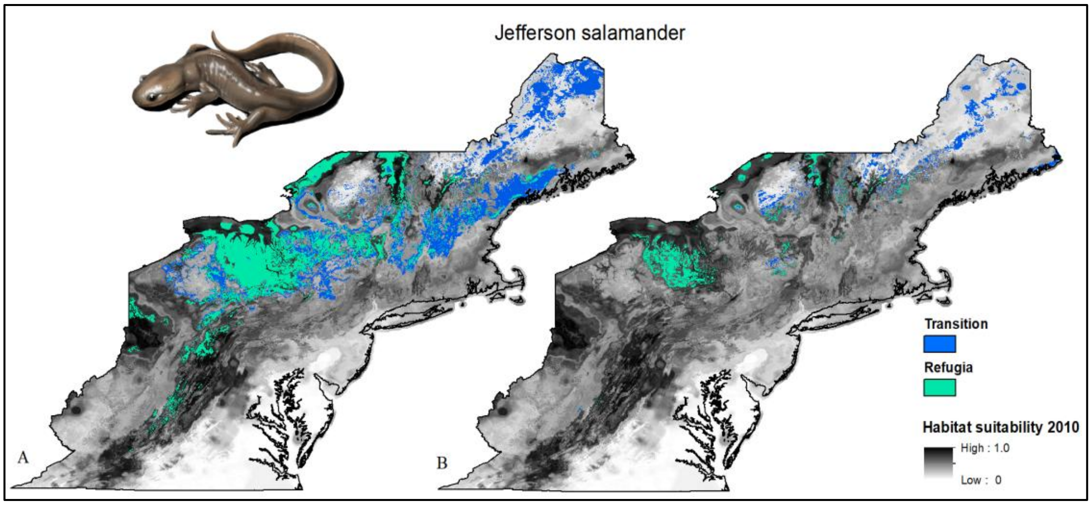

Figure 2.19: Map A 2080 RCP scenario 4.5 and Map B RCP scenario 8.5 displaying the areas predicted to be transition (blue) and refugia (green) for Jefferson salamander. Base map of habitat suitability in 2010, black is suitable habitat with a gradient going to unsuitable habitat in white. Illustration by Sara Wisner.

In map A, RCP 4.5 it shows that there is a large area of refugia in New York and an area of transition that surrounds it. This refugia area can still be seen in map B of RCP 8.5 but not in the same amount, it has decrease significantly and no longer has transition areas around it. In RCP 4.5 there is a high amount of refugia going north and you can see by the base map that it is an area that use to not be suitable habitat. The same can be seen in RCP 8.5 but in lower quantities.

Jefferson salamander only had refugia under RCP scenario 8.5 in the Appalachian trail HUC10 units. For the Appalachian trail, APPA: Southern Piedmont and APPA: Taconic Mountains had a high percentage of refugia in RCP 4.5 with 16.0% and 22% but it was low under RCP 8.5. The opposite was true when looking at APPA: White Mountains (29.0%) and APPA: Southern Green Mountain (17.4%); they were higher under RCP 8.5 and lower under RCP 4.5. Jefferson lost refugia in the Appalachian trail HUC units between RCP 4.5 and 8.5 in APPA: Champlain Glacial Lake & Marine Plains and APPA: Sebago-Ossipee Hills & Plains, APPA: Taconic Foothills, APPA: Hudson

Highlands, APPA: Hudson Limestone Valley, APPA: Great Valley of Virginia, APPA: Ridge & Valley and APPA: Western Allegheny Mountain & Valley. However, it gained refugia from 4.5 to 8.5 in APPA: Catskill Mountains. The park unit with highest percentage of refugia (RCP 4.5) was FLNI with 14.34%. The highest for RCP scenario 8.5 was APPA: White Mountains with 29%.

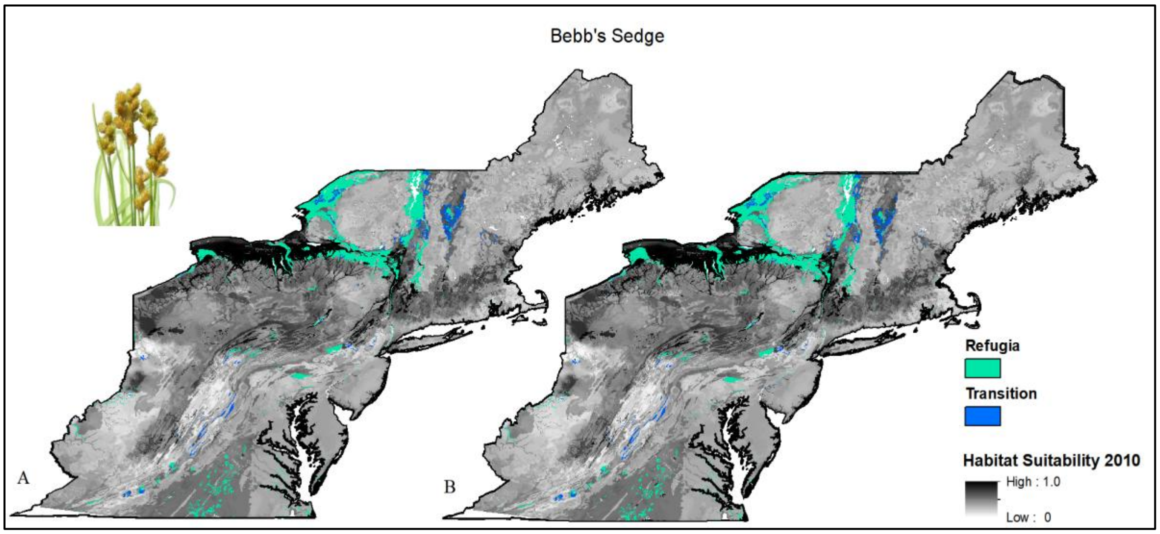

Figure 2.20: Map A 2080 RCP scenario 4.5 and Map B RCP scenario 8.5 displaying the areas predicted to be transition (blue) and refugia (green) for Bebb's sedge. Base map of habitat suitability in 2010, black is suitable habitat with a gradient going to unsuitable habitat in white. Illustration by Sara Wisner.

For both RCP scenarios there is an absence of suitable habitat in what was previously a considerable amount in 2010, the area of black in the northwest region. There is more refugia than transition areas for Bebb's sedge and most of it can be found up north near New York and Vermont.

Bebb's sedge had refugia in every NPS park unit except THST, JOFL, FLINI and GEWA. The park units with the highest percentage of refugia for Bebb's sedge under RCP 4.5 and 8.5 were GATE 3.2% and DEWA 3.8%. Bebb's sedge lost refugia in RCP

8.5 SAGA. Shrubby five-fingers were only recorded to have refugia in ACAD, with 6.00% under RCP 4.5 and 10.5% under RCP 8.5.

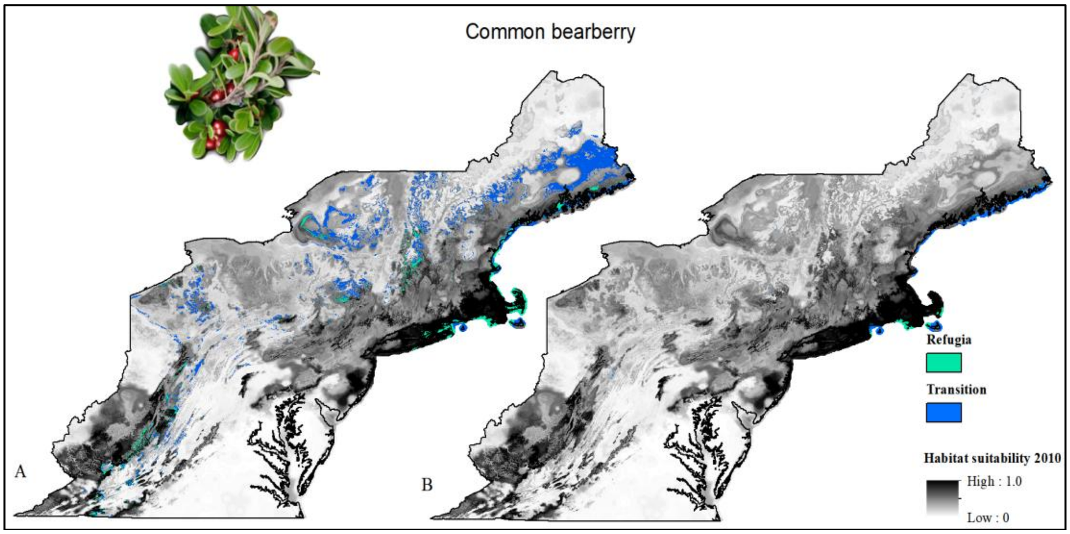

Figure 2.21: Map A 2080 RCP scenario 4.5 and Map B RCP scenario 8.5 displaying the areas predicted to be transition (blue) and refugia (green) for common bearberry. Base map of habitat suitability in 2010, black is suitable habitat with a gradient going to unsuitable habitat in white. Illustration by Sara Wisner.

Common bearberry had almost no refugia in RCP 8.5 (Figure 2.21, map B) it however did have areas of transition which was around the coastal areas of Massachusetts and Maine. Looking at the habitat suitability 2010 base map you can see that common bearberry has lost a considerable amount of suitable habitat in the Massachusetts area. In RCP 4.5 there is more areas of transition rather than refugia. In addition, there is a large transition region in Maine.

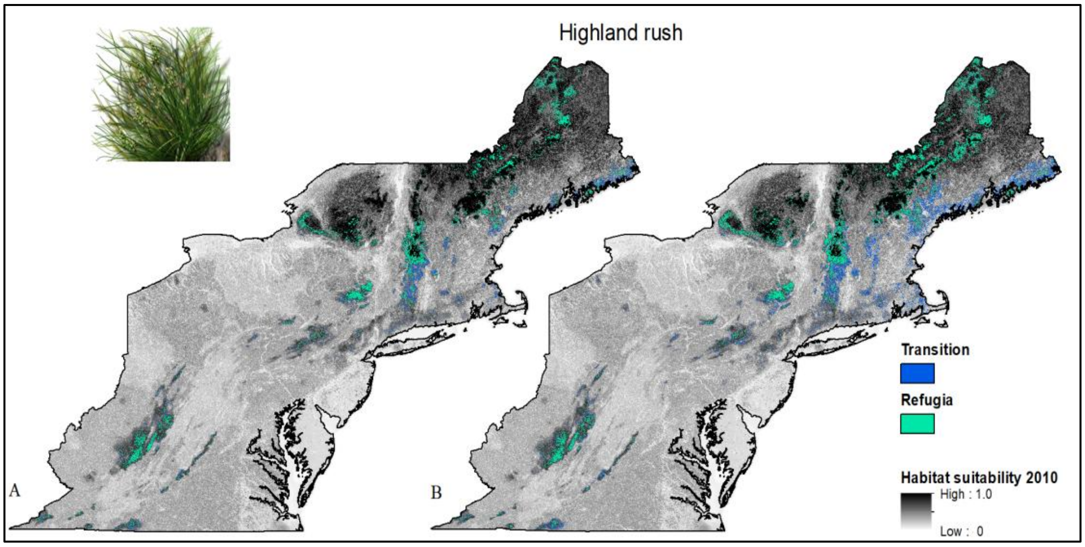

Figure 2.22: Map A 2080 RCP scenario 4.5 and Map B RCP scenario 8.5 displaying the areas predicted to be transition (blue) and refugia (green) for highland rush. Base map of habitat suitability in 2010, black is suitable habitat with a gradient going to unsuitable habitat in white. Illustration by Sara Wisner.

In RCP scenario 8.5 there was more areas of transition than in RCP 4.5. These areas of transition were interspersed along the coast of Maine and going more inland to Massachusetts, New Hampshire, and Vermont. For both RCP scenarios there is an area of refugia in the southwest region where you can see there was previously suitable habitat in 2010. In addition, there is refugia in northern most part of Maine for both future scenarios.

Highland rush only had refugia in ACAD in RCP scenario 4.5. For the Appalachian trail, the HUC10 with the highest refugia for RCP scenario 4.5 was APPA: Maine Central Mountains 39% and it was also the highest in RCP 8.5 with 38%. Highland rush gained refugia in RCP 8.5 in APPA: Central Foothills, APPA: Northern Piedmont, APPA: Sunapee Uplands, APPA: Berkshire-Vermont Uplands, and APPA: Ridge and Valley.

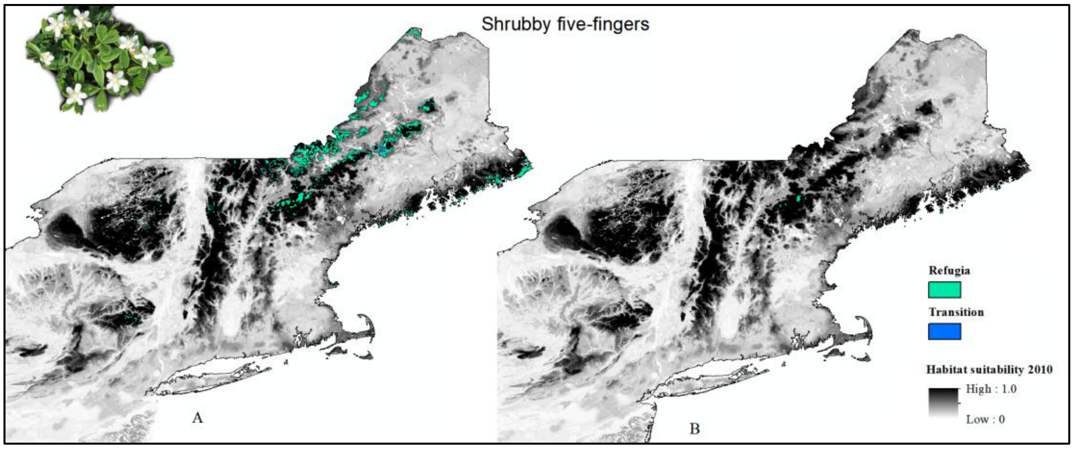

Figure 2.23: Map A 2080 RCP scenario 4.5 and Map B RCP scenario 8.5 displaying the areas predicted to be transition (blue) and refugia (green) for shrubby five-fingers. Base map of habitat suitability in 2010, black is suitable habitat with a gradient going to unsuitable habitat in white. Illustration by Sara Wisner.

Shrubby five-fingers did not have any transition in both RCP scenarios. It has very little refugia in RCP 8.5. In both maps, the refugia is found the Maine area. In addition, the only park unit it was found in was ACAD in RCP 4.5.

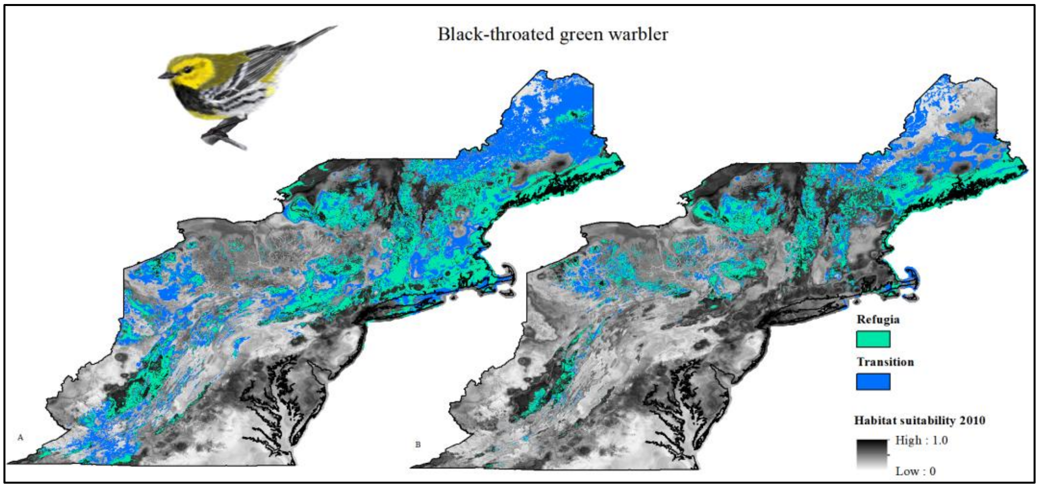

Figure 2.24: Map A, 2080 RCP scenario 4.5 and Map B. RCP scenario 8.5 displaying the areas predicted to be transition (blue) and refugia (green) for black-throated green warbler. Base map of habitat suitability in 2010, black is suitable habitat with a gradient going to unsuitable habitat in white. Illustration by Sara Wisner.

As for the black-throated green warbler, in RCP scenario 4.5 (Figure 2.24, map A) there is a substantial amount of refugia in Massachusetts, along the coast of Connecticut, Maine, New York and Long Island. These areas of refugia are surrounded by a transition zone. In addition, northern Maine has become a large transition area. An area of suitable habitat in 2010 has stayed suitable and has become a refugia in the southern region of West Virginia under RCP scenario 4.5. Under RCP scenario 8.5 (Figure 2.24, map B), Massachusetts has some refugia and transition in Cape Cod area, but it is no longer as heavily saturated in refugia like in RCP 4.5.

Black-throated green warbler had refugia in many parks, the highest percentage of refugia was in ACAD for both RCP scenarios with RCP 4.5 being 7 % and RCP 8.5 with 10%. In RCP 8.5 the black-throated green warbler gained refugia in FLINI and JOFL, meaning it did not have any refugia under RCP 4.5. There were some park units that had refugia only under RCP scenario 4.5 but not in 8.5, which were: MIMA, JOFI, LONG, SAIR, ROWI, BOST, PAGR, WEFA, VAMA, GATE, and FRLA.

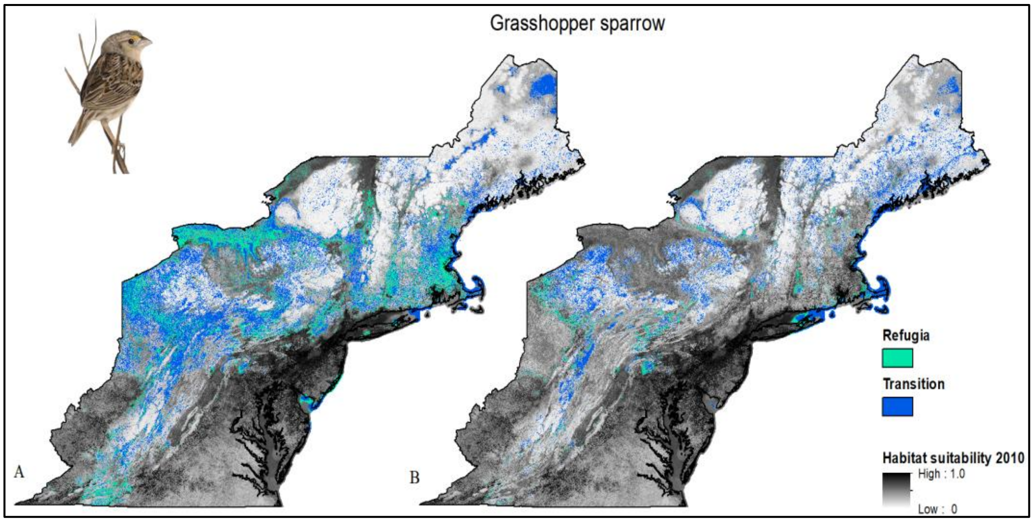

Figure 2.25: Map A 2080 RCP scenario 4.5 and Map B RCP scenario 8.5 displaying the areas predicted to be transition (blue) and refugia (green) for grasshopper sparrow. Base map of habitat suitability in 2010, black is suitable habitat with a gradient going to unsuitable habitat in white. Illustration by Sara Wisner.

Focusing on transition and refugia areas in RCP scenario 8.5 (Figure 2.25, map B) for the grasshopper sparrow you can see that a lot of the transition areas are along the coast of Massachusetts going towards Maine. There appears to be more areas of transition rather than refugia. By looking at the base map of habitat suitability of 2010 (the gray scale), you can see how the suitable area of habitat in 2010 is now vacant in 8.5. In addition, that a lot of the unsuitable habitat in the north has now become transition areas for the grasshopper sparrow, or new suitable habitat. Some areas are going to be transition areas for the grasshopper sparrow, such as Block Island, Cape Cod, and Nantucket. In RCP scenario 4.5 (Figure 2.25, map A) the grasshopper sparrow lost suitability in the northern border of NY and the western border of VT/NY, along Lake Champlain. Lake Champlain has a refugia area at the southern tip.

The park unit with the highest percentage of refugia for Grasshopper sparrow for RCP 8.5 was BOHA with 14.3% and for RCP 4.5 it was DEWA with 3.82%. Going from RCP scenario 4.5 to 8.5, grasshopper sparrow lost refugia in DEWA, GATE, SARA, FRLA, WEFA, PAGR, ROWI, MAVA, MORR, HOFU, LONG, WORI, FRHI, JOFI, MIMA, EDIS, GARI, BLUE. It gained refugia in EISE and NORI. For the Appalachian Trail, it gained refugia in RCP 8.5 in the APPA: Central Maine foothills.

Species distribution models were developed and assessed for the nine target species (Table 2.6). In the performance metrics for the pre-processing predictor models the species with the highest AUC was for Bebb's sedge with 0.92, the lowest AUC was for black-throated green warbler with an AUC of 0.61. None of the species had an AUC of below 0.60. Overall accuracy was highest in shrubby five-fingers with 0.88. However, the lowest was for the black-throated green warbler with 0.56.

Table 2.6: Performance metrics for pre-processing predictor models for each species: mean squared error (MSE), sensitivity or true positive rate (TP), specificity or true negative rate (TN), area under the receiver-operator curve (AUC), Cohen's Kappa (Kappa), overall accuracy (OA), and true skill statistic (TSS).

Species	MSE	TP	TN	AUC	KAPPA	OA	TSS
Common bearberry	0.15	0.68	0.93	0.85	0.59	0.80	0.60
Bebb's sedge	0.13	0.91	0.89	0.92	0.73	0.86	0.73
Black-throated green warbler	0.23	0.73	0.44	0.61	0.15	0.56	0.17
Blue-spotted salamander	0.20	0.68	0.76	0.76	0.44	0.72	0.44
Grasshopper Sparrow	0.19	0.78	0.70	0.79	0.47	0.74	0.47
Highland rush	0.13	0.71	0.95	0.90	0.65	0.83	0.66
Jefferson salamander	0.22	0.59	0.73	0.70	0.32	0.66	0.32
Marbled salamander	0.16	0.93	0.63	0.83	0.56	0.78	0.56
Shrubby five-fingers	0.11	0.87	0.89	0.92	0.75	0.88	0.76

Performance metrics were gathered after running each species under random forest 'rf', with n = 1000. The metrics gathered were area under the receiver-operator curve (AUC), Correlation (COR), true skill statistic (TSS), and Deviance, this output can be seen in Table 2.7. The species with the highest AUC was shrubby five-fingers with an AUC of 0.97 followed by highland rush with 0.96. The ROC for each one of the species is well above the false positive rate (Figures 15-22). The species with the highest true skill statistic was 0.92, the lowest TSS was for black-throated green warbler. No species had an AUC below 0.87. The highest AUC was with shrubby five-fingers, with a 0.97. The species with the highest Kappa was highland rush with a 0.91 it also had the highest TSS. The species with the lowest deviance was shrubby five-fingers and the highest was highland rush.

Table 2.7: Performance metrics for final model runs for each species under random forest 'rf': area under the receiver-operator curve (AUC), Correlation (COR), true skill statistic (TSS), and Deviance.

Species	Method	AUC	COR	TSS	Deviance	Kappa
Grasshopper sparrow	'rf'	0.91	0.71	0.72	0.81	0.72
Black-throated green warbler	'rf'	0.87	0.64	0.62	0.92	0.64
Marbled salamander	'rf'	0.94	0.80	0.79	0.61	0.78
Jefferson salamander	'rf'	0.90	0.70	0.68	0.82	0.66
Blue-spotted salamander	'rf'	0.93	0.77	0.76	0.69	0.77
Bebb's sedge	'rf'	0.87	0.64	0.81	1.01	0.79
Shrubby five-fingers	'rf'	0.97	0.87	0.88	0.45	0.88
Highland rush	'rf'	0.96	0.84	0.92	0.57	0.91
Common bearberry	'rf'	0.95	0.80	0.81	0.60	0.80

To figure out which variables in the models were regarded as the most important, I plotted the relative variable importance for each species. For highland rush (Appendix

B, Figure 9), the environmental variable most important to predicting occurrence were average daily minimum temperature (tmin). Bebb's sedge's most important predictor was soil pH (Appendix B, Figure 10). The variable with the most relative variable importance for the common bearberry was average annual temperature (temp) (Appendix B, Figure 12). For the last plant species, the relative variable of importance to shrubby five-fingers was tmin (Appendix B, Figure 11). The highest relative variable importance for Jefferson salamander (Appendix B, Figure 15) is precip, but for both marbled (Appendix B, Figure 13) and blue-spotted salamander (Appendix B, Figure 14) it was tmin. For the bird species, the black-throated green warbler (Appendix B, Figure 16) relative variable of importance was average annual precipitation (precip) and for grasshopper sparrow it was percent canopy cover (canopy) (Figure 2.26).

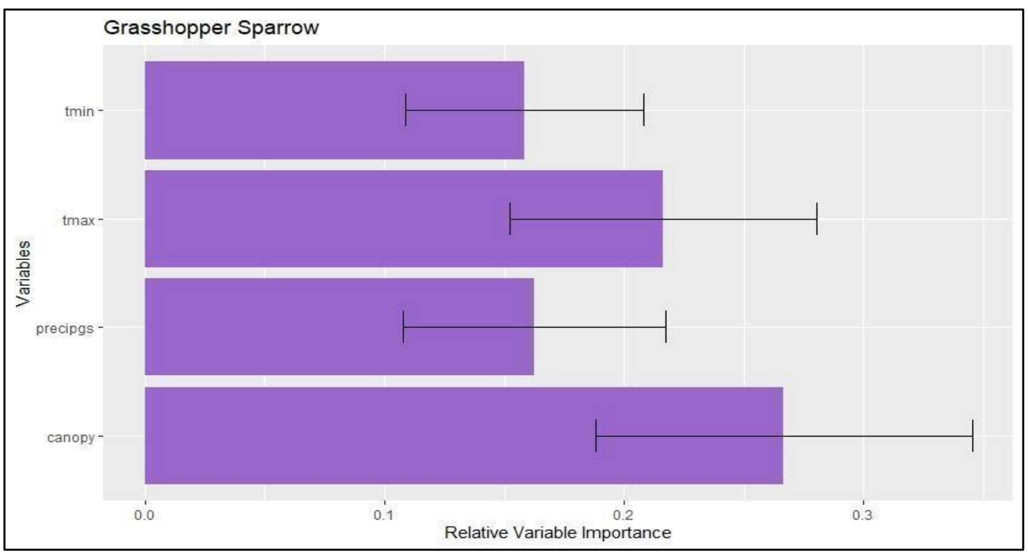

Figure 2.26: Grasshopper sparrow relative variable importance.

The plotted response curves for grasshopper sparrow (Figure 2.27) show that the species have an inverse relationship with increased canopy cover. In addition, grasshopper sparrow responds to a growing season precipitation of 100mm/year, a mean maximum summer temperature (tmax) of around 24-284°C and mean minimum winter temperature (tmin) of -4°C.

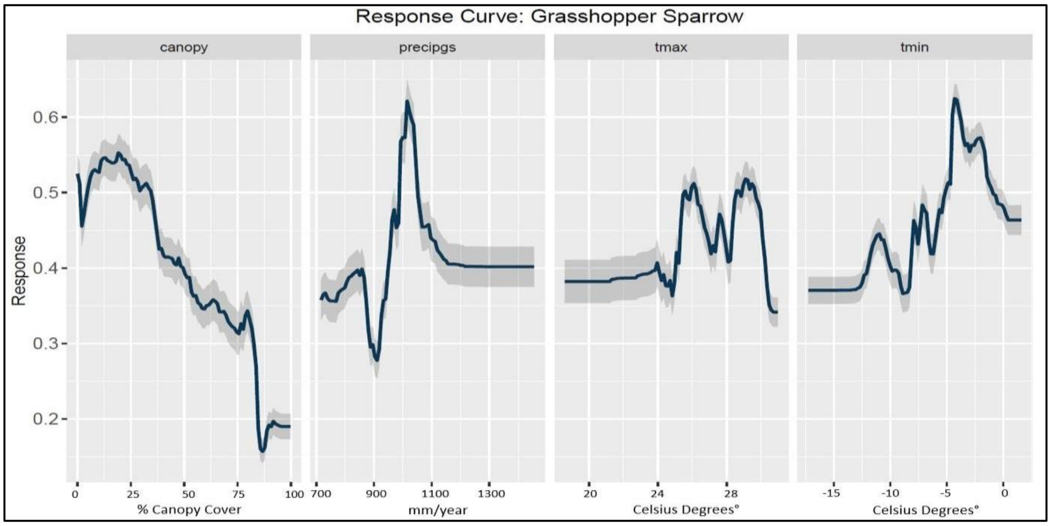

Figure 2.27: Response curve for grasshopper sparrow

As for the black-throated green warbler, its response curves show a strong response to mean maximum summer temperature (tmax) of 23°C (Figure 2.28). A peak response for 800 mm/year for annual precipitation but drops when it reaches around 1300 mm/year and levels off when the precipitation reaches 1700 mm/year.

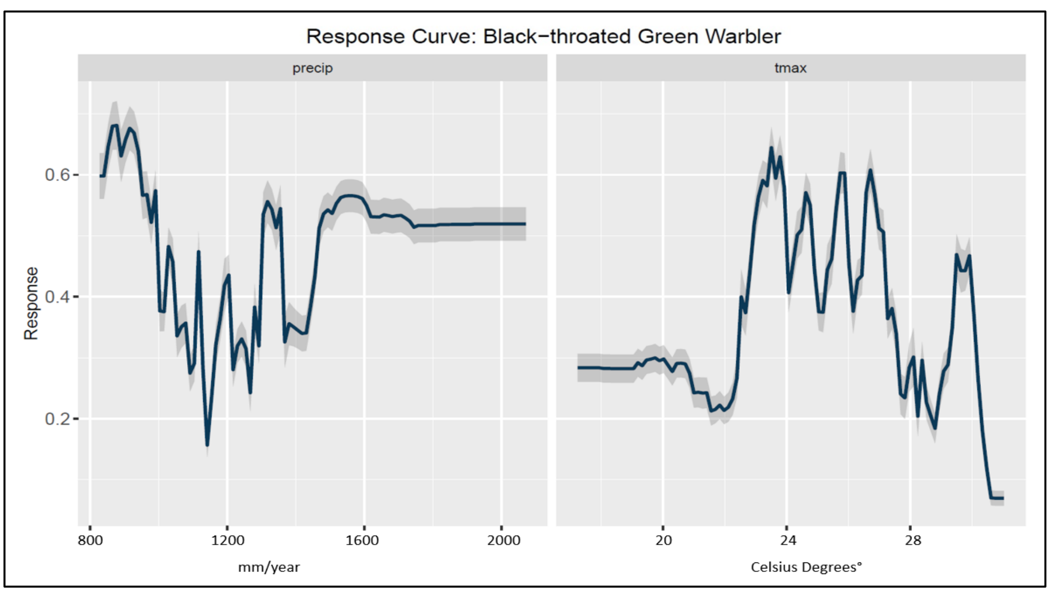

Figure 2.28: Response curve for black-throated green warbler

The response curve plot (Figure 2.29) shows that for shrubby five-fingers the species peaks when there is ~1300 mm of rain per year. Shrubby five-fingers response is stable until it reaches a mean summer temperature above 25°C -30°C, then its response plumets. In addition, it has a positive response to available water supply of ~3.5 inches but decreases once it reaches above 4 inches.

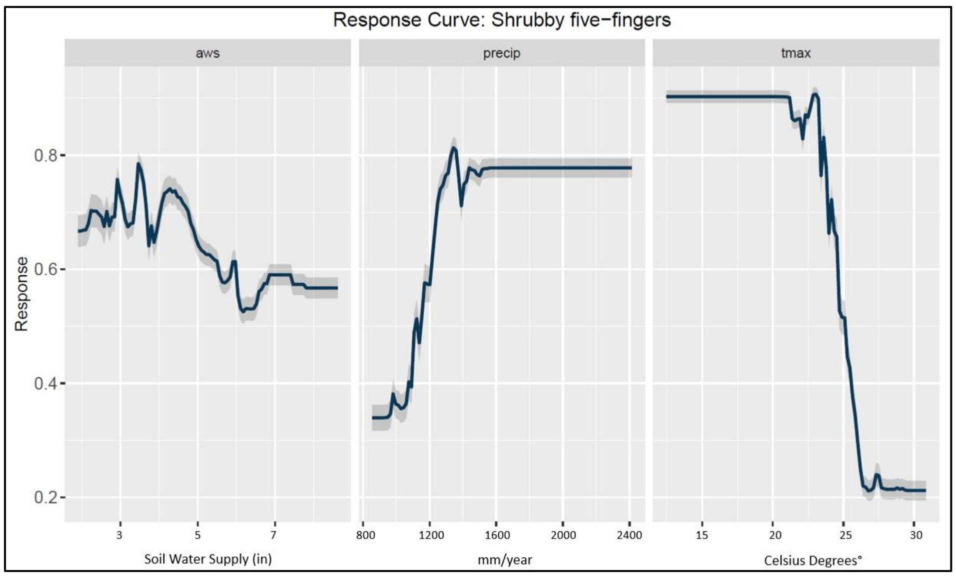

Figure 2.29: Shrubby five-fingers response curve

Bebb's sedge response curves (Figure 2.30) show it responds positively if precipitation is above 1050mm per year and responds negatively if precipitation is 1000mm per year. In addition, it has a positive response to pH levels of 5.0 to above 6.0. On the other hand, it has a negative response to minimum winter temperatures of ~-5°C.

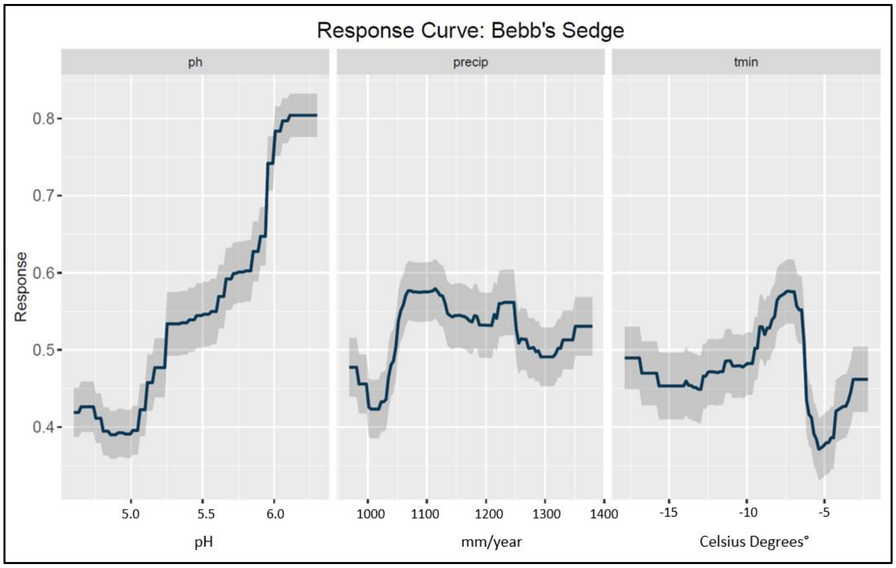

Figure 2.30: Bebb's sedge response curve

Common bearberry has a negative response when precipitation is above 1100mm per year. However, it has a peak response when precipitation is ~1250mm per year (Figure 2.31). The response also peaks when average annual temperature (temp) is ~11°C and when mean maximum summer temperature (tmax) is ~23°C, 27°C and 29°C.

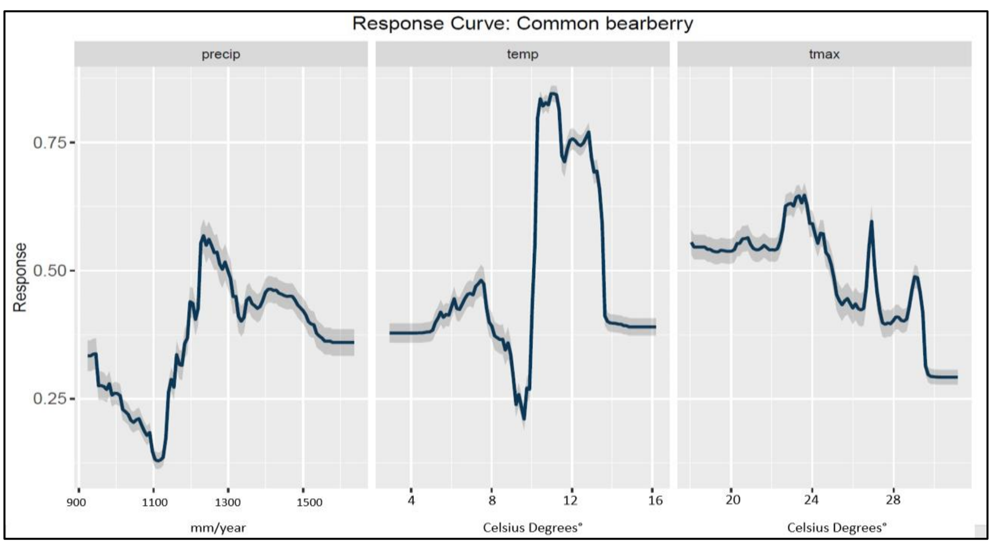

Figure 2.31: Common bearberry response curve

The response curves for highland rush reveal it prefers aspects that are 150-250 degrees and responds to precipitation above 1750 mm/year (Figure 2.32). The response curve shows that highland rush has a stable response to minimum winter temperatures below -10°C by drastically drops when temperatures reach above ~ -13°C.

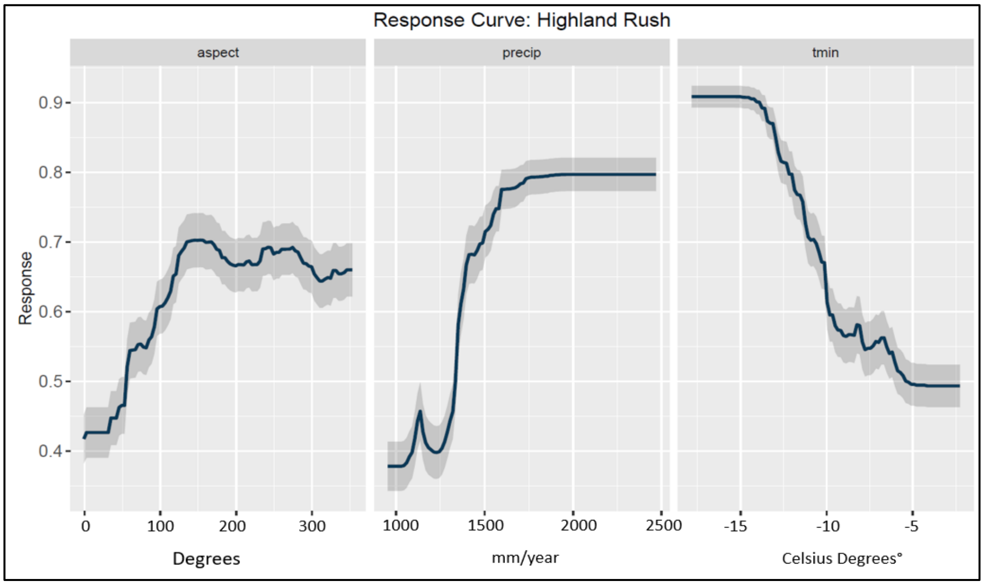

Figure 2.32: Response curves for highland rush

For the blue-spotted salamander, the response curve plot (Figure 2.33) shows that the optimum minimum winter temperature for a blue-spotted salamander is between -12°C and -10°C. In addition, it responds positively to growing season precipitation of 700-800 mm/year and it also responds to seasons that receive 1000 mm/year. The response plot of aspect for blue-spotted salamander wasn't as dramatic as the other response plots. It shows that blue-spotted salamander prefers lower aspects, showing the plot peaks very strongly at 0 degrees and peaks again at around 50°C.

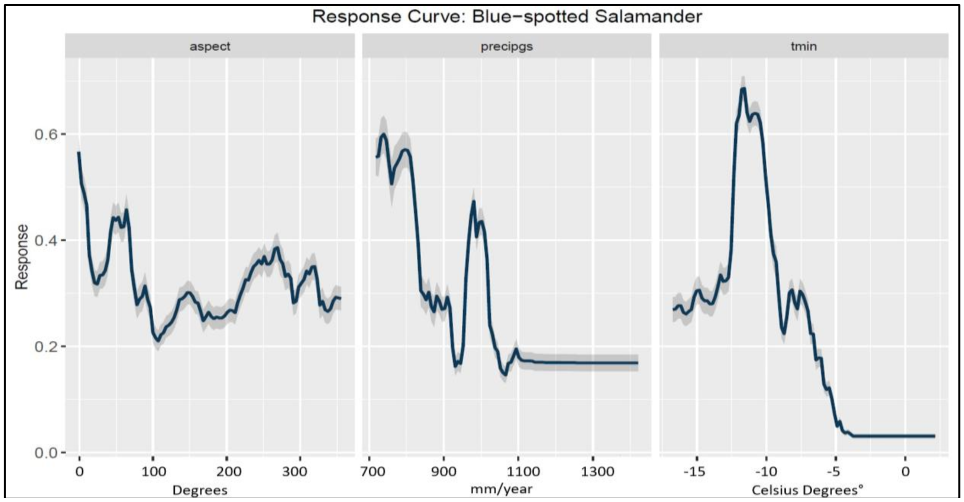

Figure 2.33: Response curves for blue-spotted salamander

Another salamander species, the Jefferson salamander has strong response to a cumulative growing degree days (gdd) of 2000 (Figure 2.34). The species has a similar response trend as the blue-spotted salamander when it comes to annual precipitation, it peaks around 1000 mm/year and 1100-1300 mm/year. However, it has the opposite response when it comes to minimum winter temperature, it peaks around -7°C.

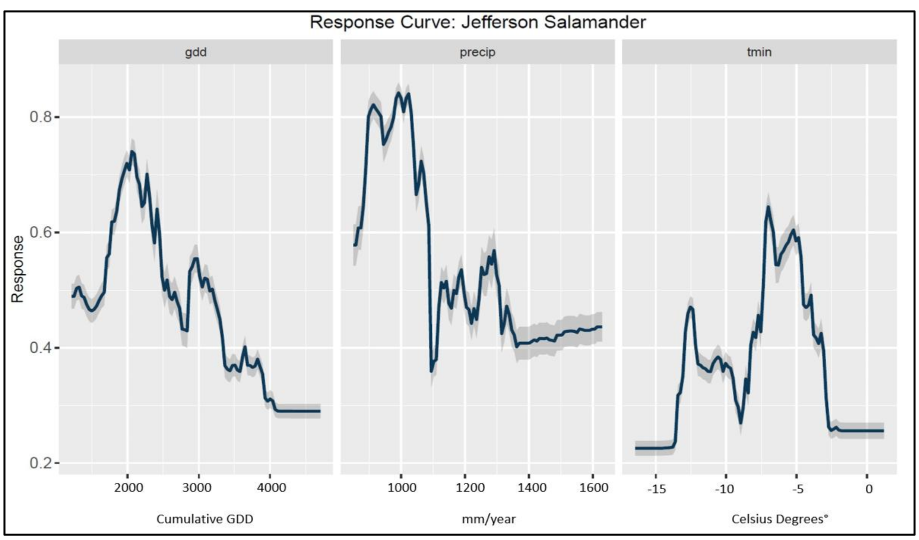

Figure 2.34: Response curve for Jefferson salamander

As for the last salamander species the marbled salamander had a strong response to both annual precipitation (precip), mean minimum winter temperature (tmin) and tmax

(Figure 2.35). The peak for annual precipitation is ~1350 mm/year and the peak for tmin is ~-3°C. The marble salamander response to tmax is relatively stable until temperatures exceed ~27°C.

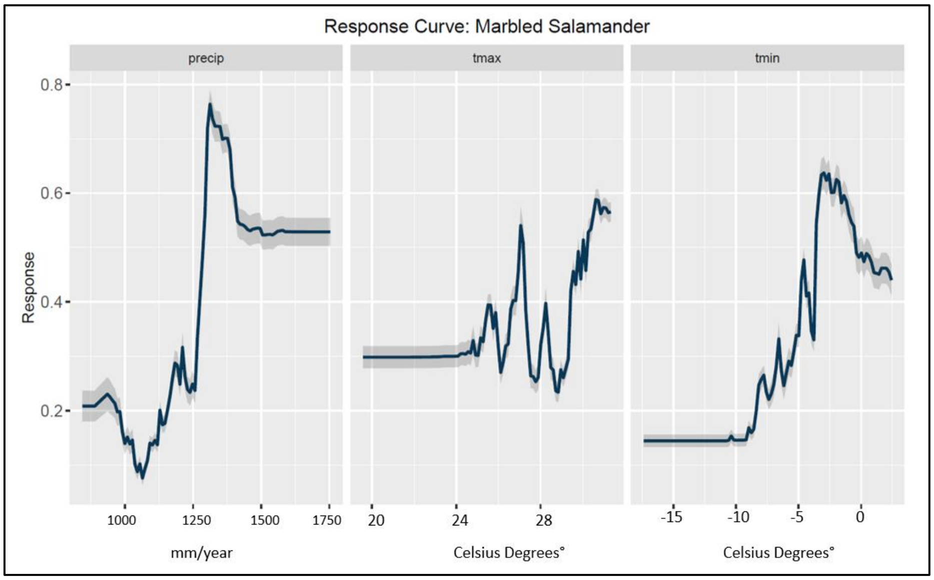

Figure 2.35: Response curve for marbled salamander.

2.5 Discussion

I produced highly predictive maps of climate change refugia for nine priority species for the Northeast Region of the National Park Service. These maps included an accurate prediction of how species ranges will move under the effects of climate change.

Compared to the plant species, the avian and salamander species had more parks with refugia and a greater amount of refugia in the NER. In addition, both had a greater amount of transition than the plant species. These predictions could be in result to the inability of the plant species to move, whereas the other species are mobile and can track their niches.

Grasshopper sparrow's response curve of responding to lower levels of tree canopy correlates with the grasshopper sparrow preferred habitat of grasslands (Figure

2.27). In addition, both the black-throated green warbler and grasshopper sparrow responded to lower levels of annual precipitation (precip) and growing season precipitation (precipgs). Precipitation can affect bird populations indirectly, altering abundance or availability of invertebrate prey (Carroll et al., 2011), impacts on vegetation structure, distribution of disease vectors, flowering and fruiting of plant species (Mac Nally et al., 2014); or directly through nesting survival (Sillett et al., 2000; Anctilet al., 2014).

The response curves show that Bebb's sedge, shrubby five-fingers, and common bearberry are tracking areas that will remain cooler and with higher annual precipitation. However, since they are a sessile species they are at risk since they cannot move to those ranges in an appropriate time. This is shown in the climate change refugia maps, as there is an overall decrease in the amount of suitable habitat in both climatic scenarios. In addition, it shows that they are going towards areas that are predicted to have lower temperatures and precipitation. It is also interesting to note, that the areas in which Bebb's sedge refugia were location were areas near surrounding water bodies / sources. These areas could have lower temperatures. It was found to be along the Hudson River, Lake Champlain, Lake Ontario and Oneida Lake to name a few. This matches Bebb's sedge life history of preferring habitat along river edges and having higher moisture.

The three salamander species had the highest percentage of refugia in COLO, SHEN, MABI, ACAD and FLNI. Contrary to the Jefferson salamander and blue-spotted salamanders' refugia maps, the marbled salamander is predicted to have more refugia and suitable habitat in the southern region of the Northeast region. All the salamander transition areas are moving northward, this is most likely due to the species tracking the cooler temperature gradients as they shift north with climate change. It is plausible for marbled and Jefferson salamanders to go to higher elevations by tracking their niches, because in their species' background they have been found at high elevations of 30-355m (for marbled salamanders) and 1700ft (Jefferson salamanders).

The species with the most amount of refugia was the marbled salamander. Marbled salamander's range was located primarily in the south. It's response curves (Figure 2.35) revealed that it has more of a tolerance than the other species to higher degrees of mean maximum summer temperature (tmax) and mean minimum winter temperature (tmin) and has the ability to inhabit drier areas (Bishop 1941). However, it is still apparent that even though it has a higher tolerance than the other species, it is still moving its range due to changing climate. In addition, because the maps are only of the NER, we cannot see how the species is responding in the south. It is possible to assume that it is most likely losing suitable habitat further south with increasing global temperatures.

The species with the lowest amount of refugia was shrubby five-fingers. The plant species had very little transition areas compared to the vertebrate species and the other plants. Shrubby five-fingers had no transition areas and the only source of refugia was found in the region of Maine. The response curve revealed that shrubby five-fingers have a very strong negative response to increases in tmax. So, it is only logical to suspect with increasing global temperatures that it would greatly impact the shrubby five-fingers. In addition, shrubby five-fingers do not have a large range within the northeast, so it is not hard to imagine them having smaller amounts of transition and refugia areas, nor suitable habitat.

It is important to consider that lower percentage to no refugia in certain park units does not mean that the species has a low level of refugia overall. The species might have higher suitability and refugia outside the park units. In addition, the species could have never been found in the park unit to begin with.

The percentage of climate change refugia in each park unit ranged between RCP scenarios. However, there was a trend of the highest percentage of refugia was in the large hectare park units. The large park units have more predicted refugia in them and are often transition zones because they are predicted to have cooler temperatures. This is because they lie in higher elevations and or lower in sea level. These park units are predicted to have lower mean winter temperatures (tmin), mean maximum summer temperature (tmax), and a lower amount of annual precipitation (including growing season precipitation). This all corresponds to species tracking cooler temperature gradients as they shift north with climate change. In addition, they would gravitate to areas with less severe precipitation events. The areas that were once suitable habitat and have become unsuitable, are areas that are predicted to have an increase in annual precipitation, average temperature, mean winter temperatures, and maximum summer temperatures. Species that cannot tolerate these changes will try to move to newly suitable habitats within their niches.

During my modeling, to define areas of high suitability as climate change refugia, I used the MaxSens+Spec method. I used this method because it determines the best threshold for each species by extracting the occurrence probability values in each presence record; binarizing predictions using each value obtained in 1 (thresholds); calculating SEN and SPE for each threshold; and searching for which threshold has the optimum maximum SEN and SPE. It also minimizes the error rate for negative observations and the mean of the error rate for positive observations (Cantor et al. 1991). In addition, species with low observed prevalence in their models or species with low predictive power were the most sensitive to the choice of threshold (Freeman et al. 2008). Thus, it is preferable to the fixed threshold approach (e.g., any probability above 0.5 is considering present), which has been determined to be one of the worst methods (Liu et al., 2005). Nenzen and Araujo (2011), along with earlier findings by Thuiller (2004), found that choice of thresholds strongly affect projections of range shifts due to climate change.

When choosing my modeling process there was some downsides to consider to each method. For instance, the svm algorithm is not suited to large data sets and does not perform well if the target classes are overlapping (has more noise) (Elith et al 2006, Franklin 2010). In addition, it will underperform if each data point exceeds the number of training data samples. Generalized linear modeling disadvantages are that the predictor variables need to be uncorrelated, it is unable to detect non-linearity directly (this can be corrected manually) (Elith et al 2006, Franklin 2010, Guisan et al. 2002, Hastie et al. 2009). The limitations of boosted regression trees are that it requires at least two variables, and it needs absence points (De'Ath 2007, Elith et al. 2008, Franklin 2010). Both MARS and bioclim tend to overfit their model predictions (Araujo and Peterson 2012, Booth et al. 2014, Elith et al. 2006, Friedman 1991, Hastie et al. 2009, Leathwick et al. 2006). In addition, BIOCLIM cannot use categorical data nor does not account for interactions of predictor variables (Araujo and Peterson 2012, Booth et al. 2014).

The downsides to the modeling method I chose, random forest (rf), is that it can sometimes overfit datasets that are "noisy" and can be biased in favor of categorical predictor variables (Breiman 2001, Cutler et al. 2007, Franklin 2010, Hastie et al. 2009). However, random forest has been shown to have higher prediction accuracy than ordinary decision trees in SDM and other applications (Prasad et al., 2006; Cutler et al., 2007). It can handle many predictor variables and even provide estimates of the importance of each. Random forest maintains its accuracy even when a large proportion of the data is missing. It has also been shown to have higher prediction accuracy than ordinary decision trees in SDM and is considered one of the most accurate learning algorithms (Prasad et al., 2006; Cutler et al., 2007).

Because confirmed absences are very difficult to obtain, they require higher levels of sampling effort to ensure reliability and they can also be especially hard to obtain for mobile species (Mackenzie & Royle 2005), I created pseudo absences in my models. To mitigate for a lack of absence data, pseudo-absences or background data are commonly generated. To cope with a lack of absence data, sometimes presence-only models have been used (Graham et al. 2004b), although they perform less well than presence-absence models (Elith et al. 2006). However, there are some drawbacks in generating pseudo-absence data as well. One of the draw backs of pseudo-absences is that, if the pseudo points are geographically disparate from the location of the presence points, the predictive models will be weakened to tease out the fine scale conditions that restrain a species distribution (VanDerWal et al. 2009).

The performance metrics of my models showed that AUC/ROC were all well above 0.80, meaning my models had the capability to accurately predict the probability of occurrence (Table 2.7). The AUC/ROC graphs for each one of the species reveal that it is well above the false positive rate (Figure 2.26 and Appendix B: Figures 1-8). In order to evaluate how well the models, separate presences from absences, I calculated the true skill statistic or TSS as {1 - maximum (sensitivity + specificity)}, where sensitivity and specificity are calculated based on the probability threshold for which their sum is maximized (Franklin 2010). Like Kappa, TSS ranges from -1 to +1, where +1 shows a perfect agreement and values that are zero or less indicate an evaluation no better than random. In addition, they consider both omission and commission of errors and success from random guessing (Allouche et al. 2006). Unlike Kappa, TSS is not affected by prevalence and is not affected by the size of the validation set (Allouche et al. 2006). If the proportions of presences and absences in the validation set are equal, then TSS is seen as a special case of kappa (Allouche et al. 2006).

Kappa score for black-throated green warbler and Jefferson salamander was low in the preprocessing performance models (Table 2.6) but increased when the final model was run with rf. None of my species had a kappa score of less than 0.60 in my final models, meaning that the data are reliable. Excellent Kappa is considered >0.75; good 0.40 > K > 0.75; and poor Kappa is <0.40, according to Landis and Koch (1977). The Kappa statistic is highly dependent on a species' prevalence (Allouche et al. 2006) and is thus likely low due to the low prevalence of these species. The TSS for all my species was > 0.60, with highland rush having the highest with 0.92. This shows that my models can accurately separate the absences and presences in the modeling. In addition, my models did not have high collinearity between predictor variables.

However, my models did have limitations. To inform management and conservation initiatives, it is critical to predict shifts in species distribution ranges (Elsen et al., 2020), but it can be challenging to estimate climate change effects with SDMs alone (White et al., 2018). Ignoring possible biotic interactions, my research focused purely on estimating possible shifts in distributions with gradual changes in climatic conditions. Indirect impacts of climate change, such as invasive species and disease dynamics, that might alter habitat suitability are not captured. For these simulations I held habitat constant based on 2010. However, these simulations do not include land-use and human disturbance. In addition, my models do not incorporate forest succession and disturbance, which matters for species that are dependent on it. Furthermore, these models do not incorporate biotic interactions, such as competition or predation. Species responses in nature are modified depending on their interactions with other species, within the same or different trophic levels. The occurrence data could have a bias, due to the survey. Species are generally recorded in their best habitat, and they are not recorded in marginal areas. To get a more accurate representation of habitat suitability surveys need to record species in these marginal areas. The future predictions could potentially have a wider range than predicted. In addition, the resolution of the environmental / predictor layers often does not allow for a fine scale view of what is occurring in small park units. This can result in pixels overlapping outside of the park units. However, having a coarse view (absence of biotic factors) of the changing landscape due to climate change can still show an accurate view of how the environment and its species are changing. This would allow for managers and stakeholders to make decisions in how they want to manage their parks and its resources for climate change.

Management plans need to consider the species current threats as well as their vulnerability to climate change. Mapping transition areas allow managers to be able to see where species ranges are predicted to shift under climate change, allowing them to implement management plans in those newly transition areas. In addition, they can use these predictions to conserve or acquire land that will become a new habitat. As suggested by the stakeholders in Chapter 1, managers should work with outside partners to prioritize landscape acquisitions. Allocating more land would provide protection when climate shifts and allow more opportunities for species to persist in these new transition areas. Another strategy is adding buffers around existing reserves, allowing more movement for the species that dwell there (Lawler 2009). In addition, with the creation of these data products managers could try to allocate funding to help with climate change research and adaptation strategies.

Some other management strategies gathered from literature say for grasshopper sparrows breeding season, mid-April to late August, avoid disturbing nesting habitat such as with burning, heavy grazing, or haying (Stewart 1975, Whitmore 1981, Frawley 1989, Rodenhouse et al. 1995, Vickery 1996). It is suggested that treatments can be done several weeks before the arrival of adult grasshopper sparrows on the breeding grounds (early spring), or after the breeding season during the fall (Renken 1983, Martin and Gavin 1995). Another suggestion, like Bobolink management, is to leave adjacent untreated areas, for fledglings or late renesting birds to take refuge (Bollinger 1988). Although not currently in decline, management plans for the black-throated green warbler could help deter this species from future climatic impacts. Development of monitoring protocol that determines states breeding population, nest sites, nesting success, site fidelity. In addition, conduct surveys to determine wintering locations, and migration corridors for black-throated green warbler.

For salamander species, including Jefferson, blue-spotted and marbled salamanders, management plans should focus on maintaining vernal pool habitat for breeding. In addition, maintaining and preserving upland habitat and dispersal corridors. Habitat surveys should be conducted to assess the size and configuration of upland habitat, the proximity of occupied habitat to development, roads, and other sources of disturbance (NH SWAP. 2015). In addition, genotype surveys should be utilized to see the degree of isolation, presence of hybrids and if there is any genotype exchange between other local populations (NH SWAP. 2015).

For shrub species, a good management strategy would be isolating areas from hikers in which highland rush, shrubby five-fingers, common bearberry and bebb's sedge are found, so these species do not get trampled. In addition, adding relocation practices help transition these species in habitat that will be deemed suitable in the future.

2.6 Conclusion

Mapping climate change refugia is an important tool in helping preserve and protect species from the effects of climate change. Likewise, translational ecology is an important framework to elicit priorities, engage natural resource managers, and ultimately implement the best available science in the creation of these refugia maps. This project has allowed the formulation of climate change refugia maps that could help the National Park Service better manage their time and allocate funds towards projects that are vital in protecting and preserving species and resources.

Species will be unequally impacted by the effects of climate change. Species that are sessile, such as shrubs, could feel the effects more than other species because they cannot move to newly suitable habitat. Relocation practices could be implemented to help these species. In addition, a key climate adaptation action is to increase habitat connectivity for freshwater, terrestrial and marine systems, enabling the dispersal of species and allowing them to follow physiological niches as habitats and environmental conditions shift (McGuire et al. 2016). Each species reacts to changing climatic variables differently. To effectively address climate induced shifts in animal and plant populations, there must be an ecosystem-based and landscape-scale conservation and management approach (Lenoir and Svenning 2014, NCA4 Ecosystems chapter).

Putting refugia conservation efforts for the Northeast into adaptive management practices can help current limitations by identifying data, management actions and reducing system uncertainty due to climate change (Williams, 2011). The persistence of resources in refugia areas resonates with managers because it acknowledges the opportunity to conserve resources within areas they already protect under legislation and agency policies (Morelli et al. 2016). It allows managers to retrofit already existing management plans to better cater to their parks and their species. However, management capacity and approach may be different within each management unit, as seen from Chapter 1 there are many underfunded and short-staffed park units. The data products created, and the cooperation underscored by this project will hopefully serve as a catalyst in pursuing research grants and other management practices. In addition, I hope that from this study managers and stakeholders are inspired to continue to build a relationship in which the best science is created.

APPENDIX A

THE TABLES

Table 1: List of the National Park units (from largest to smallest) of the Northeast Region, along with the Unit code that corresponds to the NPS park name.

UNIT CODE	UNIT NAME	STATE	Hectares [ha]
SHEN	Shenandoah National Park	VA	127873
DEWA	Delaware Water Gap National Recreation Area	PA	48978
NERI	New River Gorge National River	VA	45784
UPDE	Upper Delaware Scenic and Recreational River	PA	41475
CACO	Cape Cod National Seashore	MA	32414
ASIS	Assateague Island National Seashore	MD	31861
ACAD	Acadia National Park	ME	30662
GATE	Gateway National Recreation Area	NY	19068
FIIS	Fire Island National Seashore	NY	13853
GARI	Gauley River National Recreation Area	WV	7324
COLO	Colonial National Historical Park	VA	6017
RICH	Richmond National Battlefield Park	VA	5189
GETT	Gettysburg National Military Park	PA	4213

BLUE	Bluestone National Scenic River	WV	2799
SARA	Saratoga National Historical Park	NY	2690
VAFO	Valley Forge National Historical Park	PA	2390
CEBE	Cedar Creek and Belle Grove National Historical Park	VA	2328
PETE	Petersburg National Battlefield	VA	1777
FLNI	Flight 93 National Memorial	PA	1566
MORR	Morristown National Historical Park	NJ	1194
BOHA	Boston Harbor Islands National Recreation Area	MA	1181
APCO	Appomattox Court House National Historical Park	VA	1142
ALPO	Allegheny Portage Railroad National Historic Site	PA	916
FRST	First State National Historical Park	DE	793
MIMA	Minute Man National Historical Park	MA	763
HOFR	Home of Franklin D. Roosevelt National Historic Site	NY	654
FONE	Fort Necessity National Battlefield	PA	629
HOFU	Hopewell Furnace National Historic Site	PA	589

MABI	Marsh-Billings-Rockefeller National Historical Park	VT	498
EISE	Eisenhower National Historic Site	PA	475
FRHI	Friendship Hill National Historic Site	PA	463
GEWA	George Washington Birthplace National Monument	VA	431
MAVA	Martin Van Buren National Historic Site	NY	220
THST	Thomas Stone National Historic Site	MD	217
BOWA	Booker T. Washington National Monument	VA	155
VAMA	Vanderbilt Mansion National Historic Site	NY	153
SAGA	Saint-Gaudens National Historic Site	NH	144
LOWE	Lowell National Historical Park	MA	141
ELRO	Eleanor Roosevelt National Historic Site	NY	129
JOFL	Johnstown Flood National Memorial	PA	125
SAHI	Sagamore Hill National Historic Site	NY	58
WEFA	Weir Farm National Historic Site	CT	49
HAMP	Hampton National Historic Site	MD	42
SPAR	Springfield Armory National Historic Site	MA	39.68

STEA	Steamtown National Historic Site	PA	39
PAGR	Paterson Great Falls National Historical Park	NJ	36
INDE	Independence National Historical Park	PA	33
BOST	Boston National Historical Park	MA	32
FOMC	Fort McHenry National Monument and Historic Shrine	MD	31
STLI	Statue Of Liberty National Monument	NY	30
NEBE	New Bedford Whaling National Historical Park	MA	22
SACR	Saint Croix Island International Historic Site	ME	20
GOIS	Governors Island National Monument	NY	16
EDIS	Thomas Edison National Historical Park	NJ	14
FOST	Fort Stanwix National Monument	NY	12
ADAM	Adams National Historical Park	MA	10
SAIR	Saugus Iron Works National Historic Site	MA	9
FRED	Fredericksburg	VA	7
SAMA	Salem Maritime National Historic Site	MA	7
WORI	Women's Rights National Historical Park	NY	5

FRLA	Frederick Law Olmsted National Historic Site	MA	5
SAPA	Saint Paul's Church National Historic Site	NY	4
ROWI	Roger Williams National Memorial	RI	3
LONG	Longfellow House-Washington's Headquarters National Historic Site	MA	1
HAGR	Hamilton Grange National Memorial	NY	1
CACL	Castle Clinton National Monument	NY	0.9
THRI	Theodore Roosevelt Inaugural National Historic Site	NY	0.89
MAWA	Maggie L. Walker National Historic Site	VA	0.84
GEGR	General Grant National Memorial	NY	0.52
BOAF	Boston African American National Historic Site	MA	0.44
EDAL	Edgar Allan Poe National Historic Site	PA	0.37
FEHA	Federal Hall National Memorial	NY	0.34
AFBG	African Burial Ground National Monument	NY	0.25
THRB	Theodore Roosevelt Birthplace National Historic Site	NY	0.08
JOFI	John Fitzgerald Kennedy National Historic Site	MA	0.07

THKO	Thaddeus Kosciuszko National Memorial	PA	0.02

Table 2: Appalachian Trail units (from largest to smallest) broken down into ecoregions that interact the trail and the size of the unit in hectares.

UNIT NAME	Hectares [ha]
APPA: Southern Blue Ridge Mountains	1067454
APPA: Great Valley of Virginia	748748
APPA: Ridge and Valley	629009
APPA: Northern Blue Ridge Mountains	621759
APPA: Maine Central Mountains	607858
APPA: Hudson Highlands	582203
APPA: Northern Ridge and Valley	571023
APPA: Northern Great Valley	566345
APPA: Mahoosic Rangely Lakes	452077
APPA: Northern Piedmont	328568
APPA: Taconic Mountains	300759
APPA: Hudson Limestone Valley	293035
APPA: Berkshire-Vermont Upland	280868

APPA: White Mountains	273975
APPA: Southern Green Mountain	232612
APPA: Gettysburg Piedmont Lowland	226172
APPA: Southern Piedmont	214651
APPA: Taconic Foothills	205513
APPA: Central Maine Foothills	193668
APPA: Eastern Allegheny Plateau	188426
APPA: Connecticut Lakes	156717
APPA: Lynchburg Belt	146541
APPA: Sunapee Uplands	121763
APPA: Western Maine Foothills	109177
APPA: Kittatinny-Shawangunk Ridges	89915
APPA: St. John Upland	89323
APPA: Northern Piedmont	86489
APPA: Western Allegheny Mountain and Valley	74222
APPA: Sebago-Ossipee Hills and Plains	68520
APPA: Reading Prong	54102

APPA: Central Blue Ridge Mountains	52851
APPA: Northern Green Mountain	51748
APPA: Pocono Plateau	29049
APPA: Newark	23389
APPA: Piedmont Upland	22843
APPA: Eastern Coal Fields	20377
APPA: Catskill Mountains	17670
APPA: Aroostook Hills	10232
APPA: Triassic Basins	7354
APPA: Maine-New Brunswick Lowlands	6522
APPA: Champlain Glacial Lake and Marine Plains	1791
APPA: Central Maine Embayment	1441

Table 3: Example of the glm model runs to evaluate the best predictor variables by AIC and checking variance inflation factor.

glm1 <- glm(presBg ~ canopy + aspect + as.factor(nlcd) + temp + precipgs, data = environ, family ="binomial") slm1 <- step(glm1) vif(slm2)
glm2 <- glm(presBg ~ canopy + aspect + as.factor(nlcd) + temp + precip, data = environ, family ="binomial") slm2<- step(glm2) vif(slm2)
glm3 <- glm(presBg ~ canopy + aspect + as.factor(nlcd) + temp + tmax, data = environ, family ="binomial") slm3 <- step(glm3) vif(slm3)
glm4 <- glm(presBg ~ canopy + aspect + as.factor(nlcd) + tmin + precipgs, data = environ, family ="binomial") slm4 <- step(glm4) vif(slm4)
glm5 <- glm(presBg ~ canopy + aspect + as.factor(nlcd) + tmin + precip, data = environ, family ="binomial") slm5 <- step(glm5) vif(slm5)
glm6 <- glm(presBg ~ canopy + aspect + as.factor(nlcd) + tmin + tmax, data = environ, family ="binomial") slm6 <- step(glm6) vif(slm6)
glm7 <- glm(presBg ~ canopy + aspect + as.factor(nlcd) + tmin + gdd, data = environ, family ="binomial") slm7 <- step(glm7) vif(slm7)
glm8 <- glm(presBg ~ canopy + aspect + as.factor(nlcd) + gdd + precip, data = environ, family ="binomial") slm8 <- step(glm8) vif(slm8)
glm9 <- glm(presBg ~ canopy + aspect + as.factor(nlcd) + gdd + precipgs, data = environ, family ="binomial") slm9 <- step(glm9) vif(slm9)
glm10 <- glm(presBg ~ canopy + aspect + as.factor(nlcd) + tmax + precip, data = environ, family ="binomial") slm10 <- step(glm10) vif(slm10)

```
glm11 <- glm(presBg ~ canopy + aspect + as.factor(nlcd) + tmax + precipgs, data = environ, family ="binomial")
slm11 <- step(glm11)
vif(slm11)
```

```
glm12 <- glm(presBg ~ canopy + aspect + as.factor(nlcd) + tmax + precip + tmin, data = environ, family ="binomial")
slm12 <- step(glm12)
vif(slm12)
```

```
glm13 <- glm(presBg ~ canopy + aspect + as.factor(nlcd) + tmax + precipgs + tmin, data = environ, family ="binomial")
slm13 <- step(glm13)
vif(slm13)
```

```
glm14 <- glm(presBg ~ canopy + aspect + as.factor(nlcd) + tmax + precip + temp, data = environ, family ="binomial")
slm14 <- step(glm14)
vif(slm14)
```

```
glm15 <- glm(presBg ~ canopy + aspect + as.factor(nlcd) + tmax + precipgs + temp, data = environ, family ="binomial")
slm15 <- step(glm15)
vif(slm15)
```

glm16 <- glm(presBg ~ canopy + aspect + as.factor(nlcd) + gdd + precip + tmin, data = environ, family ="binomial")
slm16 <- step(glm16)
vif(slm16)

```
glm17 <- glm(presBg ~ canopy + aspect + as.factor(nlcd) + gdd + precipgs + tmin, data = environ, family ="binomial")
slm17 <- step(glm17)
vif(slm17)
```

```
glm18 <- glm(presBg ~ canopy + aspect + as.factor(nlcd) + tmax + temp, data = environ, family ="binomial")
slm18 <- step(glm18)
vif(slm18)
```

Model ID	df	AIC
slm1	3	625.0964
slm2	3	617.0047
slm3	3	642.7613
slm4	2	626.2043
slm5	3	620.2766
slm6	1	649.3973
slm7	3	645.0915
slm8	3	612.5073
slm9	3	621.4636
slm10	3	618.6656
slm11	2	626.2043
slm12	3	618.6656

slm13	2	626.2043
slm14	3	617.0047
slm15	3	625.0964
slm16	**4**	**605.9867**
slm17	4	612.3420
slm18	3	642.7613

vif(**slm16**)		
gdd	precip	tmin
5.720131	1.086103	5.558490

Table 4: Percentage of refugia for each park unit

Unit Code	Species	2080 RCP 4.5	2080 RCP 8.5
ACAD	Marbled salamander	0	0
	Jefferson salamander	0	0
	Blue-spotted salamander	5.2	6.2
	Shrubby five-fingers	5.84	10.5
	Bebb’s sedge	0.3	0.30
	Highland rush	0.10	0
	Common bearberry	5.00	6.00
	Grasshopper sparrow	0	0
	Black-throated green warbler	7.42	10.00
ASIS	Marbled salamander	5	4
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb’s sedge	1.2	1.20
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	0	0
	Black-throated green warbler	0	0
BLUE	Marbled salamander	0.01	0.01
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb’s sedge	0.1	0.07
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	1.08	0
	Black-throated green warbler	0	0
COLO	Marbled salamander	2.23	1.50
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb’s sedge	2.3	2.40
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	0	0
	Black-throated green warbler	0	0
DEWA	Marbled salamander	2.50	2.31
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb’s sedge	3.2	3.24
	Highland rush	0	0

	Common bearberry	0	0
	Grasshopper sparrow	3.84	0
	Black-throated green warbler	5.20	0.11
FIIS	Marbled salamander	0	1.02
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb’s sedge	2.1	2.13
	Highland rush	0	0
	Common bearberry	1.40	0
	Grasshopper sparrow	0.04	9.5
	Black-throated green warbler	4.00	0
FRED	Marbled salamander	0.01	0.02
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb’s sedge	0.4	0.40
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	0	0
	Black-throated green warbler	0	0
GARI	Marbled salamander	0.52	1.20
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb’s sedge	0.1	0.09
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	1.23	0
	Black-throated green warbler	0.61	0
INDE	Marbled salamander	1.00	1.00
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb’s sedge	0.4	0.40
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	0	0
	Black-throated green warbler	0	0
LOWE	Marbled salamander	0	0
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb’s sedge	0.6	0.43
	Highland rush	0	0

	Common bearberry	0	0
	Grasshopper sparrow	2.11	4.20
	Black-throated green warbler	0	0
NERI	Marbled salamander	1.00	2.00
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb's sedge	0.7	0.73
	Highland rush	0	0
	Common bearberry	4.93	0
	Grasshopper sparrow	2.74	1.34
	Black-throated green warbler	2.04	0.11
SACR	Marbled salamander	0	0
	Jefferson salamander	0	0
	Blue-spotted salamander	1.0	1.61
	Shrubby five-fingers	0	0
	Bebb's sedge	0.02	0.02
	Highland rush	0.08	0.05
	Common bearberry	0	0
	Grasshopper sparrow	0	0
	Black-throated green warbler	0.42	0.93
SHEN	Marbled salamander	11.0	9.33
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb's sedge	2.4	2.12
	Highland rush	3.10	2.23
	Common bearberry	0.10	0
	Grasshopper sparrow	0.51	3.00
	Black-throated green warbler	2.51	0.41
STEA	Marbled salamander	0	0
	Jefferson salamander	4.64	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb's sedge	0.5	0.60
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	0.92	1.34
	Black-throated green warbler	0.10	0
STLI	Marbled salamander	0	0
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb's sedge	0.7	0.71
	Highland rush	0	0

	Common bearberry	0	0
	Grasshopper sparrow	0	0
	Black-throated green warbler	0	0
CEBE	Marbled salamander	2.00	1.30
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb’s sedge	0.9	0.80
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	0	0
	Black-throated green warbler	0	0
HOFR	Marbled salamander	0	0
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb’s sedge	0.5	0.52
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	0.43	1.00
	Black-throated green warbler	0	0
BOHA	Marbled salamander	0	1.00
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb’s sedge	1.3	1.35
	Highland rush	0	0
	Common bearberry	2.50	0
	Grasshopper sparrow	4.00	14.3
	Black-throated green warbler	2.00	0.51
SAPA	Marbled salamander	0	0
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb’s sedge	1.0	1.00
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	0	0
	Black-throated green warbler	0	0
CACL	Marbled salamander	0	0
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb’s sedge	0.6	0.64
	Highland rush	0	0

	Common bearberry	0	0
	Grasshopper sparrow	0	0
	Black-throated green warbler	0	0
EDIS	Marbled salamander	0.30	0.30
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb's sedge	1.1	1.14
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	0.45	0
	Black-throated green warbler	0.10	0
AFBG	Marbled salamander	0	0
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb's sedge	0.7	0.74
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	0	0
	Black-throated green warbler	0	0
VAFO	Marbled salamander	0.04	0.03
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb's sedge	0.8	0.90
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	0	0
	Black-throated green warbler	0	0
EDAL	Marbled salamander	1.00	1.00
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb's sedge	0.4	0.40
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	0	0
	Black-throated green warbler	0	0
BOAF	Marbled salamander	0	0.50
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb's sedge	1.0	1.34
	Highland rush	0	0

	Common bearberry	1.90	2.00
	Grasshopper sparrow	0	0
	Black-throated green warbler	0.44	0
ADAM	Marbled salamander	0	0.30
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb’s sedge	0.9	1.00
	Highland rush	0	0
	Common bearberry	1.13	1.34
	Grasshopper sparrow	0	0
	Black-throated green warbler	1.00	0
THST	Marbled salamander	1.10	0.83
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb’s sedge	0	0
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	0	0
	Black-throated green warbler	0	0
SAMA	Marbled salamander	0	0.20
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb’s sedge	0.7	0.74
	Highland rush	0	0
	Common bearberry	2.00	0
	Grasshopper sparrow	1.00	2.32
	Black-throated green warbler	0.14	0
BOWA	Marbled salamander	1.03	1.00
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb’s sedge	0.1	0.11
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	0	0
	Black-throated green warbler	0	0
FOST	Marbled salamander	0	0
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0.44
	Shrubby five-fingers	0	0
	Bebb’s sedge	0.8	0.90
	Highland rush	0	0

	Common bearberry	0	0
	Grasshopper sparrow	1.00	2.32
	Black-throated green warbler	0	0
THKO	Marbled salamander	0.80	0.60
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb's sedge	0.2	0.24
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	0	0
	Black-throated green warbler	0	0
APCO	Marbled salamander	2.00	1.33
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb's sedge	0.2	0.24
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	0	0
	Black-throated green warbler	0	0
MIMA	Marbled salamander	0	0.01
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb's sedge	1.1	1.20
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	1.94	0
	Black-throated green warbler	1.00	0
PETE	Marbled salamander	2.00	2.00
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb's sedge	0.9	1.00
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	0	0
	Black-throated green warbler	0	0
SAGA	Marbled salamander	0	0
	Jefferson salamander	4.54	0
	Blue-spotted salamander	1.91	1.20
	Shrubby five-fingers	0	0
	Bebb's sedge	0.01	0
	Highland rush	0	0

	Common bearberry	0	0
	Grasshopper sparrow	0.08	0.09
	Black-throated green warbler	0	0
JOFI	Marbled salamander	0	0.34
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb’s sedge	1.1	1.11
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	2.00	0
	Black-throated green warbler	1.0	0
ELRO	Marbled salamander	0	0
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb’s sedge	0.4	0.40
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	0.40	0.71
	Black-throated green warbler	0	0
FRHI	Marbled salamander	0.04	0.03
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb’s sedge	0.1	0.11
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	0.14	0
	Black-throated green warbler	0	0
THRB	Marbled salamander	0	0
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb’s sedge	0.7	0.81
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	0	0
	Black-throated green warbler	0	0
NEBE	Marbled salamander	0	0.24
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb’s sedge	0.7	0.81
	Highland rush	0	0

	Common bearberry	0.82	0
	Grasshopper sparrow	0.35	3.40
	Black-throated green warbler	1.00	0.40
SAHI	Marbled salamander	0	0
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb's sedge	0.4	0.40
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	0	0
	Black-throated green warbler	0	0
WORI	Marbled salamander	0	0
	Jefferson salamander	0.30	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb's sedge	2.1	2.12
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	2.50	0
	Black-throated green warbler	0	0
LONG	Marbled salamander	0	0.40
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb's sedge	1.1	1.14
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	1.84	0
	Black-throated green warbler	0.52	0
HOFU	Marbled salamander	0.20	0.20
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb's sedge	0.03	0.03
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	0.08	0
	Black-throated green warbler	0	0
SPAR	Marbled salamander	0	0
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb's sedge	1.2	1.22
	Highland rush	0	0

	Common bearberry	0	0
	Grasshopper sparrow	2.33	6.33
	Black-throated green warbler	0	0
MAWA	Marbled salamander	1.00	0.51
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb's sedge	0.2	0.20
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	0	0
	Black-throated green warbler	0	0
MORR	Marbled salamander	1.30	1.00
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb's sedge	1.2	1.20
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	0.33	0
	Black-throated green warbler	0.02	0
MAVA	Marbled salamander	0	0
	Jefferson salamander	10.0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb's sedge	0.6	0.70
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	0.50	0
	Black-throated green warbler	0.13	0
GOIS	Marbled salamander	0	0
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb's sedge	0.7	0.70
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	0	0
	Black-throated green warbler	0	0
JOFL	Marbled salamander	0	0
	Jefferson salamander	0.61	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb's sedge	0	0
	Highland rush	0	0

	Common bearberry	0	0
	Grasshopper sparrow	1.00	2.23
	Black-throated green warbler	0	0.12
FLNI	Marbled salamander	0	0
	Jefferson salamander	14.34	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb’s sedge	0	0
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	0.04	0.09
	Black-throated green warbler	0	1.26
MABI	Marbled salamander	0	0
	Jefferson salamander	0.40	0
	Blue-spotted salamander	7.51	5.14
	Shrubby five-fingers	0	0
	Bebb’s sedge	0.4	0.50
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	0.22	0.30
	Black-throated green warbler	0.24	1.10
EISE	Marbled salamander	0	0
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb’s sedge	0.06	0.06
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	0	0.18
	Black-throated green warbler	0	0
FONE	Marbled salamander	0.10	1.00
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb’s sedge	0.2	0.22
	Highland rush	0.20	0.12
	Common bearberry	0.04	0
	Grasshopper sparrow	0.45	0.35
	Black-throated green warbler	1.00	0.12
FEHA	Marbled salamander	0	0
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb’s sedge	0.7	0.70
	Highland rush	0	0

	Common bearberry	0	0
	Grasshopper sparrow	0	0
	Black-throated green warbler	0	0
FOMC	Marbled salamander	1.00	0.72
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb’s sedge	0.02	0.02
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	0	0
	Black-throated green warbler	0	0
SAIR	Marbled salamander	0	0.31
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb’s sedge	0.8	0.84
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	1.50	2.40
	Black-throated green warbler	1.00	0
ROWI	Marbled salamander	0	1.00
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb’s sedge	1.0	1.10
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	0.45	0
	Black-throated green warbler	0.71	0
ALPO	Marbled salamander	0.03	0.20
	Jefferson salamander	9.00	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb’s sedge	0.3	0.20
	Highland rush	0	0
	Common bearberry	0.30	0
	Grasshopper sparrow	1.27	0.80
	Black-throated green warbler	0.13	1.10
GETT	Marbled salamander	0	0
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb’s sedge	0.1	0.13
	Highland rush	0	0

	Common bearberry	0	0
	Grasshopper sparrow	0.02	4.01
	Black-throated green warbler	0	0
BOST	Marbled salamander	0	1.00
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb's sedge	1.4	1.40
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	3.00	4.73
	Black-throated green warbler	1.00	0
GEGR	Marbled salamander	0	0
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb's sedge	0.9	0.90
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	0	0
	Black-throated green warbler	0	0
RICH	Marbled salamander	11.0	7.00
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb's sedge	1.1	1.12
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	0	0
	Black-throated green warbler	0	0
FRST	Marbled salamander	3.00	2.00
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb's sedge	0.9	1.00
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	0	0
	Black-throated green warbler	0	0
PAGR	Marbled salamander	1.00	1.00
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb's sedge	1.2	1.24
	Highland rush	0	0

	Common bearberry	0	0
	Grasshopper sparrow	0.10	0
	Black-throated green warbler	0.01	0
WEFA	Marbled salamander	0.02	0.04
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb's sedge	0.3	0.33
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	0.18	0
	Black-throated green warbler	0.20	0
THRI	Marbled salamander	0	0
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb's sedge	0.9	0.90
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	2.00	0.30
	Black-throated green warbler	0.09	0
VAMA	Marbled salamander	0.01	0.01
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb's sedge	0.4	0.40
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	0	0
	Black-throated green warbler	0.04	0
GATE	Marbled salamander	0.40	1.50
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb's sedge	3.7	3.90
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	0.25	0
	Black-throated green warbler	1.01	0
UPDE	Marbled salamander	1.00	0.45
	Jefferson salamander	3.33	0
	Blue-spotted salamander	1.91	2.10
	Shrubby five-fingers	0	0
	Bebb's sedge	0.21	0.20
	Highland rush	0	0

	Common bearberry	0	0
	Grasshopper sparrow	2.10	2.00
	Black-throated green warbler	2.14	2.00
CACO	Marbled salamander	0	0
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb's sedge	0.6	0.63
	Highland rush	0	0
	Common bearberry	44.30	94.01
	Grasshopper sparrow	0.02	0.10
	Black-throated green warbler	0	0
SARA	Marbled salamander	0	0
	Jefferson salamander	3.93	0
	Blue-spotted salamander	5.10	4.60
	Shrubby five-fingers	0	0
	Bebb's sedge	1.3	1.62
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	0.21	0
	Black-throated green warbler	0	0
FRLA	Marbled salamander	0	0.24
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb's sedge	1.2	1.14
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	2.00	0
	Black-throated green warbler	1.00	0
GEWA	Marbled salamander	0.30	1.00
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb's sedge	0	0
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	0	0
	Black-throated green warbler	0	0
HAGR	Marbled salamander	0	0
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb's sedge	1.0	1.00
	Highland rush	0	0

	Common bearberry	0	0
	Grasshopper sparrow	0	0
	Black-throated green warbler	0	0
HAMP	Marbled salamander	0.32	0.23
	Jefferson salamander	0	0
	Blue-spotted salamander	0	0
	Shrubby five-fingers	0	0
	Bebb’s sedge	0.8	0.80
	Highland rush	0	0
	Common bearberry	0	0
	Grasshopper sparrow	0	0
	Black-throated green warbler	0	0

APPENDIX B

THE FIGURES

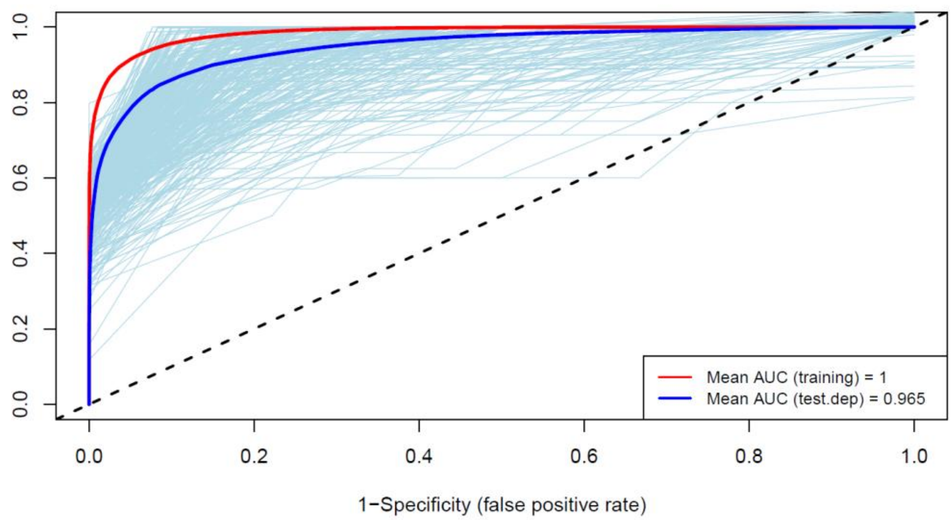

Figure 1: AUC/RUC for highland rush.

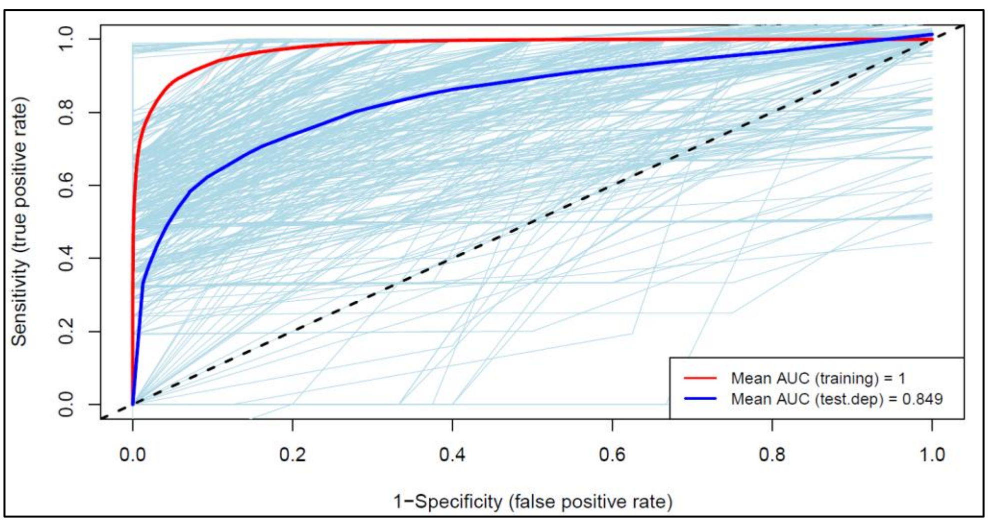

Figure 2: AUC/RUC for Bebb's sedge.

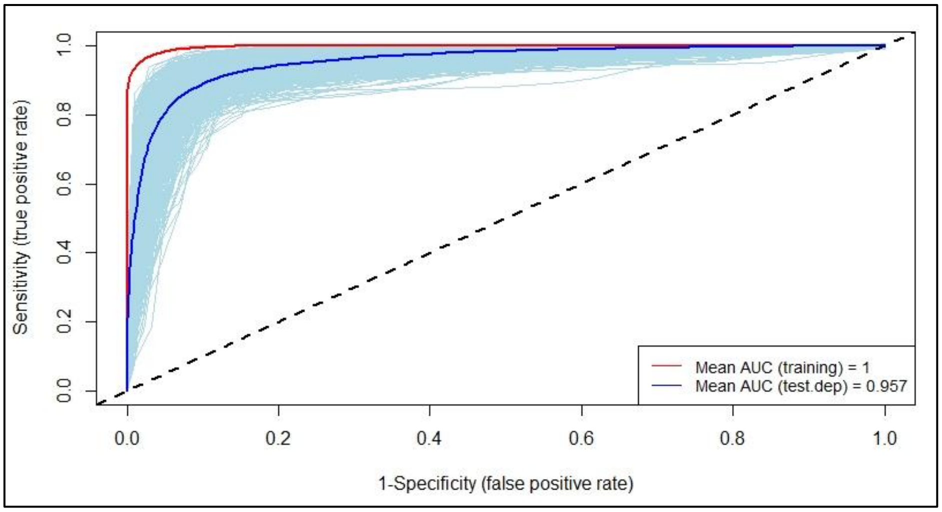

Figure 3: AUC/RUC for common bearberry.

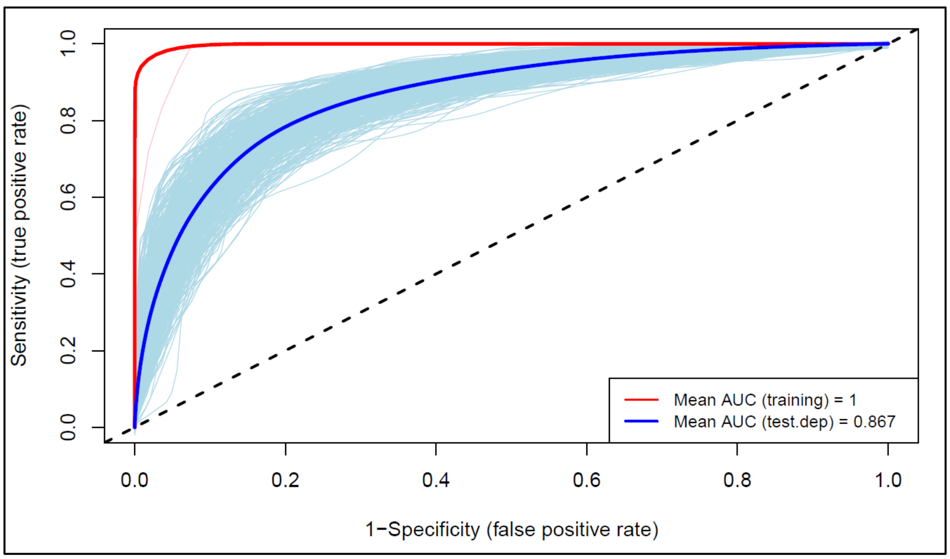

Figure 4: AUC/RUC for black-throated green warbler.

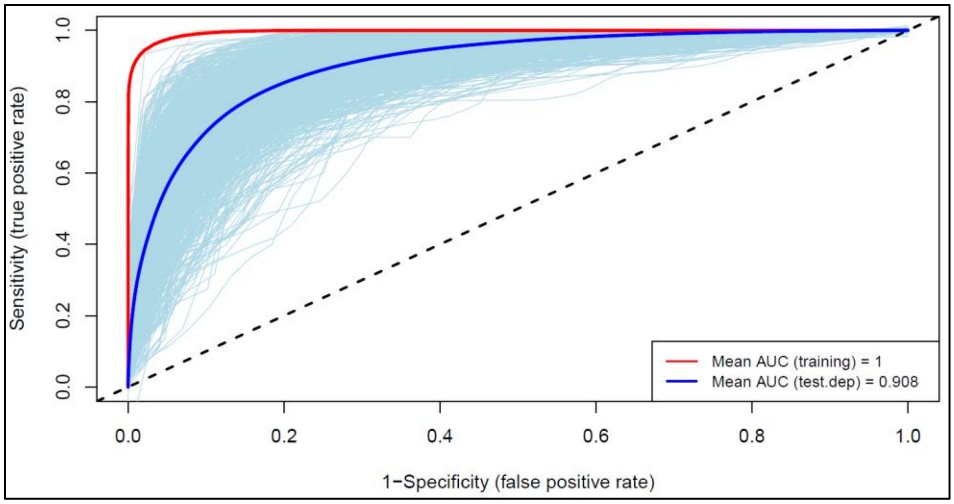

Figure 5: AUC/RUC for grasshopper sparrow.

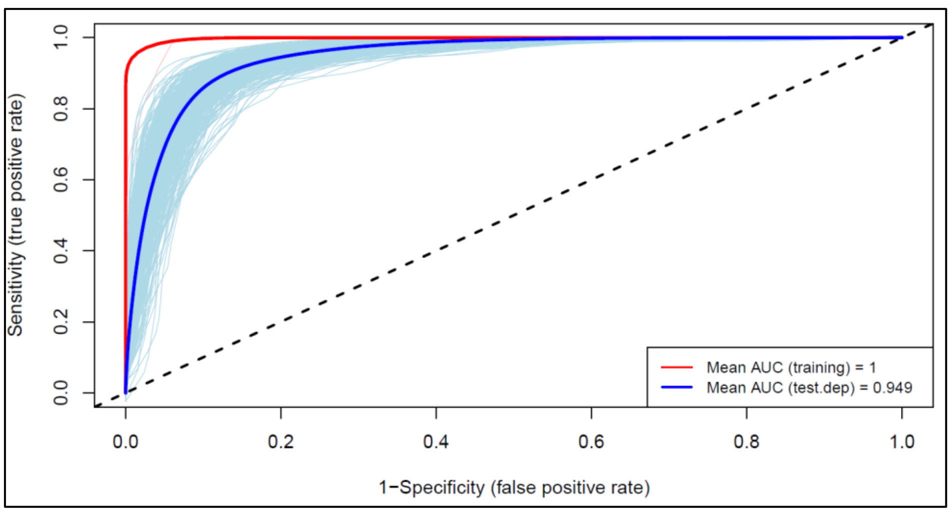

Figure 6: AUC/RUC for marbled salamander.

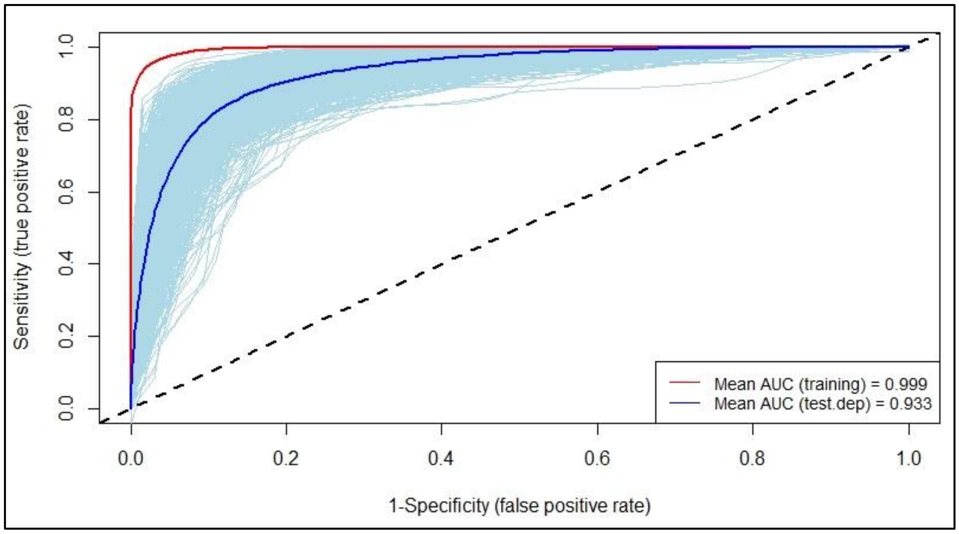

Figure 7: AUC/RUC for blue-spotted salamander.

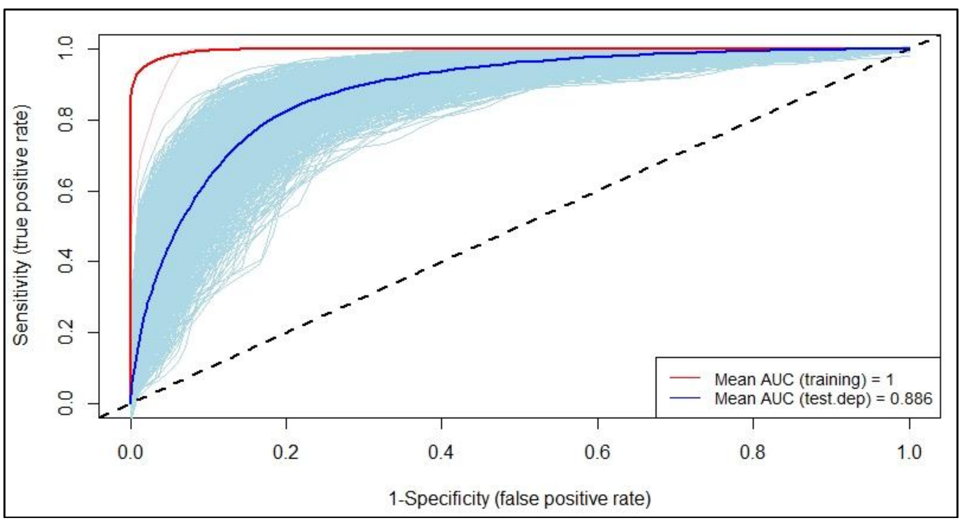

Figure 8: AUC/RUC for Jefferson salamander.

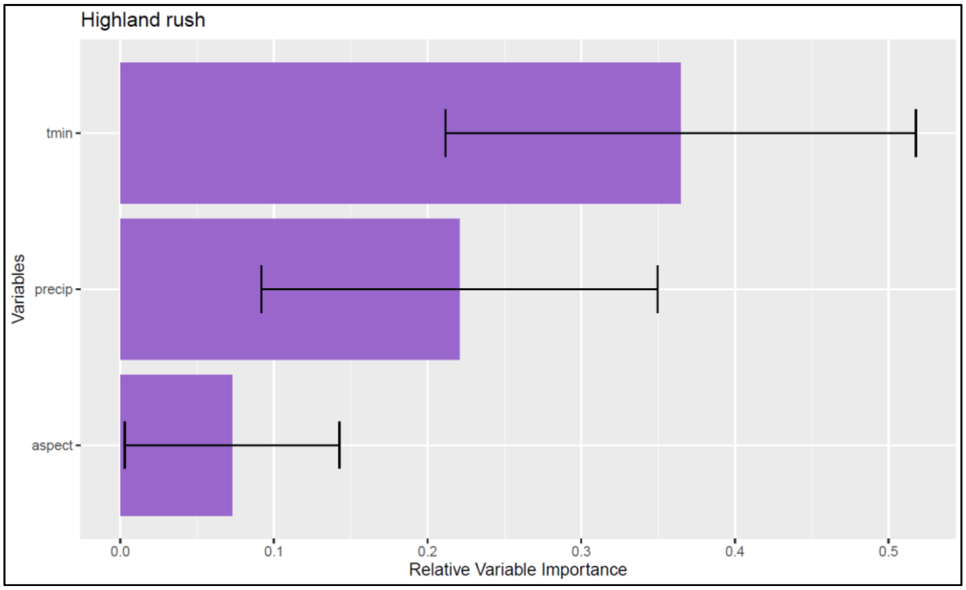

Figure 9: Relative variable importance for highland rush.

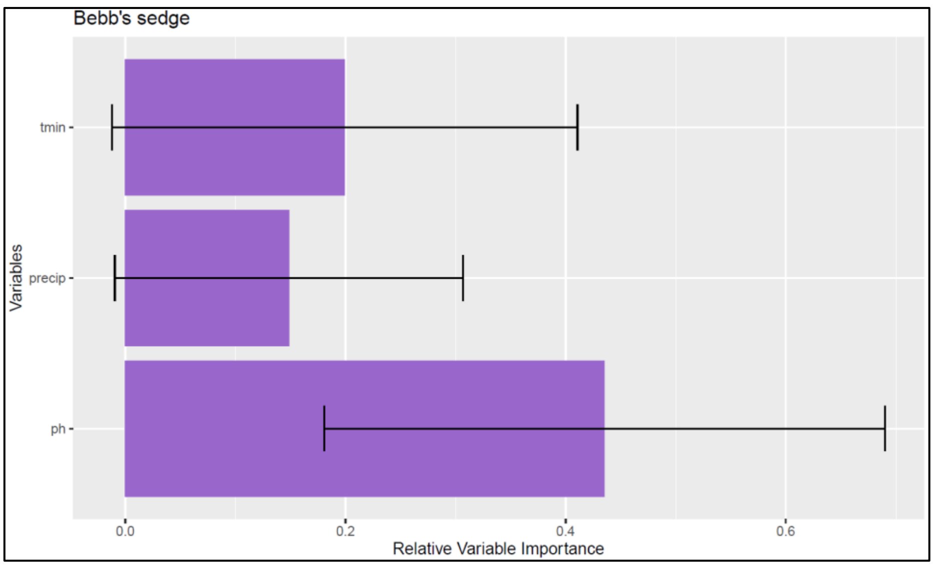

Figure 10: Relative variable importance for Bebb's sedge.

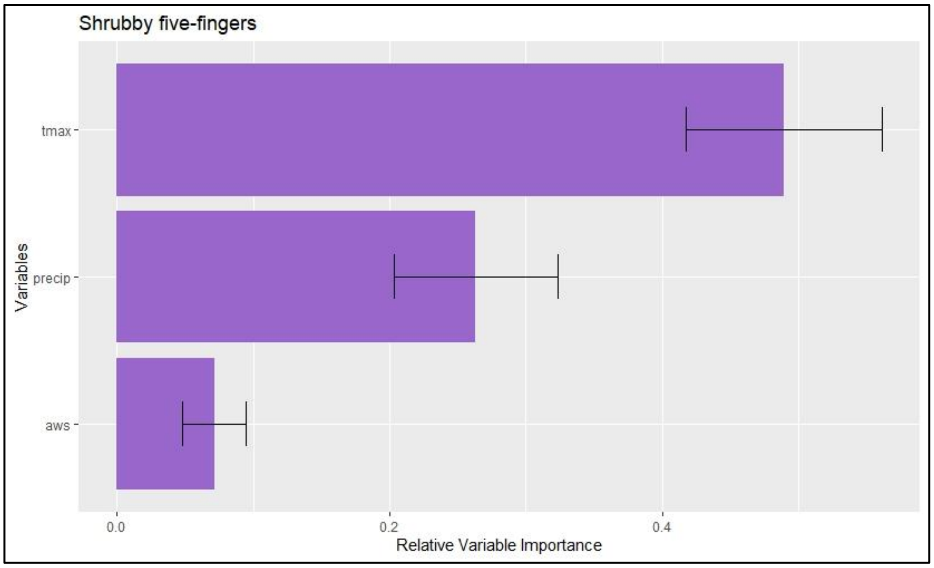

Figure 11: Relative variable importance for shrubby five-fingers.

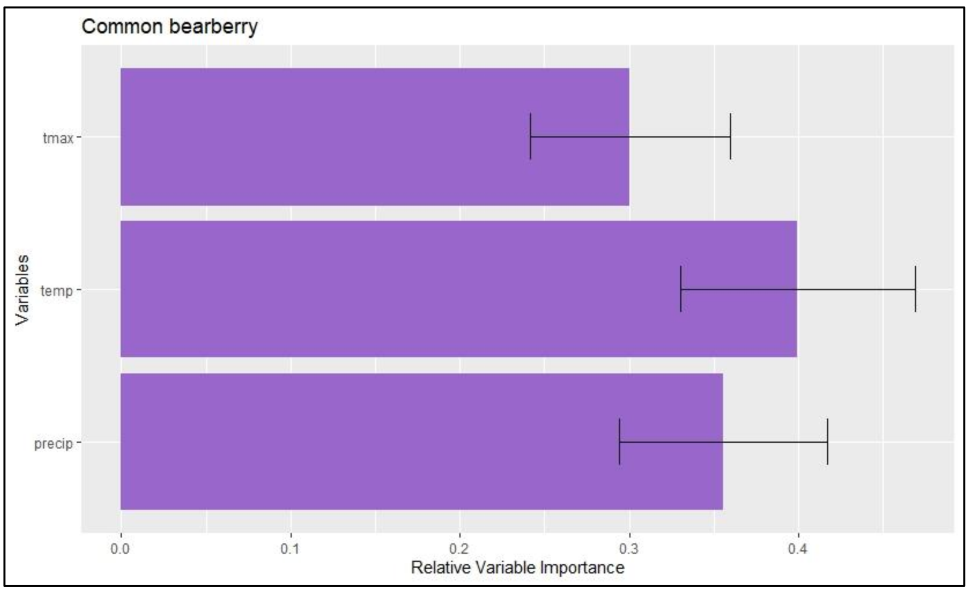

Figure 12: Relative variable importance for common bearberry.

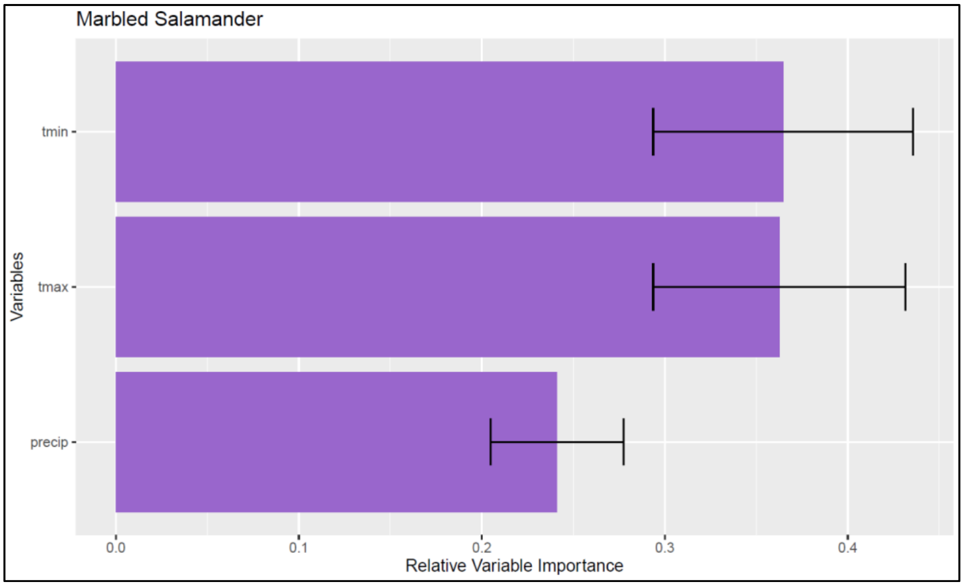

Figure 13: Relative variable importance for marbled salamander.

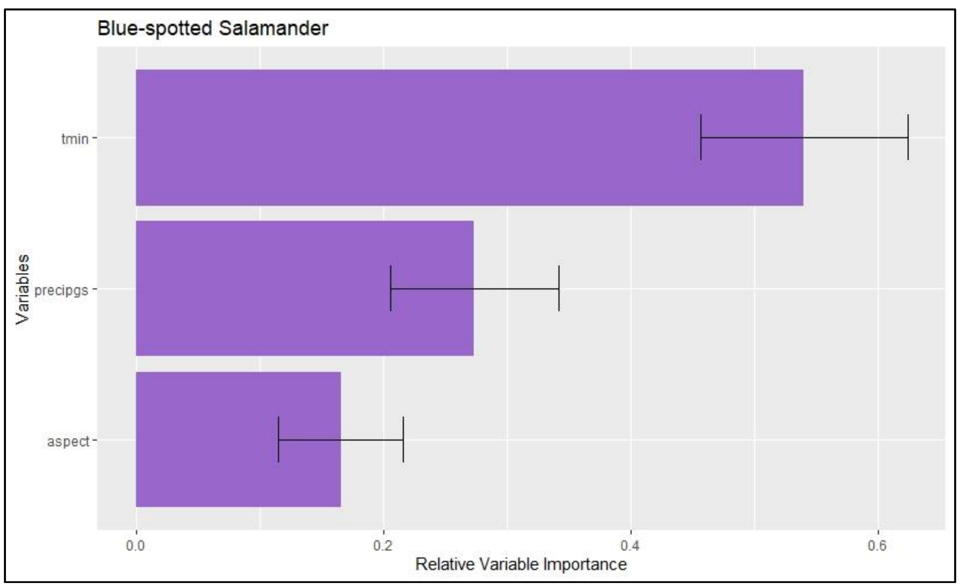

Figure 14: Relative variable importance for blue-spotted salamander.

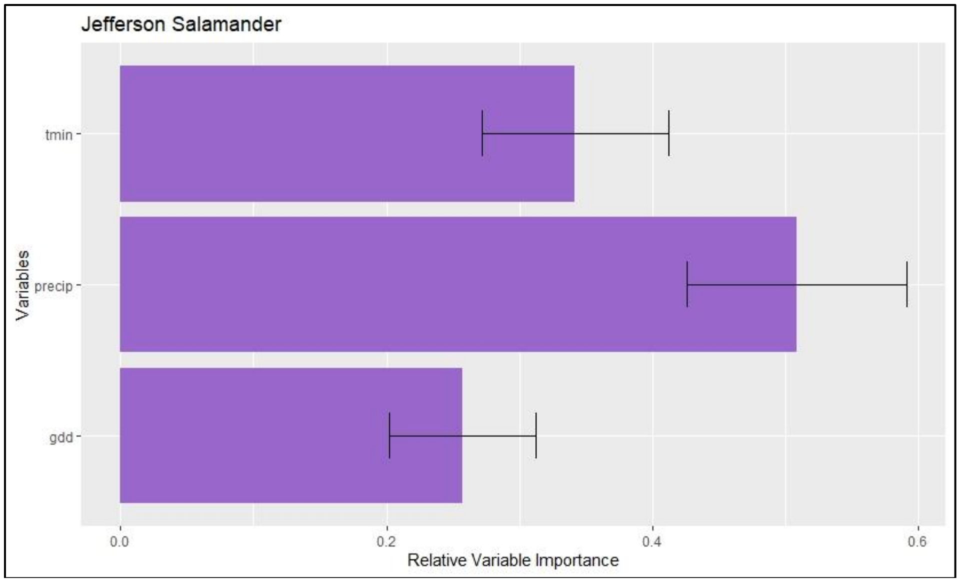

Figure 15: Relative variable importance for Jefferson salamander.

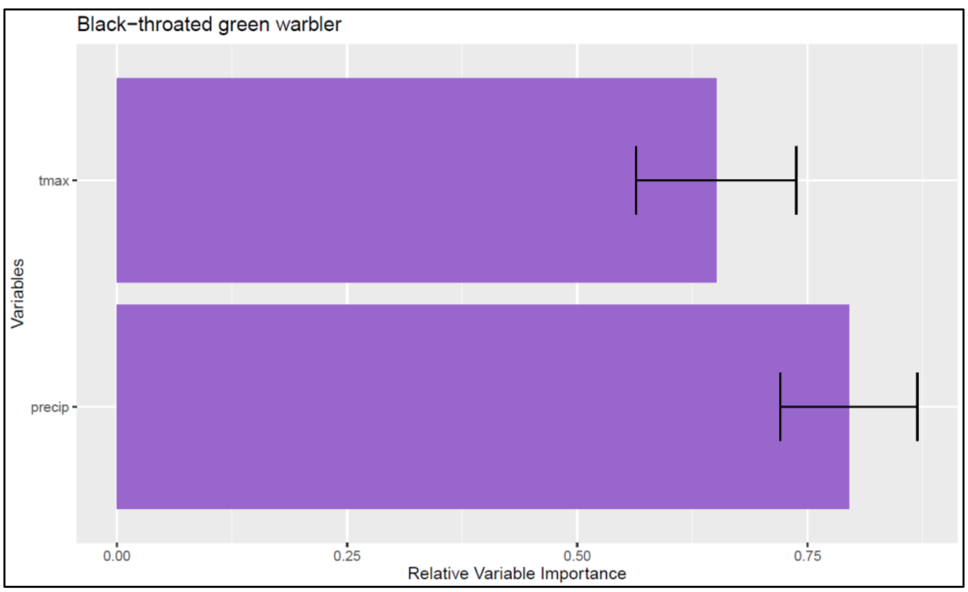

Figure 16: Relative variable importance for black-throated green warbler.

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