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# INCORPORATING CLIMATE CHANGE REFUGIA INTO CLIMATE ADAPTATION IN THE ACADIA NATIONAL PARK REGION

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## 1. Introduction

Climate change is predicted to have significant impacts on New England's biodiversity. If emissions continue unabated, mean global temperature is predicted to rise by 3-5 °C by the end of the century, and well beyond the range of natural variability (Rawlins et al. 2012, Collins et al. 2013). The northeastern US is predicted to experience rising sea levels (Horton et al. 2014), an increase in minimum winter temperatures (Sillmann et al. 2013), and an increase in the magnitude, frequency, and duration of heat waves, droughts, and extreme precipitation events (Meehl & Tebaldi 2004, Alexander et al. 2006, Walsh et al. 2014). Changes are already evident in Acadia National Park (ACAD). Between 1895 and 2010, total annual precipitation has significantly increased in ACAD by 16% and temperatures by 0.8 °C and the rate of temperature increase in the park is expected to be 3-6 times greater by 2100, particularly in inland portions (Gonzalez 2014). These climatic changes are expected to have dramatic and cascading effects on ecological systems through physiological stressors, mismatches in phenology, shifts in community composition, and exacerbation of existing stressors like fragmentation, and invasive species (Staudinger et al. 2015). Many species are already shifting to higher latitudes or altitudes (Staudinger et al. 2013) particularly at the edges of their range (Morelli et al. 2012).

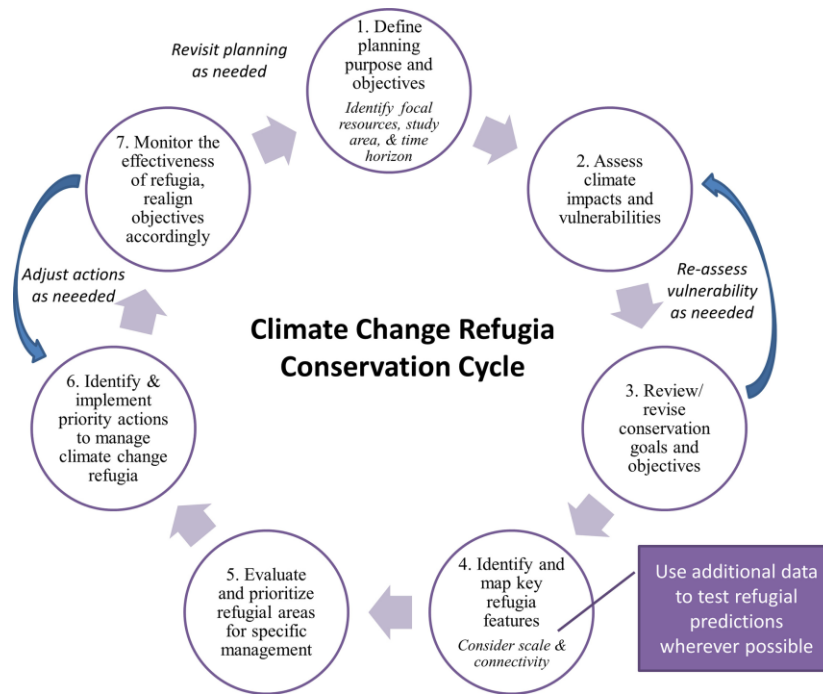
Identifying climate change refugia for representative species can provide valuable information for adapting to climate change (Morelli et al. 2016, Maher et al. 2017). Climate change refugia are areas relatively buffered from contemporary climate change over time that enable persistence of valued physical, ecological, and socio-cultural resources (Morelli et al. 2016). Many of the physical characteristics that tend to create climate change refugia through microclimatic gradients, such as high spatial heterogeneity in topography and habitat, proximity to large water bodies, and regular inland diffusion of coastal fog (Ashcroft 2010, Dobrowski 2011, Morelli et al. 2016) are present in ACAD. Using climate models to predict changes in the distribution of habitats and species has been identified as an important research priority for guiding management in ACAD (Roman and Babson 2013). However, to date, most models of future habitat suitability for ACAD park species have been conducted at coarse spatial scales, limiting the ability to identify localized climate change refugia (Fisichelli et al. 2014).

In this study, we leveraged fine-scale climate and land change mapping products developed through the North Atlantic Landscape Conservation Cooperative's Designing Sustainable Landscapes (DSL) project (McGarigal et al. 2017) to identify and prioritize climate change refugia for a suite of representative species found in ACAD and the surrounding region. This project is one of the first to pioneer the application of the climate change refugia conservation cycle (CCRCC; Morelli et al. 2016), a framework that was recently developed by the National Park Service (NPS), USDA Forest Service (USFS), and academic scientists. We used a knowledge coproduction approach (Meadow et al. 2015, Wall et al. 2017) throughout the project to engage stakeholders and partners from the NPS, the Schoodic Institute, Wild Acadia, Maine Natural History Observatory (MNHO), Maine Department of Inland Fisheries and Wildlife (IF&W), US Fish and Wildlife Service (USFWS), the Maine Department of Agriculture, Conservation, and Forestry, the Nature Conservancy, Blue Hill Heritage Trust, the Downeast Conservation Network, and partners from the Northeast Climate Science Adaptation Center's (NECASC) Refugia Research Coalition ([climaterefugia.org](http://climaterefugia.org)), to ensure that our work was effectively guided by and informing on-the-ground management.

## 2. Methods

### 2.1 Initial Stakeholder Meeting

Following the CCRCC (Fig. 1; step 1), Dr. Smetzer and Dr. Morelli met with ACAD and other relevant stakeholders in June of 2018 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 giving an overview of climate change refugia, and the fine-scale climate data available for the project. At the meeting the group discussed the spatial scale for presenting results, which habitats were most important to represent, and local opportunities to use the data products. The group identified a broad list of focal species for the project. Important considerations included identifying species 1) that are near but not at the southern edge or half of their range in Maine, 2) that are good indicators for specific focal habitats about which the stakeholders are concerned, 3) that represent valuable socio-cultural resources for visitors, 4) for which our work could nicely complement existing research in the region, and 5) for which adequate occurrence data are available.



**Figure 1.** Climate change refugia conservation cycle (Morelli et al. 2016)

We drew upon existing climate change vulnerability assessments for ACAD, Maine, and other northeastern states and the expertise of stakeholders to help focus the discussion on species vulnerable to climate change and of high conservation need (Fig. 1; step 2). This meeting resulted in a wide list of potential species for modeling. To finalize the candidate species list, we considered the priority/ranks given to each species by the group, the climate change vulnerability of each species, where Maine is in the species' geographic range, availability of environmental predictors, and availability of occurrence data. We also tried to ensure we represented multiple habitats, and taxa (Table 1).

## 2.2 Ecological Modeling

Distribution models had already been developed for a number of the species identified by the group (Table 1). We developed statistical models to identify climate change refugia for the remainder of the species. We developed models based on observational data from within the Humid Temperate Domain (Bailey et al. 1994). This restriction helped to minimize model commission errors by avoiding situations in which relatively similar but spatially distant climate conditions are included in models as both suitable—based on presence locations and unsuitable—based on absences (Lobo et al. 2010). The extent of the Humid Temperate Domain provides enough geographic range to contain locations where individuals are absent due to unfavorable climatic conditions, while also including climate variation beyond what is currently found in Maine, to represent climate conditions that are likely to occur in the region over the next century or so.

### 2.2.1 Presence-only species data

We gathered occurrence data for the three woody shrubs, northern flying squirrel, and mink frog using iNaturalist, the EPA's National Aquatic Resource Surveys, and Nature's Phenology Notebook, and GBIF (GBIF.org 2019). These data sources are all presence-only data; no data points with recorded absences for the species are available. We only included human observations with a spatial accuracy of at least 800m, the resolution of the climate data before statistical downscaling. We overlaid the study area with 1km grids, and randomly sampled one observation from each grid to minimize spatial bias in the sampling. We generated 5000 random background points for each species within the spatial extent of the observation points, because a random sampling of background points within the extent of the presence data, and a large ratio of background to presence points is recommended for generalized linear models based on presence-only data (Massin-Barbet et al. 2012). We used the pairwise distance sampling method of Hijmans (2012) to eliminate spatial sorting bias which can lead to spurious conclusions during model evaluation for presence-only data (Galante et al. 2018). This process resulted in 86 presence points for Three-toothed cinquefoil, 306 for Labrador Tea, 37 for Black crowberry, 41 for Mink Frog, and 36 for Northern Flying Squirrel.

### 2.2.2 Presence-absence species data

We gathered eBird bird occurrence data (Johnston et al. 2019; Sullivan et al., 2014) from 2000-2018 for American Bittern, Black-throated Green Warbler, Chestnut-sided Warbler, and Olive-sided Flycatcher. We limited the analysis to complete checklists to provide both presence and absence data for each species (Fink et al. 2010), and data from June to restrict our analysis to the breeding season. To standardize the surveys in terms of effort, we restricted the analysis to data from "stationary" or "traveling" protocols conducted during daylight hours, with a maximum of three hour search time, and with a maximum of ten observers (Fink et al. 2010). We used only traveling protocols of 1km or less, to match the spatial resolution of the climate data, and to minimize error in the reported location of the checklist data (Johnston et al. 2019).

Spatial and temporal bias are a potential problem with eBird data, because sampling is typically non-random. For instance, birders may sample more densely near urban or populated areas, and near popular birding areas. To address spatial and temporal bias, we overlaid the study area with 5km grids, and randomly sampled one checklist from each grid within each week (Johnston et al.

2019). There are typically significantly more non-detections than detections in eBird data, leading to class bias. To help minimize this class imbalance, we sampled detections and non-detections separately in the grid sampling, but retained all detection checklists for American Bittern and Olive-sided Flycatcher, as these species were relatively rare in the eBird data. In addition, for the eBird data, we used only a random subset of the absence data for each species in models, to balance the number of observations from each response class. This helps to reduce class bias, and leads to improved model performance in logistic regression models based on presence-absence data (Salas-Eljatiba et al. 2018). This process resulted in 778 presence records for American Bittern, 4,640 for Black-Throated Green Warblers, 5,723 for Chestnut-sided Warblers, 2,005 for Magnolia Warblers, and 303 for Olive-sided Flycatcher.

### **2.2.3 Environmental predictors**

We used climate data derived by the UMass Designing Sustainable Landscapes (DSL) project and the Northeast Climate Adaptation Science Center (CASC) using data from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 5 multi-model dataset, and the 800m resolution Parameter-elevation Relationships on Independent Slopes Model (PRISM) dataset developed by Oregon State University (McGarigal et al. 2017). The PRISM dataset incorporates many of the physiographic factors that can influence climate (Daly et al. 2008), and subsequently lead to climate change refugia such as elevation, coastal proximity, aspect, topographic position, and orographic effects. We used six climate variables at 800m resolution representing 30-year normals averaged across 1981-2010 to develop species distribution models: mean annual temperature, minimum winter temperature, maximum summer temperature, growing degree days, total annual precipitation and growing season precipitation. We used the same predicted climate variables for 2080 under standard Representative Concentration Pathways (RCP) 4.5 and 8.5, with the data statistically downscaled to 30m resolution by bilinear interpolation (McGarigal et al. 2017).

We included 30m resolution elevation and canopy cover data in the models for all species, to represent potential sources of climate change refugia that might occur at a finer scale than was encapsulated in the PRISM data. We retrieved 30m resolution elevation data from the National Elevation Dataset (<https://nationalmap.gov/elevation.html>) compiled for the coterminous United States by the Landfire program (<https://www.landfire.gov/elevation.php>). We obtained 30m resolution percent canopy cover from the USGS 2011 National Land Cover Database (NLCD; Homer et al. 2015). We used the 30m resolution U.S. 2011 National Land Cover Database (Wickham et al. 2018) to describe land cover. We summarized percent cover of the land classifications in rectangular buffers of 150m around each point (5 x 5 cell neighborhood) as this spatial scale has been apt for many avian species in prior analyses of distribution (Fink et al. 2010).

We included a unique suite of environmental predictors for each species we modeled (Table 2) based on the ecology of the species, input from stakeholders, and a literature review (Appendix A). We extracted a suite of environmental predictors relevant to plant species from the Natural Resources Conservation Service soil surveys (Natural Resources Conservation Service 2018), including soil pH, depth to a resistant layer (e.g. bedrock), soil organic matter, depth to water table, soil drainage, and available water supply (the total volume of water available to plants when the soil is at field capacity).



#### **2.2.4 Statistical Models**

We used generalized linear models with a logit link (logistic regression) to model the relationship between occupancy and the predictor variables. This method is particularly apt for presence-only data because model accuracy is less influenced by the choice of pseudo-absence points than machine-learning approaches, particularly at low sample sizes (Massin-Barbet et al. 2012). We used 80% of the data to fit the models, and 20% to test the models; however, for species with low sample sizes we trained the model with 75% of the observation to ensure enough detections for model evaluation. We tested whether the elevation data were collinear with the climate variables, as these were already incorporated at a broader spatial scale in the PRISM data, but collinearity was not problematic. There was high collinearity within the temperature variables and the precipitation variables. We calculated the variance inflation factor for models run on all two- and three-level subsets of climate variables to identify any possible combinations that could be considered together in models. For each species, we subsequently used forwards and backwards stepwise selection on a suite of global models, each of which contained a possible grouping of climate variables, and germane environmental predictors (Table 2). We also included a suite of effort covariates in models based on eBird data: the time a survey began, duration of surveys, number of observers, and distance travelled (Johnston et al. 2018). We used Akaike's Information Criteria (AIC) to compare the resulting models (Lawson et al. 2014; Galante et al. 2018).

#### **2.2.5 Model evaluation**

We assessed model calibration (i.e. agreement in the proportion of occupied sites in the observations and predictions) with calibration plots (Phillips and Elith 2010) using the *sdm* package (Naimi and Araujo 2016), and followed the methods of Johnston et al. (2019) if models required calibration. We used the holdout testing data to develop receiver-operator curves (ROC) for each species and identify the binary transformation threshold that maximized the sum of sensitivity and specificity (Liu et al. 2016). We calculated a suite of performance metrics for each species using the *PresenceAbsence* package (Freeman and Moisen 2008) including mean squared error (MSE), area under the ROC curve (AUC), the true skill statistic (TSS), Cohen's Kappa, overall accuracy (OA), sensitivity or true-positive rate (TP), and specificity or true-negative rate (TN).

#### **2.2.6 Mapping climate change refugia**

We developed a suite of mapping products to represent climate change impacts and potential refugia across Maine. We used the "best" models – as determined by AIC – to predict current probability of occurrence across Maine for each species. For the bird species, we also included effort variables in predictions, predicting for a single observer, completing a 0.5 km travelling survey for one hour, at 6am. We used the same models and current habitat values to predict occurrence in 2080 under RCP 4.5 and RCP 8.5. In mapping current and future probability of occupancy, we masked out all developed sites and open water for all species except American Bittern and Mink Frog, using 30m resolution landcover data from the UMass Amherst DSL project. For American Bittern we only predicted on freshwater wetlands, and for Mink Frog we only predicted on open freshwater habitats, including wetlands. For each modeled species we also calculated and mapped the percent change in probability of occupancy for each cell across the landscape under RCP 4.5 and RCP 8.5.

Finally, we developed interactive web tools to help visualize potential climate change refugia for each species (<<http://rpubs.com/jsmetzer/496972>>). Climate change refugia are locations where current and future probability of occupancy overlap; however, the probability threshold for calling a cell “occupied” could vary from species to species or from individual to individual based on management goals. The interactive web tools therefore show future probability of occupancy, but allow users to only display locations that are above a user-defined current probability of occupancy. We set each interactive map to open with a display that only shows locations that are in the upper quantile of current probability of occupancy values.

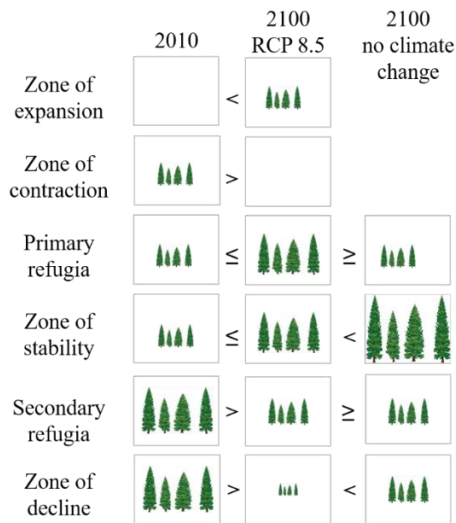
We calculated a suite of occupancy and change metrics for each of the species we modeled. First, we calculated the percent of occupied cells in all of Maine in 2010, and 2080. This statistic represent a metric of relative rarity, as this calculation included all locations in Maine regardless of habitat value. For instance, developed areas and open water bodies were included in this metric for all species, regardless of whether the species is terrestrial or aquatic. For each species, we also calculated the percent change in probability of occupancy for each cell across the landscape, and averaged this percent change across all of Maine. This metric represents how severely the climate change predictions impacted the species on average across all of Maine. Finally we applied a binary threshold to each species’ current probability of occupancy map to represent each cell as occupied or unoccupied, based on the probability of occupancy for each species that maximized the sum of true positive and true negative rate for testing data. We used this to calculate the change in the number of cells **occupied** by the species from 2010 to 2080, to estimate loss of potentially viable habitat. All statistical analyses, data visualization and mapping for all species were performed in the R statistical software environment version 3.6.0 (R Core Team 2019).

### 2.3 Tree Climate Change Refugia

We developed maps of potential climate change refugia using data products developed by Duveneck and Thompson (2017). The input data were 250m resolution estimates of above-ground biomass ( $\text{g/m}^2$ ) for each tree species across the landscape, based on simulation models that incorporate forest dynamics, forest ecosystem processes, and climate variation. We used three primary data sources from Duveneck and Thompson (2017) – 1) estimates of above-ground biomass in 2010, 2) estimates of above-ground biomass for 2100 under a continuation of recent climate conditions, and 3) estimates of above-ground biomass for 2100 under representative concentration pathway (RCP 8.5). We specifically used 2100 estimates based on two global circulation models, the Hadley Global Environment Model v2-Earth System (HADGE) model, and the Community Climate System Model v4.0 (CCSM4) global circulation model. The former represents a best-case tree growth scenario, and the latter a worst-case scenario. All estimates for 2100 include simulated changes due to forest dynamics and succession.

We used these data to classify locations into six mutually-exclusive zones for the tree species (Fig. 2) . We classified any locations at which a species was predicted to occur in 2100 under RCP 8.5, but not predicted to occur in 2010 as a potential **zone of expansion**, and identified any locations at which the opposite was predicted to occur as a potential **zone of contraction**. We categorized any locations where a species’ (non-zero) above-ground biomass in 2100 under RCP

8.5 was expected to be greater than or equal to both 2010 values and 2100 values under simulations with no climate change as **primary climate change refugia**. We also identified **secondary refugia** – locations where a species’ above-ground biomass was expected to decrease by 2100 under RCP 8.5, compared to 2010, but is estimated to be greater than or equal to the 2100 predictions under simulations with no climate change. This category recognizes locations at which the species may decline due to forest dynamics, but at which micro-climactic factors may buffer the species from climate change. We classified locations with greater increases by 2100 under no climate change compared to RCP 8.5 as potential **zones of stability**. These represent areas that may not be buffered from climate change per se, but may experience an increase or at least no change in biomass for the species regardless, due to forest dynamics. Finally, we identified potential **zones of decline** – locations at which a species’ above-ground biomass in 2100 under RCP 8.5 is non-zero, but is less than that predicted for 2010, and for 2100 under a continuation of climate conditions. This category recognizes locations at which the species is expected to decline, but will not be absent by 2100.



**Figure 2.** Zonal categories for tree species. Forest dynamics are simulated in both future scenarios, so “2100 no climate change” represents forest change through succession and community dynamics, “2100 RCP 8.5” represents forest change through succession and community dynamics, as well as climate impacts. The difference between 2100 no climate change and 2100 RCP 8.5 represents the isolated effects of climate change.

We developed a suite of mapping products, and change metrics for each tree species. We generated maps displaying above ground biomass within climate change refugia for each species, under both the Hadley and CCSM4 global circulation models. We displayed these in interactive maps, on which a user can show only cells that contain a user-defined minimum value for above-ground biomass. For each species, we generated maps showing the change in biomass across all cells from 2010 to 2100 under both the Hadley and CCSM4 global circulation models. To summarize the condition of each species across Maine, we calculated the percent of cells in each zonal category for each species, and calculated the average change in biomass across all the cells from 2010 to 2100.

## 2.4 Climate Change Refugia from Designing Sustainable Landscapes Project

We made interactive maps using climate change refugia data products developed by the UMass Designing Sustainable Landscapes project. This project modeled species’ prevalence, climate niche, and habitat niche separately (McGarigal et al. 2016). They used logistic regression to

build **climate niche** models, with data from eBird, Breeding Bird Surveys, etc. (Table 1), and the climate data described earlier. They used the program HABIT@ to build a spatially explicit GIS model of current **habitat capability**, with specification of habitat needs dictated by expert opinion and literature review. This GIS model also incorporated land-use change in terms of urban growth to simulate habitat capability in 2080. They also used presence data to build a **prevalence** model that predicts occurrence solely on spatial distribution, and thus can capture biogeographic factors like interspecific interactions and disease that can influence species' distributions. These three metrics are multiplied for each species to determine **landscape capability**, a composite metric of relative probability of occurrence based on habitat, climate and other biogeographic factors. Landscape capability ranges from 0 – or no habitat – to 1, the best habitat and climate conditions in the Northeastern US. These results were used to map **climate change refugia** – places where a species' current and future climate niche overlaps. The web applications displays the location of these climate change refugia, displaying the landscape capability value for each cell in 2080. Importantly, 2080 landscape capability includes averaged results from thousands of simulations under an urban growth model.

## 2.5 Second Stakeholder Meeting

We met with a group of eighteen stakeholders a second time to present and discuss the data products, and to work as a group to identify opportunities to apply the results into ongoing work locally. Before the meeting we derived a list of questions to help guide and structure discussions, and generated posters displaying ecological and climate relationships for each species. We sent the online interactive maps to participants before the meeting, and had these online resources, and overview paper maps available for participants to peruse during the meeting. In addition, before the meeting, we asked participants if they had a specific project in mind for which they might be able to use some of the climate change refugia results. We told participants to alert us if they wanted to work in small breakout groups to discuss how to apply the climate change refugia results to these projects at the meeting. We received four project descriptions, and made paper maps of the germane species covering each projects' geographic location.

During this meeting we reviewed the modeling process and how to interpret the various derived data products. We encouraged questions throughout, particularly given the three different data streams. We gave participants time to explore the data products and posters in pairs, then came back together as a group to discuss any remaining questions or concerns about the results, and any opportunity to address these concerns by validating results with local data. We next facilitated a discussion with a series of guided questions. Our 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 specifically asked participants to:

1. **Individually:** write down three activities you already do in your day to day work that could impact the focal species and their habitats.
2. **Discuss in small groups:** what are some concrete ways that the climate change refugia results might inform or change the way that you approach the regular day to day management and conservation actions you already do....i.e. the tasks you just listed?

- a. **Follow up to the broader group:** at what scale were you thinking about using the results?
- b. **Follow up to the broader group:** We have a lot of different organizations in the room – what opportunities are there to work across organizations?
- c. **Follow up to the broader group:** What do you see as some of the main barriers to using these climate change refugia results to inform your work?

We asked participants to share their ideas out after each question, and had note takers record all the responses. The purpose of the first question was to help people think about what they already do in their day to day work. Our motivation in this question was to help identify and highlight ways that these data products can be incorporated into **existing activities and responsibilities** – to frame climate change refugia as a tool for refining existing work, rather than as an additional task or responsibility. We asked people to share their responses with the larger group, and wrote down the list of activities for all to see. The second question asked people to identify concrete ways that the activities listed could be modified, refined, changed, or otherwise informed by the climate change refugia project. We asked participants to work in small groups on this, to help facilitate everyone having a chance to speak and participate, to give people a chance to gather their thoughts in a lower-stakes environment before sharing to the broader group, and to give an opportunity for managers with different perspectives and roles to discuss applications. The moderator and note takers moved from one small group to the next, listening in, and taking notes. The groups were then asked to share out. As the larger group discussed the ideas that were shared, we asked the follow-up questions to help facilitate and guide the wider-group discussion.

In the afternoon, we had the four participants that identified applied projects serve as facilitators for the breakout groups. Each facilitator led a small group discussion about how they could incorporate the climate change refugia results into their respective projects. This structure – similar to a respondent moderator focus group (Kamberelis and Dimitriadis 2005) – is thought to increase the variety and honesty of responses, and improve group dynamics (Nyumba et al. 2017). Our goals here were to:

1. provide the project leaders with an opportunity to workshop and discuss how to apply the climate change refugia results with a diverse body of managers, with varying perspectives and expertise
2. give all participants the experience of thinking through how to apply climate change refugia to a specific project, to facilitate their ability to lead a discussion within their home organizations
3. to help participants identify what additional information, materials, or spatial data layers would be useful to have ready while discussing application of climate change refugia with their colleagues
4. give the facilitator ideas about how information can be synthesized and presented more effectively to stakeholders in the future

Each project leader gave a short overview of their projects to the rest of the participants who subsequently self-selected to work with the various project leaders. The facilitator and note takers again circulated through the groups, taking notes. We ended by re-convening the groups and asking people to share out about what went well and what did not in their process and approach. We asked the groups to identify any additional information that would help them in

applying the climate change refugia to their respective projects, and asked them to share any insights or outcomes that resulted from the process. After the meeting ended we sent a survey to the participants asking them to rate their experience, to provide feedback on the meeting, and how likely they are to actually use any of the data products moving forward.

### 3. Results

#### 3.1 Statistical Models

Model performance was excellent for Three-toothed Cinquefoil and Black Crowberry, and strong for all other species except Mink Frog Northern Flying Squirrel (Table 3). The Kappa statistic was low for Mink Frog and Northern Flying Squirrel; however, 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 AUC was  $> 0.5$  for all species, and  $> 0.8$  for all species except Mink Frog and Northern Flying Squirrel. Similarly the TSS was  $> 0.6$  for all species except Mink Frog and Northern Flying Squirrel.

Temperature variables were important for every species, particularly growing degree days and minimum winter temperatures (Table 2). Labrador Tea ( $\beta = -0.00005$ ;  $p < 0.001$ ), Black-throated Green Warbler ( $\beta = -0.00004$ ;  $p < 0.001$ ), Chestnut-sided Warbler ( $\beta = -0.00004$ ;  $p < 0.001$ ) and Magnolia Warbler occurrence ( $\beta = -0.00005$ ;  $p < 0.001$ ) were inversely related to growing degree days, while Three-toothed Cinquefoil showed a positive relationship ( $\beta = 0.00003$ ;  $p = 0.04$ ). Mink Frog ( $\beta = -0.005$ ;  $p < 0.001$ ), American Bittern ( $\beta = -0.004$ ;  $p < 0.001$ ), Olive-sided Flycatcher ( $\beta = -0.002$ ;  $p < 0.001$ ), and Chestnut-sided Warbler occupancy ( $\beta = -0.001$ ;  $p < 0.001$ ) were predicted to decrease at higher winter temperatures, but Black-throated Green Warblers showed the opposite relationship ( $\beta = 0.006$ ;  $p = 0.005$ ). Occurrence of Three-toothed Cinquefoil ( $\beta = -0.017$ ;  $p < 0.001$ ), Black Crowberry ( $\beta = -0.011$ ;  $p < 0.001$ ), Olive-sided Flycatcher ( $\beta = -0.002$ ;  $p = 0.01$ ), and Northern Flying Squirrel ( $\beta = -0.002$ ;  $p = 0.09$ ), were all negatively related to maximum summer temperatures.

Precipitation variables were important for seven out of ten species, with all but one species showing a positive relationship with precipitation (Table 2). Labrador Tea ( $\beta = 0.00002$ ;  $p < 0.001$ ), Mink Frog ( $\beta = 0.00006$ ;  $p < 0.001$ ), Black-throated Green Warbler ( $\beta = 0.00002$ ;  $p < 0.001$ ), and Northern Flying Squirrel occupancy ( $\beta = 0.00003$ ;  $p = 0.003$ ) were all positively influenced by annual precipitation, and Chestnut-sided Warbler occurrence was positively related to growing season precipitation ( $\beta = 0.00002$ ;  $p < 0.001$ ). In contrast, American Bittern occupancy was inversely related to growing season precipitation ( $\beta = -0.00001$ ;  $p = 0.03$ ).

The model results were intuitive in regards to the ecological relationships for each species (Fig 3). Tree-toothed Cinquefoil occurrence was greatest at higher elevations ( $\beta = 0.002$ ;  $p < 0.001$ ), in areas with low canopy cover ( $\beta = -0.035$ ;  $p < 0.001$ ), in dry soils ( $\beta = -0.081$ ;  $p < 0.001$ ) with high organic content ( $\beta = 0.01$ ;  $p = 0.01$ ). Black Crowberry was most common at lower elevation sites ( $\beta = -0.0052$ ;  $p = 0.01$ ) with low canopy cover ( $\beta = -0.03$ ;  $p < 0.001$ ), on dry soils ( $\beta = -0.546$ ;  $p = 0.03$ ), with low pH ( $\beta = -2.084$ ;  $p = 0.05$ ), and high organic content ( $\beta = 0.051$ ;  $p = 0.06$ ). Labrador Tea occupancy was greatest in low-elevation sites ( $\beta = -0.001$ ;  $p = 0.05=4$ ), with low canopy cover ( $\beta = -0.011$ ;  $p < 0.001$ ), and on very well-drained soils, where the water table was shallow ( $\beta = -0.023$ ;  $p = 0.04$ ).

Mink Frog occurrence was greatest where canopy cover was low, presumably reflecting its aquatic preferences ( $\beta = -0.036$ ;  $p < 0.001$ ). Northern flying squirrels were positively associated with percent cover of conifers ( $\beta = 1.778$ ;  $p = 0.003$ ). American Bittern occupancy was greatest at lower elevation sites ( $\beta = -0.001$ ;  $p = 0.003$ ) with low canopy cover ( $\beta = -0.023$ ;  $p < 0.001$ ), and high cover of woody wetlands ( $\beta = 3.163$ ;  $p < 0.001$ ), emergent wetlands ( $\beta = 3.708$ ;  $p < 0.001$ ), and open water ( $\beta = 1.460$ ;  $p < 0.001$ ). Black-throated Green Warbler was most commonly predicted as sites with high canopy cover ( $\beta = 1.422$ ;  $p < 0.001$ ), and was positively associated with deciduous ( $\beta = 1.164$ ;  $p < 0.001$ ), coniferous ( $\beta = 1.500$ ;  $p < 0.001$ ), and mixed forests ( $\beta = 1.916$ ;  $p < 0.001$ ). Chestnut-sided Warblers were more common at higher elevation sites ( $\beta = 1.679$ ;  $p = 0.08$ ), and in areas with high percent cover of hardwood ( $\beta = 1.370$ ;  $p < 0.001$ ) and mixed forests ( $\beta = 4.471$ ;  $p = 0.03$ ). Magnolia Warbler occurrence was positively related to high canopy cover ( $\beta = 1.370$ ;  $p < 0.001$ ), and coniferous ( $\beta = 1.148$ ;  $p = 0.001$ ) and mixed forest ( $\beta = 1.055$ ;  $p < 0.001$ ). Olive-sided Flycatcher occupancy was associated with percent cover of woody wetlands ( $\beta = 2.408$ ;  $p < 0.001$ ) and mixed forest ( $\beta = 0.891$ ;  $p = 0.16$ ).

### 3.2 Climate Change Refugia

Of all the species modeled with this project, the shrubs were predicted to have the largest change in probability of occupancy across the state from 2010 to 2080 regardless of the RCP scenario, and the greatest decrease in viable habitat (Table 4). Although Black Crowberry was predicted to exhibit the lowest decline in mean probability of occupancy from 2010 to 2080 under RCP 4.5 (-83.7%), it exhibited the biggest change of the shrub species between RCP 4.5 and RCP 8.5. Mink frogs exhibited the next largest decline in mean probability of occupancy across the state at -70.3 and -91.6 % under RCP 4.5 and 8.5 respectively, as well as the next largest decline in habitat area in Maine by 2080. The birds were predicted to generally fare better under RCP 4.5 than the other species, with habitat decline ranging from 1.17% for Chestnut-sided Warbler, to 16.82% for Olive-sided Flycatcher. However, of all the taxa, the birds exhibited the greatest differences in predictions between RCP 4.5 and 8.5. For instance, Chestnut-sided Warbler habitat loss between RCP 4.5 and 8.5 changed by a factor of 37, from 1.17% to 43.31%. Although Northern Flying Squirrels were predicted to lose less habitat than all the bird species under RCP 4.5, it's predicted loss of 42.28% habitat under RCP 8.5 was lower than that of the Olive-sided Flycatcher, Magnolia Warbler, and Chestnut-sided Warbler.

All the tree species were predicted to exhibit an overall increase in occupied area in Maine by 2100 under RCP 8.5, for both the CCSM4 and Hadley GCM (Table 5). Only paper birch was predicted to experience a decrease in above ground biomass, when averaged across the state by 2100, and only under the CCSM4 GCM. This result is likely related to the species' tendency to occupy disturbed sites, and the fact that the model did not include any active forest management. Climate change refugia (secondary and primary refugia together) was the largest zone category for Red Spruce and Northern White Cedar under both GCMs, whereas the zone of stability represented the most expansive zone for Balsam Fir under both GCMs. Paper Birch was the only species for which the zone of expansion was the largest. Since this species relies on disturbance, these results indicate that the species may be able to persist and expand into areas in the future in places where natural and human disturbance create openings.

The amount of refugia differed greatly across species. For instance, Bicknell's Thrush, Mink Frog, and the three shrub species were all predicted to have very little climate change refugia in Maine, whereas Black-throated Green Warblers were predicted to occur with fairly high probability in the future across much of Maine. Saltmarsh Sparrow showed some potential expansion into new regions in Maine.

Despite these differences, there were some clear geographic patterns that emerged in the location of climate change refugia across Maine. Many species – including Virginia Rail, Common Loon, Moose, Northern White Cedar, and Red Spruce – showed a large concentration of climate change refugia in northern areas of Maine. A number of species (Ruffed Grouse, Paper Birch, Olive-sided Flycatcher, Chestnut-sided and Magnolia Warbler) were predicted to show a distinct gradient in occupancy from coastal to inland areas, with overall higher occupancy in 2080 in inland areas. In contrast, Balsam Fir showed the opposite pattern with more climate change refugia area, and higher predicted above-ground biomass near the coast than inland. However, Balsam Fir was predicted to have a particularly valuable refugia area in the coastal region northeast of Addison Maine.

A number of other species also exhibited climate change refugia in coastal and montane regions. The eastern coast of Maine represented the only climate change refugia for Black Crowberry. Paper Birch was predicted to have a small hotspot of refugia along the coast between Lubec and Calais. Chestnut-sided and Magnolia Warblers also were predicted to have high probability of occupancy along the eastern portion of Maine's coast. Coastal and montane regions represented important climate change refugia for Red Spruce Three-toothed Cinquefoil, Labrador Tea, and Northern Flying Squirrel, particularly eastern sections of the coast, and montane regions near Mount Katahdin. Montane regions were the only climate change refugia for Bicknell's Thrush.

### **3.2 Second Stakeholder Meeting**

The participants listed a wide range of daily activities that could impact the focal species or their habitats (Table 6), and were able to use this list to identify some concrete ways in which climate change refugia maps could inform or guide these activities. Participants noted that they would use these results at multiple different scales, suggesting that a broad scale was appropriate for thinking about acquisition and collaboration, and a finer scale in thinking about how to manage specific parcels. At the broadest level, participants from multiple agencies recommended that the climate change refugia maps were valuable for identifying gaps in protected areas, and subsequently for identifying and prioritizing areas for acquisition across the landscape. Numerous stakeholders also proposed using the maps to prioritize areas for ongoing management work, like invasive species control, trail maintenance, and visitor management. In specific, Acadia National Park staff discussed using the climate change refugia data layers to help guide the expected increases in visitation and traffic in the western mountains.

Many participants identified concrete ways that the climate change refugia could be used to help guide planning and management at finer spatial scales. For instance, a participant proposed that the climate change refugia maps can identify species that might serve as a stewardship priority in an area that is already owned and protected – importantly, species that they might not think of otherwise as a stewardship priority. A participant from the Maine Natural Areas program pointed out the value in using climate change refugia in rigorously preserved areas such as Acadia

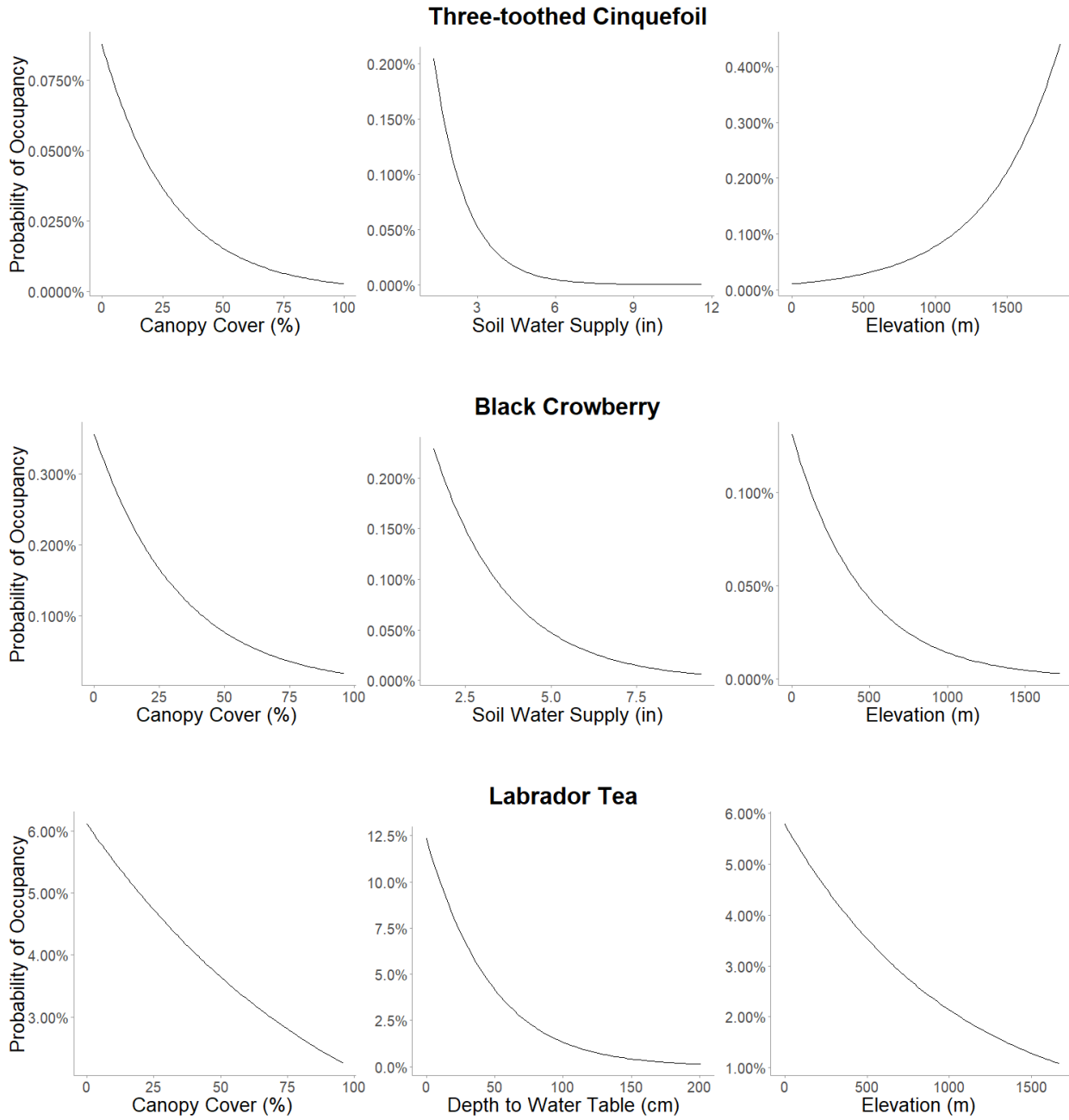


Natural Park to set benchmarks and baselines for guiding forest management in areas under multiple use, continued management, or otherwise less protection. In line with this, another participant proposed that the results could be used to identify areas that might be more stressed in the future, and thus more vulnerable to invasive species. A stakeholder from the Maine Department of Inland Fisheries and Wildlife planned to use the project results to help inform upcoming updates to the state wildlife action plan. Finally, ACAD staff advised using the results to help inform which species should be included in Cadillac Mountain restoration, to identify where other mountain top restoration activities might be beneficial, and to identify potential locations for managed relocation.

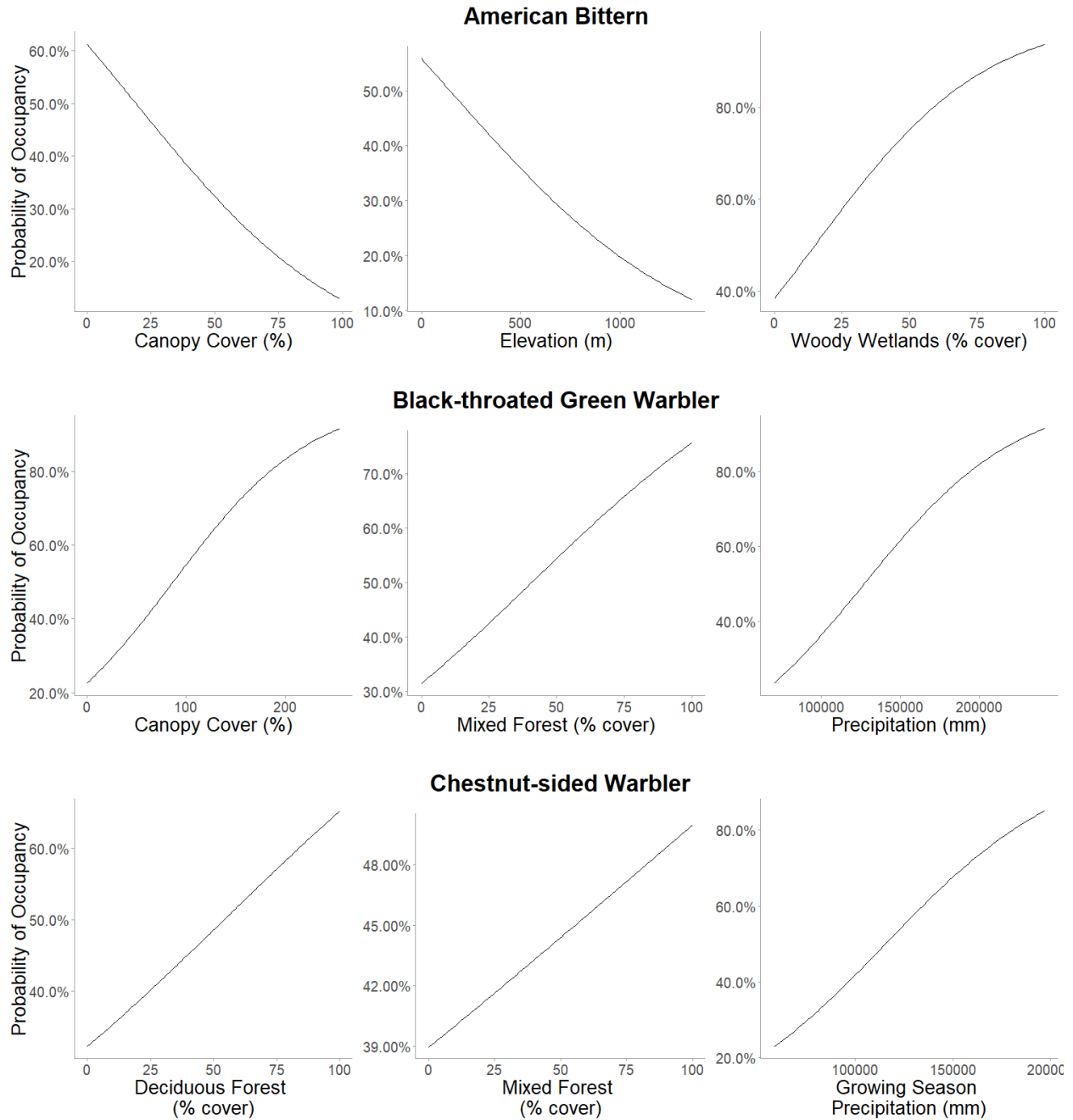
Many participants proposed using climate change refugia to guide experiments and monitoring. For instance, one participant noted that mink frogs are challenging to monitor due to rarity and low detectability. This participant planned to use the maps to help inform locations for targeting monitoring of mink frogs. ACAD park staff noted that the Bass Harbor area in the south of ACAD is predicted to provide climate change refugia for many of the modeled species, but is not being monitored. They proposed initiating monitoring in the area, as this region is also vulnerable to sea-level rise. Other ACAD staff indicated they would use the results to inform the location of citizen science activities and field work for graduate students – for instance, in the Bass Harbor area. Participants pointed out that targeted monitoring in potential refugia also has the added benefit of providing data for model validation. Another participant proposed using the climate change refugia results to help identify locations for siting experiments that can help test hypotheses about how plant species respond to differences in climate. In turn, these experiments could also help to validate some of the climate change refugia results.

Finally, outreach and communication was another important and reoccurring theme in the discussion of how to use climate change refugia. Participants anticipated using the maps in outreach – to show the public and potential donors motivating reasons to acquire, protect, and manage locations that are expected to be more resilient to change. In this same vein, the participants also noted the leverage of communicating about the importance of coastal Maine and islands as climate change refugia for multiple species, and the subsequent value in protecting and managing coastal and island resources. A number of the workshop participants decided to organize a subsequent meeting to discuss opportunities to collaborate on island management and conservation across different agencies and organizations. Finally, a participant also noted that climate change refugia offer a hopeful story to give to people. They explained that the “doom and gloom” of climate change can make people feel incapacitated, and unwilling to act. Climate change refugia provide some hope, and some concrete avenues for action, all in the form of attractive maps of charismatic and iconic species.

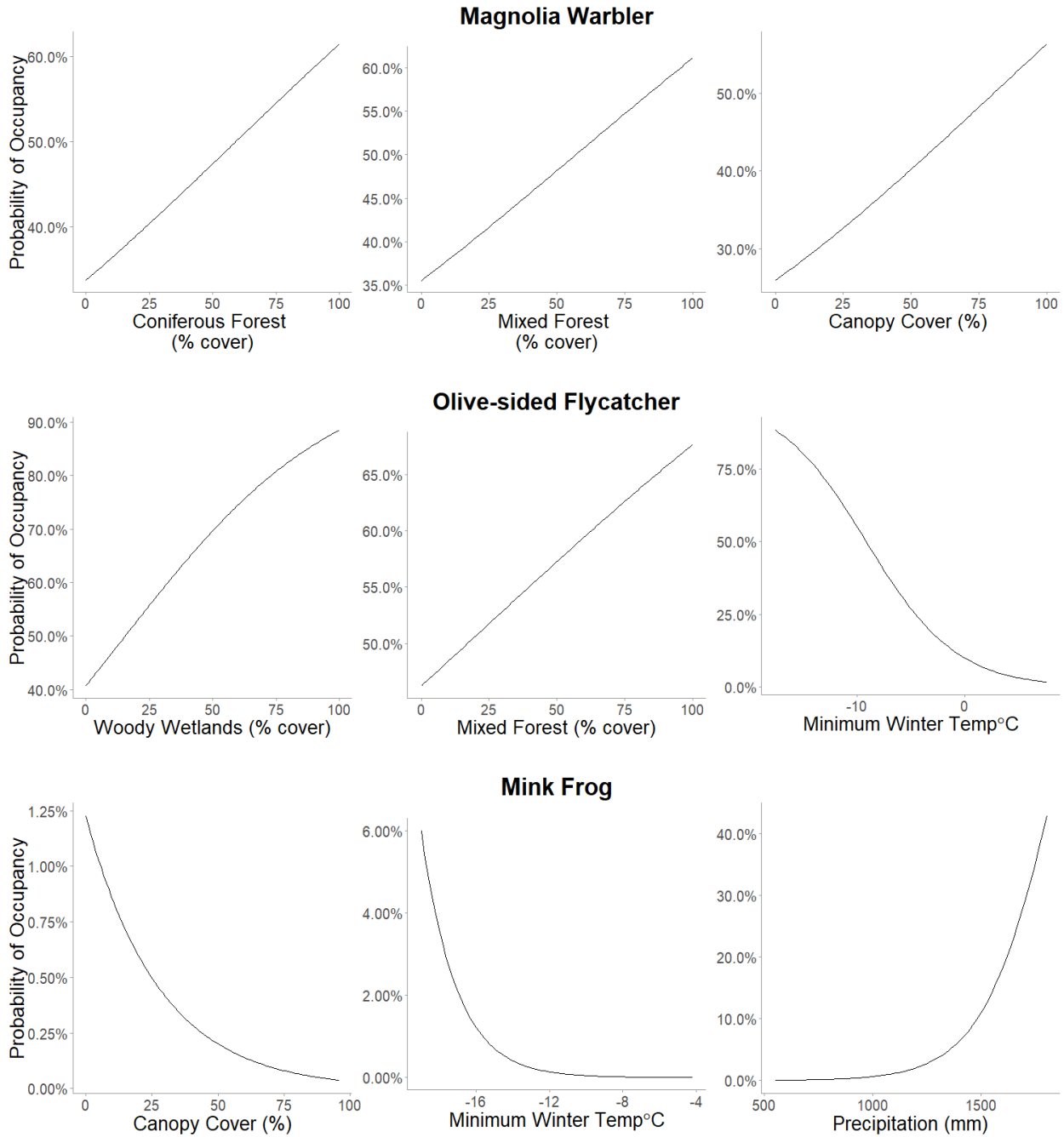
**Figure 3.** Top three environmental predictors for each species. Climate variables were included for some species.



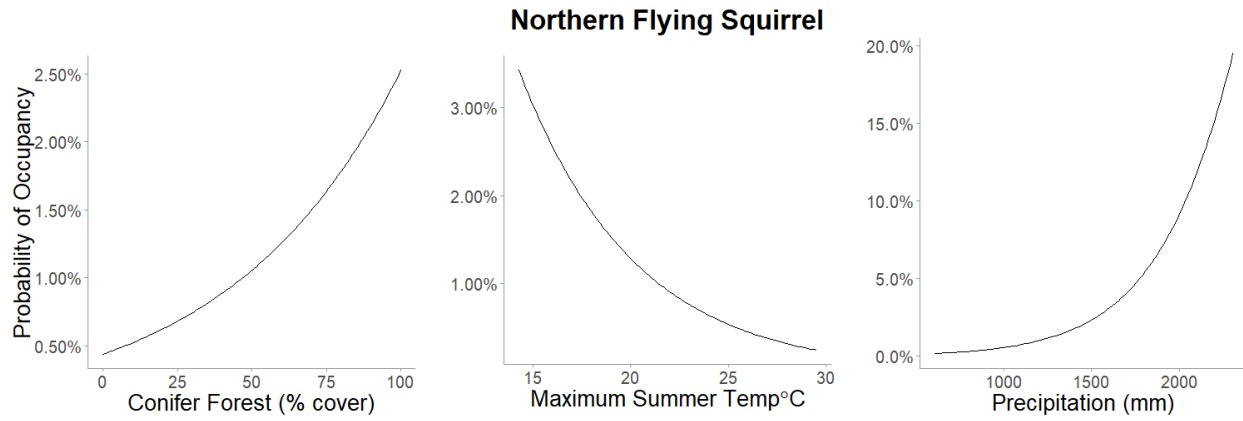
**Figure 3.** (Cont'd) Top three environmental predictors for each species. Climate variables were included for some species.



**Figure 3.** (Cont'd) Top three environmental predictors for each species. Climate variables were included for some species.



**Figure 3.** (Cont'd) Top three environmental predictors for each species. Climate variables were included for some species.



**Table 1.** Candidate focal species for climate change refugia modeling. Models were developed for each species by either this project (SCS), Duveneck and Thompson (DT), or the Designing Sustainable Landscapes Project (DSL). Species data sources include eBird (1), iNaturalist (2), National Phenology Network (3), the National Aquatic Resource Surveys (4), Global Biodiversity Information Facility (5), the Forest Inventory and Analysis Program (6), the Breeding Bird Survey (7), and Mountain Birdwatch (8).

Species	Habitat	Model Development	Data Sources	Notes
Balsam Fir ( <i>Abies balsamea</i> )	Spruce-fir forest	DT	6	Co-occurs with Red Spruce; not specified at initial meeting
Red Spruce ( <i>Picea rubens</i> )	Spruce-fir forest	DT	6	Iconic to Acadia
Northern White Cedar ( <i>Thuja occidentalis</i> )	Cedar swamps	DT	6	Cultural importance
Paper Birch ( <i>Betula papyrifera</i> )	Disturbed, open, cool, dry early-successional areas	DT	6	Iconic & economically important
Labrador tea ( <i>Rhododendron groenlandicum</i> )	Peatlands/bogs	SCS	2,3,4	Cultural interest
Three-toothed Cinquefoil ( <i>Sibbaldiopsis tridentata</i> )	Rocky headlands	SCS	2	Cadillac Mt. restoration
Black crowberry ( <i>Empetrum nigrum</i> )	Coastal bluffs, bogs, alpine	SCS	2	Host plant for <i>Plebejus idas empetri</i>
Mink Frog ( <i>Lithobates septentrionalis</i> )	Wooded ponds swamps & streams	SCS	2,5	Rare but can be locally abundant where it does occur. No refugia in coastal Maine
Northern flying squirrel ( <i>Glaucomys sabrinus</i> )	Coniferous and mixed forests	SCS	2,5	Poor model performance
Moose ( <i>Alces alces</i> )	Coniferous and early successional forests, and wetland	DSL	NA	

**Table 1.** (Cont'd)

<b>Species</b>	<b>Habitat</b>	<b>Model Development</b>	<b>Data Sources</b>	<b>Notes</b>
Black-throated Green Warbler ( <i>Setophaga virens</i> )	Spruce-fir and transitional forest	SCS	1	
Olive-sided Flycatcher ( <i>Contopus cooperi</i> )	Moist openings in spruce-fir	SCS	1	
Magnolia Warbler ( <i>Setophaga magnolia</i> )	Spruce-fir forest	SCS	1	Not specified at the initial meeting
Chestnut-sided Warbler ( <i>Setophaga pensylvanica</i> )	Early-successional hardwood forest	SCS	1	Not specified at the initial meeting
American bittern ( <i>Botaurus lentiginosus</i> )	Freshwater & brackish marsh	SCS	1	
Common Loon ( <i>Gavia immer</i> )	Cold lakes	DSL	7	
Saltmarsh Sparrow ( <i>Ammodramus caudacutus</i> )	Estuarine emergent marshes	DSL	6	Not currently in study area but predicted to expand into it
Ruffed Grouse ( <i>Bonasa umbellus</i> )	Mixed-aged forests close to open habitat	DSL	7	
Virginia Rail ( <i>Rallus limicola</i> )	Freshwater & brackish tidal marshes	DSL	1	
Bicknell's Thrush ( <i>Catharus bicknelli</i> )	Montane spruce-fir forest	DSL	7,8	No refugia in coastal Maine

**Table 2.** Environmental and climate predictors included in statistical models. Landcover variables were summarized as the % cover in the 150m neighborhood. Predictors in bold were included in final “best” models. Species are American Bittern (AMBI), Black-throated Green Warbler (BTNW), Chestnut-sided Warbler (CSWA), Magnolia Warbler (MAWA), Olive-sided Flycatcher (OSFL), Three-toothed Cinquefoil (CINQ), Labrador Tea (LABT), Black Crowberry (CROW), Northern Flying Squirrel (NFSQ) and Mink Frog (MINK).

Variables	AMBI	BTNW	CSWA	MAWA	OSFL	CINQ	LABT	CROW	NFSQ	MINK
canopy cover	<b>X</b>	<b>X</b>	x	<b>X</b>	x	<b>X</b>	<b>X</b>	<b>X</b>	x	<b>X</b>
elevation	<b>X</b>	<b>X</b>	<b>X</b>	x	x	<b>X</b>	<b>X</b>	<b>X</b>	x	x
mean annual temp	x	x	x	x	x	x	x	x	x	x
min winter temp	<b>X</b>	<b>X</b>	<b>X</b>	x	<b>X</b>	x	x	x	x	<b>X</b>
max summer temp	x	x	x	x	<b>X</b>	<b>X</b>	x	<b>X</b>	<b>X</b>	x
growing degree days	x	<b>X</b>	<b>X</b>	<b>X</b>	x	<b>X</b>	<b>X</b>	x	x	x
total annual precip	x	<b>X</b>	x	x	x	x	<b>X</b>	x	<b>X</b>	<b>X</b>
growing season precip	<b>X</b>	x	<b>X</b>	<b>X</b>	x	x	x	x	x	x
open water	<b>X</b>				x					x
deciduous forest		<b>X</b>	<b>X</b>						x	
coniferous forest		<b>X</b>		<b>X</b>	x				<b>X</b>	
mixed forest		<b>X</b>	<b>X</b>	<b>X</b>	x				x	
woody wetlands	<b>X</b>				<b>X</b>					x
emergent wetlands	<b>X</b>				x					x
soil depth						<b>X</b>				
soil pH						x	x	<b>X</b>		
soil organic matter						<b>X</b>	x	<b>X</b>		
available water supply						<b>X</b>	x	<b>X</b>		
depth to water table							<b>X</b>			
soil drainage class							<b>X</b>	x		



**Table 3.** Performance metrics for models, including 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
Three-toothed cinquefoil	0.096	0.864	0.976	0.982	0.857	0.937	0.839
Labrador tea	0.116	0.606	0.886	0.823	0.478	0.831	0.492
Black crowberry	0.043	0.889	0.988	0.907	0.876	0.978	0.876
American Bittern	0.106	0.897	0.897	0.925	0.793	0.897	0.793
Black-throated green warbler	0.132	0.872	0.769	0.888	0.641	0.821	0.641
Chestnut-sided Warbler	0.135	0.993	0.700	0.877	0.633	0.816	0.633
Magnolia Warbler	0.098	0.940	0.805	0.931	0.746	0.873	0.746
Olive-sided flycatcher	0.181	0.710	0.812	0.819	0.522	0.761	0.522
Mink Frog	0.098	0.750	0.614	0.673	0.153	0.628	0.364
Northern Flying Squirrel	0.089	0.455	0.718	0.520	0.085	0.694	0.173

**Table 4.** Metrics of change in occupancy for modeled species. Metrics include mean absolute change (occupancy change), and mean percent change in probability of occupancy across all cells in Maine from 2010 to 2080 (% occ change), percent of occupied cells in all of Maine in 2010, and 2080 (% area), and percent loss of occupied cells across Maine from 2010 to 2080 (% area lost). The percent of the occupied area in Maine in 2010 and 2080, and the percent loss of occupied cells across Maine from 2010 to 2080 were calculated by transforming probability of occupancy in 2010 and 2080 in each cell to zero (not occupied) or one (occupied) based on the threshold probability (thresh) that maximized the sum of true positive and true negative rate for each species.

Species	thresh	2010		RCP 4.5			RCP 8.5	
		% Maine occupied	% decline occupancy	% of Maine occupied	% habitat lost	% decline in occupancy	% Maine occupied	% habitat lost
Black Crowberry	0.055	0.81	93.8	0.08	90.76	99.5	0.01	98.51
Labrador Tea	0.240	5.50	83.7	0.21	96.17	98.0	0.005	99.90
Three-toothed Cinquefoil	0.150	1.41	94.7	0.09	93.61	99.6	0.02	98.50
American Bittern	0.465	4.46	16.4	4.11	7.93	36.8	3.19	28.50
Black-throated Green Warbler	0.450	40.65	8.1	40.01	1.57	25.2	36.07	11.27
Chestnut-sided Warbler	0.400	40.42	18.1	39.94	1.17	51.6	22.91	43.31
Magnolia Warbler	0.410	40.43	18.3	39.07	3.33	55.8	20.54	49.18
Olive-sided Flycatcher	0.560	40.36	20.9	33.57	16.82	48.6	11.66	71.12
Mink Frog	0.012	3.92	70.3	2.14	45.31	91.6	0.25	93.56
Northern Flying Squirrel	0.011	30.92	13.6	25.38	17.90	34.6	17.84	42.28

**Table 5.** Summary statistics for tree response to climate change. Metrics include the predicted change in above-biomass (g/m<sup>2</sup>) from 2010 to 2100 averaged across all occupied 250 m cells in Maine, the percent of Maine predicted to be occupied by the species in 2010 and 2100, the percent change in occupied area from 2010 to 2100, and the percent of Maine predicted to be in each zonal category in 2100. All metrics for 2100 are reported for RCP 8.5 and two global circulation models.

<b>Metric</b>	<b>CCSM4</b>				<b>Hadley</b>			
	Red Spruce	Balsam Fir	Northern White Cedar	Paper Birch	Red Spruce	Balsam Fir	Northern White Cedar	Paper Birch
Change in above-ground biomass	1.29	0.56	0.67	-0.04	1.43	0.68	1.01	0.003
Percent of Maine occupied 2010	22.72	26.46	10.95	15.79	22.72	26.46	10.95	15.79
Percent of Maine occupied 2100	30.20	35.37	11.99	21.30	28.67	34.24	11.82	20.23
Percent change in occupied area	24.74	25.20	8.68	25.83	20.73	22.74	7.40	21.93
<b>Zonal categories</b>								
Zone of expansion	8.86	10.03	4.30	9.63	7.78	9.10	4.08	8.73
Primary refugia	11.57	7.54	4.69	4.52	11.68	8.93	5.90	5.38
Secondary refugia	0.76	1.79	0.31	3.07	0.73	1.91	0.24	3.00
Zone of stability	7.00	11.44	2.01	1.93	6.54	10.08	1.17	1.49
Zone of decline	1.72	4.56	0.68	2.14	1.94	4.22	0.42	1.64
Zone of contraction	1.39	1.12	3.26	4.13	1.84	1.31	3.21	4.29

**Table 6.** Activities listed by stakeholders that could impact focal species or their habitats.

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Monitoring	Forest policy
Communicating to visitors/tourists	Land acquisition
Experiments	Easement acquisition
State and municipal planning	Forest stewardship
Restoration work	Forest management
Trail management	Engaging and influencing funders
Communicating science	Climate action and policy
Invasive species management	Transportation planning

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## **Appendix A. Literature review of species' ecology**

### **American Bittern**

The American Bittern (*Botaurus lentiginosus*) breeds from Newfoundland to British Columbia, and as far south as Virginia and central California. They winter in the east from coastal Maryland through the southeastern US and Gulf coast, and in the west from coastal areas of the Pacific Northwest through California, Mexico and Central America. They are very secretive and solitary animals, so their life history and ecology are poorly understood (Lowther et al. 2009). American bitterns primarily inhabit freshwater marshes, bogs and fens, and wet meadows with sluggish streams characterized by emergent grasses, sedges, bulrushes and cattails, but can occasionally be found in brackish wetlands (DeGraaf and Rudis 1986). American bitterns are area sensitive, so primarily occupy larger wetlands and tend to avoid areas with exotic invasive species like reed canarygrass (Glisson et al. 2015). They forage in emergent vegetation, water, and shallow bottoms for frogs, reptiles, shellfish and crustaceans, small fishes and mammals, insects, and spiders (DeGraaf and Rudis 1986). They nest on the ground or on a platform over water in dense vegetation (Lowther et al. 2009). Migratory behavior is poorly understood for American bittern, and some southern populations may remain sedentary (Lowther et al. 2009).

The American Bittern has undergone significant population declines at the continental level. Primary threats to this species appear to be habitat degradation and decline in prey species (particularly amphibians) from acid deposition, eutrophication, siltation, chemical contamination of wetlands, and human disturbance (Lowther et al. 2009).

The American Bittern is considered to have medium climate change vulnerability in Maine (Whitman et al. 2013). Climate change may result in habitat loss and range shifts for the American bittern. The freshwater habitats that this species inhabits are very vulnerable to climate change (Kundzewicz et al. 2007), since changes in temperature and precipitation can influence wetland hydroperiod, depth and size, and drought and increased storm intensity can adversely affect water quality (Steen and Powell 2012). Flooding can also cause loss of nests (Whitman et al. 2013). The impact of habitat loss and fragmentation may be heightened for this species, as small remaining patches of habitat may not be viable for breeding (Glisson et al. 2015). The coastal habitats that this species occasionally occupies are also very vulnerable to climate change (Kundzewicz et al. 2007). For instance, climate change and sea level rise are likely to reduce habitat quality in brackish marshes by increasing salinity and shifting these habitats toward salt-tolerant vegetation (Woodrey et al. 2012). Some coastal wetlands and marshes may entirely disappear because accretion may not be able to keep pace with future rates of sea level rise (Galbraith et al. 2002). Finally, climate-mediated shifts in regional abundance could alter both the structure of wetland communities, and prey populations (Kelly and Condeso 2014). Projections under the most severe climate change scenarios also suggest that this species could experience an eastward range shift (Steen and Powell 2012).

### **Black Crowberry**

*Empetrum nigrum*, commonly known as black crowberry, is a small low-growing, woody shrub. *E. nigrum* has a circumboreal distribution throughout Greenland and northern Europe, and in North America from Alaska, to Labrador, and Newfoundland. In the eastern United States, the species is distributed from Minnesota to Maine, and south to New Jersey and Pennsylvania. In

North America, *E. nigrum* is found in areas with cool temperatures, and high rainfall in summer, but in a range of habitats and elevations. The species can be found from alpine zones to sea levels, and in habitats including coastal bluffs, and exposed sea cliffs, sphagnum bogs or muskegs, open conifer woodlands, and open tundra and rock fields (Robin 1992). It is often associated with black (*Picea mariana*) and white spruce (*P. glauca*) as a dominant understory species. Reflecting its broad habitat distribution, *E. nigrum* is tolerant of a wide range of soils (sandy to rocky soils, glacial till, and alluvial deposits) and soil moisture and pH conditions. However, it is an indicator of nitrogen-poor soils, and is intolerant of prolonged water exposure, favoring sites with better drainage.

*E. nigrum* is an ecologically and culturally important species. The species is used in traditional cultures to produce, wine and juice, and is medically used as a diuretic and antibiotic (Altan and Özdemir 2004). In the Atlantic shores of North America, it is a keystone species of coastal heaths, and plays an important role in reducing coastal erosion, creating organic moist soils (Mallik 2003). Juveniles of *E. nigrum* largely develop in the shade of canopy trees, but primarily persist into adulthood in open heathland where the canopy trees die. Given this niche-shift, and the fact that *E. nigrum* can also exhibit allelopathic interference with trees, the species is thought to be important to maintaining shrub habitats (Mallik 2003). *E. nigrum* also serves as the host plant for the Crowberry Blue (*Plebejus idas empetri*), a regional endemic butterfly of Downeast Maine and the Maritime Provinces. This butterfly is a Priority 2 Species of Greatest Conservation Need, and a G5T5 State Special Species that is thought to be moderately vulnerable to climate change (Whitman et al. 2013). The more abundant *E. nigrum* can thus also serve as an indicator for where habitat protection can be prioritized for the Crowberry Blue.

There is a large body of literature on climate change impacts to *E. nigrum* in Scandinavia, but not in the US. There is wide evidence of the species moving northward across Europe (Buizer et al. 2012), and dendroecological studies have shown that *E. nigrum* is in fact sensitive to shifts in climate (Buntgen et al., 2015; Myers-Smith et al., 2015). Climate change is predicted to impact the distribution of *E. nigrum* through phenological advances of flowering, fruiting and leaf out associated with longer growing seasons (Parmesan and Yohe 2003, Parmesan 2006, Root et al 2003, Førlund et al 2004, Linderholm 2006).

### **Black-throated Green Warbler**

The Black-throated Green Warbler breeds across the northern US and Canada from Alberta to Newfoundland. In the eastern US one sub-species breeds in the Great Lakes area, New England, New York and Pennsylvania, in higher-elevation areas of the Appalachians, while another sub-species is found in swamps on the southeastern US coastal plain (Morse and Poole 2005). The Black-throated Green Warbler is a long-distance migrant, wintering in Mexico, Central America and the West Indies. This is one of the more common species in northeastern coniferous forests, but can also be found in mixed and broadleaf forests (Morse and Poole 2005), and exhibits differing (though specific) habitat associations throughout its range (Collins 1983).

Black-throated Green Warbler populations are thought to be stable or even increasing through much of their range (Partners in Flight 2019). Loss of wintering habitats is one of the main threats to this species (Morse and Poole 2005). Habitat fragmentation can also pose a serious

threat, as it is an interior forest species, and requires large unfragmented forest parcels (Hobson and Bayne 2000)

The Black-throated Green Warbler is predicted to decrease in abundance throughout the eastern US due to climate change and associated declines in Balsam Fir, Striped Maple, and Yellow Birch (Matthews et al. 2004). The Black-throated Green Warbler is thought to have medium climate change vulnerability in Maine (Whitman et al. 2014), and in specific, to show small to large declines by 2100 in the Acadia National Park region under moderate and severe climate change scenarios respectively (Fisichelli et al. 2014). This species is likely to have less conifer cover in Maine in the future, as northern conifer forests are shifting northward (Iverson and Prasad, 2001, Iverson et al. 2008, Smith 2007). This is important, as loss of locally-important tree species can impact populations of Black-throated Green Warblers. For instance, in southern New England, the Black-throated Green Warbler is strongly associated with Eastern Hemlock (*Tsuga canadensis*), and has shown marked concurrent declines with the loss of this tree species to the Hemlock Woolly Adelgid (*Adelges tsugae*; Morgan et al. 2002). Black-throated Green Warblers showed similar declines in southern Appalachian Spruce-Fir forests with the loss of trees to the Balsam Woolly Adelgid (*A. piceae*; Rabenold et al. 2008). Climate change is expected to facilitate the northern expansion of *Adelges* species (Paradis et al. 2008), potentially hastening the decline of important tree species.

Changes in phenology could also have serious consequences for the Black-throated Green Warbler. Although climate change is causing earlier spring leaf-out in the breeding range of Black-throated Green Warblers, the species showed no evidence of earlier migration or arrival on the breeding grounds (Strode 2003). This could result in mismatches between migration timing and peak breeding-season food resources, particularly for long-distance migrants (Faaborg et al. 2010).

### **Chestnut-sided Warbler**

The Chestnut-sided Warbler breeds across Canada from Nova Scotia to Saskatchewan. In the US it breeds west into northern Minnesota and the northern Great Lakes, in New England, New York and Pennsylvania, and in high-elevation areas of the Appalachians. They are a specialist of early-successional habitats, preferring openings with tall, dense, understory vegetation and low canopy-cover of overstory trees (Smetzer et al. 2014). Though they prefer deciduous species, they can be found in mixed forests as well. Chestnut-sided Warblers are a long-distance migrant, wintering in South America. This species has shown a 45% decrease in population size from 1966 to 2015 (Partners in Flight 2019), and is predicted to have low climate change vulnerability in Maine (Whitman et al. 2013). The deciduous and mixed-forests upon which the species relies are expected to persist and even increase in Maine, so ample habitat may remain, as long as the species is managed for early-successional habitat creation.

### **Labrador Tea**

*Rhododendron groenlandicum*, commonly known as Labrador tea, is an evergreen shrub in the Ericaceae family. *R. groenlandicum* is found in the north from Alaska to Newfoundland, and in coastal Greenland. In the eastern United States, the species is distributed from Minnesota to Maine, and south to New Jersey and Pennsylvania. *R. groenlandicum* is associated with nutrient poor, acidic soils (Gucker 2006). It competes strongly for soil nutrients by forming associations

with ericoid mycorrhizae (Malloch & Malloch 1981). *R. groenlandicum* can grow on a range of soil textures, including coarse glacial deposits, fine-textured clay soils, and glacial, fluvio-glacial, and organic deposits (Hébert & Thiffault 2011). Given its high need for water, *R. groenlandicum* is typically found moist areas, but can also be found in drier sites (Hébert & Thiffault 2011); though the depth to the water table can influence its occurrence in wetter soils (Gucker 2006). *R. groenlandicum* can tolerate a range of light conditions (Thiffault et al. 2015). For instance, it is often associated with other ericaceous species in early phases of bog succession, with black spruce, northern white cedar in later stages of bog succession, and can also be found in open conifer woodlands (Hébert & Thiffault 2011).

There is little study in the literature to date on the potential impacts of climate change on *R. groenlandicum*. The species is thought to have a relatively broad climate niche in terms of temperature and precipitation (Hébert & Thiffault 2011). *R. groenlandicum* is of ecological interest as it can have a large impact on forest growth and succession by heavily competing for nutrients and producing allelochemicals (Rowe et al. 2017). Furthermore, *R. groenlandicum* has cultural significance as a food, medicine and tea for aboriginal peoples and European settlers (Gucker 2006).

### **Magnolia Warbler**

The Magnolia Warbler breeds across much of Canada and New England, and in the eastern US can be found south into high-elevation areas of the Appalachian mountains. This species is considered a boreal forest breeder, but is also associated with Yellow Birch (*Betula alleghaniensis*; Matthews et al. 20014). It nests largely in spruces (*Picea* spp.) in the northern portion of its range, and in Eastern Hemlock in more southern reaches (Dunn and Hall 2010). Though Magnolia Warblers are strongly associated with coniferous cover, they can be found in a wide variety of seral stages – from recent clear-cuts to mature forests – but are more abundant in the latter (DeGraaf et al. 1998). Magnolia Warbler populations are thought to be stable or even slightly increasing through much of their range (Partners in Flight 2019).

The Magnolia Warbler is predicted to decrease in abundance throughout the eastern US due to climate change and associated declines in Balsam Fir; however, small pockets are predicted to persist in higher-elevation areas, particularly where Yellow Birch also persists on the landscape (Matthews et al. 20014). Climate change vulnerability is thought to be medium for the Magnolia Warbler in Maine (Whitman et al. 2013). In the Acadia National Park region, the species is predicted to show large declines under both moderate and severe climate change scenarios (Fisichelli et al. 2014). The boreal forests that this species primarily occupies are expected to become less common and possibly locally extinct from the Northeastern US under severe climate projections (Rodenhouse et al. 2008). A reduction in range is expected for species that inhabit montane spruce-fir forests at the southern edge of their range (Rodenhouse et al. 2008). Although Magnolia Warblers have not demonstrated northward shifts in its range like more southern species, similar patterns may ensue in the future for this and other northern species under severe climate projections (Hitch and Leberg 2007). Changes in phenology could also have serious consequences for Magnolia Warbler. Like the Black-throated Green Warbler, this long-distance migrant does not appear to be arriving earlier to the breeding grounds, despite earlier onset of spring (Strode 2003), and may be similarly prone to phenological mismatches (Faaborg et al. 2010).



## **Mink Frog**

While many anurans reach their northern range limits in Maine, the Mink Frog (*Rana septentrionalis*) is a cold-adapted species near its southern range limits in Maine. This species is the northernmost anuran in North America, found only above the 43<sup>rd</sup> parallel from Newfoundland to Minnesota (Hedeon 1986). Mink Frogs are highly susceptible to desiccation, so are seldom found on land, and only on nights with heavy precipitation (Hedeon 1986, Casper, 2005). They primarily breed in rivers, lakes and ponds – particularly in areas of dense aquatic vegetation – but can also be found in streams, pools, puddles and ditches (Hedeon 1971). Mink frogs prefer slow-moving waters (Popescu and Gibbs 2009). They are more associated with very local habitat features like pond size, and presence of beavers than landscape-scale variables (Popescu and Gibbs 2009). In addition to temperatures, predation by American Bullfrogs (*Rana catesbeiana*; Moore 1952) may also restrict the Mink Frog's geographic range, and they do show a mild negative relationship with this species (Popescue and Gibbs 2009).

Mink Frogs are thought to be highly vulnerable to climate change in Maine because Maine is at the southern edge of its range, and because the species depends on cold water habitats (Whitman et al. 2013). Climate change may impact Mink Frogs through increases in average annual temperatures, and in maximum summer temperatures. The females lay submerged egg masses that are very large; without cool, oxygen rich water, the embryos at the center of these large egg masses can die from suffocation and poison the remaining embryos during decomposition (Moore 1949). Thus, survival of embryos is thought to only be viable if mean monthly summer temperatures remain below 21°C (Hedeon 1986). Reflecting this, Mink Frog pond occupancy in New York state responded strongly to maximum July temperatures with a sharp reduction above 21°C (Popescu and Gibbs 2009). Climate change is expected to cause a reduction in spring and summer runoff, and increased droughts in New England (Huntington 2003), which could have important impacts on pond hydroperiods during Mink Frog embryo development (Popescu and Gibbs 2009).

Some potential climate change impacts of Mink Frogs can also be inferred based on other anuran species. For instance, other anurans have shown shifts in phenology, with spring calling starting 10-13 days earlier than in previous decades (Gibbs and Breisch 2001). Increases in temperatures have also led to die-offs of some anurans (Piha et al. 2007), surges in disease epidemics (Pounds et al. 2006), and increases in inter-specific predation due to changes in the timing and overlap of breeding periods (Beebee 2002).

Although Mink Frogs may be negatively impacted by climate change, Popescu and Gibbs (2009) propose that declines could be minimized by managing for increased beaver activity. They argue that beaver activity can convert terrestrial areas to new breeding habitat, convert lotic waters to more-preferable lentic habitats, and importantly, create lentic habitats with relatively high levels of water flow, and thus particularly high oxygen levels. Furthermore, they contend that the mosaic of wetlands, and connected stream channels that often adjoin and connect multiple beaver ponds can potentially also increase habitat availability, and mobility through the landscape for Mink Frogs. Finally, because beavers increase the amount of open water present on the landscape during droughts (Hood and Bayley, 2008), management of beavers is thought to provide an important tool in maintaining amphibian habitats during drought years (Stevens et al., 2007). Thus, managing beaver activity may be particularly beneficial to Mink Frogs, that are highly sensitive to desiccation.

### **Northern Flying Squirrel**

The Northern Flying Squirrel is found across Canada, and into Alaska, and in areas of the northern Rocky Mountains. In the eastern US, the species can be found in the northern Great Lakes areas, in New England, and as far south as northern Pennsylvania; however, there are isolated populations at higher elevations in the Appalachians (Weigl 2007). The northern flying squirrel inhabits boreal, coniferous, and mixed forests (Weigl 2007), but reaches its highest abundance in mature coniferous forest (Patterson 2010, Smith 2007). The northern flying squirrel is highly sensitive to forest fragmentation and cannot disperse effectively across large forest fragments, so closed canopies of mature forests are important to allow for efficient movement (Smith et al. 2013).

The northern flying squirrel is considered a keystone species. It distributes fecal pellets with fungal spores and nitrogen fixing bacteria throughout the forest, and is an important prey species for birds and other mammals (Smith 2012). Mycorrhizal fungi are an important constituent of the diet of northern flying squirrels throughout their range; the fungi also form mutualistic associations with tree root systems, making northern flying squirrels an important component of the forests they inhabit (Weigl 2007).

Northern flying squirrels are threatened by climate change induced habitat loss. The northern forests that the northern flying squirrel inhabits are shifting northward (Iverson and Prasad, 2001, Iverson et al. 2008, Smith 2007). Climate change may also decrease the fungi and lichen that are important food sources for the northern flying squirrel.

Climate change may also cause increased interactions with southern flying squirrels. Southern flying squirrels are superior competitors, and are asymptomatic carriers of an intestinal parasite that causes significant mortality to northern flying squirrels (Smith 2007). This parasite appears to be limited by cold weather, allowing the species to co-occur in northern areas (Great Lakes area, New England, Ontario, and Nova Scotia; Weigl 2007). However, in the southern end of their range, northern flying squirrels appear to be limited by the presence of southern flying squirrels (Smith 2007, Weigl 2007). Habitat and temperature changes are already allowing southern flying squirrels to expand northward, and are causing a subsequent decline of northern flying squirrels (Garroway 2010). A warmer climate is likely to be favorable to the southern flying squirrel, and its pathogen, with negative impacts for northern flying squirrels. In addition to this potential negative interaction between the two species, documented recent range expansions in southern flying squirrels in response to warm winters have been associated with hybridization of the two species in the Great Lakes region and Pennsylvania (Garroway et al. 2010).

### **Olive-sided Flycatcher**

The Olive-sided Flycatcher breeds across much of Canada, in part of the Rockies and Sierra Nevada Mountains, and in northern New England. This long-distance migrant winters in the mountains of Panama and in the Andes. Olive-sided flycatchers are typically associated with pine barrens and spruce-fir forests (Ralston et al. 2015), particularly those with meadow, bog, or forestry cut openings with tall prominent trees or snags (Altman and Sallabanks 2012). These birds are historically dependent on openings created by fire, but often use silvicultural (forest management) openings. Olive-sided flycatchers hunt for aerial arthropods (flying bugs like flies

and cicadas) from an elevated perch (Robertson 2012), and are rather specialized in diet. This species has the longest migration of any flycatcher in North America, and exhibits a particularly early fall departure from breeding grounds as well as a late spring arrival, most likely in response to availability of insects that are highly responsive and vulnerable to cold temperatures (Altman and Sallabanks 2012).

The olive-sided flycatcher is listed by the International Union for the Conservation of Nature (IUCN) as “Near Threatened” (Ralston et al. 2015). They have had an annual decline of around 3.5% from 1966-2013 across their range, and have lost 78% of their population since 1970 (Partners in Flight 2019). Causes for declines are unknown, but may be linked to loss of breeding habitat through fire suppression, and the ‘ecological trap’ of silvicultural openings where predators are more abundant (Altman and Sallabanks 2012). Since the species has shown declines, even as the disturbed habitats it prefers have generally increased throughout its breeding range, loss of habitat on the wintering grounds may also be driving population trends (Partners in Flight 2019). The Olive-sided Flycatcher is considered to have medium climate change vulnerability in Maine (Whitman et al. 2013).

Climate change may threaten the mountain-top boreal forests that olive-sided flycatchers occupy, as these forests are likely to become less common in the US under severe climate projections (Rodenhouse et al. 2008). Climate-induced changes in the timing of seasonal events could also have serious consequences for this long-distance migrant. Studies have shown that birds are arriving earlier to their breeding grounds across the northern U.S. (Marra et al. 2005, Wilson 2013). Climate variability could worsen these timing problems, since late spring storms and extreme weather events can kill migrating birds (Dionne et al. 2008, Zumeta and Holmes 1978). However, many long-distance migrants have not shifted their spring arrival dates as much as short-distance migrants (Miller-Rushing et al. 2008). As a result, mismatches between migration dates and food resources have been reported for many long-distance migrants (Faaborg et al. 2010). Indeed, many aerial insectivores, particularly long-distance migrants like Olive-sided Flycatchers, have exhibited significant declines that are very likely related to food shortages and mismatches between insect abundance and timing of life history events (Nebel et al. 2010).

### **Three-toothed Cinquefoil**

*Sibbaldiopsis tridentata* is a creeping, rhizomatous shrub, commonly known as three-toothed cinquefoil. It is found in Greenland, the Northwest Territories and northern Quebec, in the northern United States from Wisconsin to Maine, and in disjunct southern Appalachian populations as far south as northern Georgia. *S. tridentata* is distributed in a variety of habitats and elevations across its range, including exposed mountaintop habitats in the northeastern US, rocky coastal headlands on the Maine shoreline, high-elevation rock outcrops and exposed rocky balds in the southern Appalachians, and outcrops and high-elevation plateaus in West Virginia (Bresowar & Walker 2011). Many of these habitat types are characterized by shallow soils that do not retain water well, minimal canopy cover, high sun exposure, and a relatively short growing season (Horton & Culatta 2016). *S. tridentata* can grow on a variety of soil and rock substrates but is thought to be a calcifuge (Wiser 1998). As such, the species is thought to typically occur on soils with a relatively high pH.

There is limited literature to date on potential impacts of climate change on *S. tridentata*. In Acadia National Park, *S. tridentata* spring leaf-out was shown to be earlier in warmer microclimates (MacKenzie et al. 2018), indicating a future phenological response to climate change. In general, plant species in rock outcrop communities may be particularly impacted by reduced water availability in the future, given the higher cloud ceiling, reduced cloud immersion and greater evaporative demands that are expected to accompany climate change in many regions (Horton & Culatta 2016).

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