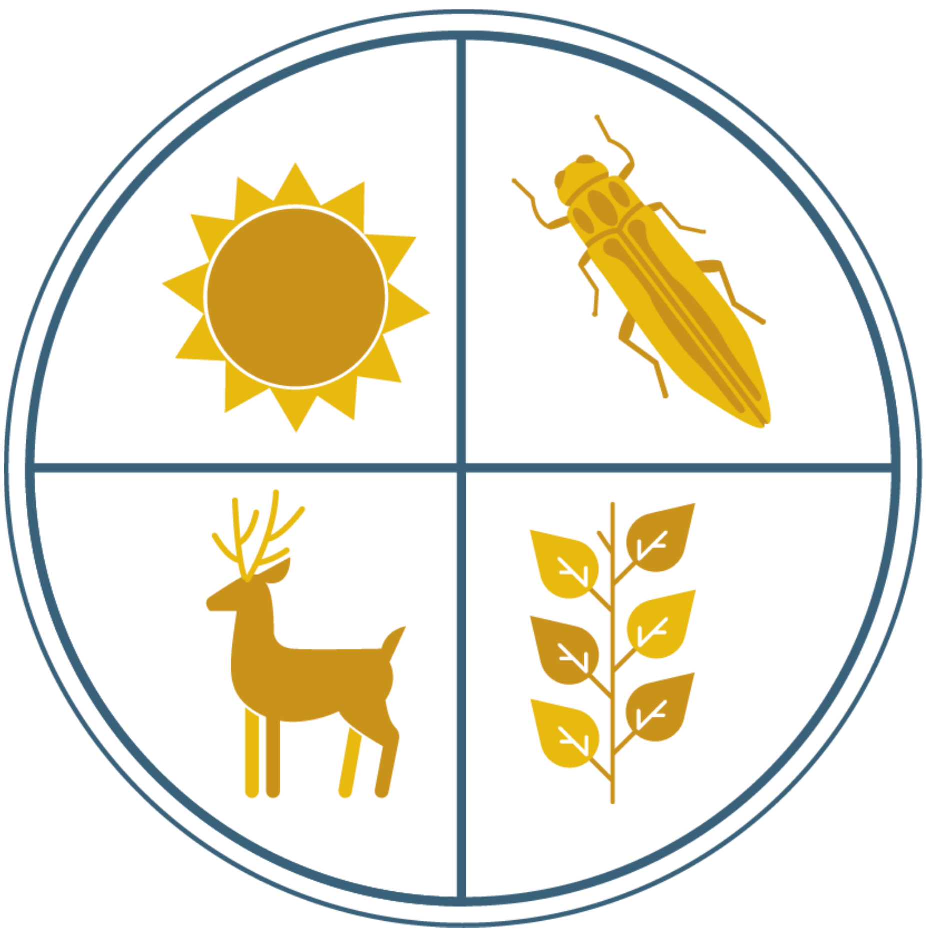
Assessment of Forest Vulnerabilities in Mass Audubon Wildlife Sanctuaries

in the Central and West Regions



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Date: February 28, 2024

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Please cite as: Marks, C.O. 2024. Assessment of Forest Vulnerabilities in Mass Audubon Wildlife Sanctuaries in the Central and West Regions. Mass Audubon, Lincoln, Massachusetts, USA.

Acknowledgements: This research was funded by a grant from the Lookout Foundation. The author is especially grateful to Tom Lautzenheiser for detailed editorial comments on the draft report on the climate change vulnerability assessments. Integrated moisture index map data were computed by Amara Chittenden with guidance from Christian Marks, Tom Lautzenheiser, and Jack Nessen. All other maps were prepared by Christian Marks. Wildlife sanctuary landcover maps prepared by Tom Lautzenheiser for earlier Ecological Management Reports were instrumental in developing these maps. Dashboards for the final maps posted on ArcGIS on-line were prepared by Jack Nessen. The author is also grateful to Mass Audubon colleagues Tom Lautzenheiser, Josh Rapp, Andrew Randazzo, Jeff Collins, and Luke Nave from the Northern Institute of Applied Climate Science for their suggestions and comments in developing the assessment methods.

Cover diagram credits: Christian O. Marks

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Executive Summary

The forests in Mass Audubon's care are under threat from the interacting effects of climate change, pests and diseases, intensive browsing by high deer populations, and invasion by non-native plant species. This report provides a comprehensive assessment of these threats at the forest stand level for the 34 wildlife sanctuaries comprising Mass Audubon's Central and Western Regions, including over 19,000 acres of forests, wetlands, and fields. A combination of field-based survey and geospatial data modeling and analysis informs the assessment.

A resilient forest is one where productivity and a closed tree canopy recover quickly after a major disturbance such as a drought or a pest outbreak. A resistant forest is one that suffers little damage from disturbances in the first place. The confluence of climate change with an increasing number of introduced pests and diseases will increase the frequency of major disturbances. Management recommendations to increase forest resilience and resistance from this assessment include the following:

- Open more Mass Audubon wildlife sanctuaries to deer hunting;
- Dramatically increase the pace of suppressing non-native plant infestations at Mass Audubon wildlife sanctuaries over the next decade with licensed contractors. Estimates for non-native plant infestation areas in the assessed sanctuaries are about **1,100 acres** for severe vulnerability and **2,400 acres** for moderate vulnerability.
- Initiate a climate change adaptation tree planting program implemented by staff and volunteers.
- Restore stream channel morphology to benefit stream biota and reduce flood hazards. Specific actions to consider include dam removals (Rutland Brook, West Mountain), undoing channelization (Broad Meadow Brook), or adding logs to channels (Arcadia, Laughing Brook).
- Rehabilitate hayfields that have been substantially invaded by woody plants including by non-native species.
- Restore rich mesic forest herb layers within Mass Audubon Wildlife Sanctuaries, where opportunities to do so exist.
- Refine Mass Audubon land protection priorities through the lens of climate change, including a focus on:
  - Expanding protection adjacent to the least-vulnerable wildlife sanctuaries.
  - Protect canyons, coves, and steep ravines on properties neighboring Mass Audubon wildlife sanctuaries, which could provide cool moist micro-refuges from climate change.
  - Expanding land protection in large floodplain areas that reduce flood hazards.

To complement this report, there are web maps that show [spatial variation of vulnerabilities and associated acreages for each wildlife sanctuary].

Introduction

Why do climate change vulnerability assessments?

There are at least the following 3 compelling reasons for doing vulnerability assessments:

1. Vulnerability assessments and the associated management recommendations offer an opportunity to be proactive rather than reactive. For example, one could introduce trees of species that are better adapted to the future climate.
2. Considering likely climate change impacts provides a new perspective to re-evaluate management actions. For example, these assessments could direct land protection efforts towards expanding sanctuaries that are the least vulnerable.
3. The quantitative nature of the assessment is useful for developing estimates of management and associated fundraising needs, as well as to build a more compelling case for policy and advocacy activities.

How will climate change affect Massachusetts forests?

Climate change has been described as a "threat multiplier" by the US Department of Defense and the UN Security Council, among other organizations. This term implies that the interactions among climate change and other threats are as serious as, or perhaps even more serious than the climate change threat by itself. Indeed, "threat multiplier" is an apt description of the expected climate change impacts on forests in Massachusetts. Specifically, climate change will likely worsen impacts by pests and diseases, browsing by unnaturally high deer populations, and invasion of non-native plants in the following ways:

- Milder winters allow new pests to establish such as the recent arrival of southern pine beetle (*Dendroctonus frontalis*) in southeastern Massachusetts, and remove climatic constraints on population growth of already established non-native pests such as hemlock woolly adelgid (*Adelges tsugae*).
- Die-offs of trees that open the forest canopy create opportunities for non-native plants to invade from the surroundings.
- Browsing by large deer herds and competition by non-native plants reduce growth and survival of native tree seedlings, thereby impairing forest recovery from canopy disturbances (Dey et al. 2019).

This assessment of forest vulnerabilities considers the combined impacts of climate change, pests, diseases, deer browsing, non-native plant invasions, and the interactions among them.

Threat Interactions

The multiplicative nature of the interactions among forest threats implies that progress in managing one can help mitigate the impacts of the others. A resilient forest is one where productivity and a closed tree canopy recover quickly after a major disturbance such as a hurricane or a pest outbreak. Ideally, the composition of the new generation of trees growing into canopy gaps following a disturbance would be of species that are less vulnerable than the trees that died. Unfortunately, deer herbivory frequently depresses recruitment of such desirable native species. Management actions that reduce the impact of browsing by deer and non-native plant competition could improve forest recovery, enabling the establishment of a more resilient forest. Alternatively, abundant seed from non-native plants at a site could lead to a kind of "invasive species meltdown" where the impacts of non-native species could promote invasion by other non-native species. For example, at Elm Hill Wildlife Sanctuary there are stands of white ash (*Fraxinus americana*) trees that recently died from a non-native emerald ash borer (*Agrilus planipennis*) infestation. These native ashes are being replaced by a dense tangle of non-native shrubs and lianas (i.e. woody vines). The non-native round-leaf bittersweet (*Celastrus orbiculatus*) lianas are causing further damage by overtopping and breaking saplings and trees. Although deer browse on bittersweet, liana growth still outpaces that of any native trees in the area. It is doubtful that such non-native weed tangles could recover a closed canopy forest of native trees anytime soon without active management intervention. Suppression of non-native plant infestations and deer herbivory is a tangible way to increase forest resilience to the impending impacts of climate change. Reducing the abundance of seeds spreading from mature non-native shrubs and lianas is more important to resilience than eradicating all non-native plants. This prioritization could substantially reduce the effort in non-native plant management for the species such as bittersweet where most seeds are produced by individuals growing in sunny habitats such as a forest edge or an abandoned field.

Carbon Offset Project Vulnerability

The need for increasing management efforts to mitigate forest vulnerabilities is becoming urgent if forests are to act as carbon sinks. While forests ravaged by megadroughts, bark beetles, and wildfires in western North America have garnered a lot of media attention, the outlook for forests in northeastern North America is also dire. Consider the 10 wildlife sanctuaries comprising Mass Audubon's forest carbon offset project as a representative sample of forests in central and western Massachusetts. By 2050, half the trees in the project area will be vulnerable to dying from climate change, and/or pests and diseases (Table 1). Mass die-offs of canopy trees associated with these vulnerabilities would likely tip the balance from these sanctuaries being a net carbon sink to becoming a net carbon source over this period. Such alarming pest and disease hazards to forest carbon storage were quantified in several northeastern North American forests (Gunn et al. 2014, Case et al. 2017, Fei et al. 2019, Finzi et al. 2020).

The surviving forests at the forest carbon offset project sites will be highly dependent on the continued health of just two species: northern red oak (*Quercus rubra*) and red maple (*Acer rubrum*) (see Table 1). Neither of these species is reproducing satisfactorily in the sanctuaries where deer browsing is severe. Moreover, if we are unlucky, a new pest or disease attacking maples or oaks could arrive in Massachusetts. Possibilities include the arrival of oak wilt, to which red oaks are susceptible, from the Midwest, or Asian longhorned beetle (*Anoplophora glabripennis*), whose preferred hosts are maples, escaping from eradication efforts in central Massachusetts (Haavik 2019). Such a worst-case scenario is not unrealistic given that one major new pest or pathogen has been arriving in the region about once per decade (Appendix 2). Assuming this trend continues, we can expect a couple more genera to be devastated by a new pest or disease by 2050, and possibly all common tree genera in Massachusetts as soon as by the end of this century.

In the past, when a tree species suffered a population collapse form the introduction of a new pest or disease, there have always been other species that could take the place of the species that was devasted by the pest or pathogen. Some Mass Audubon wildlife sanctuaries will soon run out of unimpacted tree species that can take over canopy tree functions. Even in the unlikely scenario that no new pests or diseases arrive in the region, the combination of climate change, non-native pests, and diseases is jeopardizing the forest carbon sequestration goal called for by the State of Massachusetts's Clean Energy and Climate Plan for 2050. It would be timely for Mass Audubon conservation scientists and government relations staff to increase awareness of the severity of this climate change vulnerability among state elected officials and the public along with specific recommendations on how to mitigate it.

Table 1: Initial tree inventory on the carbon offset project's 212 forest plots in 2016. These plots are a representative sample of the forests covering the entire project area, which includes the following 10 Mass Audubon wildlife sanctuaries: Cold Brook, Graves Farm, High Ledges, Old Baldy, Pleasant Valley, Poor Farm Hill, Rutland Brook, Wachusett Meadow, West Mountain, and Whetstone Wood.

Species Common Name	Vulnerabilities	% of Basal Area
Eastern Hemlock	Climate, pests	23.0
Red Maple		19.8
Eastern White Pine	Climate, disease	18.9
Northern Red Oak		14.4
American Beech	Disease	3.5
Yellow Birch		3.2
Sugar Maple		3.1
Black Birch		3.1
Black Cherry		2.5
Red Spruce	Climate	2.2
Paper Birch	Climate	2.0
White Ash	Pest	1.9
White Oak		0.9
Other Species		1.0
Subtotal Vulnerable		51.5
Subtotal Not Vulnerable		48.5
Total		100.0

Management Recommendations

The following management actions could contribute to mitigating the impacts of climate change on forests in Mass Audubon wildlife sanctuaries:

- Open Mass Audubon properties to deer hunting. Ideally, all Mass Audubon properties where deer browsing is severe or moderate would be included (see summary map 6 for deer impact assessment). The deer population and its impact on vegetation should be monitored to evaluate progress. Larger properties should be the priority for hunting and deer monitoring because it is more difficult to have an impact on properties that make up only a fraction of a deer's home range.
- Dramatically increase the pace of suppressing priority non-native plant infestations at Mass Audubon wildlife sanctuaries over the next decade with contractors that are licensed to apply herbicides. The first step is to raise funding to match USDA Natural

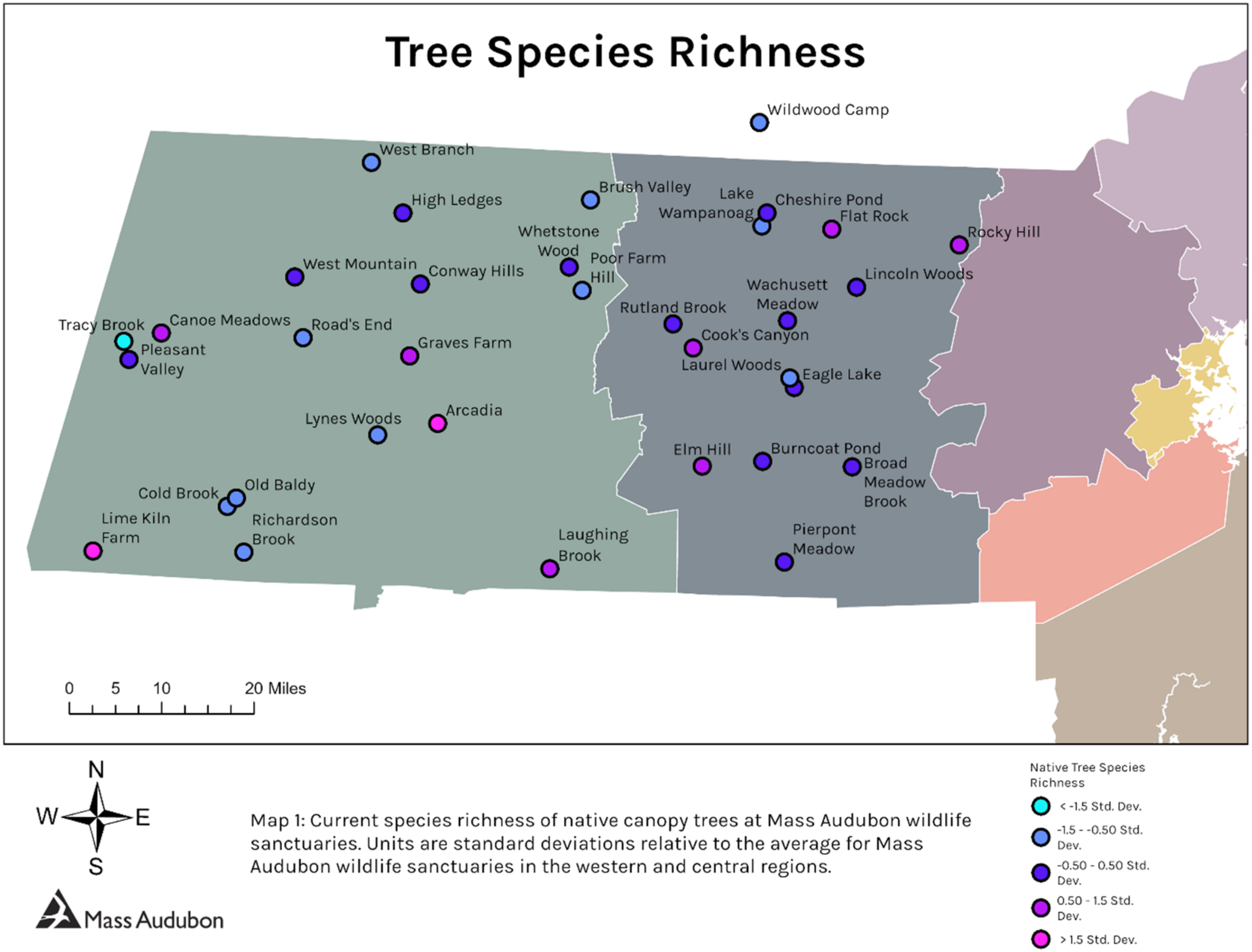
Resource Conservation Service grants such as RCPP. Estimates for non-native plant infestation areas in central and western region Massachusetts Audubon wildlife sanctuaries are about **1,100 acres** for severe vulnerability and **2,400 acres** for moderate vulnerability (Summary table 4). Applying the 2023 fiscal year Natural Resources Conservation Service's Conservation rates for Practice Standard 314, Brush Management, of $174.32/acre for "Chemical, Difficult & Follow-up" and $102.01/acre for "Chemical, Moderate & Follow-up", the estimated total cost is around $437,000. This number should be rounded up to $500,000 to account for inflation over the next decade. If NRCS continues to cover 75% of costs, Mass Audubon would need to raise $125,000 total or a minimum of **$12,500 per year** to adequately suppress non-native plant invasions on its western and central region wildlife sanctuaries over the next decade. Staff time required to prepare plans, obtain permits, and manage grants and contracts is an additional cost. Spatial variation in severity of non-native plant invasion vulnerability across each assessed sanctuary is mapped in the West and Central Sanctuary Vulnerability web maps.

- Initiate a climate change adaptation tree planting program implemented by staff and volunteers. While some wildlife sanctuaries have a high species richness including many species adapted to future conditions (Summary maps 1-3), there are many wildlife sanctuaries that could benefit from plantings that augment the present species mix with eastern North America species that are adapted to a warmer climate than the climate that the sanctuary presently experiences. Twice annually (in spring and fall), the program could plant trees and/or do maintenance on previous plantings. The goal would be to plant a total of around 300 tree seedlings with protection against deer browse at each of 15 to 20 wildlife sanctuaries over a decade. Assuming a cost of $50/tree (tree=15, post=10, wire mesh=10, logistics & miscellaneous=5), the cost of materials would be $180,000 - $240,000 total over a decade, or on average around **$21,000 per year**. Staff time spent organizing volunteer days, participating in plantings, and doing monitoring is an additional cost. Recommendations for planting sites and species choices are detailed on the Climate Change Adaptation Tree Planting web maps that are associated with this vulnerability assessment.
- Restore stream channel morphology to benefit stream biota and reduce flood hazards. Specific actions that could reduce downstream flood hazard and restore habitat include dam removals (Rutland Brook, West Mountain), undoing channelization (Broad Meadow Brook), or adding logs to channels that lack structural diversity (Arcadia, Laughing Brook).
- Identify potential sites for restoring rich mesic forest herb layers within Mass Audubon Wildlife Sanctuaries. Understory herbs that disperse only short distances such as ant-dispersed spring ephemeral wildflowers may not have recovered after agricultural fields reverted to forest across the region. Rich mesic forest habitats are now also threatened by climate change and intense deer browsing. The integrated moisture index maps developed for the assessments can help identify sites that are likely to have adequate moisture. Some of these rich mesic sites may not work as restoration sites because of intense deer browsing or evergreen tree dominance. Actual restoration may require waiting for an opportune moment such as the mortality of the hemlock overstory that subsequently creates a jumble of large woody debris that deters deer from entering the area. In other cases, all the requisite factors for restoration may be present now.

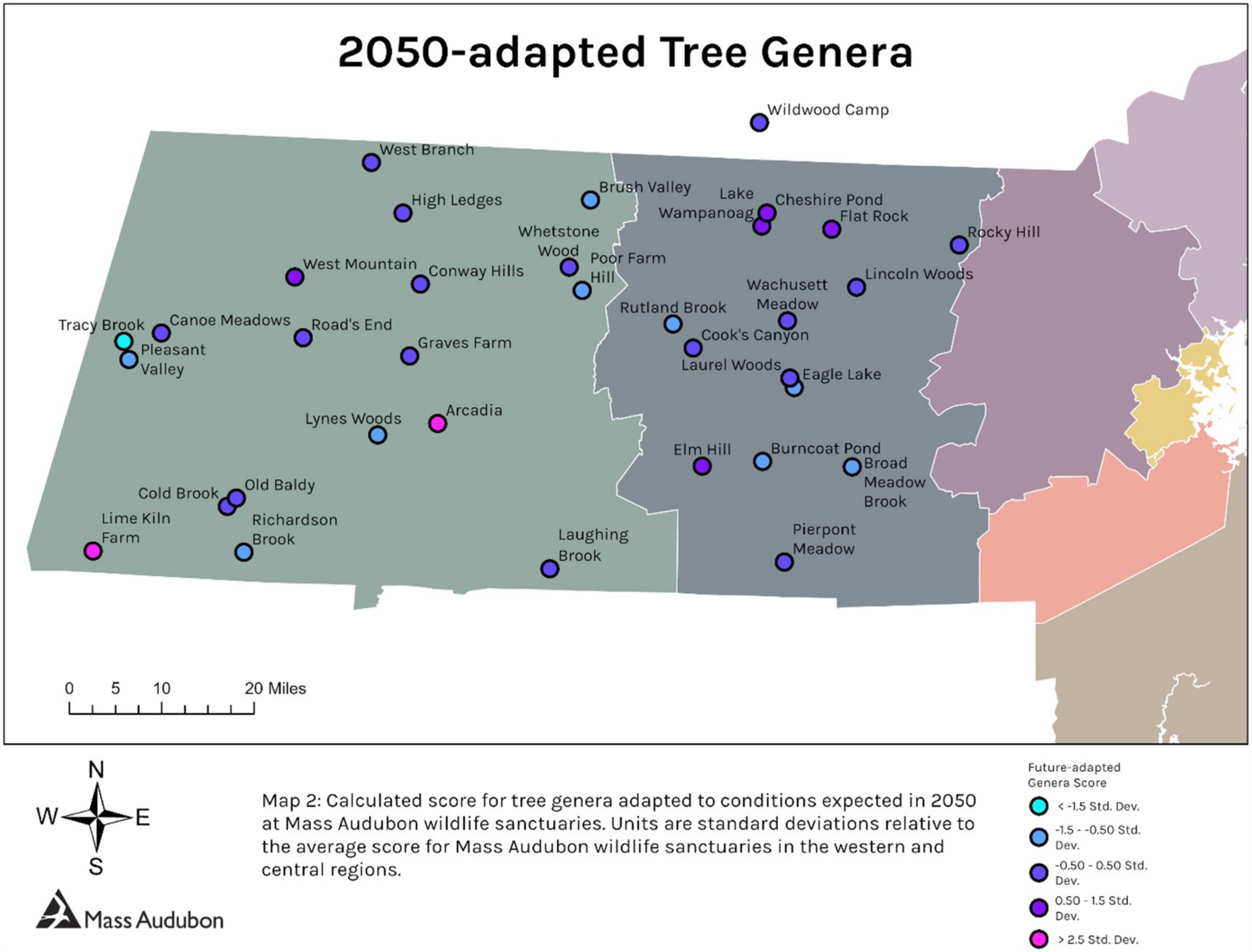
- Refine Mass Audubon land protection priorities through the lens of climate change, as follows:
    - Expand protection around the wildlife sanctuaries that are the least vulnerable to climate change (see assessment summary maps).
    - Canyons, coves, and steep ravines on properties neighboring Mass Audubon wildlife sanctuaries could provide cool moist micro-refuges from climate change and should therefore be a high priority for land acquisition.
    - Floodplains provide vital flood attenuation functions that are expected to be even more valuable for protecting people and infrastructure under a changing climate. Floodplain wildlife sanctuaries such as Arcadia WS also stand out in terms of their native species richness (summary map 1), including rare and threatened species. Expanding land protection in large floodplain areas should be a high priority.
- Rehabilitate hayfields that have been substantially invaded by woody plants including by non-native species. This practice may include herbicide application, tilling, and seeding forage grasses and forbs, and occasional prescribed burns. Non-native woody plants around the edges of the fields need to be controlled because most non-native plant invasions into neighboring forest emanate from field edges. Hayfields that could support nesting grassland birds such as bobolinks (*Dolichonyx oryzivorus*) should be a priority. Other fields that are not viable as grassland bird habitat to justify the upkeep cost should be considered for reforestation, which is also an opportunity for implementing a climate change adaptation tree planting.

This assessment and its management recommendations is not a report card on the past management of these Mass Audubon properties. Rather this assessment investigates how to expand and modify the successful past ecological management efforts from a climate change perspective. The assessment maps and report tables quantify the vulnerabilities that would develop in the absence of management actions. Although not all vulnerabilities can be avoided, management actions can mitigate many vulnerabilities.

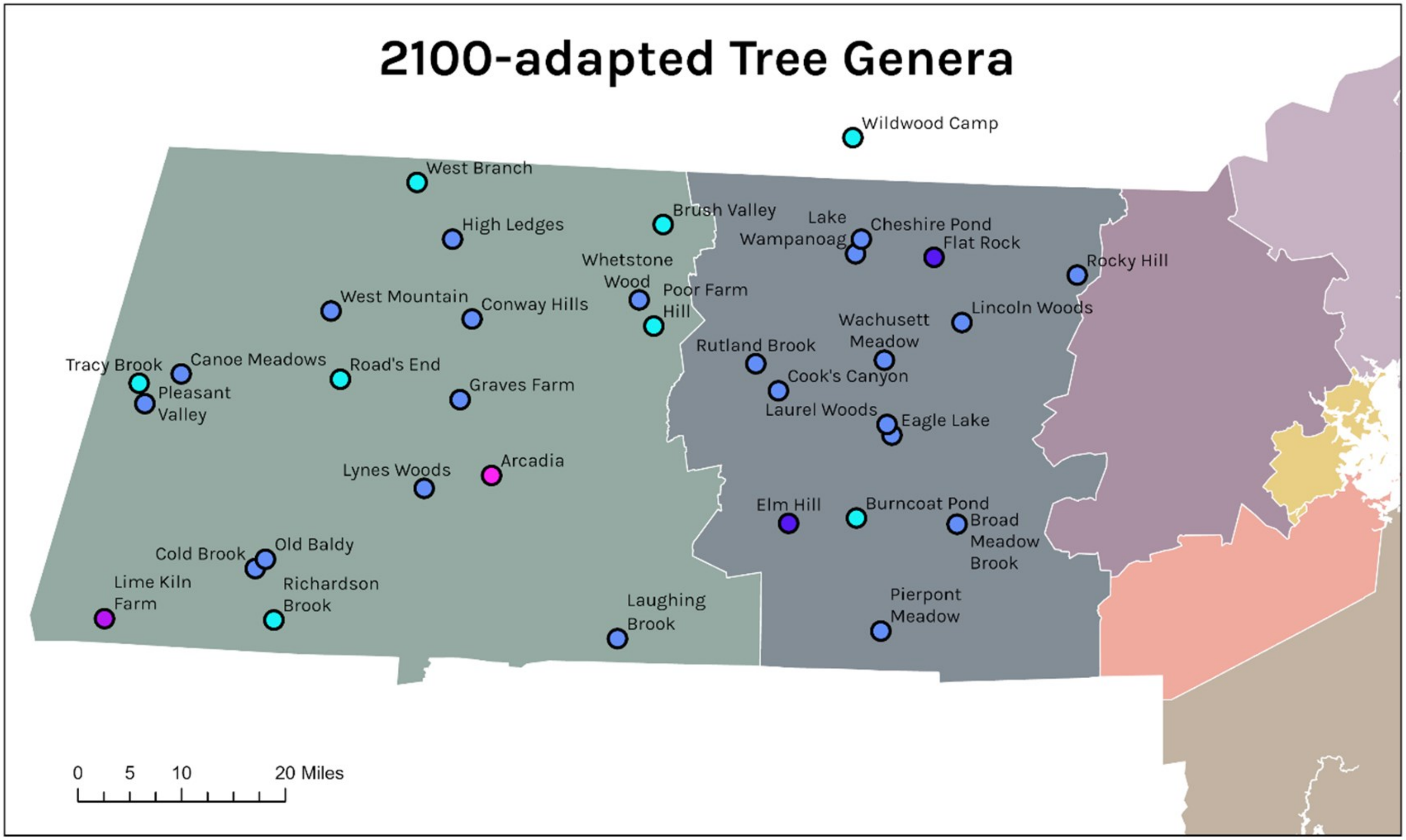
Summary Maps



Map 1: Current species richness of native canopy trees at Mass Audubon wildlife sanctuaries. Units are standard deviations relative to the average for Mass Audubon wildlife sanctuaries in the western and central regions.



Map 2: Calculated score for tree genera adapted to conditions expected in 2050 at Mass Audubon wildlife sanctuaries. Units are standard deviations relative to the average score for Mass Audubon wildlife sanctuaries in the western and central regions.



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Map 3: Calculated score for tree genera adapted to conditions expected in 2100 at Mass Audubon wildlife sanctuaries. Units are standard deviations relative to the average score for Mass Audubon wildlife sanctuaries in the western and central regions.

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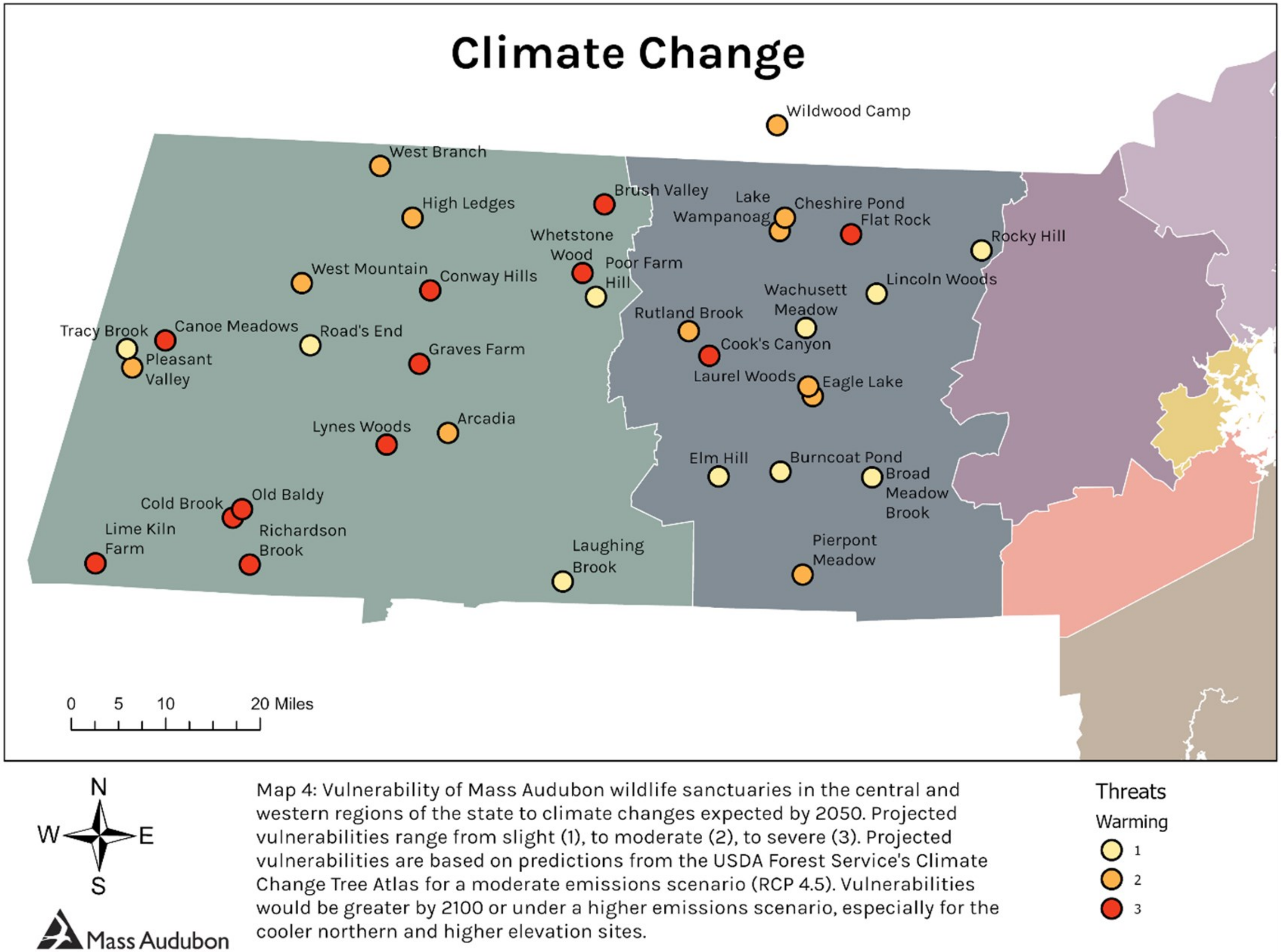
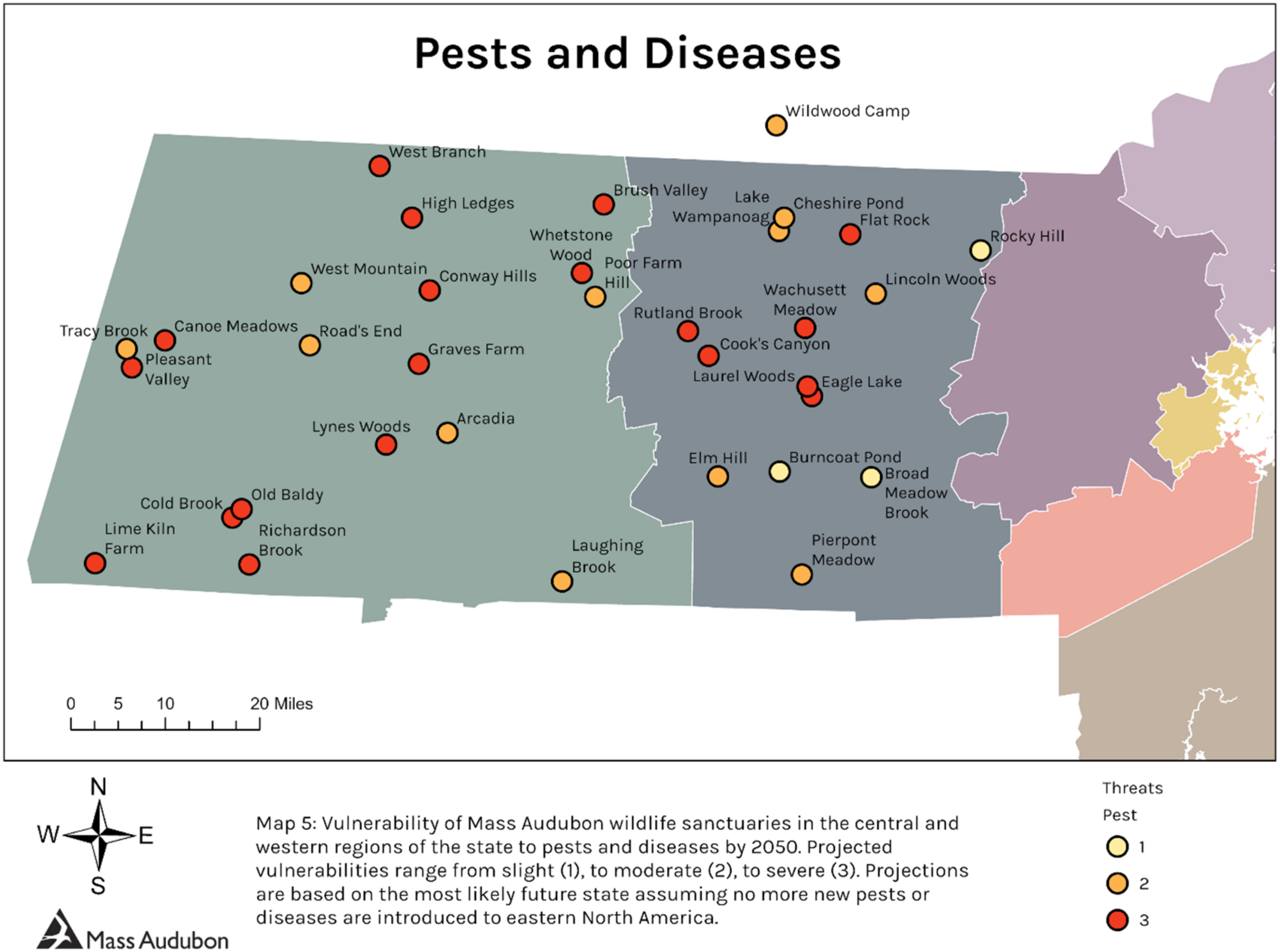
Future-adapted Genera Score

Genera 2100

- < -0.50 Std. Dev.
- -0.50 - 0.50 Std. Dev.
- 0.50 - 1.5 Std. Dev.
- 1.5 - 2.5 Std. Dev.
- > 2.5 Std. Dev.



Map 4: Vulnerability of Mass Audubon wildlife sanctuaries in the central and western regions of the state to climate changes expected by 2050. Projected vulnerabilities range from slight (1), to moderate (2), to severe (3). Projected vulnerabilities are based on predictions from the USDA Forest Service's Climate Change Tree Atlas for a moderate emissions scenario (RCP 4.5). Vulnerabilities would be greater by 2100 or under a higher emissions scenario, especially for the cooler northern and higher elevation sites.



Map 5: Vulnerability of Mass Audubon wildlife sanctuaries in the central and western regions of the state to pests and diseases by 2050. Projected vulnerabilities range from slight (1), to moderate (2), to severe (3). Projections are based on the most likely future state assuming no more new pests or diseases are introduced to eastern North America.

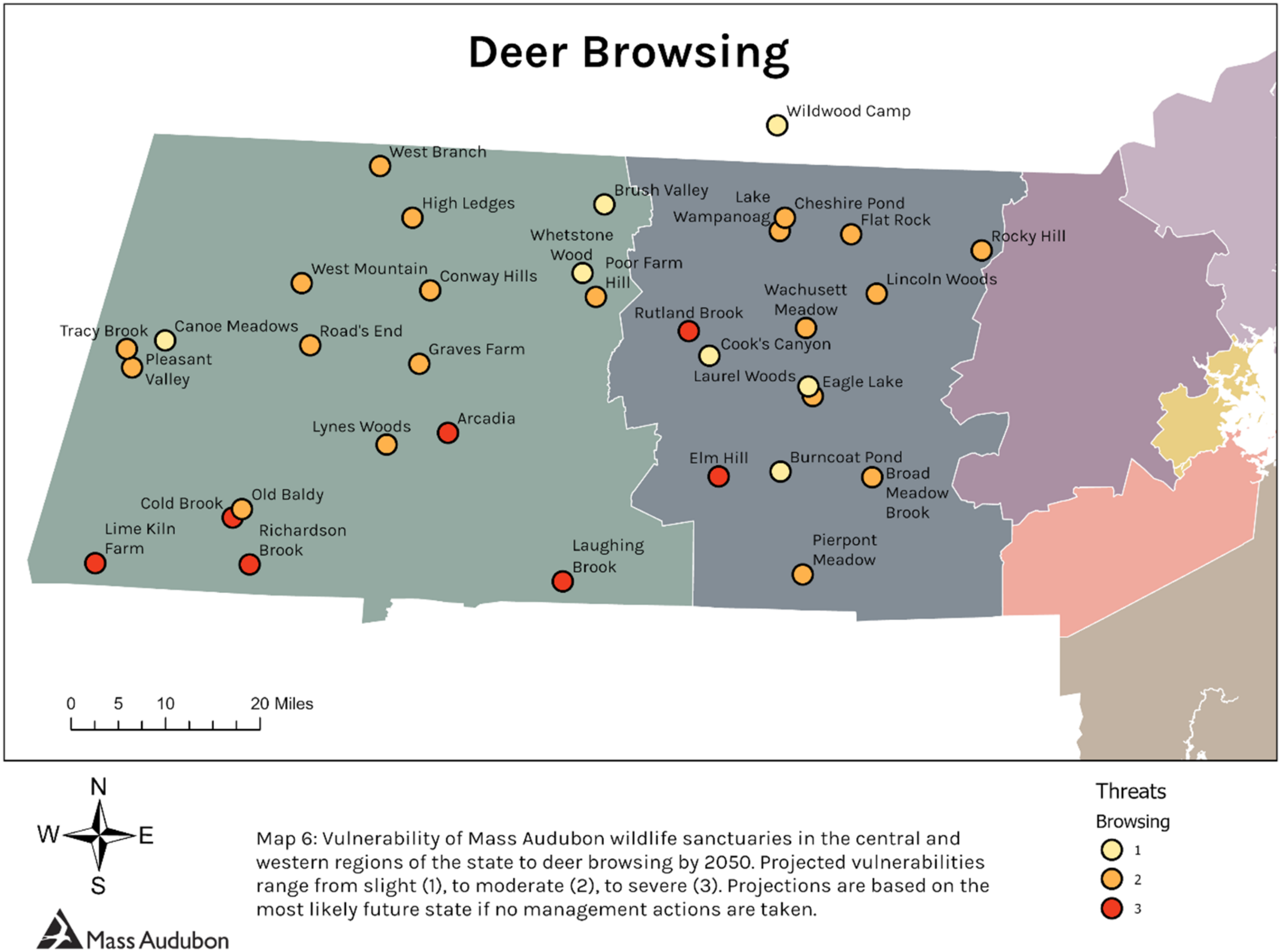
Threats

Pest

1

2

3



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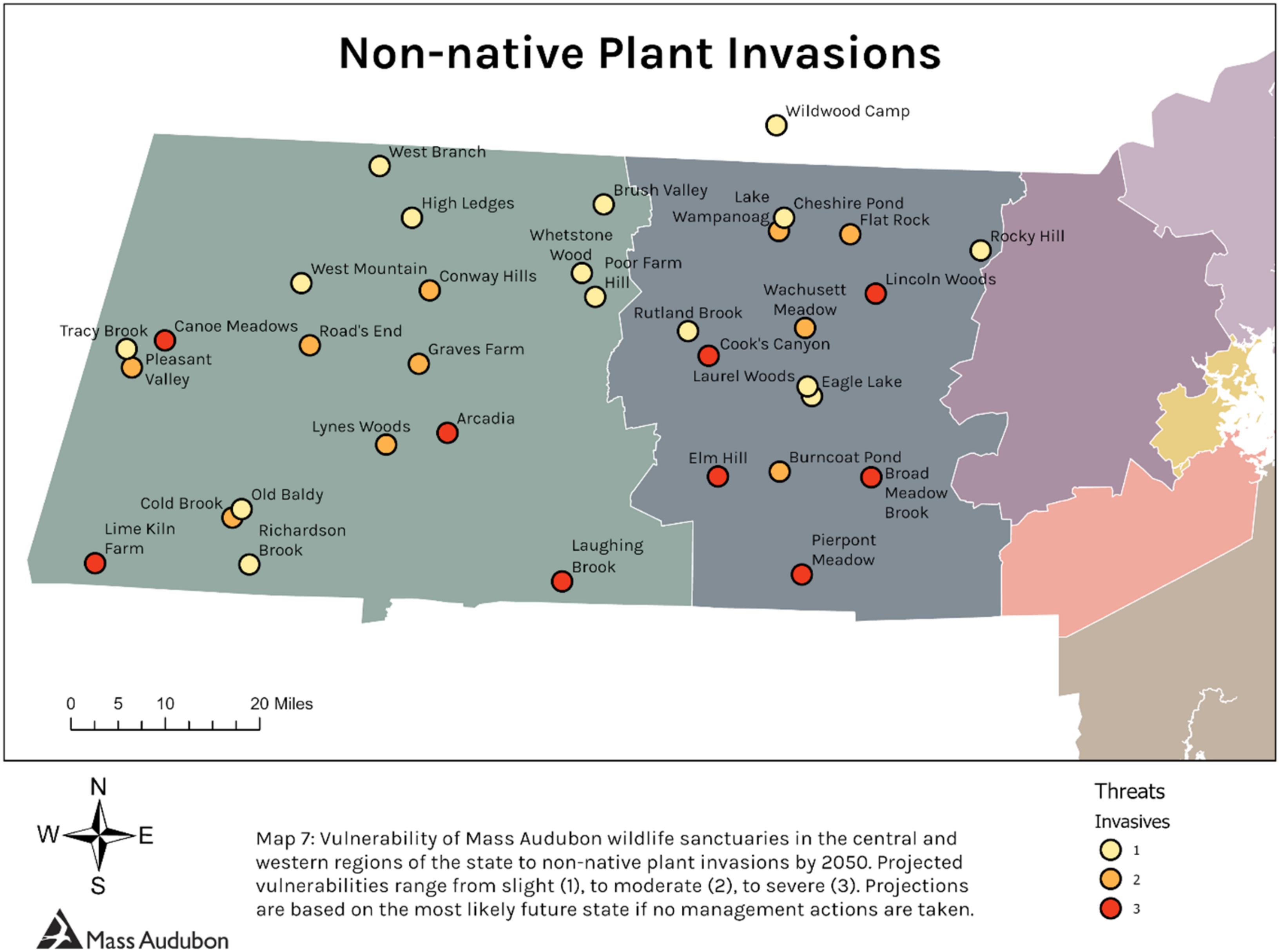
Map 6: Vulnerability of Mass Audubon wildlife sanctuaries in the central and western regions of the state to deer browsing by 2050. Projected vulnerabilities range from slight (1), to moderate (2), to severe (3). Projections are based on the most likely future state if no management actions are taken.



Map 7: Vulnerability of Mass Audubon wildlife sanctuaries in the central and western regions of the state to non-native plant invasions by 2050. Projected vulnerabilities range from slight (1), to moderate (2), to severe (3). Projections are based on the most likely future state if no management actions are taken.

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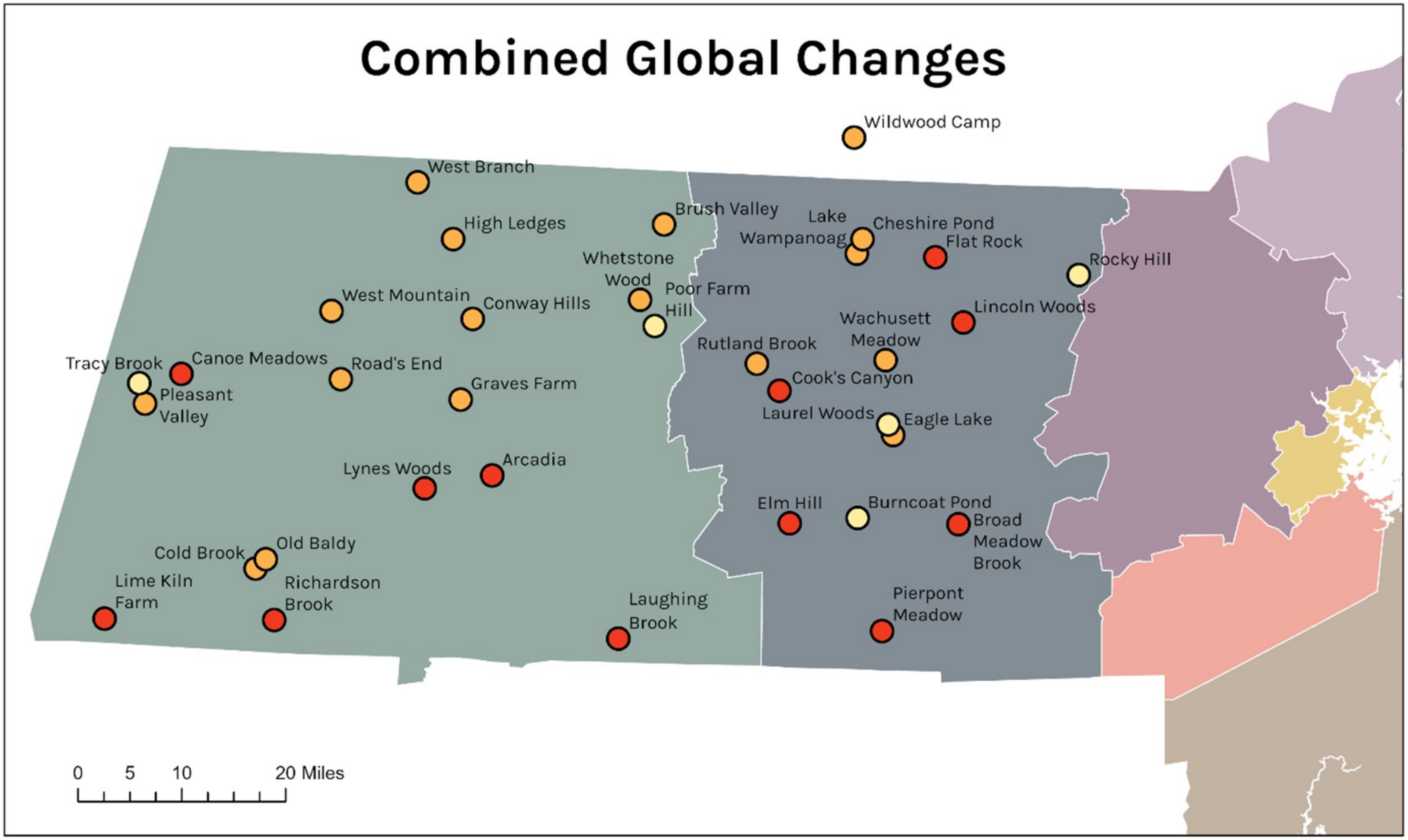

Map 8: Vulnerability of Mass Audubon wildlife sanctuaries in the central and western regions of the state to global changes expected by 2050. Global changes included in the combined vulnerability include climate change, diseases and pests, deer herbivory, and non-native plant invasions. Projected vulnerabilities range from slight (1), to moderate (2), to severe (3). Projections are based on the most likely future state if no management actions are taken.

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Summary Tables

Table 1: **Combined change** - habitat areas (acres) in Mass Audubon wildlife sanctuaries in the Central and West Regions classified by vulnerability by 2050 in the absence of management actions. The combined change vulnerability assessment combines the impacts of climate change, non-native plant invasions, browsing intensity, diseases, and pests. Management actions could alter current trajectories and the consequent outcomes.

REGION	HABITAT	SLIGHT	MODERATE	SEVERE	TOTAL
CENTRAL	Upland	2133	2584	1500	6217
	Wetland	489	308	146	943
	Forest	2134	2613	1399	6146
	Non-forest	488	279	248	1015
	Subtotal	2622	2892	1646	7160
WEST	Upland	2929	4604	3482	11015
	Wetland	456	367	286	1109
	Forest	2552	4666	3593	10811
	Non-forest	833	306	174	1313
	Subtotal	3385	4971	3768	12124
TOTAL		6007	7863	5414	19284

Table 2: **Climate change** - habitat areas (acres) in Mass Audubon wildlife sanctuaries in the Central and West Regions classified by assessed climate change vulnerability by 2050. Management actions could alter current trajectories and these projected outcomes.

REGION	HABITAT	SLIGHT	MODERATE	SEVERE	TOTAL
CENTRAL	Upland	3185	2576	455	6217
	Wetland	721	152	70	942
	Forest	2995	2657	492	6145
	Non-forest	911	71	33	1014
	Subtotal	3906	2728	525	7159
WEST	Upland	3845	4664	2507	11015
	Wetland	801	188	120	1109
	Forest	3410	4785	2616	10811
	Non-forest	1236	67	10	1313
	Subtotal	4646	4851	2626	12124
TOTAL		8552	7579	3152	19283

Table 3: **Pests & diseases** - habitat areas (acres) in Mass Audubon wildlife sanctuaries in the Central and West Regions classified by assessed disease and pest vulnerability by 2050. Management actions could alter this vulnerability.

REGION	HABITAT	SLIGHT	MODERATE	SEVERE	TOTAL
CENTRAL	Upland	2681	2336	1200	6217
	Wetland	753	145	45	943
	Forest	2465	2447	1232	6144
	Non-forest	969	33	12	1014
	Subtotal	3434	2481	1245	7160
WEST	Upland	3775	4385	2856	11016
	Wetland	728	193	187	1108
	Forest	3281	4507	3022	10810
	Non-forest	1222	71	20	1313
	Subtotal	4503	4578	3043	12124
TOTAL		7937	7059	4288	19284

Table 4: **Non-native plant invasions** - habitat areas (acres) in Mass Audubon wildlife sanctuaries in the Central and West Regions classified by projected severity of invasion by non-native plants by 2050 in the absence of management actions. Management actions could diminish this degradation.

REGION	HABITAT	SLIGHT	MODERATE	SEVERE	TOTAL
CENTRAL	Upland	5221	560	436	6217
	Wetland	658	212	72	942
	Forest	5333	515	297	6145
	Non-forest	546	257	212	1015
	Subtotal	5879	772	508	7159
WEST	Upland	9355	1164	496	11015
	Wetland	559	444	106	1109
	Forest	9085	1293	433	10811
	Non-forest	829	315	169	1313
	Subtotal	9913	1608	602	12124
TOTAL		15793	2380	1111	19283

Methods Summary

Predicting the future state of a forest involves uncertainty especially as global change creates increasingly novel ecosystems. For that reason, the assessment is based on predictions for 2050, a sufficiently near-term date that extrapolating current trends is reasonable. Many unpredictable events are likely to occur in the longer term. For example, a hurricane occurring, or a new disease arriving are unpredictable events that are unlikely to happen in any one year but are increasingly likely to occur at some time over a longer period. The date of 2050 is also convenient for planning management actions because the ambitious forest carbon sequestration goal called for by the State of Massachusetts's Clean Energy and Climate Plan is for 2050.

This vulnerability assessment at the forest stand level builds on prior regional scale assessments by others, including frameworks developed by the Northern Institute of Applied Climate Science (NIACS), which acts as a knowledge hub for climate change vulnerability assessments and climate change adaptation project plans (Butler et al. 2015, Janowiak et al. 2018, Northern Institute of Applied Climate Science 2023). A review of the recent scientific literature on climate change vulnerabilities and adaptation strategies also helped to build on the collective expertise of the research community. Most forest climate change vulnerability assessments in the eastern United States, including this one, relied on the empirical models relating tree species distributions to climate and soils developed by the USDA Forest Service. The model predictions are available in map form through the Climate Change Tree Atlas, now in its 4th edition (Prasad, AM; Iverson, LR; Peters, MP; Matthews 2014). These predicted tree abundance responses to climate change are summarized for Massachusetts in Appendix 1. However, there is much climatic variation within the state of Massachusetts (Figure 1), which required an assessment in the local context of each wildlife sanctuary.

When assessing the likely future state of a forest, it is important to consider the local factors that affect future tree species abundances, which include the following:

- **local climate** – climate varies substantially across central and western Massachusetts (Figure 1 on next page). In particular, the higher elevations in the Berkshire Mountains of western Massachusetts (e.g. West Mountain Wildlife Sanctuary) and the southern end of the Wapack Mountain Range in central Massachusetts (e.g. Cheshire Pond Wildlife Sanctuary) have a noticeably colder climate. These cool local climates support outliers of northern forest types such as spruce – fir.
- **local soils** – some plant species indicate either nutrient rich soils such as basswood (*Tilia americana*) or nutrient poor soils such as scarlet oak (*Quercus coccinea*), much as some plants indicate a history of flooding such as silver maple (*Acer saccharinum*) or fire such as pitch pine (*Pinus rigida*). Since plants share soil preferences with other species, it is possible to use these indicator species to assess if the soils at a site would be appropriate for another species that is presently absent but might be introduced under a warmer climate. Indicator species were noted during field visits of sites and aided in helping to define distinct habitat patches such as rich mesic deciduous forest.

USDA Plant Cold Hardiness Zone Map (2023 update)

Temp (F)	Zone	Temp (C)
-60 to -55	1a	-51.1 to -48.3
-55 to -50	1b	-48.3 to -45.6
-50 to -45	2a	-45.6 to -42.8
-45 to -40	2b	-42.8 to -40
-40 to -35	3a	-40 to -37.2
-35 to -30	3b	-37.2 to -34.4
-30 to -25	4a	-34.4 to -31.7
-25 to -20	4b	-31.7 to -28.9
-20 to -15	5a	-28.9 to -26.1
-15 to -10	5b	-26.1 to -23.3
-10 to -5	6a	-23.3 to -20.6
-5 to 0	6b	-20.6 to -17.8
0 to 5	7a	-17.8 to -15
5 to 10	7b	-15 to -12.2

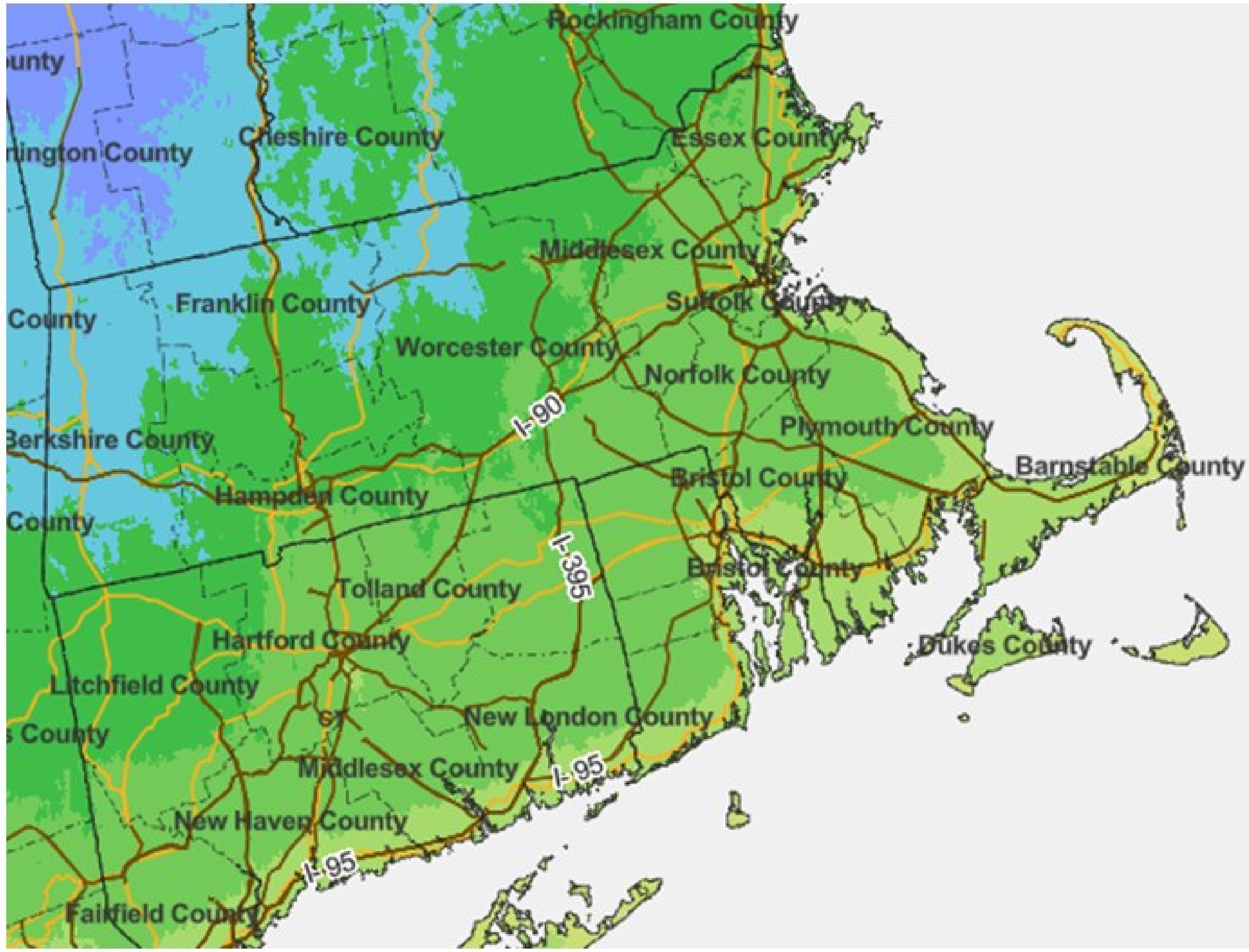


Figure 1: Plant cold hardiness zones in Massachusetts that are based on winter minimum temperatures. Winter minimum temperatures are warmer in the milder coastal parts of southeastern Massachusetts, whereas the higher elevations in the northwestern part of the state experience the coldest winters.

- **moisture availability** – turnover in forest types across a variable topography are related to moisture gradients. For example, sugar maple – white ash forest is often on east-facing slopes that receive sun during the cooler morning hours, whereas oak – hickory forest is often on west-facing and south-facing slopes that receive sun during the hotter midday and afternoon hours. Cool, shaded north-facing slopes and steep ravines tend to be dominated by hemlock – birch forest, while dry hilltops and sandy sites are often dominated by pine – oak forest. Similarly, wetlands and floodplains support distinct forest types. The warmer the weather, the more water a tree needs. Consequently, trees at the trailing edge of the distribution tend to become increasingly restricted to the moister part of their habitat such as the margins around wetlands. Similarly, at the advancing edge of the distribution, many species are restricted to the warmer parts of their habitat, such as south facing slopes. Several GIS datasets helped to define habitat patches differing in moisture. A wetlands shape file exists for Massachusetts to map the wettest habitats. For uplands, we computed an integrated moisture index that was mapped at a 10x10 m resolution over the entire state. The moisture index combined downslope accumulation of surface runoff, the effect of slope and aspect on insolation, and the water storage capacity of the soil.
- **forest succession** – forest composition is constantly shifting over time as conditions change. The dominant form of change over the last century has been succession following abandonment of agricultural fields. Abandoned fields are initially colonized by pioneers such as eastern white pine (*Pinus strobus*), aspen (*Populus tremuloides, P. grandidentata*), and black cherry (*Prunus serotina*) that gradually give way to more shade tolerant species such as hemlock (*Tsuga canadensis*), sugar maple (*Acer saccharum*), and beech (*Fagus grandifolia*). How long pioneers such as white pine persist depends on their vigor, which was noted during field visits. Pines in dense stands tend to decline in vigor whereas more widely spaced pines can remain vigorous for over two centuries. Invasion by non-native plants is dependent on the successional context. For example, a shade tolerant species such as Norway maple (*Acer platanoides*) can establish in the forest understory, whereas a shade-intolerant species such as tree of heaven (*Ailanthus altissima*) requires a sizeable canopy gap to establish. Successional trends were assessed during field visits by comparing the composition of overstory and understory trees.
- **pest and disease outbreaks** – most of the hundreds of native insect species that feed on trees do little damage to vigorous trees because the trees have evolved some resistance, although some native insects can have damaging outbreaks when forests have a high abundance of low vigor host trees. By contrast, there is an increasing number of non-native pests and diseases that can kill even vigorous trees of certain species that lack resistance. Field work identified forest stands with a high abundance of trees that are vulnerable to these severe pests and diseases (listed in Appendix 2).
- **competition by non-native plants** – the abundance of non-native plants was estimated visually in the stand and in the edge habitats around it to assess vulnerability of the habitat to becoming dominated by non-native plants either in the herb, shrub, or tree layers by 2050, assuming no management action.

- **herbivory** – the severity of deer herbivory was assessed in the field by looking at the seedlings and saplings in forest canopy gaps. Specifically, the prevalence of browsed twigs on seedlings was noted. Moreover, whether seedlings of species that are vulnerable to browsing such as red oak are successfully growing beyond the height that deer can reach is a critical threshold of browsing severity.

How to combine these factors in a vulnerability assessment? The approach taken here presents vulnerabilities as slight, moderate, or severe based on the future state that is likely to develop from the various interacting factors in the stand over the coming decades in the absence of management action. To illustrate, a likely scenario for change in a mixed forest with an overstory of red oaks and a midstory dominated by hemlock with some red maple and black birch (*Betula lenta*) might be the following: 1) as the climate warms, the hemlock, which makes up more than a quarter of the forest basal area, is killed by an expanding hemlock woolly adelgid population; 2) growth rate of overstory red oaks increases in response to a warmer climate and to being freed from hemlock competition; 3) severe browsing by deer hinders most native tree regeneration in canopy gaps except for eastern white pine, which will fare poorly under a warmer climate in the longer term; 4) non-native plants proliferate in the many canopy gaps that were opened by the hemlock die-off. Such an ecologically undesirable future state would be assessed as severely vulnerable. Alternative approaches to this scoring approach were also considered, but ultimately rejected. For example, simply assigning scores to individual factors and averaging yields an index that would be difficult to interpret at best and could be misleading at worst because it would not account for important interactions among the factors. Instead, we focused on the likely outcome of current trends and their interactions extrapolated to 2050.

Management recommendations follow directly from the assessment scoring and suggest how the trajectory of the forest might be directed towards a more desirable future state, if possible and/or desirable. In the above example, the management actions would be to introduce deer hunting and to control the non-native plant populations that have already invaded around the edges of the forest. The detailed methods of how vulnerabilities were assessed can be found in the last section of this report.

Regional Summary

Climate Change

Temperature

Global warming is increasing. For instance, in 2023, ocean temperatures, which dominate the global climate and sea level rise, hit a new record high for the fifth year in a row (Cheng et al. 2023, You 2024). According to the Copernicus Climate Change Service, 2023 was officially the hottest year on record. Indeed, the past decade is the warmest on record (World Meteorological Organization 2023).

While global warming is still increasing, the rate of increase in greenhouse gas emissions is slowing. At the time of the Paris Climate Summit in 2016, the world was mostly still following a worst-case scenario for emissions. Substantial progress has been made since then in curbing emissions. Consequently, global climate change projections are now on a trajectory towards around 3°C (5.5°F) warming rather than over 4°C (7°F) warming (Pörtner et al. 2022). This progress could encourage more ambitious emissions reductions policies that would limit global warming to around 2°C (3.5°F), but those ambitious goals would be more challenging to implement. A further challenge for reducing emissions is that the world's population is projected to reach 10 billion humans by around 2050, according to the US Census Bureau's estimates.

According to the NOAA National Centers for Environmental Information's State Climate Summary for Massachusetts 2022, temperatures in Massachusetts have risen almost 2°C (3.5°F) since the beginning of the 20th century. They further project that the total amount of warming in Massachusetts by the end of the century could range from the current 2°C (3.5°F) to over 8°C (14°F), depending on the future emissions scenario and which part of the Bell curve of model outputs one looks at. Given current trends away from the worst-case emissions scenario, a cautiously optimistic expectation for Massachusetts might be less than a 2.75°C (5°F) warming by the end of the century. A warming of 2.25 - 2.75°C (4 - 5°F) is roughly equivalent to the difference in annual average temperature between Boston and Philadelphia. However, a latitudinal comparison of average annual temperatures, although illustrative, does not paint a full picture. For example, the Massachusetts climate may also be becoming more "maritime" and less "continental" because warming is greater in winter than in summer and greater at nighttime than during daytime (Contosta et al. 2019).

The USDA Forest Service, Oregon State University, and the Conservation Biology Institute developed a seedlot selection tool (Howe et al. 2023), which allows users to find the present day location that is the closest match to the projected future climate of a tree planting site. This tool's underlying assumption is that seeds sourced from the match location may be better adapted to the future climate of the planting site than local seed sources. This tool projects the following matches based on mean coldest month temperature and summer heat-moisture index, two climate variables that strongly affect plant species distributions, and assuming an RCP4.5 greenhouse gas emissions scenario:

- For warmer sites in the Central and West Region such as Arcadia and Broad Meadow Brook, the best 2050 matches include the coast of Long Island Sound, northern New Jersey, and southeastern Pennsylvania. By 2100, the best match shifts southward into northern Maryland.

- For coldest sites in the Central and West Region such as West Mountain, the best 2050 climate match is the triangle among Torrington, Waterbury, and New Milford Connecticut. By 2100, the best match shifts southward into northern New Jersey.
- For the warmer Boston metro area, the best 2050 climate matches are Cape Cod, Long Island, and especially northern Maryland. By 2100, the best match shifts southward into southern New Jersey and the Shanandoah Valley of northern Virginia.
- For Cape Cod, Nantucket, and Martha's Vineyard, which have a milder maritime climate, the best 2050 climate matches are present-day Cape May, Washington, DC, and the Piedmont region of Virginia. But, by 2100, the best climate matches shift either southwards or closer to the coast of Virginia.

While it is tempting to transform forest composition to match the projected future climate, it is important to remember that those warm-climate adapted species may not thrive under the current climate in many cases. For instance, at the Arcadia floodplain forest planting site, a late frost in spring 2023 killed foliage of planted tulip tree (*Liriodendron tulipifera*) and shagbark hickory (*Carya ovata*) seedlings. Both species are near their current northern range limit at Arcadia. Most of the affected seedlings grew a new set of leaves in the following weeks, but the damage no doubt slowed their growth relative to more cold hardy species that were undamaged. The level of damage suggests that planting a few individuals of warm-climate adapted species to grow seed trees that give the forest more options for adapting species composition in the future is an appropriate management action but, actions that attempt to transform the species composition more radically would be premature.

Rainfall

Although projection of rainfall by Global Climate Models are variable, there is agreement across many models that average precipitation is likely to increase in northeastern North America (Trancoso et al. 2024). Climate models also predict more frequent pluvials (periods of elevated rainfall) in eastern North America (Wu et al. 2023). Indeed, satellite measurements indicate an increase in pluvials in the northeastern United States over recent decades (Rodell and Li 2023). Much of the increase is expected as rainfall in late fall and early winter when it may not do much to alleviate summer droughts (Janowiak et al. 2018). More frequent and more severe droughts are expected as climate change continues because plants use more water in hot weather, and higher temperatures increase evaporation from soils (Li et al. 2023). According to data from the US Drought Monitor, around 40% of Massachusetts experienced extreme drought conditions in August-September of 2016, 2020, and 2022, compared to no severe droughts in the prior 15 years. By contrast, July 2023, which had over 10 inches of rain in Boston, was the second wettest on record according to local news outlets. In parts of the Connecticut River Valley, rainfall was substantially more, which led to an unusual July flood in the floodplains at Arcadia Wildlife Sanctuary. These recent events lend credence to the climate change prediction that precipitation is likely to have greater variability leading to both more frequent flooding and more frequent droughts.

Glaze Ice

Various forms of freezing precipitation can cause glaze to accumulate on twigs and branches. In extreme cases, glaze buildup from ice storms can cause branches and trees to break over extensive areas, even when winds are not strong (Siccama et al. 1976, Manion et al. 2001). Such ice storm damage is a frequent occurrence in the Berkshire Highlands of western Massachusetts, but much less common in coastal southeastern Massachusetts (Changnon and Karl 2003, Cortinas Jr. et al. 2004). Although ice storms damage most trees, not all trees are equally affected. A study from the southeastern United States has suggested that ice storm frequency could be a factor in limiting some species at the northern edge of their distributions (Lu et al. 2020). The study found that deciduous trees suffered less damage than evergreen pines, which suffered less than evergreen broadleaved species. The current restriction of the only evergreen broadleaf tree species in Massachusetts, American holly (*Ilex opaca*), to the southeastern part of the state is consistent with this hypothesis.

Freezing rain typically occurs in a relatively narrow temperature band just below the freezing point (Houston and Changnon 2007). A modeling study of freezing rain found that the present-day freezing rain maximum over eastern North America will shift poleward and weaken with the result that freezing rain events will decrease significantly in the eastern United States and the Atlantic Provinces in Canada (Lambert and Hansen 2011). A reduction in ice storm damage with climate change may allow susceptible tree species to expand their range.

Wind

Historically, wind was the most common natural forest disturbance in southern New England (Papaik and Canham 2006). Extreme wind events such as hurricanes and tornados can cause entire forest canopies to be destroyed (Curtis 1943). Historical ecologists have shown that hard-to-predict, singular events such as hurricanes can shape forests for decades to centuries (Pederson et al 2014). Most of the time, wind damage is more selective, toppling some emergent and some of the weaker canopy trees but leaving stronger canopy trees or less exposed subcanopy trees unscathed. Trees of some genera such as spruce have shallow root systems, as do trees that grow in swamps or on rock ledges, which increases their vulnerability to wind throw (Canham et al. 2001). Some modelling studies predict increasing hurricane damages in the southeastern United States due to global warming, but little change in the northeastern United States (Balaguru et al. 2023).

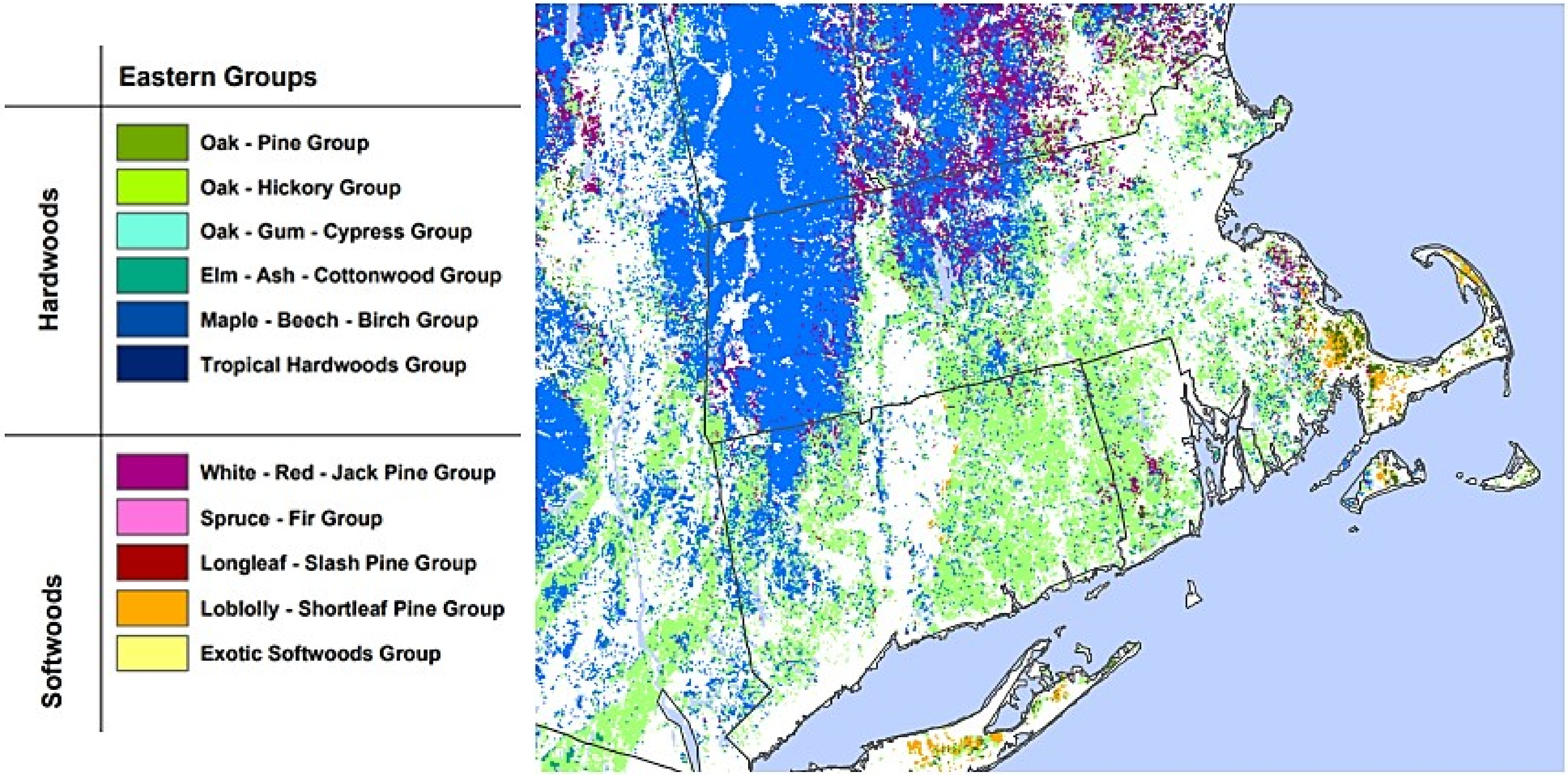


Figure 2: Map of US forest types based on the Forest Service's Forest Inventory and Analysis (FIA) plot data, zoomed in on Massachusetts. The common Massachusetts forest types include the following: Oak – Pitch Pine on Cape Cod and Islands (orange); Oak – Hickory – Chestnut Type (green) in the South-Central Region and neighboring Connecticut and Rhode Island; White Pine Type (purple) in the North-Central Region and neighboring New Hampshire; Maple – Beech – Birch – Hemlock Type (blue) in the Western Region and neighboring Vermont. Scattered patches of the White Pine Type occur locally within the other forest types where it frequently colonizes abandoned fields. In Massachusetts, the Spruce – Fir Type (pink) is restricted to the coldest spots within the Maple – Beech – Birch – Hemlock Type. The Elm – Ash – Cottonwood Type is restricted to swamps and floodplains. The other forest types in the legend do not occur in Massachusetts.

Forests

There is a climate-associated tension zone between two forest types that runs diagonally through central Massachusetts. To the southeast of the tension zone, oak – hickory forests predominate, and to the northwest, maple – beech – birch – hemlock forests predominate (Figure 2 on previous page). The oak – hickory type is associated with drier and/or more nutrient poor soils, ground fires, and especially a warmer climate. In contrast, the maple – beech – birch – hemlock types are associated with moister and/or more nutrient rich soils, infrequent disturbance, and especially a colder climate (compare figure 2 on previous page to figure 1 on page 18).

Oak-Hickory Forest

The oak – hickory forest type has suffered a lot of ecological damage in the past, yet it is expected to be relatively resistant to climate change in Massachusetts because it is at the northern end of its range here. Historically, American chestnut (*Castanea dentata*) was co-dominant with oaks and hickories in this forest type. The introduction of spongy moth (*Lymantria dispar*) in the mid-1800s followed by the spread of chestnut blight (*Cryphonectria parasitica*) in the early 1900s was tragic for oaks, chestnut, and the wildlife and economies that depended on these valuable trees. In response, managers introduced several biological controls for spongy moth. Although not implemented according to modern scientific standards, the biological controls have reduced the impact of spongy moth to less frequent outbreaks that are smaller in extent than in the past and last at most 3 years. Nevertheless, spongy moth outbreaks can occasionally still cause substantial tree mortality, such as the 2015 to 2017 spongy moth outbreak at Laughing Brook Wildlife Sanctuary. Forests where more than half of the trees are oaks are more susceptible to spongy moth outbreaks (Coleman 2023).

A century of breeding chestnuts has not yet produced selections that are sufficiently resistant to chestnut blight to restore this species. However, researchers have recently developed hypovirulent strains of the chestnut blight pathogen (Stauder et al. 2019) and a highly disease resistant American chestnut with a transgene (Newhouse et al. 2014). There is some hope that these types of new technological developments in combination with continued breeding will eventually lead to the opportunity to restore American chestnut with disease resistant trees. Given that chestnut is well adapted to a warmer future climate, these innovations offer an opportunity not only to restore a valuable tree species, but also to adapt Massachusetts forests to climate change. Aside from restoring chestnut, maintaining resilience in this forest type will require management of deer populations because oak regeneration is vulnerable to browsing. Historically, oak – hickory – chestnut forests are also associated with fire, and many oak silviculture researchers have argued that re-introducing prescribed fires is an essential component of restoring oak forests (Abrams 2003, Hart and Buchanan 2012, Iverson et al. 2017).

Maple-Beech-Birch-Hemlock Forest

Many of the species in the maple – beech – birch – hemlock forest type are vulnerable to climate change (Appendix 1). Of the species in this forest type, beech (*Fagus grandifolia*) is the best adapted to a warmer climate, but beech was devasted by beech bark disease over recent decades. Now, beech leaf disease, which appears to be caused by a nematode

(*Litylenchus crenatae mccannii*), is killing the remaining beech that had survived beech bark disease.

Hemlock comprises about a quarter of the trees in the Mass Audubon forest carbon offset project area and continues to increase in abundance as forest succession progresses in these aging stands of trees. This northern conifer species thrives in cool moist habitats such as north facing slopes, ravines, and along headwater streams. Unfortunately, hemlock is highly threatened by a warmer climate. Currently, Western Massachusetts still has sufficiently cold winters in most years to prevent hemlock woolly adelgid (*Adelges tsugae*) populations from overwhelming hemlock (*Tsuga canadensis*) trees, but a small amount of warming could allow an outbreak of adelgid. For example, most of the hemlock in Connecticut have died from adelgid outbreaks. Black birch (*Betula lenta*) currently dominates the regeneration in canopy gaps in this forest type. Black birch saplings suffered more die-back during the summer drought of 2022 than other trees, which suggests that it may not be a desirable replacement for hemlock under climate change. Thinning dense hemlock stands in the southern Appalachians increased tree vigor and resistance to hemlock woolly adelgid infestation (Mayfield et al. 2023). However, canopies should not be thinned at sites where non-native plants are likely to invade into the resulting canopy gaps.

Sugar maple (*Acer saccharum*) dominates at sites that are richer in nutrients and higher in soil pH than the sites dominated by beech or hemlock. Cooler east-facing slopes and coves that also offer more favorable moisture conditions in addition to more nutrient rich soils are especially favorable to the development of sugar maple dominated rich mesic forest. These sites are perhaps the best opportunity to foster the development of old growth forest structure because sugar maple is both long-lived and relatively resistant to climate change. However, these sites are not without problems. White ash (*Fraxinus americana*) is frequently co-dominant with sugar maple in rich mesic forest. Unfortunately, white ash is currently suffering a die-off from the recently arrived emerald ash borer (*Agrilus planipennis*).

Spruce-Fir Forest

The spruce – fir forest is a northern forest type that occurs in only the coldest locations in Massachusetts such as the top of West Mountain or at Cheshire Pond Wildlife Sanctuary. These forests are already at their climatic limit and are consequently imminently threatened by climate change. Abundant soil moisture can buffer against the impacts of climate change. Consequently, red spruce (*Picea rubens*), black spruce (*Picea mariana*), balsam fir (*Abies balsamea*), and tamarack (*Larix laricina*) have hung on the longest in cool riparian areas such as around Lake Wampanoag and Cheshire Pond. Many of the red spruce seedlings on West Mountain appear to have died in the summer drought of 2022. Even in the absence of such extreme events, northern conifer species' growth is reduced by greater vapor pressure deficits that are associated with global warming (Mirabel et al. 2023).

Pine Forest

Pine forests are common throughout the state. Eastern white pine (*Pinus strobus*) is often able to colonize abandoned fields before other species, while red pine (*Pinus resinosa*) has been planted frequently. Pitch pine (*Pinus rigida*) is common on drought prone and nutrient poor sites, often with a history of fire, especially in southeastern Massachusetts, but also occurs on Flat Rock and at Laughing Brook Wildlife Sanctuary. Pines are light demanding species that become stressed if stands are too dense. Stressed pines are vulnerable to attack by pests such as southern pine beetle (*Dendroctonus frontalis*), in the case of pitch pine. In addition, white pine and especially red pine are vulnerable to climate change. Most of the red pine plantations in Mass Audubon wildlife sanctuaries have already died, except at Wildwood Camp in New Hampshire, which has a colder climate. Needle cast disease is a fungal pathogen that kills the second-year needles on white pines, thereby substantially reducing tree vigor. Reducing the density of mature pine stands through commercial thinning can improve tree vigor and climate change resistance (Bergdahl et al. 2022). Note that canopies should only be opened by stand thinning at sites where non-native plants are unlikely to invade the resulting canopy gaps.

Other Forest Types

Urban, floodplain, and riparian forests have exceptionally high ecosystem service values, including for mitigating the impacts of climate change such as flood hazards. Floodplain tree species have been popular as urban trees because the stresses of floodplain life such as burial of roots by sediments have prepared these species well for stressful urban conditions. Indeed, before the spread of Dutch elm disease (*Ophiostoma ulmi* and *O. novo-ulmi*), American elm (*Ulmus americana*), a floodplain tree species, was the dominant tree of urban forests in New England. Floodplain forests are among the most species rich Massachusetts forests. For example, Arcadia Wildlife Sanctuary's floodplain forests have the greatest tree species richness among Central and West Region wildlife sanctuaries (see summary maps). Most floodplain tree species are well adapted to a warmer future climate. Conservation of floodplain and riparian forests is even more valuable from the perspective of climate change adaptation than it already was from a biodiversity conservation perspective. Similarly, in urban areas, mitigating climate change is another incentive for increasing native tree cover.

Forest Resilience

An ideal forest for biodiversity conservation, carbon sequestration, and resilience to climate change is diverse in terms of structure and species richness. Greater species richness helps adapt the forest to climate change by having species that together are adapted to a broader range of climate conditions. More diverse mixtures of tree species have also been shown to moderate microclimate more, have a larger leaf area, and greater productivity (Beugnon et al. 2021, Zhang et al. 2022). Some forest pest outbreaks such as spongy moth are less likely when host species are relatively less abundant, as is the case in species rich forests (Haynes et al. 2022). A forest with multiple canopy layers supports more bird species (Müller et al. 2010, Carrasco et al. 2019, Burns et al. 2020), and more fully utilizes incident light, thereby increasing productivity and carbon sequestration (Braghiere et al. 2019, Ameray et al. 2021).

The largest trees in a forest often contribute disproportionally to carbon sequestration (D'Amato et al. 2017, Keeton 2018). Unfortunately, a diverse structure that includes exceptionally large old trees as is characteristic of many "old growth" forests is increasingly unlikely to develop in Massachusetts forests because the longevity of more and more species is cut short by non-native pests and diseases. Massachusetts forest types where developing an "old growth" structure is still plausible are the following: 1) mature sugar maple stands, ideally with a large component of species that are well adapted to a warmer climate such as tulip tree, basswood, and hickories, and 2) mature stands with diverse oaks, where other warm-climate-adapted tree species such as hickories make up at least half of the stand. Ecologically motivated partial harvests could accelerate the development of a forest with such a diverse size structure and a diverse species mix that is well adapted to future conditions. Ironically, canopy tree die-offs from pests and diseases can also help to restore a more diverse age structure in the relatively uniform forests that predominate currently (Choi et al. 2023). In the case of conifers with wood that decays slowly, a die-off could also restore the deadwood component of forest structure that is much more prominent in "old growth" forests (McGarvey et al. 2015, Barton and Keeton 2018). A dense tangle of downed logs also appears to discourage deer from browsing tree seedlings in the affected area. Therefore, salvage logging is not recommended for conservation land.

Intense browsing by deer or competition from non-native plants can undermine the ability of forests to recover from canopy disturbances, whether from harvests, storms, or pest outbreaks (Fike and Niering 1999, Dey et al. 2019). Harvests should be avoided on any wildlife sanctuary where either deer browsing is intense or where non-native plants are likely to invade. Reducing severity of deer browsing and suppressing non-native plant infestations is a key management action that can increase forest resilience to climate change and other future disturbances. Among non-native plants, lianas (i.e. woody vines) such as round-leaf bittersweet (*Celastrus orbiculatus*), porcelain berry (*Ampelopsis brevipedunculata*), and hardy kiwi (*Actinidia arguta*) are particularly damaging because they can break saplings and even mature trees (Marks and Canham 2015). Other non-native lianas such as kudzu (*Pueraria montana*) could invade Mass Audubon wildlife sanctuaries with climate change (Evans et al. 2024). Early detection and rapid response will be important to avoid other lianas from having the large impact that non-native bittersweet is already having. Lianas have been shown to be more competitive relative to trees in disturbed sites, warmer climates, and at elevated CO_2 concentrations (Mohan et al. 2006, Körner 2009, Senghor K. Ngute et al. 2024). Clearly, lianas should be a priority for non-native plant species management, especially where forest carbon storage in trees is a management objective.

Canopy gaps from an ecological harvest or from a canopy tree die-off or abandoned fields are opportunities to plant tree seedlings from species that would augment the diversity of species that are adapted to future conditions. In most of Massachusetts, deer browsing is too severe for planted tree seedlings to grow into the sapling size without being protected by a wire mesh cage or a slash wall. Deer preferentially browse planted seedlings because fertilizer use in the nursery increases nutrient content of foliage, twigs, and buds compared with wild seedlings. The high cost of protecting seedlings with cages limits the size of plantings. Rather than trying to transition the forest composition immediately with a large-scale planting, a more economical approach is to create options for the forest to change its composition on its own by planting a few future seed trees of species that are currently absent or rare on the site.

The wisdom in the small-scale future seed tree planting approach is that it avoids trying to guess what the best species for the site will be in 50 or 100 years, which is prone to errors. For example, about a century ago, foresters planted many reforestation sites in Massachusetts with red pine. Red pine appeared to be an ideal tree from a forestry perspective at the time, but now these red pine plantings are among the first Massachusetts trees to die from climate change. Our current ability to predict the future may not be much better. Instead of committing to a few species on a large scale, a diversity of seed trees allows the forest to adjust its own path as the environment changes in unpredictable ways.

When planting trees intended to seed a future forest, genetic diversity that includes adaptations to a variety of environmental conditions is important. As a rule of thumb, one should generally plant 20 to 40 unrelated genotypes per species. Given the large uncertainty around climate change, those genotypes should ideally encompass several provenances that are a good match for a range of future climate predictions for the site. It is also important to remember that, in many species, genetic diversity is greatest in their glacial refuges; after glaciation only a small fraction of the genetic diversity migrated poleward from refuges. The genotypes that migrated north are sometimes the ones that were best at dispersing, not necessarily the ones that are best adapted to the environment in the expanded range. Only provenance testing can establish what the best adapted genotypes are under a particular climate. Unfortunately, provenance testing has not been done for most deciduous tree species in eastern North America. In the absence of provenance tests, a prudent strategy might be to plant mostly genotypes from sites with a reasonably good match for both the current and the likely future climates. One could supplement the climate matched provenances with a few genotypes from the glacial refuges that likely harbor more diversity, if the genotypes from the glacial refuges have sufficient cold hardiness to survive under the current climate. Sourcing of planting stock from desired provenances is currently challenging in states that do not have a state nursery, such as Massachusetts. Overcoming these planting stock challenges may require new initiatives by the conservation and forestry community.

Grasslands and Shrublands

The relatively humid climate that prevails in New England favors the succession of grasslands to shrublands and eventually to forest. Preventing succession of grassland to forest requires fire, flooding, or other disturbance that is frequent and intense enough to kill trees. Scrub oak shrublands and pitch pine barrens are maintained by fire. Fire requires flammable fuels such as dense mountain laurel or scrub oaks, accumulated pine needle or oak leaf litter, or topsoil made mostly of organic matter. These fuels are typical of dry sites where nutrients are scarce such as the sandy soils on Cape Cod. In central and western Massachusetts, fire-adapted communities such as pitch pine and scrub oak barrens are relatively rare, occurring mainly on rock ledges and in glacially deposited sand plains. A hotter climate should make lightning more common and dry out fuels more frequently. However, fire suppression has dramatically reduced the occurrence of fire. The dense settlement in the region makes it unlikely that policies to promptly extinguish wildfires will change in the foreseeable future. However, it may be feasible to introduce prescribed burns at suitable sites where fire-adapted vegetation is being restored.

Most grasslands in Mass Audubon Central and West Region wildlife sanctuaries are cultural (i.e. man-made). The decline in agriculture in New England and the associated abandonment of fields has resulted in steep long-term decline in many grassland bird species (Walsh and Servison 2017). Grazing or mowing can slow succession of these cultural grasslands to woody plant dominance, but it does not prevent succession, especially when mowing is only late in the growing season or infrequent, as is typical when mangers want to avoid harming nesting grassland birds. Consequently, herbicide application and/or plowing and seeding of forage species is needed about once a decade to maintain grass dominance. The shrubs and lianas (i.e. woody vines) that typically invade fields include many non-native species. This non-native woody plant invasion tends to be most extreme around the edges. These field-edge non-native plant infestations can spread into surrounding forest habitats and thereby undermine their resilience to climate change. Thus, the suppression of non-native plants in and around the edges of grasslands through mowing and herbicides is an important component of managing sanctuaries for resilience to climate change. The most economical way to get fields mowed is by haying them. As an alternative to hay, one could manage a succession toward native forest in fields that are too small or too isolated to be of much value as grassland habitat. Reforesting could also have a localized cooling effect because cleared land has a warmer microclimate than forest (De Frenne et al. 2021).

Wetlands and Ponds

Most wetlands in central and western Massachusetts are either beaver wetlands or vernal pools. Vernal pools are usually small in area and typically have an overhanging forest canopy from the surrounding trees. Beaver wetlands may be ponds and marshes for many decades, but often they were forests when beavers colonized the site, and eventually return to being forest following beaver abandonment. Given this close relationship between forests and wetlands in the region, it is reasonable to include wetlands in an assessment of forest climate change vulnerabilities.

Beaver dams can slow stream flows and thereby reduce flood hazards and increase soil water recharge (Nislow et al. 2024). Beaver ponds on small streams that are prone to drying up seasonally can provide more permanent water where fish can find refuge during dry spells. When beavers have depleted nearby food sources, they abandon their ponds. As dams break down and ponds drain, early successional habitat is created. Even when maintained by beavers, dams usually allow passage of fish. By contrast, mill dams rarely allow passage of fish and water levels are chronically raised in the impoundments behind them. Large impoundments also allow invasion by warm water lake fish species that can compete with and displace stream fishes. For these reasons, mill dam removals are recommended from a climate change adaptation perspective, whereas beaver dams should be removed (or bypassed) only where they interfere with infrastructure such as plugging culverts.

Hydroperiod, the time that vernal pools hold water before drying out seasonally, determines vernal pool species assemblage because species differ in larval development times (Colburn 2004). Both hydroperiod and development times depend on temperature. Development times also depend on the abundance of food. Some species are detritivores (fingernail clams, aquatic sow bugs) which require deciduous tree litter, whereas others graze on algae (snails) which requires ample light, while still other species are more predatory (salamanders) (Colburn 2004). Consequently, the vernal pool species assemblages vary dramatically not only among pools but also from year to year. The hydroperiod of small vernal pools is especially variable from year to year. The adaptations of vernal pool species to these highly variable environmental conditions should also confer resilience to climate change. Some species can survive dry periods by burying into the mud where they become dormant, while others disperse among a variety of vernal pools within proximity that differ in their size and the duration of their hydroperiod. In wood frogs (*Lithobates sylvaticus*), for example, dispersal distance is about 1 km; while for many other vernal pool amphibians it is only a few hundred meters (Colburn 2004). Creating vernal pools in abandoned fields or drained impoundments might increase vernal pool community resilience if the created pools are part of a cluster of multiple pools. However, ponds and wetlands with permanent water have predatory species such as fish and American bullfrogs (*Lithobates catesbeianus*) that are a potential threat to smaller vernal pool species. For example, fairy shrimp only survive in absence of fish. Removing small man-made dams to drain impoundments may therefore increase resilience of nearby vernal pools.

Streams

Cold water stream fishes such as brook trout (*Salvelinus fontinalis*) and slimy sculpin (*Cottus cognatus*) are sensitive to warm water temperatures. Periods of exposure to warm water temperatures cause physiological stress in cold water fishes and may make them more susceptible to pathogens and parasites (Ohmus and Orklund 2015). Cold water fishes thrive in streams that rarely have warm temperatures such as mountain streams fed by glaciers. In the absence of glaciers, such as in Massachusetts, cold water fishes need to be able to migrate to cooler microhabitats. Consequently, it is important to remove barriers to migration such as dams and perched culverts to allow these temperature sensitive species to thrive in marginal habitats. Cooler microhabitats include cutbanks on meandering streams where the stream has eroded shaded shelters under the overhanging bank, as well as deeper pools, and especially cold groundwater seeps. Climate change adaptation strategies for streams can therefore include the following:

- restoring meandering to previously straightened channels
- coarse wood addition to incised channels with a paucity of in-channel wood
- reducing the amount of warming of waters upstream by building stormwater control measures in urban areas that redirect warm (and potentially polluted) runoff from impervious surfaces into the soil
- removing dams where water is exposed to the sun in impoundments.

More generally, habitat management and watershed conservation actions that slow flows would benefit not only cold water fishes but also reduce flooding hazards for people and infrastructure (Nislow et al. 2024). Reforesting riparian buffers in fields to shade streams may also be beneficial. Protection of forested watersheds where most rainfall still infiltrates into the soil would help preserve the cool groundwater inputs into the associated stream. Improving water quality may help compensate for increasing temperatures.

Birds

Milder winters are likely to directly affect bird populations. Migratory birds may be able to overwinter further inland and further north than previously. For example, many waterfowl migrate only as far as they need to find large waterbodies that do not freeze over entirely. Year-round residents that are limited by harsh winters, could expand their range. For instance, barn owls, which are sensitive to extreme cold, have had only a minor presence in Massachusetts, mainly in the mildest coastal southeastern parts of the state (Walsh and Servison 2017). Population trends associated with increasing winter survival are initially expected to be obscured by interannual variability in winter weather but should emerge as global warming proceeds further.

Forest birds will likely be affected by climate change indirectly via changes in the vegetation that they depend on for food and habitat. The die-offs of canopy trees that are expected from the combination of climate change and emerging pests and diseases over the coming decades could affect birds in the following ways:

1) The Climate Change Tree Atlas (Prasad, AM; Iverson, LR; Peters, MP; Matthews 2014) predicts a large decline in evergreen conifers such as red spruce and eastern hemlock. We can expect declines in bird species that are denizens of hemlock-dominated habitats such as black-throated green warbler (*Dendroica virens*), or of Boreal Forest / Taiga such as Swainson's thrush (*Catharus ustulatus*), blackburnian warbler (*Dendroica fusca*) and magnolia warbler (*Setophaga magnolia*).
2) Most Massachusetts forests are relatively even-aged mature forests that established at the peak of agricultural field abandonment around a century ago. These forests lack deadwood, canopy gaps, and patches of saplings compared with old growth forests, which has contributed to the dramatic population decline of the wood thrush (*Hylocichla mustelina*) and other birds with similar habitat requirements. As an example, wood thrush require forests that are made up of multiple layers. From the ground up:
   - Decaying logs and leaf litter blanket the forest floor, providing a constant food supply of insects and other invertebrates.
   - Small shrubs and saplings provide places to hide from predators.
   - In the subcanopy layer, young trees offer viewpoints, theaters for mating-call performances, and ideal nesting sites.

   When common canopy tree species such as hemlock suffer a major die-off in the coming decades, the amount of deadwood and canopy gaps will increase, and a more multi-layered forest could develop, especially if tree seedlings and shrubs are not impacted by excessive deer browsing. Thus, forest birds that favor multi-layered forest habitats like wood thrush could benefit from a wave of climate change associated tree mortality.

3) Outbreaks of certain insect pests can be a boon for the bird species that feed on them. For example, spongy moth caterpillars are fed on by some birds such as cuckoos, blue jays, orioles, downy woodpeckers, gray catbirds, and common grackles. Black-capped chickadee, will also feed on egg masses and can sometimes cause substantial egg mortality (Mccullough et al. 1999). Woodpeckers like to feast on the abundant larvae of emerald ash borer and elm bark beetles (Flower et al. 2014, Duan et al. 2022). Woodpecker populations are already increasing in Massachusetts as forests are becoming older (Walsh and Servison 2017), and this population trend is likely to continue with the waves of tree mortality expected from climate change and pest outbreaks. The coming decades are poised to become a golden age for woodpeckers in Massachusetts.

Predictions of future population changes due to climate change for individual bird species are presented on the USDA Forest Service Northern Research Station's Climate Change Bird Atlas website (Matthews, SN; Iverson, LR; Prasad, AM; Peters 2014). These models have varying degrees of reliability and do not include all Massachusetts birds but offer some interesting insights for some species.

Mammals

Climate change will likely affect mammal species distributions. Based on the natural history of New England mammals (DeGraaf and Yamasaki 2000), one might expect the following changes:

- Snowshoe hare (*Lepus americanus*) is near its southern range limit in Massachusetts. Snowshoe hares require dense shrub layer cover of either conifers (preferred in winter) or hardwoods (preferred in summer). Decline of dense shrub layers, loss of shade tolerant conifers, and a warming climate with less snow could lead to a dramatic decline of snowshoe hare populations.

- North American porcupine (*Erethizon dorsatum*) may be affected by the expected coming demise of hemlock and white pine, which are important winter foods, especially hemlock cambium, needles, and buds. However, porcupine will also feed on bark of sugar maple and birch. Porcupines consume a wider range of foods in summer including large quantities of basswood, aspen, elm, and birch leaves.
- Fisher (*Pekania pennanti*) is near its southern range limit and prey on both snowshoe hare and porcupines, which may decline with climate change.
- Northern flying squirrel (*Glaucomys sabrinus*) may be increasingly replaced by southern flying squirrel (*Glaucomys volans*), which may coincide with the projected decline of northern conifers.
- Virginia opossum (*Didelphis virginiana*) have expanded their range northward in recent decades and would likely benefit from a warmer climate.

Reptiles and Amphibians

Ectotherms such as reptiles and amphibians are generally much more sensitive to temperature than endotherms (Taylor et al. 2021). For example, sex of hatchlings is determined by nest temperature in many turtle species. Hibernating frogs may also be at increasing risk due to late frosts, less snow cover, and warmer winter temperatures (Corn 2005, Miller et al. 2018). Massachusetts is near the range limit of several amphibian and reptile species that are likely to be affected by changes in climate. For instance, the northern leopard frog (*Lithobates pipiens*) might be expected to suffer, whereas the eastern box turtle (*Terrapene carolina carolina*) might be expected to benefit from climate change, based on their range limits.

Vernal pools provide important breeding habitat for some amphibians such as wood frogs and spring peepers (*Pseudacris crucifer*). Climate change may alter the timing of when vernal pools dry out. Amphibians may respond by shifting the timing of breeding (Todd et al. 2011). However, faster metabolic rates and increased food availability in warmer water may accelerate development to compensate for earlier drying of pools, as was shown in experimental mesocosms (O'Regan et al. 2014).

Insects

Phenology quantifies seasonal events in the life cycle of plants and animals such as the timing of flowering or laying of eggs. As the climate warms, phenological events may shift earlier in the season at different rates, which may result in phenological mismatches between insects and their hosts (Forrest 2016, Bell et al. 2019, Uphus et al. 2023). For example, flowering may no longer coincide with arrival of specialist pollinators, or a plant may become more or less vulnerable to a herbivorous insect depending on if its leaves had time to mature before the herbivore begins feeding. However, in theory, phenological mismatches should result in rapid evolution to restore trophic interactions (Renner and Zohner 2018).

Many insect pest populations are limited by cold winter temperatures. Milder future winter temperatures would remove this limitation, thereby allowing new pests to establish and certain existing pest populations to expand (Haavik 2019). For example, Nantucket and Martha's Vineyard recently had their first outbreaks of southern pine beetle, which is feeding on the locally dominant pitch pines. In central and western Massachusetts, the established hemlock woolly adelgid population is poised to explode with a slight warming of winter temperatures (see Figure 3). Eastern hemlock is the most abundant tree species in the Mass Audubon Wildlife Sanctuaries participating in the forest carbon offset project, where hemlock comprises more than a quarter of the basal area. The survival of biological controls of non-native pests may similarly be limited by cold winter temperatures.

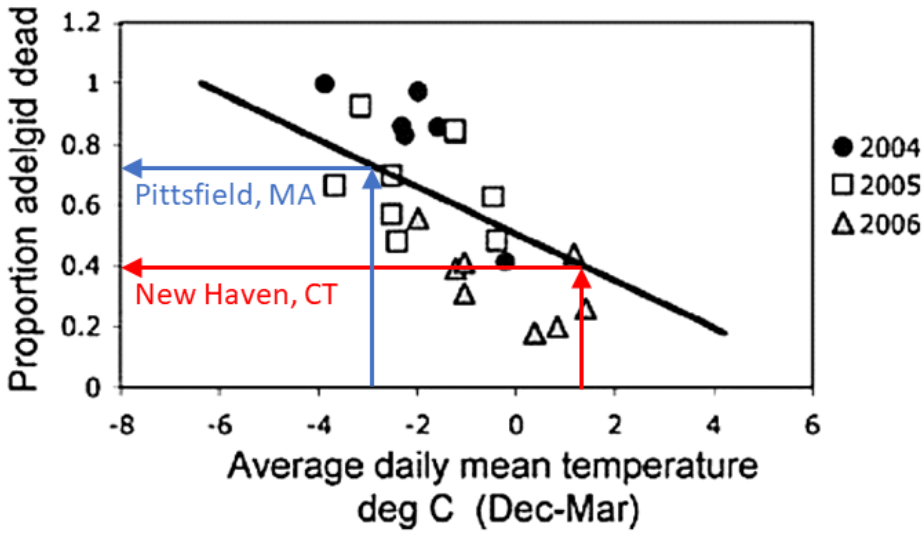


Figure 3: Hemlock woolly adelgid winter survival as a function of winter temperatures in southern New England (adapted from Paradis et al. 2008). Note the shift from most adelgid surviving in most winters to most adelgid dying in most winters when comparing New Haven on the coast of Connecticut and Pittsfield, which is less than 80 miles further north and inland in Massachusetts.

Infrastructure and Programming

Infrastructure in central and western Massachusetts is less directly threatened by climate change than in the coastal wildlife sanctuaries where sea level rise could cause flooding during a storm surge and eventually submerge land and buildings permanently. The primary concern for infrastructure in central and western Massachusetts is dead trees falling on trails, boardwalks, program areas, powerlines, or buildings. Developing cost effective ways to manage dead trees along trails is an imminent need. For instance, there are many dead oaks along trails at Laughing Brook Wildlife Sanctuary that died following the 2015 to 2017 outbreak of spongy moth. Similarly, there are numerous dead pines along the trails at Cooks Canyon Wildlife Sanctuary. The abundant white ash at Pleasant Valley Wildlife Sanctuary that are now dying from emerald ash borer attack will soon become a hazard along trails there. Dead trees along trails will become an increasing problem as the climate continues to warm.

Loss of tree canopy can affect nature play spaces by removing much appreciated shade. Sometimes the loss of canopy may be due to climate change or pests, but at other times it may be because the trees were non-native and therefore needed to be cut down to enhance forest resilience. For instance, the non-native Norway maples (*Acer platanoides*) in the play area at Broad Meadow Brook are spreading into the surrounding forest. Some nature play areas may need to be moved either in anticipation of or in response to climate change and pest outbreaks.

Lyme disease and other diseases spread by ticks or mosquitoes are a serious threat to the health of people that spend a lot of time in nature such as the participants and councilors at Mass Audubon summer camps. The location of Wildwood Camp in New Hampshire has a colder winter temperature than the Massachusetts wildlife sanctuaries which helps to limit tick populations, but that could change as the climate warms. Summer camp directors should keep up to date with the tick threat and the best ways to manage it such as the current clinical trials of Lyme disease vaccines. Similarly, poison ivy (*Toxicodendron radicans*) which is currently mostly absent at Wildwood Camp could spread under a warmer climate. Poison ivy appears to be benefitting from rising CO_2 levels in the atmosphere (Mohan et al. 2006). One could argue that poison ivy should be treated like an invasive plant at Wildwood Camp (i.e. with chemical herbicides in a rapid response to early detection).

Wildlife Sanctuary Vulnerabilities

The following sections provide the detailed assessment for individual wildlife sanctuaries. Included are all the Mass Audubon wildlife sanctuaries in the Central and West Regions plus Waseeka Wildlife Sanctuary form the Metro West Region and Wildwood Camp in New Hampshire. These sanctuaries were part of the initial set of forest vulnerability assessments conducted in 2022 and 2023.

How to read summaries for individual wildlife sanctuaries?

The summary for each wildlife sanctuary starts with a four-panel diagram that concisely summarizes the level of vulnerability. The diagram includes a sun to symbolize vulnerability to climate change; an emerald ash borer to symbolize the vulnerability to diseases and pests; a stag to symbolize the vulnerability to intense browsing; and a bittersweet liana twinning to symbolize the vulnerability to non-native plant invasion. The darker the shade of brown the more severe the vulnerability (from slight to moderate to severe). There are also ArcGIS on-line maps that illustrate the spatial variability of these vulnerabilities at the scale of individual stands of trees, or habitat features such as wetlands and fields. The associated maps of vulnerabilities for each assessed sanctuary are available in ArcGIS on-line. These maps are not reproduced in the report to keep it from becoming too long.

The diagram is followed by a section that summarizes the key vulnerabilities for the sanctuary, and a section that summarizes the associated management recommendations for mitigating the vulnerabilities. The final section lists the canopy tree species that occur in the wildlife sanctuary. The lists classify the species by how their population is likely to be affected by the combination of climate change, pests, and diseases by the year 2050 at the sanctuary (i.e. benefit, decline, or neutral). Tree species that are neither likely to decline or benefit in the next couple of decades are classified as neutral. Similarly, species that may benefit from a warmer climate but are unlikely to realize much benefit because most soils are inappropriate at the wildlife sanctuary are also classified as neutral. Species that are too small to reach the forest canopy at the site are not included in the list. Likewise, non-native tree species are not included in the list. These lists are intended to inform decisions about the need for and type of climate change adaptation tree planting that may be appropriate at the wildlife sanctuary. For the 10 wildlife sanctuaries that are part of the Mass Audubon forest carbon offset project, there is also a graphical summary of forest composition based on the forest carbon monitoring plots on the sanctuary.

Arcadia

Vulnerabilities:

- **Climate**: the floodplain forests at Arcadia are composed of species that are resilient to climate change, whereas the upland forests in the south of the sanctuary contain stands of white pine and especially hemlock that are vulnerable to climate change. Arcadia also has an exceptionally high tree species richness that includes many species that are likely to benefit form a warmer climate. Additionally, some species adapted to a warmer future climate were planted in a floodplain reforestation project.
- **Pests and diseases**: American chestnut was likely a co-dominant tree species in the upland forests and American elm likewise in the floodplain forests before the spread of non-native fungal diseases. Another important floodplain tree species, green ash (*Fraxinus pennsylvanica*), is currently being decimated by emerald ash borer. The extensive hemlock and white pine stands in the uplands at Arcadia are threatened by hemlock woolly adelgid and needle cast disease, respectively.
- **Browsing**: There is a large deer herd that appears to reside mainly within the Arcadia Wildlife Sanctuary lands. The combination of extensive fields, shrublands, and forests provides ideal habitat for deer. Experience with tree planting has shown that tree regeneration is severely impacted by deer browse at Arcadia. Planted trees of any species need to be protected from deer browsing to survive.
- **Non-native plants**: Fields, floodplain forests, and especially shrublands and field edges at Arcadia have been invaded by non-native plants. In many areas, non-native plants are already dominant. The most threatening of these non-native invaders is round-leaved bittersweet, which thrives in the floodplain forests' understory and can climb trees along forest edges, where it breaks saplings and even mature trees.

- **Combined change**: Overall, Arcadia is severely vulnerable to the combined impact of climate change, diseases, pests, browsing, and non-native plant invasion threats. This overall vulnerability could be reduced to moderate if the severity of deer browsing, and the abundance of non-native plants are sufficiently reduced from current levels through active management. Specifically, the potential impacts on the forest canopy are local, and there are ample tree species that are adapted to future conditions that could fill canopy gaps, provided that tree regeneration is not impaired by deer browsing and non-native plant competition.

Management recommendations:

1. Open the wildlife sanctuary to an organized deer hunt annually to substantially reduce the impact of deer browsing. Monitor the deer population and the impact of deer browsing.
2. Continue maintenance of the climate change adaptation floodplain forest plantings. Future planting that replaces planted trees that have died could include floodplain tree species that were not available for the earlier climate change adaptation planting such as swamp cottonwood (*Populus heterophylla*), bitternut hickory (*Carya cordiformis*), swamp chestnut oak (*Quercus michauxii*), overcup oak (*Quercus lyrata*), bald cypress (*Taxodium distichum*), and yellow buckeye (*Aesculus flava*). Consider implementing another tree planting in some of the abandoned fields such as next to the transfer station on Easthampton Road before non-native plants invade these locations more intensively. The former orchard is another potential location for a climate change adaptation tree planting. One possible idea that might fit well with programming at Arcadia could be to restore the orchard as an orchard, but using native fruit tree species such as pawpaw (*Asimina triloba*), common persimmon (*Diospyros virginiana*), and red mulberry (*Morus rubra*).
3. Raise funding for contracts to suppress non-native plants in the most severely invaded areas, such as the abandoned orchard, or the most recently acquired properties by Potash Road and Old Springfield Road. Subsequently, expand non-native plant suppression efforts to areas that are less severely invaded, but of high conservation value, such as the rich high terrace floodplain forest along River Trail where round-leaved bittersweet is proliferating in the understory.
4. Modify how shrublands and field edges are managed to reduce invasion by non-native plants from these areas into neighboring forests. Currently, fields are gradually succeeding to more woody vegetation including non-native shrubs and especially round-leaved bittersweet under a regime of one annual late season mowing. Rehabilitating hayfields could both control invasive woody plants and improve habitat for bobolinks. Similarly, the present management regimen of clearing of shrublands with a brontosaurus every few years has resulted in a high dominance of black locust (*Robinia pseudoacacia*) clones in those areas. Black locust, although native to eastern North America, is problematic not only because the clones are near monocultures but also because black locust fixes nitrogen. A modified management prescription for these locust shrublands should be considered. Some shrubby field edges have a mix of weedy non-native shrubbery and rich high terrace tree saplings such as black walnut (*Juglans nigra*), butternut (*Juglans cinerea*), northern hackberry (*Celtis occidentalis*), and basswood (e.g. along Curtis Nook Trail). These saplings should

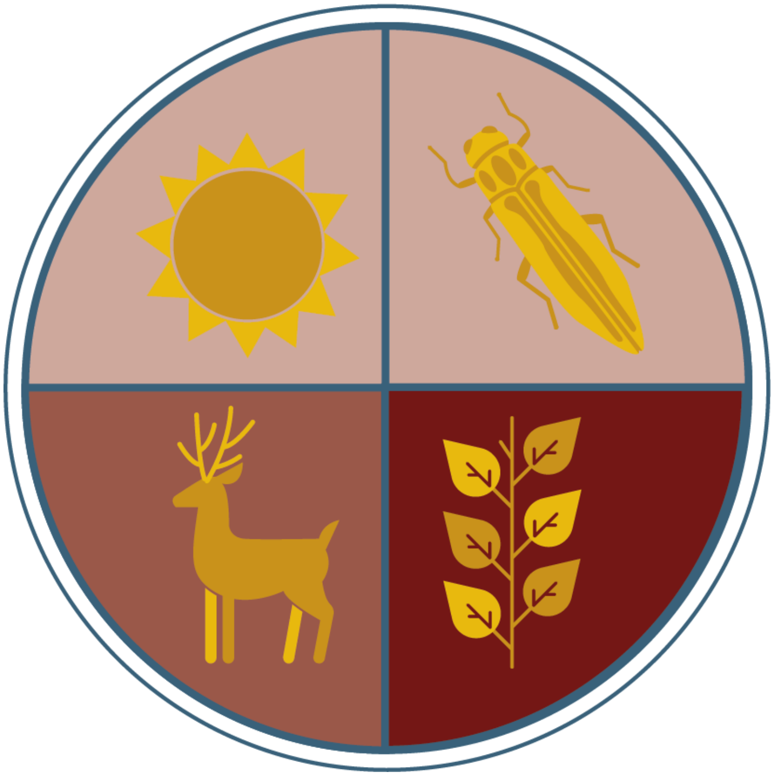
be allowed to mature because of the rarity of rich high terrace floodplain forest, while carefully suppressing non-native invaders within these areas, especially round-leaved bittersweet lianas that could otherwise destroy the saplings. Another strategy for forest edges, could be to replace aggressive tall clonal herbaceous invaders such as Japanese knotweed (*Reynoutria japonica*) with equally tall and clonally spreading native wildflowers (e.g. *Eupatorium maculatum, Helianthus decapetalus, Helianthus tuberosus,* and *Rudbeckia laciniata*).

5. Nashawannuck Brook in the southwestern corner of Arcadia flows through clay varves that offer little resistance to channel incision. Flashy flows from the upstream watershed have resulted in substantial channel incision. The city of Northampton's acquisition of the former Pine Grove Golf Course as conservation land comprising most of the brook's headwaters offers an opportunity to restore the headwater stream geomorphology and hydrological functioning collaboratively with the city. Downstream, in Arcadia, Mass Audubon could do a coarse woody debris addition to help repair the channel geomorphology and slow the flow. This could be a "chop and drop" operation done with help from experts at Trout Unlimited. "Dropping" some riparian hemlock which are threatened by climate change and disease would thin the stand, thereby increasing the vigor of the remaining hemlocks.
6. Prioritize protecting more floodplain properties near Arcadia because floodplains provide flood attenuation functions that will be increasingly valuable as floods become more frequent and severe with climate change.

Native canopy tree species list:

- Benefit: white oak (*Quercus alba*), black oak (*Q. velutina*), pin oak, swamp white oak, basswood, Kentucky coffeetree (*Gymnocladus dioicus*), northern catalpa (*Catalpa speciosa*), black locust, shagbark hickory, bitternut hickory, northern hackberry, tulip tree, sycamore (*Platanus occidentalis*)
- Neutral: black birch, red oak, red maple, black cherry, bigtooth aspen (*Populus grandidentata*), black walnut, eastern cottonwood (*Populus deltoides*), black willow (*Salix nigra*), silver maple, sugar maple, trembling aspen (*P. tremuloides*)
- Decline: white pine, hemlock, green ash, white ash, American elm, chestnut, butternut

Broad Meadow Brook



Vulnerabilities:

- **Climate**: The forests at Broad Meadow Brook are at the northern end of the range of the oak-hickory forest type, and therefore can survive a substantially warmer climate, and would likely even benefit from a warmer climate. By contrast, the aquatic ecosystems along Broad Meadow Brook are already highly degraded by a flashy flow regime and pollution due to the headwaters being covered in impervious surfaces. More frequent extreme rainfall events and warmer temperatures would likely exacerbate these ecological problems in the brook.
- **Pests and diseases**: Chestnut was likely a co-dominant tree species in the upland forests and American elm likewise in the riparian forests before the spread of non-native fungal diseases. The now dominant oaks in the uplands and maples in the bottomlands are not immediately threatened by pests and diseases, although there may be some future mortality from spongy moth or Asian long-horned beetle (*Anoplophora glabripennis*) outbreaks, respectively.
- **Browsing**: The impact of deer browsing at Broad Meadow Brook appears to be moderate, with some oak seedlings succeeding at growing into the sapling stage. The small resident deer herd appears to spend much of their time in the less accessible woods east of the marsh that is next to Troiano Brookside Trail.
- **Non-native plants**: Non-native plants are few in the oak-hickory forests covering the uplands, especially in the southwestern part of the sanctuary, a rarity in an urban greenspace. By contrast, the riparian wetlands and young forests that grew on abandoned land in the eastern bottomlands, and especially in the northern part of the sanctuary are replete with non-native plants. The open woods along Piggery Trail

in the north are a worst-case scenario where the dominant trees, shrubs, lianas, and herbs are all non-native.

- **Combined change**: The northern and eastern lowlands at Broad Meadow Brook are severely vulnerable to the combined impact of climate change, diseases, and pests, browsing, and non-native plant invasion threats. By contrast, the southwestern oak dominated uplands have low vulnerability. The pivotal challenges will be to suppress non-native plants in the eastern and northern parts of the sanctuary and mitigating at least some of the hydrological alteration in the sanctuary's namesake brook.

Management recommendations:

1. Implement stream restoration on Broad Meadow Brook. With an entirely urbanized watershed upstream of the sanctuary, one needs to accept that complete restoration of the flow regime and water quality is not feasible. Rather the brook in the sanctuary is a novel ecosystem. But, one can attempt to attenuate some of the flashiness in streamflow through a combination of riparian wetland and channel restoration in the sanctuary and upstream measures that increase soil infiltration of rainfall. Non-native plant invasions in the wetlands and riparian forests such as common reed (*Phragmites australis*) should be controlled as part of the hydrological restoration projects to prevent non-native plants from invading the areas disturbed by construction activities. Replanting of riparian trees following daylighting and re-meandering of the stream channel is also an opportunity to plant some floodplain tree species adapted to a slightly warmer climate that currently are not present on the sanctuary (e.g. sweetgum (*Liquidambar styraciflua*), bitternut hickory (*Carya cordiformis*), swamp white oak (*Quercus bicolor*), pin oak (*Q. palustris*), tulip tree, sycamore) or disease resistant selections of American elm (e.g. Valley Forge, Prairie Expedition, Saint Croix, Princeton).
2. Raise funding for contracts to suppress non-native plants in the most severely invaded areas, such as along Piggery Trail and Frog Pond Trail. The weedy open woodlands along Piggery Trail are so severely invaded that managers should consider clearing the area entirely as a first step to establishing native vegetation. One option is to seed a wildflower meadow that can be maintained by mowing. Another option is to plant a forest of fast growing early successional trees that spread with runners to establish a closed tree canopy quickly such as sassafras (*Sassafras albidum*) or aspens. Still another option would be to create a structurally diverse habitat that combines meadow with some climate change adaptation tree planting. By contrast with the weedy area on Piggery Trail, the young forest along Frog Pond Trail includes a mixture of native and non-native trees that could be thinned to release the native trees from non-native competition. An ideal time for this invasive species control work could be while Frog Pond Trail is closed due to the current beaver flooding. Managers should seek a creative solution for controlling the non-native Norway maple that dominate the slope by the nature play area, keeping in mind that delaying action will exacerbate the invasion. For example, removing the Norway maple would create canopy openings in which one could do a climate change adaptation tree planting in a highly visible area to educate the public about the topic.
3. Monitor the deer population and the impact of browsing.

Native canopy tree species list:

- Benefit: white oak, black oak, mockernut hickory (*Carya tomentosa*), pignut hickory (*Carya glabra*), shagbark hickory, black gum (*Nyssa sylvatica*), scarlet oak, chestnut oak (*Quercus prinus*)
- Neutral: black birch, red oak, yellow birch (*Betula alleghaniensis*), red maple, sugar maple, black cherry, black walnut
- Decline: white pine, paper birch (*Betula papyrifera*), white ash, butternut, American elm, green ash

Brush Valley

Vulnerabilities:

- **Climate**: The forests at Brush Valley are highly dominated by eastern hemlock, a species that is vulnerable to climate warming.
- **Pests and diseases**: The forests at Brush Valley are highly dominated by eastern hemlock, a species that is vulnerable hemlock woolly adelgid and hemlock scale.
- **Browsing**: Deer browsing impact is moderate on the southern Gales Brook parcel, and slight on the northern Rum Brook and Black Brook parcels.
- **Non-native plants**: Non-native plants are very few at Brush Valley, except for some glossy buckthorn.
- **Combined change**: Brush valley is moderately vulnerable to the combined impact of climate change, diseases, and pests. There is little that managers can do to prevent a die-off of the dominant hemlock. However, the low incidence of non-native plants and deer browsing should allow the forest to recover from such a major disturbance.

Management recommendations:

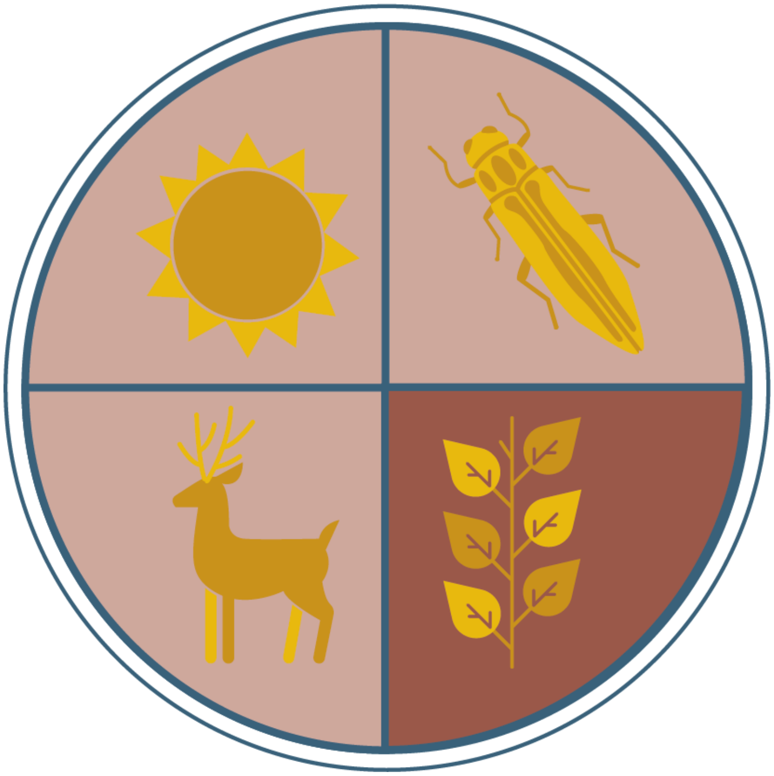
1. A die-off of the dominant hemlocks is expected under a warmer climate by 2050. Doing nothing may be the best management approach because the die-off cannot be prevented, and the forest has a high capacity to regenerate given a relatively low abundance of deer and non-native plants. Leaving the dead trees in place will increase coarse woody debris to levels consistent with old growth forests and will help protect tree seedlings from deer browsing.

2. In future, when larger canopy gaps form such as from a hemlock die-off, one could consider planting a few future seed trees of species that are better adapted to future climate conditions (e.g. hickories, tulip tree, black gum, black oak) than the present species mix on the sanctuary, or selectively protecting natural regeneration of preferred species (e.g. white oak, red oak, sugar maple) from deer browsing.
3. Monitor the deer population and the impact of browsing.

Native canopy tree species list:

- Benefit: white oak
- Neutral: black birch, red oak, yellow birch, red maple, sugar maple, black cherry, bigtooth aspen
- Decline: white pine, beech, paper birch, white ash, hemlock, black ash (*Fraxinus nigra*)

Burncoat Pond



Vulnerabilities:

- **Climate**: The oak dominated forests at Burncoat Pond will likely benefit from a warmer climate because they are at the northern range edge of this forest type.
- **Pests and diseases**: Chestnut was likely a co-dominant tree species in the upland forests before the spread of chestnut blight and is still common along Flat Rock Trail. The now dominant oaks and maples are not immediately threatened by pests and diseases, although there may be some future mortality from spongy moth or Asian long-horned beetle outbreaks, respectively. The dense stands of white pines in the south of the sanctuary are the most susceptible to disease.
- **Browsing**: The impact of deer browsing at Burncoat Pond appears to be relatively low.
- **Non-native plants**: Non-native plants are few in the mature forests but have proliferated around the fields in the northeast.
- **Combined change**: Overall, Burncoat Pond has low vulnerability to the combined impact of climate change, diseases, and pests, browsing, and non-native plant invasion threats. The largest concern are the expanding non-native plant infestations in and around the fields in the northeast of the sanctuary.

Management recommendations:

1. Raise funding for a contract to suppress non-native plants in and around the fields in the northeastern part of the sanctuary just south of Polar Spring Road. Mow the small fields on the sanctuary more frequently or reforest them to reduce the threat of re-invasion. A reforestation would be an opportunity to plant tree species that are

adapted to a slightly warmer climate but that do not yet occur on the sanctuary such as hickories, black gum, chestnut oak, and tulip tree.
2. Monitor the deer population and the impact of browsing.
3. The oak forests that dominate much of the sanctuary are adapted to occasional ground fires. Explore the feasibility of re-introducing prescribed ground fires. Prescribed fires would slow succession towards species that are less well adapted to a warmer climate than the oaks. The pond could be used as a convenient fire break.

Native canopy tree species list:

- Benefit: black oak, white oak
- Neutral: black birch, red oak, yellow birch, red maple, trembling aspen, bigtooth aspen, sugar maple, black cherry
- Decline: white pine, chestnut, beech, paper birch, American elm, white ash, hemlock

Canoe Meadows

Vulnerabilities:

- **Climate**: most of the forests at Canoe Meadows are dominated by evergreen conifers that are highly vulnerable to climate change.
- **Pests and diseases**: American elm and slippery elm (*Ulmus rubra*) were likely co-dominant tree species in swamps, riparian, and floodplain forests before the spread of Dutch elm disease. The extensive hemlock forests, red pine and white pine plantings at Canoe Meadows are threatened by pests and diseases, a vulnerability that will be exacerbated by climate stresses.
- **Browsing**: Deer browsing appears to be relatively slight. Nevertheless, planted trees in the riparian buffer along Sackett Brook needed to be protected from deer browsing by wire mesh cages.
- **Non-native plants**: Abundant non-native plants of diverse species have invaded from forest edges and along hedgerows. Some of the wetlands also contain patches of common reed. The General Electric funded cleanup of contaminated river sediments risks disturbing the site in ways that increase vulnerability to non-native plant invasions.
- **Combined change**: Overall, Canoe Meadows is severely vulnerable to the combined impact of climate change, diseases, pests, browsing, and non-native plant invasion threats. When evergreen conifer forests die off from climate change and pests, the resulting canopy gaps are likely to be invaded by non-native plants thereby bringing about a kind of invasive species meltdown. Reducing this vulnerability by controlling non-native plant infestations will be pivotal to increasing forest resilience.

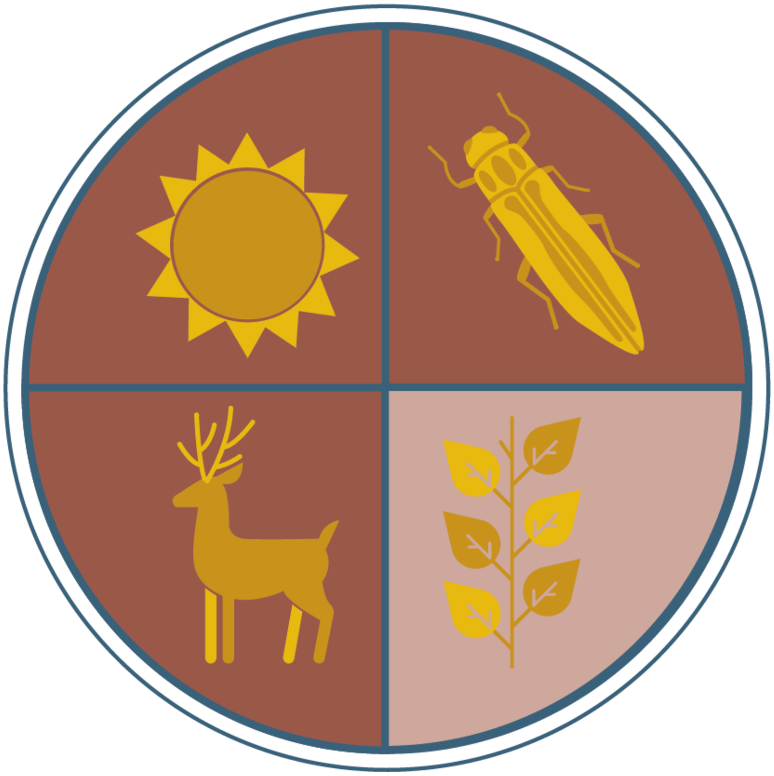
Management recommendations:

1. Raise funding for contracts to suppress non-native plants in the most severely invaded areas, such as the hedgerows along the Main Trail and the Sacred Way Trail. The rich mesic forest in the northeast of the sanctuary has maidenhair fern and black maple mixed in with a multitude of non-native plants such as garlic mustard and round-leaved bittersweet. Suppressing the non-native plants that are competing with the native rich mesic forest species should be a priority.
2. Engage with the planners of the General Electric funded Housatonic River contaminated sediment cleanup to ensure that negative impacts of cleanup activities are minimized and mitigated wherever possible on the sanctuary. Specifically, absolutely no fill should be brought onto the site to replace contaminated sediments, because fill often contains non-native plant propagules that can resprout such as rhizomes of Japanese knotweed or goutweed (*Aegopodium podagraria*). Removing sediments lowers the soil surface to a level of an earlier time when less sediments had accumulated, which is ecologically desirable. Indeed, a lower soil level may enhance floodplain habitat and function such as flood attenuation.
3. The abandoned field at the southern end of Sacred Way Trail is being invaded by non-native shrubs. Doing a combination of invasive species control and planting native trees would help restore this location. The planting could include some bottomland tree species adapted to a slightly warmer climate that currently are not present on the sanctuary (e.g. sweetgum, swamp white oak, pin oak, tulip tree, northern hackberry) or disease resistant selections of American elm (e.g. Valley Forge, Prairie Expedition, Saint Croix, Princeton). Any planting should wait until after the PCB cleanup operations are completed.
4. Acquire the General Electric-owned floodplain property that is on the south side of the sanctuary because floodplains provide flood attenuation functions that will be increasingly valuable as floods become more frequent and severe with climate change.
5. Monitor the deer population and the impact of browsing.

Native canopy tree species list:

- Benefit: bitternut hickory, sycamore
- Neutral: black birch, red oak, yellow birch, red maple, trembling aspen, bigtooth aspen, sugar maple, black cherry, black maple, silver maple, eastern cottonwood, black walnut
- Decline: white pine, beech, paper birch, American elm, white ash, hemlock, slippery elm, boxelder (*Acer negundo*), red pine

Cheshire Pond



Vulnerabilities:

- **Climate**: The forests at Cheshire Pond are dominated by northern evergreen conifers such as red spruce and hemlock that are doomed by climate warming in the long term. However, the currently still relatively cold local climate will likely delay this impact until after 2050. The bogs with their acidic soils can probably also help buffer against climate change as long as they remain saturated with water most of the time to prevent decay of accumulated organic matter.
- **Pests and diseases**: The extensive stands of eastern hemlock and eastern white pine are vulnerable to pests and diseases such as hemlock woolly adelgid and needle cast disease, respectively. However, relatively cold winter temperatures may limit hemlock woolly adelgid populations until 2050.
- **Browsing**: Browsing impact by deer is moderate at Cheshire Pond. Indeed, moose may be a more important browser than deer in this wildlife sanctuary.
- **Non-native plants**: Non-native plants are exceptionally few at Cheshire Pond.
- **Combined change**: The forests and wetlands at Cheshire Pond are moderately vulnerable to the combined impact of climate change and pests until 2050 but become severely vulnerable as warming becomes more extreme later this century.

Management recommendations:

1. Avoid hydrological alterations on the sanctuary or by abutters that could negatively impact the bog ecosystems. Drainage of bogs can result in decay of accumulated organic matter and release of large amounts of stored carbon as well as destruction of a habitat that is rare in Massachusetts.
4. Open Cheshire Pond to deer hunting (subject to all applicable state regulations). Monitor the deer population and the impact of browsing.
2. Research the idea of adapting the northern conifer swamps and bogs to climate change with Atlantic white cedar (*Chamaecyparis thyoides*) plantings which is a wetland conifer that occupies similar habitat in milder coastal climates such as on Cape Cod. The closest example of a northern conifer bog with Atlantic white cedar is in Westminster State Forest. Note that Atlantic white cedar regeneration does best in large openings such as from clear-cuts or fires. Seedlings also need protection from deer browse and could be killed by beavers raising water levels. The NRCS Atlantic White Cedar Initiative and the Massachusetts NHESP may be potential partners in managing a transition from one rare conifer wetland community type to another when the climate has warmed sufficiently.

Native canopy tree species list:

- Benefit: black oak, red oak, black gum, black birch, black cherry
- Neutral: red maple, hemlock, white pine, bigtooth aspen, yellow birch, paper birch
- Decline: beech, red spruce, balsam fir, red pine, tamarack, black spruce

Cold Brook

Vulnerabilities:

- **Climate**: Many of the stands comprising the forests at Cold Brook Wildlife Sanctuary are dominated by eastern hemlock, a species that is highly vulnerable to climate change.
- **Pests and diseases**: Beech was formerly a common tree species that was decimated by beech bark disease. The remaining beech are likely to die from beech leaf disease, which appears to be present at Cold Brook. White ash is a common tree species at Cold Brook, especially in the hardwood forests on the east facing slope of Belden Hill, where it is co-dominant with sugar maple. Emerald ash borer has recently arrived at Cold Brook but has not yet infested most ash trees. The extensive hemlock forests and dense stands of eastern white pine are threatened by hemlock woolly adelgid and needle cast disease, respectively. A warmer future climate will exacerbate the pest and disease threat for these two evergreen conifer species.
- **Browsing**: Browsing by deer is severe at Cold Brook, especially in the forests around the abandoned fields and orchards of the Minnery properties along Cold Spring Road.
- **Non-native plants**: Abundance of non-native plants is generally low in the older forest stands at Cold Brook. By contrast some abandoned fields and orchards are being invaded by non-native plants from field edges. As more fields were recently abandoned along Miner Road, the risk of non-native plant invasion from surrounding field edges is great and immediate in these areas. Some of the wetlands along Cold Spring Road have been invaded by stands of common reed that are likely expanding.

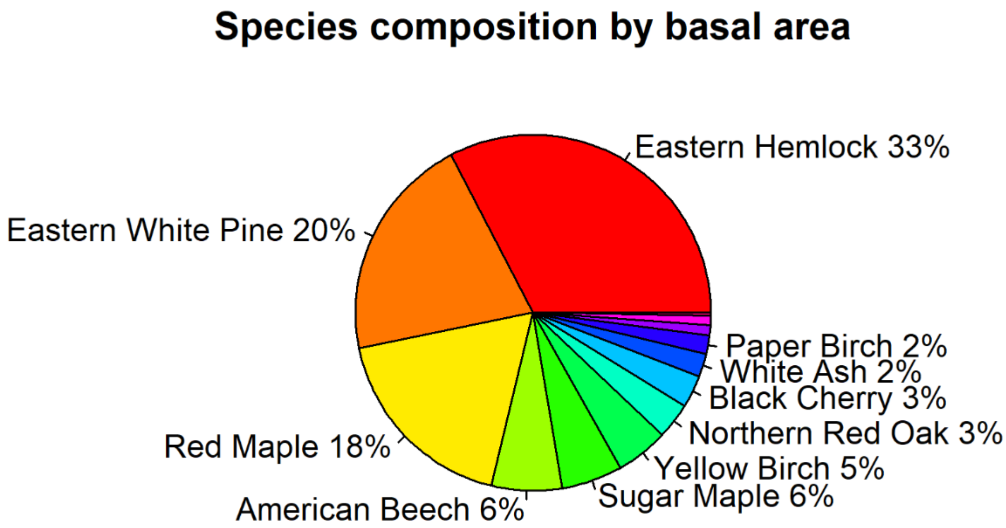
- **Combined change**: Overall, the forest canopy at Cold Spring Wildlife Sanctuary is severely vulnerable to the combined impact of climate change, diseases, and pests. Recovery from canopy tree die-offs will depend on tree regeneration not being impaired by deer browsing or non-native plant competition. Reducing the severity of deer browse dramatically from current levels and controlling emerging non-native plant infestations will be pivotal for preparing the sanctuary for climate change impacts.

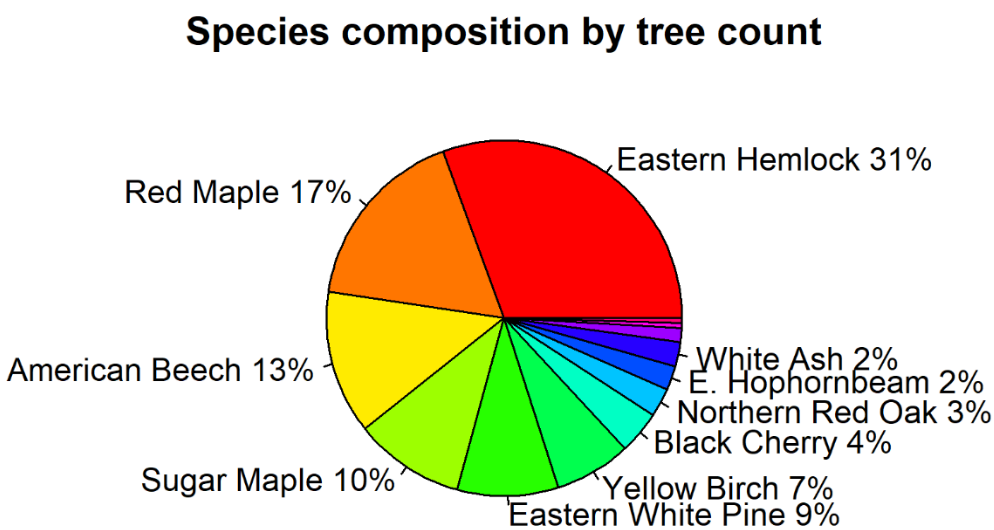
Management recommendations:

1. Control non-native plants around the edges of abandoned fields without delay to prevent invasion of the abandoned fields during this vulnerable stage of succession.
5. Open Cold Brook to deer hunting (subject to all applicable state regulations). Monitor the deer population and the impact of browsing.
2. The final step in removing the buildings at Cold Brook Wildlife Sanctuary will involve a bulldozer to fill in the building foundation holes. The same bulldozer contract could also modify the terrain in selected locations in the abandoned fields. Specifically, it is an opportunity to restore a more varied topography with vernal pools in suitable parts of the fields. A cluster of vernal pools, if variable in area and depth, could be resilient habitat for vernal pool species, in addition to restoring wetland functions.
3. Plant tree species that are better adapted to future climate conditions in some of the abandoned fields such as the area around the former Minnery homestead, while this cleared land is still open. Similarly, the abandoned fields along Miner Road could benefit from tree planting. Currently, these fields are being colonized almost exclusively by eastern white pine, a tree species that is vulnerable to climate change and disease. Potentially site appropriate tree species that are adapted to a slightly warmer climate and that do not yet occur at Cold Brook include the following: shagbark hickory, black oak, white oak, tulip tree, black gum, and yellow buckeye.
4. Release biological controls for emerald ash borer on the east side of Belden Hill, if any were to become available again for release in Massachusetts (currently production of biological controls is prioritized for states that have not yet had releases).

Native canopy tree species list:

- Benefit: bitternut hickory, basswood
- Neutral: red oak, sugar maple, red maple, black birch, yellow birch, black cherry, trembling aspen
- Decline: white pine, beech, white ash, hemlock, paper birch, American elm





Summary of forest composition in carbon inventory plots at Cold Brook Wildlife Sanctuary in 2016.

Conway Hills

Vulnerabilities:

- **Climate**: Conway Hills has large stands dominated by eastern hemlock, a species that is highly vulnerable to climate change.
- **Pests and diseases**: The extensive hemlock and eastern white pine stands in the northern half of the sanctuary are threatened by hemlock woolly adelgid and needle cast disease, respectively. A warmer future climate will exacerbate the pest and disease threat for these two evergreen conifer species. Chestnut, beech, and elm are now minor tree species that were likely more abundant before the spread of non-native diseases. White ash is a minor tree species at Conway Hills that is now threatened by emerald ash borer.
- **Browsing**: Browsing by deer is moderate at Conway Hills, although probably severe enough that species vulnerable to deer browsing such as oak will rarely grow into saplings without protection.
- **Non-native plants**: Abundance of non-native plants is rapidly increasing in the abandoned fields around the former farm site, but is modest elsewhere.
- **Combined change**: Overall, Conway Hills Wildlife Sanctuary is severely vulnerable to the combined impact of climate change, diseases, pests, browsing, and non-native plant invasion threats. Diverse tree species that are adapted to future conditions are present throughout the sanctuary and could lead a recovery following die-offs of canopy trees, provided that tree regeneration is not impaired by deer browsing and non-native plant competition.

Management recommendations:

1. Raise funding for contracts to suppress non-native plants in the most severely invaded areas. In the case of the abandoned field, invasive control, could be followed by a climate change adaptation tree planting. Potentially site appropriate tree species that are adapted to a slightly warmer climate and that do not yet occur at Conway Hills include the following: pignut hickory, tulip tree, black gum, cucumber tree (*Magnolia acuminata*), and yellow buckeye.
2. Monitor the deer population and the impact of browsing. Investigate if opening such a small property to an organized annual deer hunt is worthwhile.
3. Consider doing an ecological harvest that thins the white pine overstory in the northeastern part of the sanctuary to release trees of species that are better adapted to future conditions, and to increase vigor and thereby climate change resistance of the remaining white pine. One could install cages around naturally occurring warm-climate-adapted oak seedlings in the resulting canopy gaps to protect the seedlings against deer browse and promote their recruitment into the canopy.

Native canopy tree species list:

- Benefit: black oak, white oak, shagbark hickory, bitternut hickory, basswood
- Neutral: black birch, red oak, sugar maple, black cherry, yellow birch, red maple, bigtooth aspen, trembling aspen
- Decline: white pine, hemlock, American elm, white ash, chestnut, beech, butternut, paper birch

Cook’s Canyon

Vulnerabilities:

- **Climate**: Much of the forest at Cooks Canyon is dominated by dense stands of conifers that are highly vulnerable to climate change. Most of the red pine plantings have already died. However, maples are recruiting under the dying red pine plantings in the north, and mature oaks are abundant in the south of the sanctuary; both of which are tree genera that are well adapted to a warming climate.
- **Pests and diseases**: The abundant hemlock in the south and pines in the north of the sanctuary are vulnerable to pests and diseases. A warmer future climate will exacerbate the pest and disease threat for these conifers. Chestnut was likely a co-dominant tree species before the spread of chestnut blight. Asian long-horned beetle outbreaks could become a future threat to maples.
- **Browsing**: Browsing by deer is remarkably slight at Cooks Canyon.
- **Non-native plants**: Abundance of non-native plants is high and still increasing in the dying conifer plantations in the north of the sanctuary but is modest elsewhere. The invading non-native species include Norway maple of all age classes that are spreading in the understory. Norway maple can proliferate even in the absence of canopy gaps because of its high shade tolerance.
- **Combined change**: Overall, Cooks Canyon Wildlife Sanctuary is severely vulnerable to the combined impact of climate change, diseases, pests, browsing, and non-native plant invasion threats. Particularly concerning is that competition by non-native trees, shrubs, and lianas is already impeding forest recovery after the mortality of the red pine canopy.

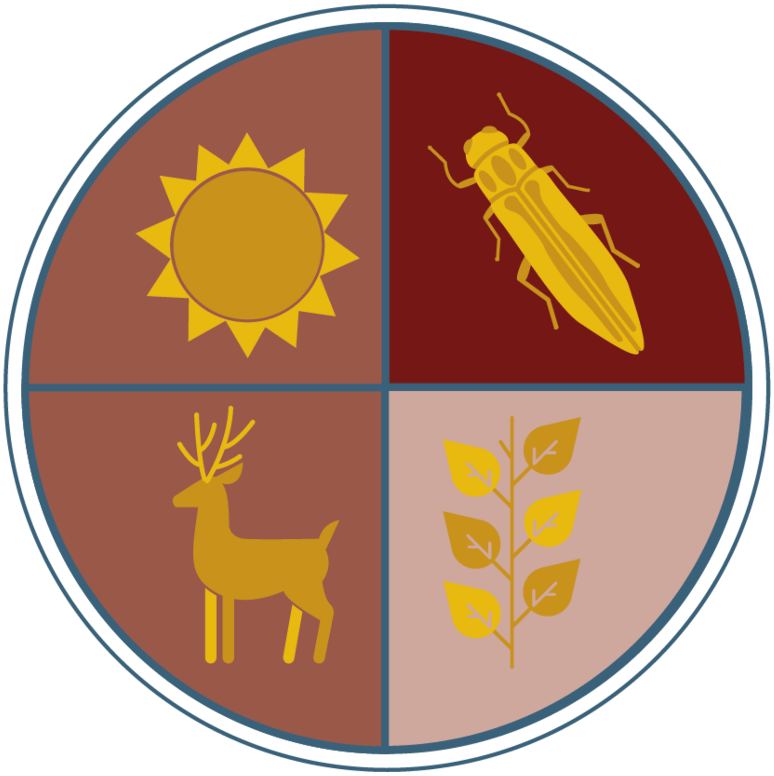
Management recommendations:

1. Raise funding for contracts to suppress non-native plants in the northern section of the sanctuary, where control of Norway maple and round-leaved bittersweet is the highest priority. The invasive plant control should include thinning the young stand of trees in the center of the sanctuary to release saplings of native tree species that are well adapted to future conditions. Tree harvests should not be considered until non-native plant infestation have been suppressed because operations that open the forest canopy would exacerbate proliferation of non-native plants.
2. Evaluate the possibility of removing the dam and associated sediments at the top of the sanctuary's namesake canyon.

Native canopy tree species list:

- Benefit: black oak, white oak, shagbark hickory, bitternut hickory, scarlet oak, black locust
- Neutral: black birch, red oak, sugar maple, black cherry, red maple, yellow birch, trembling aspen, bigtooth aspen
- Decline: white pine, hemlock, American elm, white ash, chestnut, beech, paper birch, balsam fir

Eagle Lake



Vulnerabilities:

- **Climate**: Much of the swamps and adjacent lowland forest at Eagle Lake is dominated by hemlock and red spruce, two evergreen conifers that are highly vulnerable to climate change. However, mature oaks are also abundant in most of the sanctuary; a tree genus that is well adapted to a warming climate.
- **Pests and diseases**: The abundant hemlock in the moister sites and the abundant white pines on the drier sites are vulnerable to pests and diseases. A warmer future climate will exacerbate the pest and disease threat for these conifers. Chestnut was a co-dominant tree species before the spread of chestnut blight. Potential future Asian long-horned beetle or spongy moth outbreaks could kill some maples and oaks, respectively.
- **Browsing**: The impact of deer browsing appears to be moderate.
- **Non-native plants**: Non-native plants are few in the mature forests but have proliferated in and around the fields in the north.
- **Combined change**: Overall, Eagle Lake Wildlife Sanctuary has a moderate vulnerability to the combined impact of climate change, diseases, and pests, browsing, and non-native plant invasion threats. Reducing deer browsing through active management could further moderate this vulnerability.

Management recommendations:

1. Monitor the deer population and the impact of browsing. Investigate if opening the property to an organized annual deer hunt is feasible.
2. Raise funding for a contract to suppress non-native plants in and around the fields in the north of the sanctuary. Reforest the fields to reduce the threat of re-invasion. A reforestation would be an opportunity to plant tree species that are adapted to a slightly warmer climate but that do not yet occur on the sanctuary such as hickories, chestnut oak, and American holly.
3. Enhance habitats in Asnebumskit Brook by adding logs to the channel that will slow flows and increase structural diversity.

Native canopy tree species list:

- Benefit: black oak, white oak, scarlet oak
- Neutral: black birch, red oak, yellow birch, red maple, black cherry, sugar maple, sassafras, trembling aspen, black gum
- Decline: white pine, chestnut, beech, white ash, hemlock, red spruce

Elm Hill

Vulnerabilities:

- **Climate**: Elm Hill has a high richness of tree species that are likely to benefit form a warmer climate including the oaks, hickories, and maples that dominate most of the forest.
- **Pests and diseases**: Chestnut was likely a co-dominant tree species in some upland forests and American elm was likewise in the swamps and riparian forests prior to the spread of non-native fungal diseases. White ash, an important tree species of both swamps and abandoned fields is currently being decimated by emerald ash borer. Eastern white pine is threatened by needle cast disease, but these conifers are dominant in only a few stands.
- **Browsing**: There is a large deer herd that appears to reside mainly in and around abandoned orchards and fields at Elm Hill, where they find ideal habitat. Consequently, deer browsing is severe, especially in these locations.
- **Non-native plants**: Field edges, abandoned orchards, abandoned fields, and the young forests that have established in them have been densely invaded by diverse non-native plants. The most threatening of these non-native invaders is round-leaved bittersweet, which climbs trees along forest edges and in canopy gaps, where it can destroy mature trees and suppress regeneration. Norway maple invasion emanating from the mature trees along East Main Street are also a severe threat because this species is sufficiently shade tolerant to establish in the forest understory.
- **Combined change**: Elm Hill is severely vulnerable to the combined impacts of climate change, diseases, pests, browsing, and non-native plant invasions. This

vulnerability could be reduced to moderate, if the severity of deer browsing, and the abundance of non-native plants are sufficiently reduced through active management. Specifically, the potential impacts on the forest canopy are local, and there are ample tree species that are adapted to future conditions that could fill canopy gaps, provided that tree regeneration is not impaired by deer browsing and non-native plant competition. The importance of controlling invasive plants is illustrated by the invasive species meltdown that is currently occurring in some white ash dominated stands where the non-native emerald ash borer is killing the canopy trees while non-native plants such as round-leaved bittersweet lianas are proliferating in the gaps where they are overwhelming native tree saplings.

Management recommendations:

1. Open Elm Hill to deer hunting (subject to all applicable state regulations). Monitor the deer population and the impact of browsing.
2. Expand the existing program to control non-native plants in the most severely invaded areas at Elm Hill. Treatment priorities should include the following:
    - Follow-up treatments of the edges around the fields on Buxton Hill Road in the northwest of the sanctuary that have been treated already.
    - Treatment of the non-native plants that started invading the canopy gaps that were opened by the partial harvest implemented in the north of the sanctuary.
    - Clear the non-native vegetation from the densely invaded abandoned fields on Cooley Hill, the abandoned orchards on Blanchard Hill, and the young forest of dying white ash in the east of the sanctuary north of Slab City Road. Carefully consider habitat management goals for these areas from the perspective of keeping these areas from becoming dominated by non-native plants again in the future.
3. Abandoned fields that are too small to be viable as hayfields should be reforested to reduce vulnerability to invasion by non-native plants. Reforesting of abandoned fields is an opportunity to plant tree species that are adapted to a slightly warmer climate but that do not yet occur at Elm Hill such as tulip tree, yellow buckeye, and cucumber tree, or that are currently rare at Elm Hill such as chestnut oak, black maple, and black walnut. Plantings could also include disease resistant selections of American elm (e.g. Valley Forge, Prairie Expedition, Saint Croix, Princeton), in honor of the sanctuary name.

Native canopy tree species list:

- Benefit: black oak, white oak, chestnut oak, shagbark hickory, mockernut hickory, bitternut hickory, pignut hickory, black walnut
- Neutral: red oak, red maple, trembling aspen, black birch, sugar maple, yellow birch, bigtooth aspen, black cherry, black gum, basswood, black maple
- Decline: white pine, hemlock, paper birch, beech, white ash, American elm, butternut, chestnut

Flat Rock

Vulnerabilities:

- **Climate**: Much of the forest at Flat Rock is dominated by hemlock, a species that is highly vulnerable to climate change.
- **Pests and diseases**: The abundant hemlock and white pine are vulnerable to hemlock woolly adelgid and needle cast disease, respectively. A warmer future climate will exacerbate the pest and disease threat for these conifers. Chestnut was a co-dominant tree species before the spread of chestnut blight. Potential future Asian long-horned beetle and spongy moth outbreaks could kill some maples and oaks, respectively.
- **Browsing**: The impact of deer browsing appears to be moderate, but high enough to significantly hinder regeneration in the rock ledge pitch pine barrens habitat restoration area.
- **Non-native plants**: Non-native plants are few in the forests at Flat Rock, except for the moist east-facing slope next to Overlook Reservoir.
- **Combined change**: Overall, Flat Rock is severely vulnerability to the combined impact of climate change, diseases, and pests. However, browsing impact is moderate, and non-native plant invasion threats are localized. Reducing deer browsing through active management could increase the ability of the forest to recover from future canopy tree die-offs.

Management recommendations:

1. Monitor the deer population and the impact of browsing. Investigate if opening the property to an organized annual deer hunt is feasible.
2. Implement the second phase of thinning the rock ledge pitch pine barrens habitat to reduce fire hazard and release remaining pitch pines from competition. This site had a recent wildfire. Putting out wildfires typically involves spraying of highly toxic and persistent PFAS (per- and polyfluoroalkyl substances). One could explore possibilities of alternatives such as allowing ground fires to burn until they reach firebreaks or reducing fire fuels with prescribed ground fires, that would also have ecological benefits for the pitch pine barrens vegetation.
3. Raise funding for a contract to suppress non-native plants in and around the trailhead parking lot and on the east-facing slope next to Overlook Reservoir.
4. Consider a project to transition the highly vulnerable conifer-dominated forest on Hemlock Hill to a species composition that is better adapted to future conditions such as a pitch pine oak barren with a diverse mix of oaks and hickories. Slash from the harvest could be used to build a wall around the project area that is impassable for deer to protect planted seedlings. An additional benefit of the project would be increasing the early successional habitat for shrubland birds whose populations have declined dramatically in Massachusetts. One could also open a view from the project area.

Native canopy tree species list:

- Benefit: black oak, scarlet oak, white oak, black gum, shagbark hickory
- Neutral: red oak, red maple, trembling aspen, black birch, sassafras, pitch pine, sugar maple, yellow birch, bigtooth aspen, basswood, black cherry
- Decline: white pine, hemlock, paper birch, beech, white ash, American elm, chestnut

Graves Farm

Vulnerabilities:

- **Climate**: Much of the forest at Graves Farm is dominated by dense stands of eastern hemlock, a species that is highly vulnerable to climate change.
- **Pests and diseases**: The extensive hemlock and eastern white pine stands are threatened by hemlock woolly adelgid and needle cast disease, respectively. A warmer future climate will exacerbate the pest and disease threat for these two evergreen conifer species. Chestnut, beech, and elm are now minor tree species that were likely more abundant before the spread of non-native diseases. White ash is a minor tree species at Graves Farm that is now also threatened by emerald ash borer.
- **Browsing**: Browsing by deer is moderate at Graves Farm, although probably severe enough that species vulnerable to deer browsing such as oak rarely grow into saplings.
- **Non-native plants**: Abundance of non-native plants is generally low in the mature forests, except for the southeastern part of the sanctuary, and the rich mesic forest on the east facing slope of O'Neil Hill. Woody plants including non-native species such as round-leaved bittersweet are invading several of the fields and forest edges around the fields.
- **Combined change**: Overall, Graves Farm Wildlife Sanctuary is severely vulnerable to the combined impact of climate change, diseases, pests, browsing, and non-native plant invasion threats. Diverse tree species that are adapted to future conditions are present throughout the sanctuary and could lead a recovery following die-offs of

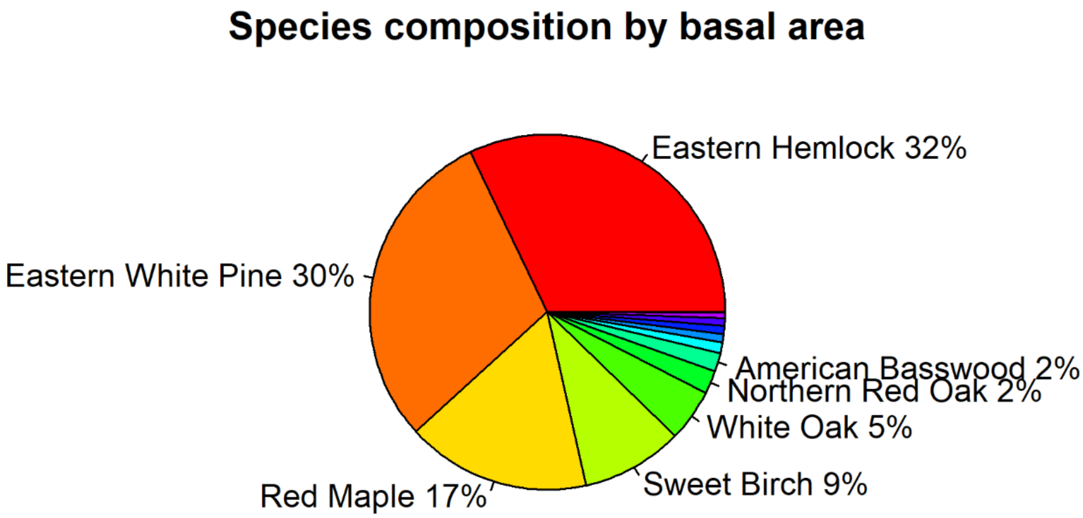
canopy trees, provided that tree regeneration is not impaired by deer browsing and non-native plant competition.

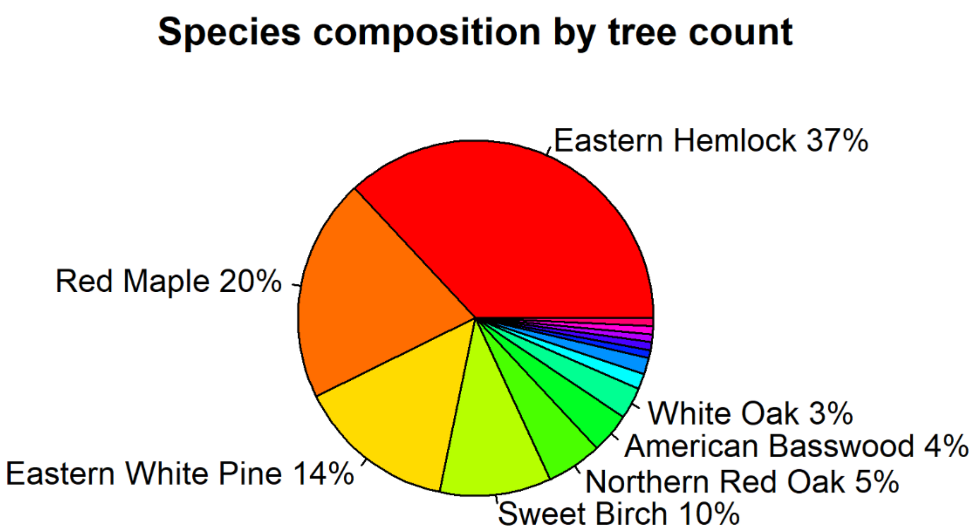
Management recommendations:

1. Monitor the deer population and the impact of browsing. Investigate if opening Graves Farm to an organized annual deer hunt is feasible.
2. Raise funding for contracts to suppress non-native plants in the most severely invaded areas. In the case of the fields, the invading woody plants should be controlled with herbicides, could be followed by ploughing, disking, and seeding timothy (*Phleum pratense*) to restore fields as bobolink grassland habitat. The canopy gaps resulting from clearing non-native plants around field edges and shrub islands are an opportunity to do climate adaptation tree planting. Appropriate species choices for an adaptation planting include the following: tulip tree, black gum, sweetgum, cucumber tree, chestnut oak, pawpaw, and yellow buckeye.
3. There is an exceptionally large white oak on O'Neil Hill Trail that is surrounded by younger competing red maples. Cutting the neighboring red maple to release this specimen oak from competition will increase its vigor. This thinning could be done as part of a staff chainsaw training. If this oak is preserved, it can act as a seed tree for the recovery of the surrounding forest when the dominant hemlock and white pine die-off. White oak is now rare on O'Neil Hill but much better adapted to a future warmer climate than the conifers that are currently dominant there.

Native canopy tree species list:

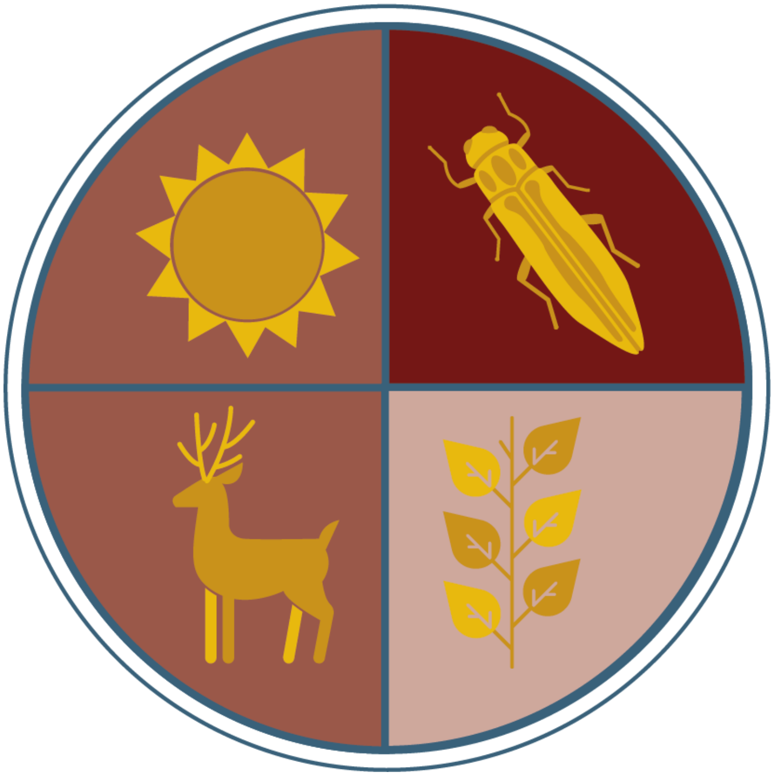
- Benefit: shagbark hickory, bitternut hickory, pignut hickory, mockernut hickory, white oak, black oak, basswood
- Neutral: red oak, black cherry, sugar maple, red maple, bigtooth aspen, black birch, yellow birch
- Decline: white pine, hemlock, paper birch, beech, white ash, American elm, chestnut, butternut





Summary of forest composition in carbon inventory plots at Graves Farm Wildlife Sanctuary in 2016.

High Ledges



Vulnerabilities:

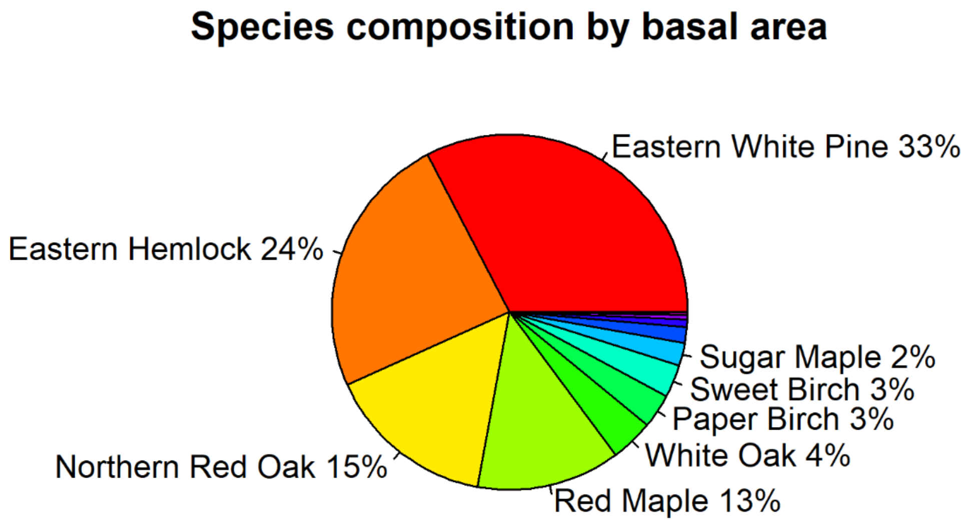
- **Climate**: High Ledges has extensive stands of eastern hemlock, a species that is highly vulnerable to climate change.
- **Pests and diseases**: Extensive hemlock and eastern white pine stands are threatened by hemlock woolly adelgid and needle cast disease, respectively. A warmer future climate will exacerbate the pest and disease threat for these two evergreen conifer species. Chestnut and beech are now minor tree species that were likely more abundant before the spread of non-native diseases. White ash is a minor tree species that is now also threatened by emerald ash borer.
- **Browsing**: Browsing by deer is moderate at High Ledges, although probably severe enough that species vulnerable to deer browsing such as oak rarely grow into saplings.
- **Non-native plants**: Abundance of non-native plants is generally low at High Ledges, except for some of the abandoned fields and field edges in The Patten.
- **Combined change**: Overall, High Ledges Wildlife Sanctuary is moderately vulnerable to the combined impact of climate change, diseases, pests, browsing, and non-native plant invasion threats. Diverse tree species that are adapted to future conditions are present throughout the sanctuary and could lead a recovery following die-offs of canopy trees, provided that tree regeneration is not impaired by deer browsing and non-native plant competition.

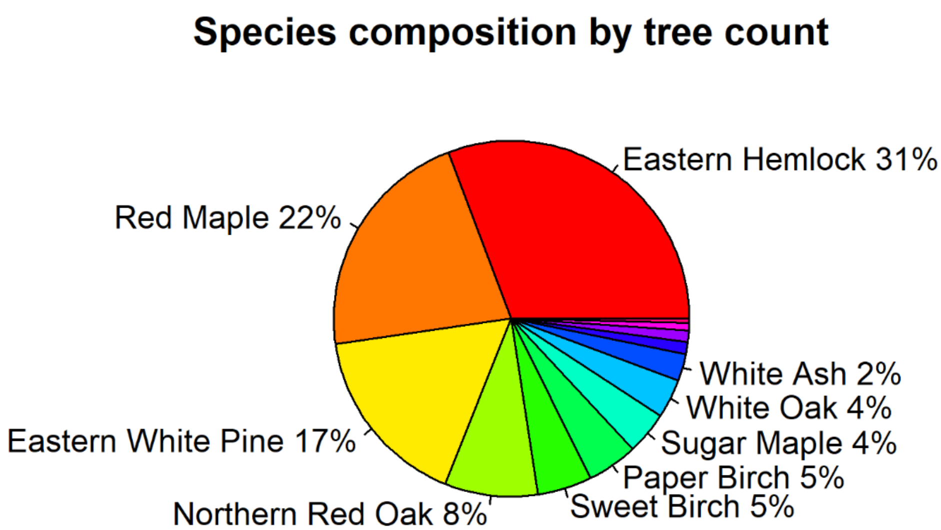
Management recommendations:

1. Monitor the deer population and the impact of browsing. Investigate if opening High Ledges to an organized annual deer hunt is feasible.
2. Raise funding for contracts to suppress non-native plant infestations in the abandoned fields and orchards in The Patton. Consider implementing a climate change adaptation tree planting in the canopy openings in the treated areas. Potentially site appropriate tree species that are adapted to a slightly warmer climate and that do not yet occur at High Ledges include the following: tulip tree, black gum, cucumber tree, and yellow buckeye.

Native canopy tree species list:

- Benefit: shagbark hickory, bitternut hickory, mockernut hickory, pignut hickory, white oak, black oak, chestnut oak, basswood
- Neutral: red oak, sugar maple, red maple, bigtooth aspen, trembling aspen, black birch, yellow birch
- Decline: white pine, hemlock, paper birch, beech, white ash, chestnut





Summary of forest composition in carbon inventory plots at High Ledges Wildlife Sanctuary in 2016.

Lake Wampanoag

Vulnerabilities:

- **Climate**: The forests at Lake Wampanoag are dominated by northern evergreen conifers such as red spruce and hemlock that are doomed by climate warming in the long term. However, the currently still relatively cold local climate may well delay this impact until after 2050.
- **Pests and diseases**: The extensive stands of eastern hemlock and eastern white pine are vulnerable to pests and diseases such as hemlock woolly adelgid and needle cast disease, respectively. However, relatively cold winter temperatures may limit hemlock woolly adelgid populations until 2050.
- **Browsing**: Browsing impact by deer is moderate at Lake Wampanoag. Indeed, moose may be a more important browser than deer in this wildlife sanctuary.
- **Non-native plants**: Non-native plants are few in the forests, but quite prominent around the edges of the field and capped landfill site.
- **Combined change**: The forests and wetlands at Lake Wampanoag are moderately vulnerable to the combined impact of climate change and pests until 2050 but become severely vulnerable as warming becomes more extreme later this century.

Management recommendations:

1. Monitor the deer population and the impact of browsing. Investigate if opening Lake Wampanoag to an organized annual deer hunt is feasible.
2. Suppress non-native plants around field edges before they become more difficult to manage. Consider planting a few trees that are adapted to a warmer climate (e.g.

white oak, black oak) in the openings around the field edges created by non-native plant suppression.

Native canopy tree species list:

- Benefit: black gum, red oak, black birch
- Neutral: red maple, trembling aspen, sugar maple, yellow birch, bigtooth aspen, black cherry, hemlock, white pine, paper birch
- Decline: beech, white ash, red spruce, balsam fir

Laughing Brook

Vulnerabilities:

- **Climate**: Most of the forests at Laughing Brook are dominated by oaks or maples, which are likely to benefit from a warmer climate. The exception is a hemlock dominated north facing slope. Hemlock is imminently threatened by a warming climate at this site.
- **Pests and diseases**: Chestnut was likely a co-dominant tree species in some upland forests and American elm was likewise in the riparian forests prior to the spread of non-native fungal diseases. The 2015 to 2017 outbreak of spongy moth thinned out the oak overstory. Eastern white pine and eastern hemlock, which are threatened by hemlock woolly adelgid and needle cast disease, respectively, are abundant or even dominant in some stands. Indeed, the dominance of these vulnerable conifers is increasing with succession.
- **Browsing**: Deer browsing is more severe at Laughing Brook than the rest of the Central and West Region Mass Audubon wildlife sanctuaries. The intense deer browsing over many years has impoverished the forest understory often only leaving the most unpalatable plants such as Japanese barberry (*Berberis thunbergii*). For example, the only native tree seedlings growing in the canopy gaps created by the recent gypsy moth outbreak are of the relatively unpalatable eastern white pine.
- **Non-native plants**: Non-native plants have proliferated in the former program areas in the decades following the removal of the nature center buildings and have started invading substantial areas of the surrounding forests. While the dry oak-dominated uplands and west-facing slopes are relatively free of non-native plants, the moister

maple-dominated east-facing slopes, intervales, and riparian forests are highly invaded by non-native plants, especially by Japanese barberry.

- **Combined change**: Laughing Brook Wildlife Sanctuary is severely vulnerable to the combined impacts of climate change, diseases, pests, browsing, and non-native plant invasions. This vulnerability could be reduced to moderate or even lower, if the severity of deer browsing, and the abundance of non-native plants are sufficiently reduced through active management. Specifically, the potential impacts on the forest canopy are local, and there are ample tree species that are adapted to a warmer climate that could fill canopy gaps, provided that tree regeneration is not impaired by deer browsing and non-native plant competition.

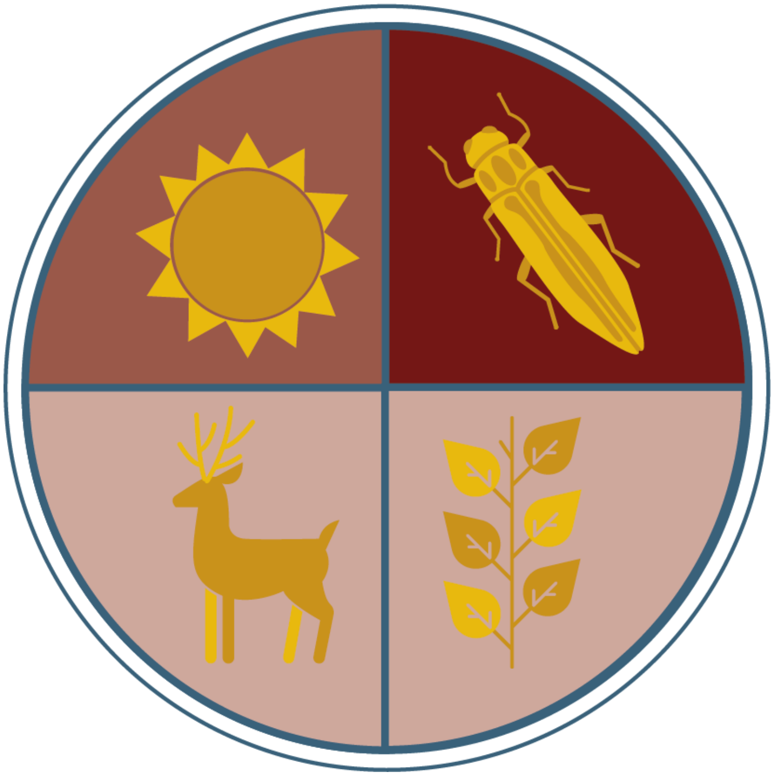
Management recommendations:

1. Open the wildlife sanctuary to an organized deer hunt annually to substantially reduce the impact of deer browsing. Monitor the deer population and impact of deer browsing.
2. Implement a coarse woody debris addition to Big Brook to slow flood flows, increase floodplain connectivity, and restore aquatic and riparian habitats.
3. When canopy gaps form after a major disturbance such as the 2015 to 2017 spongy moth outbreak, consider installing wire mesh cages around oak or hickory seedlings in gaps to protect the seedlings against deer browse, and thereby increase recruitment of these warm-climate-adapted trees.
4. Suppress the most severe non-native plant infestations of round-leaved bittersweet and non-native shrubs in and around the field and former program areas because they are a major source of non-native plant seeds dispersing into surrounding forests. Note that the field is being invaded by woody plants, both native and non-native, which will require some herbicide application to restore a grassland. Invasive plant control in the more remote forest areas is a lower priority while deer browsing is still severe.
5. In the shrubby riparian buffers, implement a climate change adaptation tree planting that could include the following species: tulip tree, sweetgum, sycamore, pin oak, black gum, yellow buckeye, and disease resistant selections of American elm (e.g. Valley Forge, Prairie Expedition, Saint Croix, Princeton).
6. Aging pitch pines and a few scrub oaks (*Quercus ilicifolia*) are still present in parts of the sanctuary, providing evidence of an ecosystem that was shaped by fire in the past. The pitch pine barrens habitat structure could be restored by a partial harvest that removes especially eastern white pines, but also red maple, birches, and some of the oaks. Once a barrens structure is restored and fuel loads have been reduced, one can explore the feasibility of implementing prescribed ground fires to restore this important process to this fire-adapted ecosystem.

Native canopy tree species list:

- Benefit: black oak, white oak, chestnut oak, scarlet oak, shagbark hickory, pignut hickory
- Neutral: black birch, red oak, red maple, sugar maple, black cherry, swamp white oak, black walnut, bigtooth aspen, pitch pine, sassafras, trembling aspen
- Decline: white pine, hemlock, white ash, American elm, beech, chestnut

Laurel Woods



Vulnerabilities:

- **Climate**: Some evergreen conifers which are vulnerable to climate change such as hemlock are common in Laurel Woods, but most of the trees are well adapted to a warmer climate.
- **Pests and diseases**: The abundant hemlock and white pines are vulnerable to hemlock woolly adelgid and needle cast disease, respectively. A warmer future climate will exacerbate the pest and disease threat for these conifers. American elm likely occurred in the swamp prior to the spread of Dutch elm disease. Currently, white ash is common in the swamp and threatened by emerald ash borer.
- **Browsing**: The impact of deer browsing appears to be slight.
- **Non-native plants**: Non-native plants are present but few at Laurel Woods.
- **Combined change**: Overall, Laurel Woods has a relatively low vulnerability to the combined impact of climate change, diseases, and pests, browsing, and non-native plant invasion threats.

Management recommendations:

1. Suppress the few occurrences of round-leaved bittersweet in the swamp to ensure that non-native plant abundance remains low.

Native canopy tree species list:

- Benefit: black oak, bitternut hickory, black gum
- Neutral: black birch, red oak, yellow birch, red maple, sugar maple, black cherry, basswood, sassafras
- Decline: white pine, white ash, hemlock, beech

Lime Kiln Farm

Vulnerabilities:

- **Climate**: Dense stands of highly vulnerable hemlock are common throughout much of Lime Kiln Farm. Spruce plantings and black ash swamps are likewise highly vulnerable to climate change.
- **Pests and diseases**: American elm was likely a co-dominant tree species in swamps before the spread of Dutch elm disease. The currently ash-dominated swamps are imminently vulnerable to emerald ash borer. Many of the forests at Lime Kiln Farm are dominated by eastern hemlock and/or white pine, which are threatened by hemlock woolly adelgid and needle cast disease, respectively. The vulnerability to hemlock woolly adelgid will be exacerbated by climate change.
- **Browsing**: Deer browsing appears to be relatively severe.
- **Non-native plants**: Abundant non-native shrubs of diverse species and round-leaved bittersweet have invaded field edges and adjacent forest. Some of the wetlands are dominated by common reed.
- **Combined change**: Overall, Lime Kiln Farm is severely vulnerable to the combined impact of climate change, diseases, pests, browsing, and non-native plant invasion threats. When evergreen conifer forests or ash swamps die off from climate change and pests, the resulting canopy gaps could be invaded by non-native plants thereby bringing about a kind of invasive species meltdown. Alternatively, controlling non-native plant infestations could reduce competition for the many native tree species at Lime Kiln Farm that are well adapted to a warmer future climate.

Management recommendations:

1. Raise funding for contracts to suppress non-native plants in the most severely invaded areas, such as the forest edges around the fields or the common reed in the marshes. Tree harvests are inadvisable until non-native plant infestation have been suppressed because opening the forest canopy would promote non-native plants.
2. Suppression of non-native plants around field edges and in hedgerows, clearing of the spruce plantations, and thinning of dense conifer stands could increase forest resilience and at the same time create canopy openings for climate change adaptation tree planting. Appropriate species for climate change adaptation planting on the calcareous soils of Lime Kiln Farm include the following: bur oak, yellow oak, northern hackberry, black maple (*Acer nigrum*), and pignut hickory in uplands; and swamp chestnut oak, overcup oak, pecan, sycamore, yellow buckeye, and pawpaw around edges of swamps.
3. Open Elm Hill to an organized annual deer hunt. Monitor the deer population and the impact of browsing.
4. One could experiment with replacing the ash that die from emerald ash borer with disease resistant selections of American elm (e.g. Valley Forge, Prairie Expedition, Saint Croix, Princeton). Elms with elevated disease resistance could be brought in by planting nursery stock or, more cost effectively, by collecting seeds from existing disease resistant elm plantings and planting the seeds directly on site.

Native canopy tree species list:

- Benefit: bur oak, black oak, white oak, swamp white oak, yellow oak, eastern red cedar (*Juniperus virginiana*), shagbark hickory, bitternut hickory, northern hackberry, basswood, tulip tree, black gum, scarlet oak
- Neutral: red oak, red maple, black birch, sugar maple, yellow birch, black cherry, bigtooth aspen, black walnut, eastern cottonwood, boxelder
- Decline: hemlock, paper birch, beech, white ash, white pine, black ash, green ash, American elm, tamarack, butternut

Lincoln Woods

Vulnerabilities:

- **Climate**: Most of the sanctuary's forests are dominated by oaks and other hardwoods that are well adapted to a warmer climate.
- **Pests and diseases**: Chestnut was likely a co-dominant tree species before the spread of chestnut blight. Eastern white pine, which is vulnerable to needle cast disease, is a common tree species in about half of the sanctuary. The swamps have white ash and American elm which are vulnerable to emerald ash borer and Dutch elm disease, respectively.
- **Browsing**: Browsing by deer is moderate at Lincoln Woods.
- **Non-native plants**: A severe Norway maple infestation emanating from mature planted trees around the parking area is spreading southward through the sanctuary. If left unchecked, the shade tolerant Norway maples will become the dominant trees throughout most of the sanctuary. The small field next to the parking lot and the tiny stream entering the sanctuary in the northwestern corner are invasion corridors for diverse other non-native plants including round-leaved bittersweet.
- **Combined change**: Overall, Lincoln Woods is severely vulnerable to the combined impact of climate change, diseases, pests, browsing, and non-native plant invasion threats. Pivotal to reducing overall vulnerability will be controlling the invasions of round-leaved bittersweet and especially Norway maple.

Management recommendations:

1. Raise funding for contracts to control Norway maple and round-leaved bittersweet throughout the sanctuary, especially in the northern half. The larger canopy gaps from felling mature Norway maple could an opportunity for climate change adaptation tree planting. Appropriate tree species to plant could include the following: mockernut hickory, pignut hickory, and American holly.
2. After controlling all the non-native plants in the field next to the parking lot, cease mowing the field and reforest the field to make it less vulnerable to re-invasion. Take advantage of the abundant existing natural regeneration in the field, for example by protecting black oak seedlings from deer browsing with wire mesh cages.
3. Monitor the impact of deer browsing.

Native canopy tree species list:

- Benefit: shagbark hickory, white oak, black oak, chestnut oak
- Neutral: red oak, black birch, black cherry, sugar maple, red maple, trembling aspen, pitch pine, basswood, black gum, swamp white oak
- Decline: white pine, white ash, American chestnut, American elm

Lynes Woods

Vulnerabilities:

- **Climate**: Eastern hemlock, a species that is highly vulnerable to climate change, is dominant or co-dominant in much of Lynes Woods.
- **Pests and diseases**: The extensive hemlock and eastern white pine stands are threatened by hemlock woolly adelgid and needle cast disease, respectively. A warmer future climate will exacerbate the pest and disease threat for these two evergreen conifer species. Beech is also common despite the past impacts of beech bark disease. The remaining beech trees are imminently threatened by beech leaf disease. White ash, which is vulnerable to emerald ash borer, is common in the northwestern part of the sanctuary.
- **Browsing**: Browsing by deer appears to be moderate at Lynes Woods.
- **Non-native plants**: Abundance of non-native plants is generally low in the mature forests at Lynes Woods. Non-native shrubs are more common in the younger forests in the northwestern part of the sanctuary and especially in and around the two remaining small fields and the trailhead parking lot.
- **Combined change**: Overall, Lynes Woods Wildlife Sanctuary is severely vulnerable to the combined impact of climate change, diseases, pests, browsing, and non-native plant invasion threats. Diverse tree species that are adapted to future conditions are present throughout the sanctuary and could lead a recovery following die-offs of canopy trees, provided that tree regeneration is not impaired by deer browsing and non-native plant competition.

Management recommendations:

1. Monitor the impact of deer browsing. Investigate if opening such a small property to an organized annual deer hunt is worthwhile.
2. Suppress non-native plants in and around the fields and parking lot. Cease mowing the two small fields and reforest them to reduce their vulnerability to re-invasion by non-native plants. A reforestation is an opportunity to do a climate change adaptation planting that could include the following species: shagbark hickory, tulip tree, and cucumber tree.

Native canopy tree species list:

- Benefit: black gum, swamp white oak, black oak, white oak
- Neutral: red oak, red maple, black birch, sugar maple, yellow birch, black cherry, trembling aspen
- Decline: hemlock, paper birch, beech, white ash, white pine

Old Baldy

Vulnerabilities:

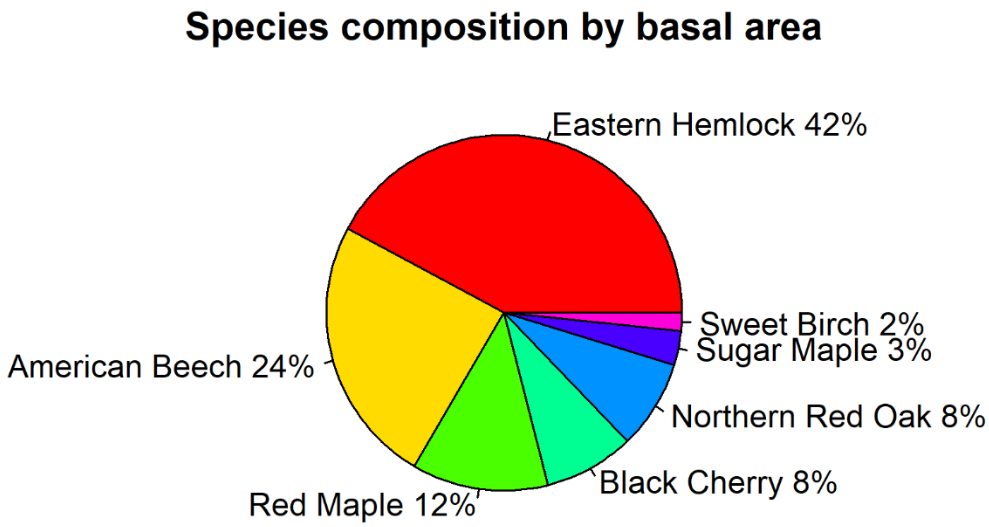
- **Climate**: Most of the forests at Old Baldy Wildlife Sanctuary are dominated by eastern hemlock, a species that is highly vulnerable to climate change.
- **Pests and diseases**: Beech is common on Old Baldy, despite beech bark disease. The remaining beech are likely to die from beech leaf disease. The dense stands of hemlock are vulnerable to hemlock scale and hemlock woolly adelgid. A warmer future climate will exacerbate the hemlock woolly adelgid threat.
- **Browsing**: Browsing by deer is moderate at Old Baldy. For example, the dense thickets of diverse native tree seedlings in the clearing on the top of Old Baldy have successfully grown into the sapling size beyond the reach of deer.
- **Non-native plants**: Non-native plants are largely absent from Old Baldy, except for a few non-native honeysuckles in the floodplain of the Farmington River.
- **Combined change**: Overall, the forest canopy at Old Baldy Wildlife Sanctuary is moderately vulnerable to the combined impact of climate change, diseases, and pests. Although the combination of a warming climate and pests will lead to a die-off of the dominant hemlocks, the relative lack of non-native plants and deer browsing should allow the forest to recover without intervention.

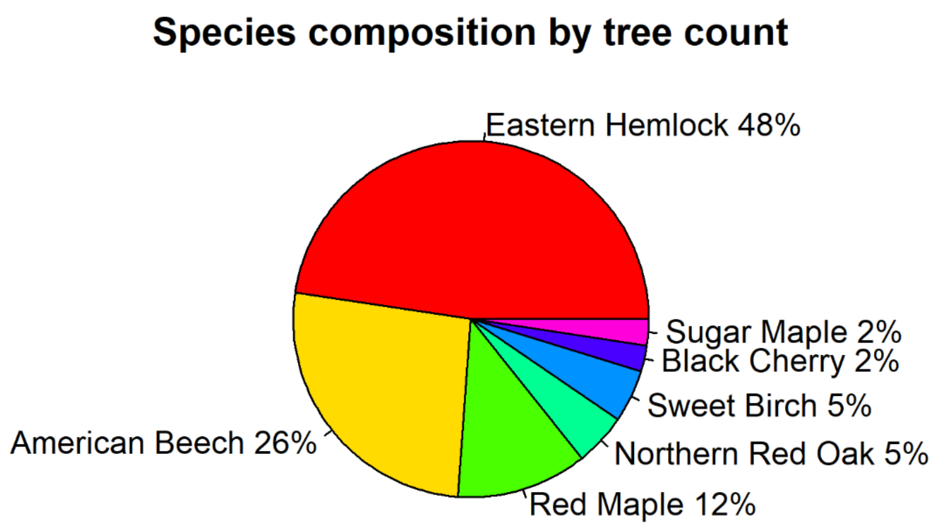
Management recommendations:

1. Open Old Baldy to deer hunting (subject to all applicable state regulations). Monitor the deer population and the impact of browsing.

Native canopy tree species list:

- Benefit: red oak, bitternut hickory, basswood
- Neutral: black birch, yellow birch, red maple, black cherry, sugar maple, bigtooth aspen
- Decline: white pine, beech, white ash, hemlock, paper birch, American elm





Summary of forest composition in carbon inventory plots at Old Baldy Wildlife Sanctuary in 2016.

Pierpont Meadow

Vulnerabilities:

- **Climate**: Few trees at Pierpont Meadow are of species that are vulnerable to climate change.
- **Pests and diseases**: Chestnut was a co-dominant tree species in most upland forests and American elm was likely more common in swamps prior to the spread of non-native fungal diseases. The dense stands of white pine in the west of the sanctuary are threatened by needle cast disease. The oak forests in the eastern part of the sanctuary were thinned by the 2015 to 2017 spongy moth outbreak. A hypothetical outbreak of Asian longhorned beetles could affect red maple swamps.
- **Browsing**: Browsing by deer appears to be moderate.
- **Non-native plants**: Fields, especially their edges, shrublands, and the young forests in the western part of the sanctuary have been severely invaded by non-native plants. The most threatening of these non-native invaders is round-leaved bittersweet, which climbs trees along forest edges, where it can destroy mature trees and suppress forest regeneration. By contrast, non-native plants are largely absent in the older oak forests of the eastern part of the sanctuary.
- **Combined change**: The western parts of Pierpont Meadow are severely vulnerable to the combined impacts of climate change, diseases, pests, browsing, and non-native plant invasions. This vulnerability could be reduced to moderate, if the severity of deer browsing, and the abundance of non-native plants are sufficiently reduced through active management. By contrast, the oak-dominated upland forests in the eastern part of the sanctuary have low vulnerability.

Management recommendations:

1. The oak dominated uplands in the eastern part of the sanctuary are highly resistant to climate change in their present state. Mass Audubon should not risk degrading that condition through any forestry activities that could open the canopy and expose the forest to non-native plant invasion and alter the canopy tree species composition.
2. Investigate the most effective management strategy for the western parts of Pierpont Meadow that are densely invaded by non-native plants. The strategy may need to include a variety of tactics that fit different invaded habitat types including fields, hedgerows, forest edges, shrublands, wetlands, young forest stands that grew in abandoned fields, and mature forests. Ideal endpoints could be either a closed canopy forest that casts deeper shade than the present forest (i.e. succession from white pine and red maple to shagbark hickory and sugar maple, which would need to be planted in the understory with deer protection), or a hayfield that is periodically ploughed, disked, and seeded to reset the succession from grassland to weedy shrubland (i.e. some shrublands may need to be cleared before re-establishing a hayfield). Around the edges of swamps, canopy gaps created by removal of non-native vegetation could be used to plant tree species that are well-adapted to future conditions, but that are not on site yet, such as the following: black gum, tulip tree, sycamore, sweetgum, swamp white oak, pin oak, or disease resistant selections of American elm (e.g. Valley Forge, Prairie Expedition, Saint Croix, Princeton).
3. Open the wildlife sanctuary to an organized annual deer hunt to substantially reduce the impact of deer browsing. Monitor the deer population and the impact of browsing.

Native canopy tree species list:

- Benefit: white oak, black oak, scarlet oak, shagbark hickory, mockernut hickory, pignut hickory
- Neutral: red oak, black birch, black cherry, red maple, trembling aspen, black gum, yellow birch, bigtooth aspen, sassafras
- Decline: white pine, white ash, American chestnut, American elm, hemlock

Pleasant Valley

Vulnerabilities:

- **Climate**: The uplands at Pleasant Valley tend to be dominated by hemlock, a tree species that is severely vulnerable to climate change; whereas the lowlands tend to be dominated by deciduous hardwoods that are much less vulnerable to climate change.
- **Pests and diseases**: Chestnut sprouts along the Trail of the Ledges suggest that this species was an important species on top of the mountain before the spread of chestnut blight, while American elm would have been more common in the riparian forests prior to the spread of Dutch elm disease. Beech was likely a more common tree species at Pleasant Valley before it was decimated by beech bark disease. The remaining beech are likely to die from beech leaf disease. White ash is a common tree species in riparian forests and on east-facing slopes. Emerald ash borer is multiplying at Pleasant Valley and some ashes have already died from this non-native pest. The extensive hemlock forests and dense stands of eastern white pine are threatened by hemlock woolly adelgid and needle cast disease, respectively. A warmer future climate will exacerbate the pest and disease threat to these two evergreen conifer species.
- **Browsing**: Browsing by deer appears to be moderate at Pleasant Valley.
- **Non-native plants**: Abundance of non-native plants is generally low in the older forest at higher elevations, whereas the lower elevations that were cleared land more recently host numerous non-native plant infestations. Especially alarming is the spread of non-native lianas such as hardy kiwi and round-leaved bittersweet, which can destroy regeneration and even mature trees along forest edges and in treefall

gaps. Some of the wetlands in the northeast of the sanctuary have been invaded by stands of common reed that may be expanding.

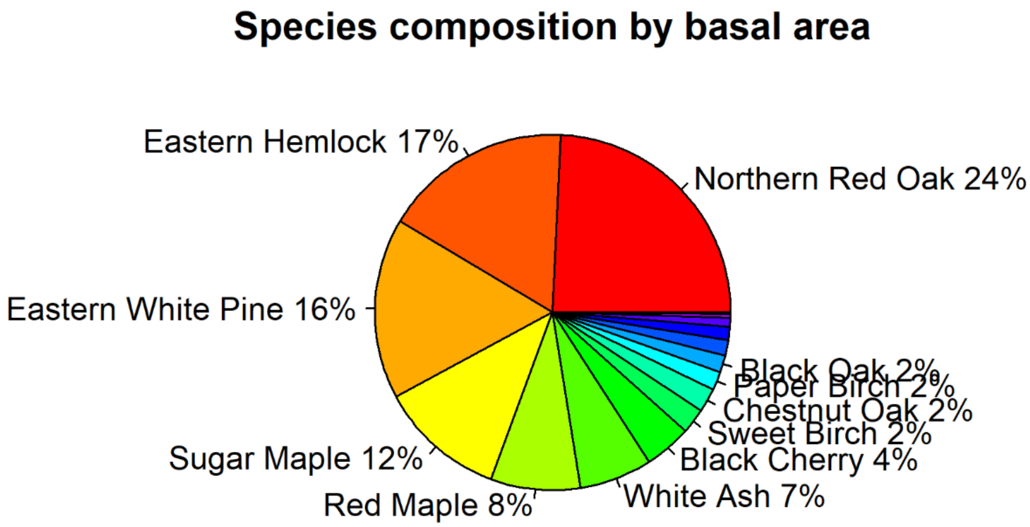
- **Combined change**: Overall, Pleasant Valley is moderately vulnerable to the combined impact of climate change, diseases, pests, deer browsing, and invasion by non-native plants. Recovery from ash tree die-offs now and hemlock tree die-offs in the future will depend on tree regeneration not being significantly impaired by deer browsing or non-native plant competition, especially lianas. Reducing the severity of browsing from current levels and controlling emerging non-native plant infestations will be pivotal for increasing forest resilience.

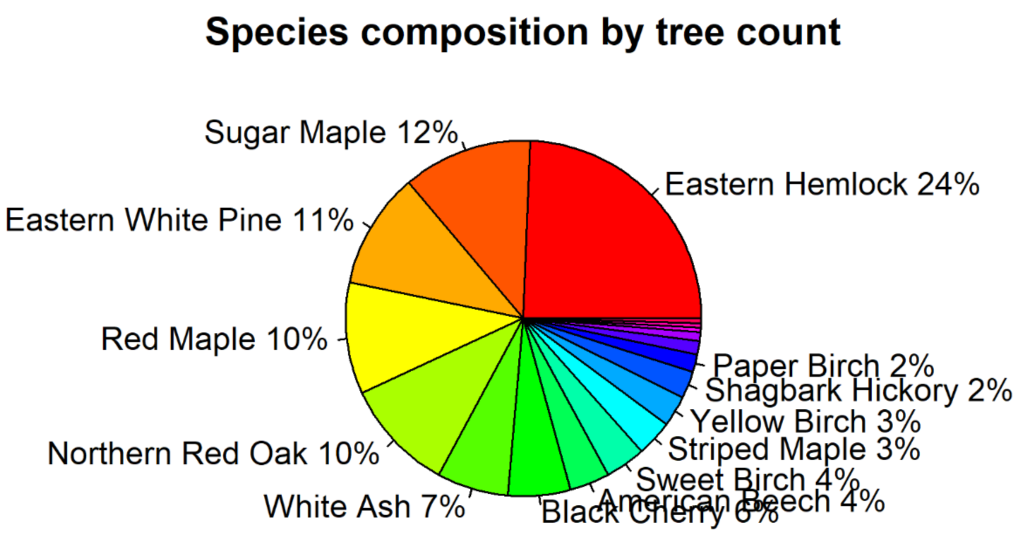
Management recommendations:

1. Raise funding for contracts to suppress non-native plants in the most severely invaded areas, such as the forest edges around the program areas, and the lowland forests around Hermit Thrush Loop. The control of lianas including both hardy kiwi and round-leaved bittersweet should be the priority in these areas. Another priority is freeing the occurrences of rich mesic forest herbs from non-native plant competition. Excellent progress was made on controlling the hardy kiwi in canopy gaps between West Mountain Road and Kennedy Park. It is important to do a follow up treatment every year or two to prevent hardy kiwi from re-invading canopy gaps in the treated area.
2. Open the wildlife sanctuary to an organized annual deer hunt to substantially reduce the impact of deer browsing. Monitor the deer population and their browsing impact.
3. In future, when larger canopy gaps open from hemlock or white pine die-offs, plant seedlings of tree species that are better adapted to future climate conditions in some of the gaps. Depending on the site conditions, some of the following tree species could be included in the planting: white oak, tulip tree, black gum, cucumber tree, pawpaw, and yellow buckeye.

Native canopy tree species list:

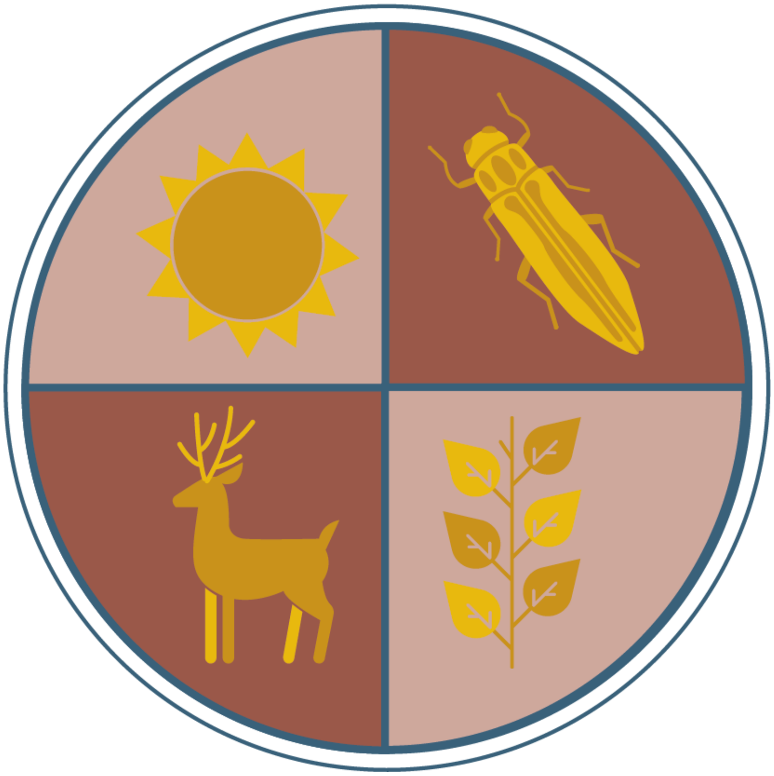
- Benefit: shagbark hickory, bitternut hickory, pignut hickory, chestnut oak, black oak
- Neutral: red oak, sugar maple, red maple, trembling aspen, bigtooth aspen, black birch, yellow birch, black cherry, basswood
- Decline: white pine, hemlock, paper birch, beech, white ash, American elm, butternut, chestnut





Summary of forest composition in carbon inventory plots at Pleasant Valley Wildlife Sanctuary in 2016.

Poor Farm Hill



Vulnerabilities:

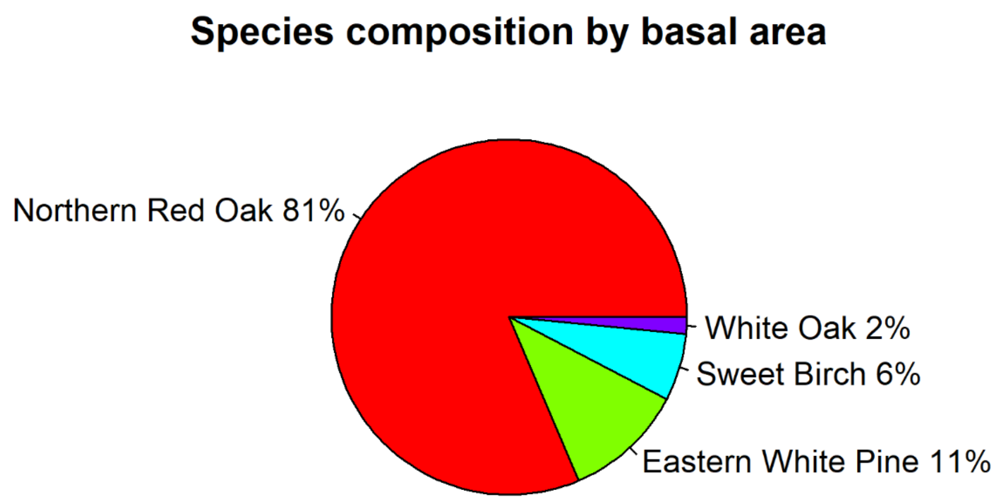
- **Climate**: The oaks that dominate much of the forests at Poor Farm Hill will likely benefit from a warmer climate because they are near the northern range limit of this forest type.
- **Pests and diseases**: Chestnut was likely a co-dominant tree species before the spread of chestnut blight and is still common in the shrub layer. Beech was likely a more common tree species at Poor Farm Hill before it was decimated by beech bark disease. The remaining beech are likely to die from beech leaf disease. The now dominant oaks and maples are not immediately threatened by pests and diseases, although there may be some future mortality from spongy moth or Asian long-horned beetle outbreaks, respectively. The dense stands of white pines in the south and hemlock in the east are vulnerable to needle cast disease and hemlock woolly adelgid, respectively.
- **Browsing**: The impact of deer browsing appears to be moderate at Poor Farm Hill.
- **Non-native plants**: Non-native plants are very few at Poor Farm Hill.
- **Combined change**: Overall, Poor Farm Hill has low vulnerability to the combined impact of climate change, diseases, and pests, browsing, and non-native plant invasions. Although pests and diseases will take their toll on the evergreen conifer component of the canopy, the forest is likely to recover well from those disturbances because deer browsing is moderate, non-native plants are largely absent, and there are lots of tree species adapted to future conditions that can fill canopy gaps.

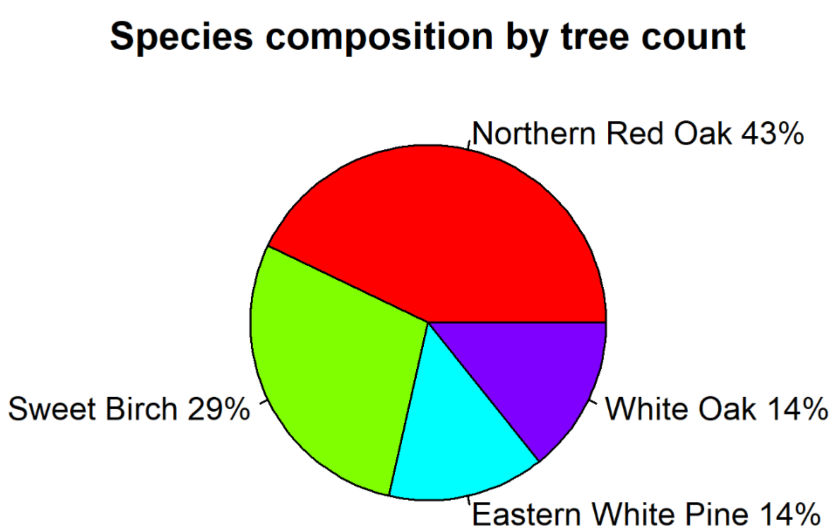
Management recommendations:

1. Thin the dense stand of tree saplings on Fred Lenherr Trail to release saplings of species that are best adapted to future conditions from competition (i.e. cut birches and retain oaks). This stand is smaller than 1 acre, small enough that the thinning could be completed as part of a staff chainsaw training.

Native canopy tree species list:

- Benefit: white oak
- Neutral: red oak, black cherry, sugar maple, red maple, yellow birch, black birch, basswood
- Decline: white pine, white ash, beech, paper birch, chestnut, hemlock





Summary of forest composition in the carbon inventory plot at Poor Farm Hill Wildlife Sanctuary in 2016. There is only a single plot on Poor Farm Hill, which is not representative of the species composition in all of the sanctuary.

Richardson Brook

Vulnerabilities:

- **Climate**: Eastern hemlock, a species that is highly vulnerable to climate change is dominant or co-dominant in most of the forests at Richardson Brook.
- **Pests and diseases**: Despite beech bark disease, beech is still common, especially on the steep south-facing slope in the east of the sanctuary. Beech sprouts are also prominent among the regeneration in the harvested area. The surviving beech population is likely to die soon from beech leaf disease. Eastern white pine and eastern hemlock are dominant or co-dominant trees in most of the sanctuary. These evergreen conifers are vulnerable to needle cast disease and hemlock woolly adelgid, respectively. A warmer future climate will exacerbate the hemlock woolly adelgid vulnerability.
- **Browsing**: Browsing by deer is severe at Richardson Brook. For example, several deer appear to spend much of their time in the harvested area, with the effect that little regeneration is growing beyond deer browse height. The few individuals that are reaching that height are of species that are the least vulnerable to deer browsing (i.e. black birch, beech, and eastern white pine).
- **Non-native plants**: Non-native plants are generally absent from Richardson Brook.
- **Combined change**: Overall, the forest canopy at Richardson Brook Wildlife Sanctuary is severely vulnerable to the combined impact of climate change, diseases, and pests. After the dominant hemlocks, pines, and beeches die from a combination of a warming climate, diseases, and pests, the forest that develops will likely be highly

dominated by birches, because browsing by deer is impairing regeneration of more desirable species such as red oak or sugar maple.

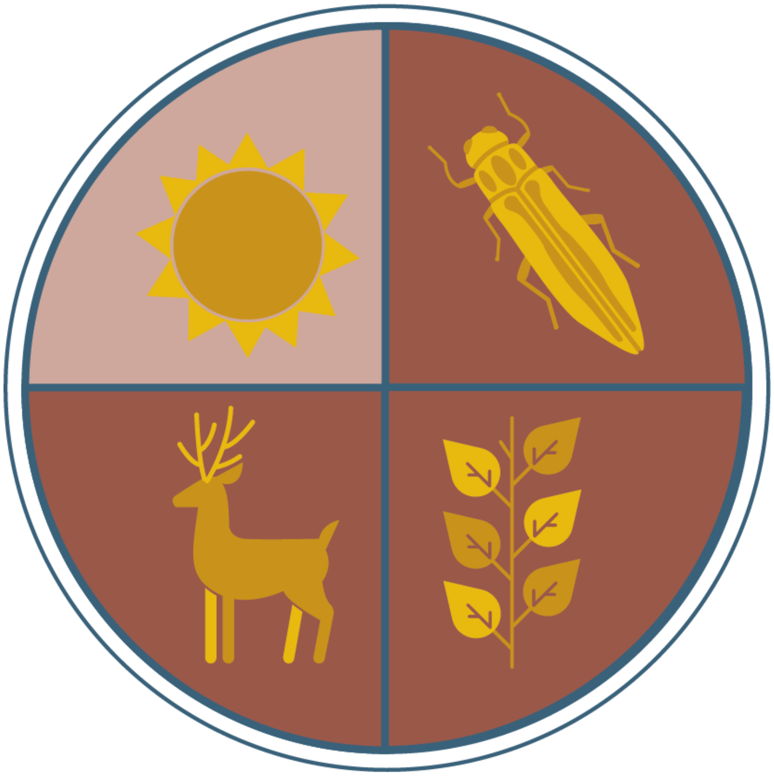
Management recommendations:

1. Open Richardson Brook to deer hunting (subject to all applicable state regulations). Monitor the impact of deer browsing.
2. Consider planting a few individuals of species that are better adapted to future conditions in a suitable part of the clearing that was cut for New England cottontail habitat, because Richardson Brook currently has very few species that would benefit from a warmer climate. Tree species that one could consider planting include the following: tulip tree, basswood, black oak, white oak, shagbark hickory, bitternut hickory.

Native canopy tree species list:

- Benefit: red oak
- Neutral: black birch, yellow birch, red maple, black cherry, sugar maple
- Decline: white pine, beech, white ash, hemlock, American elm, paper birch

Roads End



Vulnerabilities:

- **Climate**: Roads End is mostly dominated by deciduous hardwood trees that are not vulnerable to climate change. Hemlock, red spruce, and paper birch, three species that are vulnerable to climate change, are common on the cool moist northeast-facing slope that is west of Steven Brook. However, the local climate is sufficiently cool that these trees may not suffer severe climatic stress before 2050.
- **Pests and diseases**: Hemlock and/or white pine are dominant or co-dominant throughout most of the sanctuary. These evergreen conifers are threatened by hemlock woolly adelgid and needle cast disease, respectively. A warmer future climate will exacerbate the hemlock woolly adelgid threat. White ash, beech and American elm are minor tree species that are vulnerable to pests and diseases.
- **Browsing**: Browsing by deer appears to be moderate at Roads End.
- **Non-native plants**: Non-native plant abundance is generally low at Roads End with a couple of exceptions. There is an infestation of common reed in the marsh. There are Japanese knotweed and goutweed infestations emanating from the former building site at the trailhead. These infestations are spreading into the neighboring field and down the slope into the forest.
- **Combined change**: Overall, Roads End Wildlife Sanctuary is moderately vulnerable to the combined impact of climate change, diseases, pests, browsing, and non-native plant invasion threats. The forest will likely recover relatively well from climate change, pests, and disease related tree mortality, provided that deer browsing and non-native plant invasions do not become a bigger problem.

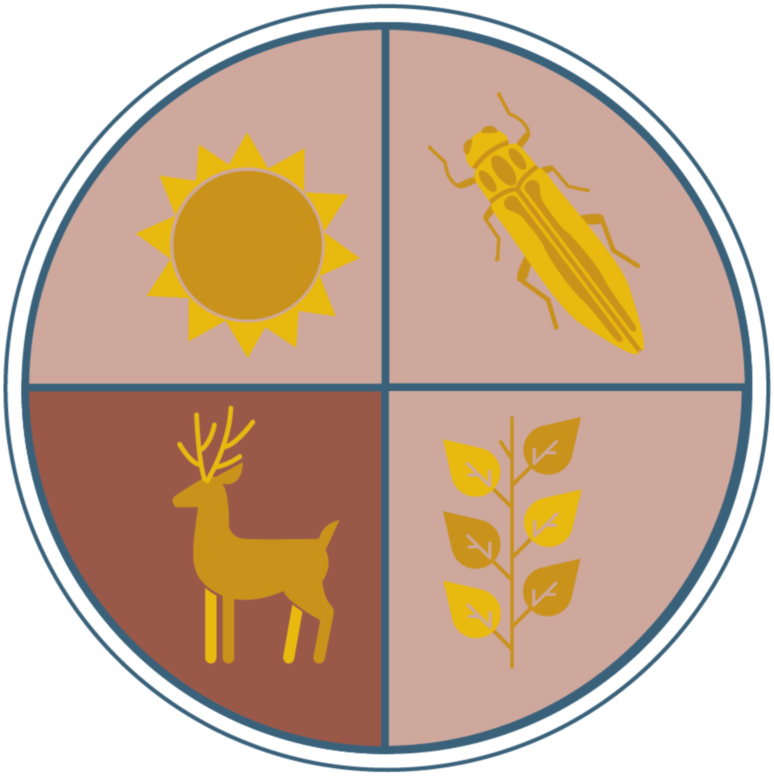
Management recommendations:

1. Monitor the impact of deer browsing.
2. Control the Japanese knotweed, goutweed, and common reed infestations before they become more difficult to eradicate.
3. Consider implementing a climate change adaptation tree planting in a part of the field. Eastern North American tree species that are well-adapted to future conditions, but that are not on the sanctuary yet, include the following: white oak, black oak, shagbark hickory, bitternut hickory, black gum, and tulip tree.

Native canopy tree species list:

- Benefit: black cherry, red oak, basswood, black birch
- Neutral: sugar maple, red maple, bigtooth aspen, trembling aspen, yellow birch
- Decline: white pine, white ash, beech, red spruce, paper birch, American elm, hemlock

Rocky Hill



Vulnerabilities:

- **Climate**: The oak dominated forests at Rocky Hill will likely benefit from a warmer climate because they are near the northern range limit of this forest type. Rocky Hill has a high tree species richness including many that are well-adapted to a warmer climate.
- **Pests and diseases**: Chestnut was a co-dominant tree species at Rocky Hill before the spread of chestnut blight and is still common in the shrub layer. The now dominant oaks are not immediately threatened by pests and diseases, although there may be some future mortality from spongy moth outbreaks. White pine is the most vulnerable to disease among the common tree species. Specifically, needle cast disease appears to be killing some pines around Long Pond.
- **Browsing**: The impact of deer browsing at Rocky Hill appears to be moderate.
- **Non-native plants**: Non-native plants are few in Rocky Hill Wildlife Sanctuary.
- **Combined change**: Overall, Rocky Hill has low vulnerability to the combined impact of climate change, diseases, and pests, browsing, and non-native plant invasion threats. The largest concern is that deer population density could increase to the point of impairing oak regeneration in the future.

Management recommendations:

1. Monitor the impact of deer browsing.
2. The oak forests that dominate much of the sanctuary are adapted to occasional ground fires. Indeed, two hilltops burned in recent years. Putting out wildfires typically involves spraying of highly toxic and persistent PFAS (per- and polyfluoroalkyl substances). One could explore possibilities of alternatives such as allowing ground fires to burn until they reach the utility corridors that could be used as firebreaks or reducing fire fuels with prescribed ground fires, that would also have ecological benefits for the fire-adapted vegetation such as scrub oak.

Native canopy tree species list:

- Benefit: pignut hickory, white oak, black oak, scarlet oak, chestnut oak
- Neutral: red oak, black birch, black cherry, sugar maple, red maple, trembling aspen, bigtooth aspen, scrub oak, swamp white oak, black gum, yellow birch
- Decline: white pine, chestnut, paper birch, white ash, American elm, hemlock, beech

Rutland Brook

Vulnerabilities:

- **Climate**: Eastern hemlock, a species that is vulnerable to climate change, is dominant in some stands, especially in the northern part of the sanctuary. However, most of the sanctuary forests are dominated by some combination of white pine, red oak, red maple, and birches, which is only moderately vulnerable to climate change.
- **Pests and diseases**: Most of the forests at Rutland Brook are dominated or co-dominated by eastern white pine or eastern hemlock, evergreen conifers that are vulnerable to needle cast disease and hemlock woolly adelgid, respectively. There are a few chestnut sprouts in the shrub layer on the lower slopes of Sherman Hill, a sign that chestnut may have been more abundant before the spread of chestnut blight. Likewise, beech was likely more abundant before the spread of beech bark disease. The widespread oaks in the sanctuary may be thinned out by future spongy moth outbreaks, while maples could conceivably suffer mortality in a hypothetical future Asian longhorned beetle outbreak.
- **Browsing**: The browsing impact appears to be severe at Rutland Brook, although not everywhere in the sanctuary. Moose are substantially contributing to browsing at Rutland brook.
- **Non-native plants**: Non-native plants are largely absent from Rutland Brook, except for some glossy buckthorn that occurs sporadically throughout. There is a common reed infestation at the northwestern end of Osgood Swamp, and a variety of non-native plants including round-leaved bittersweet is invading the sanctuary in the northeastern corner, likely originating from an abandoned field on the neighboring private property.

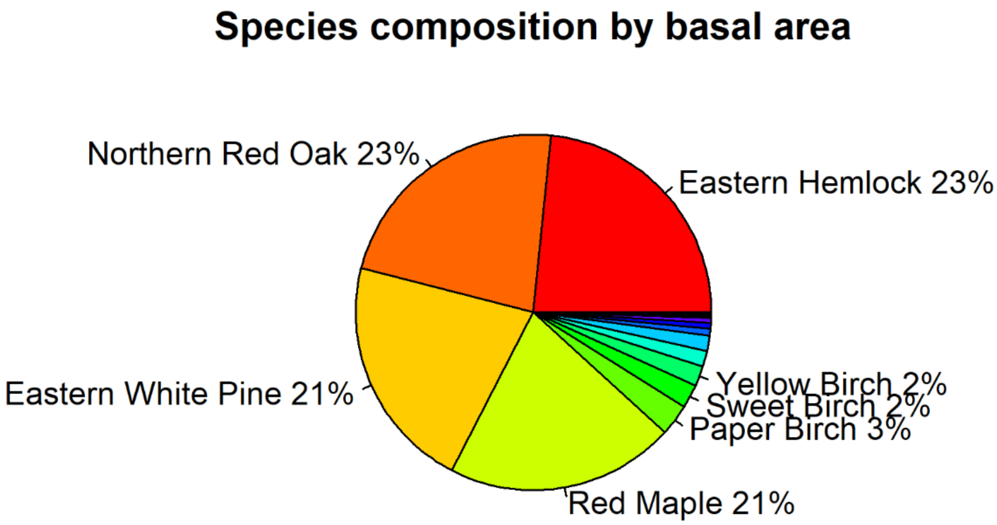
- **Combined change**: Rutland Brook is moderately vulnerable to the combined impact of climate change, diseases, pests, browsing, and non-native plant invasions. There is little that managers can do to prevent future die-offs of the dominant conifers. The widespread oaks and hickories at Rutland Brook could lead a recovery, provided that the intensity of deer browsing is sufficiently reduced.

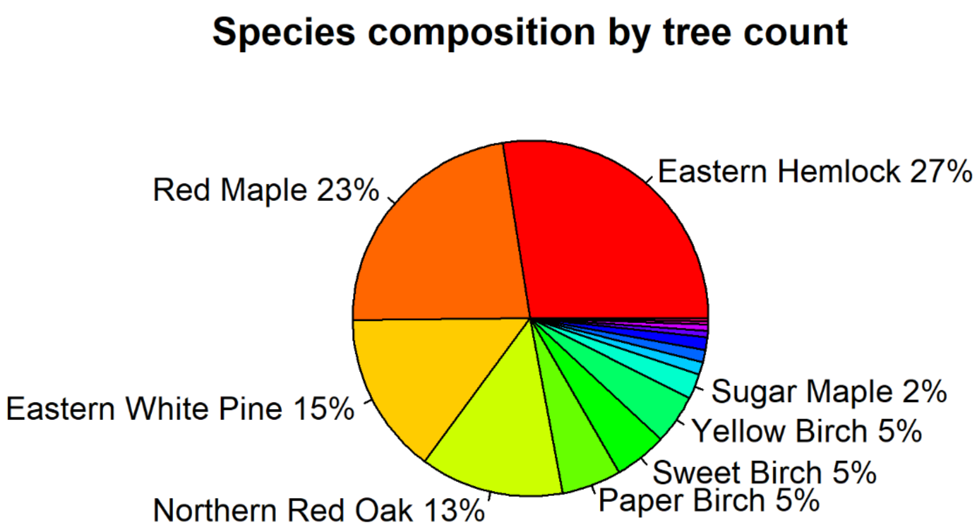
Management recommendations:

1. Open the wildlife sanctuary to an organized annual deer hunt to substantially reduce the impact of deer browsing. Monitor the deer and moose populations and their browsing impacts.
2. Suppress the localized non-native plant infestations, specifically the common reed infestation at the northwestern end of Osgood Swamp, and the round-leaved bittersweet in the northeastern corner of the sanctuary and below the Osgood Swamp dam.
3. Remove the dam and accumulated sediments from House Pond on the small tributary to Connor Pond. Cut down the mature Norway spruce (*Picea abies*) in the surrounding forest and use them as coarse woody debris to install in the restored river channel. Channel restoration will help attenuate floods.
4. Engage the Swift River Trust (a partnership of Harvard Forest, Mass Audubon, and the Trustees of Reservations) in an initiative to remove Connor Pond dam to restore free flow to the East Branch of the Swift River. Once the dam is removed, one could plant the former impoundment with floodplain tree species that are well adapted to future conditions but that do not yet occur in the sanctuary such as river birch (*Betula nigra*), sweetgum, tulip tree, black gum, swamp white oak, sycamore, pin oak, or disease resistant selections of American elm (e.g. Valley Forge, Prairie Expedition, Saint Croix, Princeton). Floodplain restoration will help attenuate floods.
5. Implement a climate change adaptation tree planting in the small field on the John Woolsey Trail. Planted upland tree species could include the following: pignut & mockernut hickories, chestnut and scarlet oaks. Equally effective as planting may be protecting natural regeneration of preferred tree species (i.e. oaks and hickories) from deer browsing with wire mesh cages in canopy openings.

Native canopy tree species list:

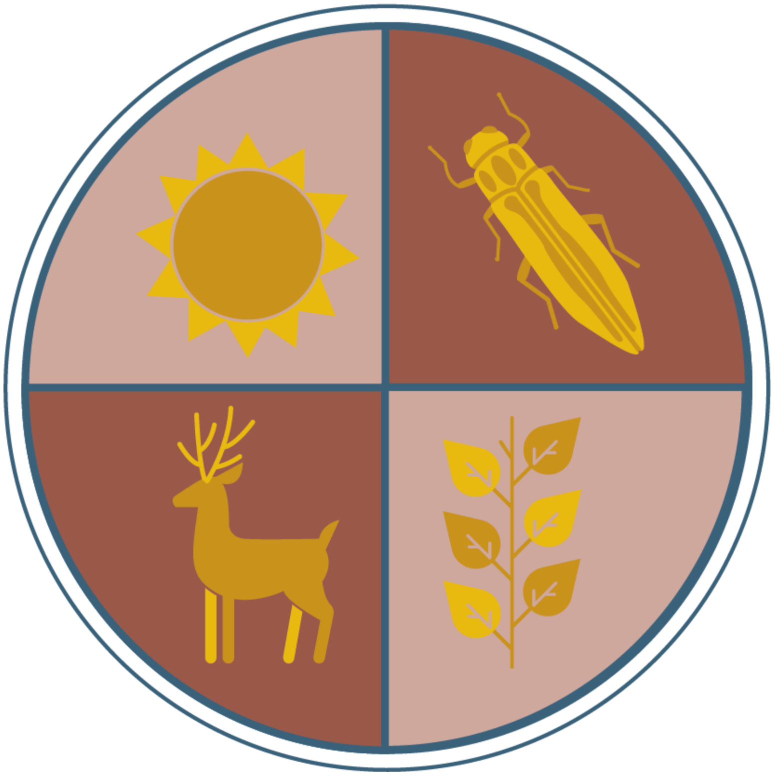
- Benefit: shagbark hickory, white oak, black oak
- Neutral: red oak, black birch, black cherry, sugar maple, red maple, yellow birch, basswood
- Decline: white pine, hemlock, beech, red pine, red spruce, chestnut, white ash, American elm, paper birch, black ash





Summary of forest composition in carbon inventory plots at Rutland Brook Wildlife Sanctuary in 2016.

Tracy Brook



Vulnerabilities:

- **Climate**: The beaver pond that covers most of the Tracy Brook Wildlife Sanctuary appears to have warm water species such as sunfish already. The surrounding white pine and red maple forest is not immediately vulnerable to climate change.
- **Pests and diseases**: The dense stand of mature white pines in the southwest is vulnerable to needle cast disease.
- **Browsing**: The impact of deer browsing appears to be moderate.
- **Non-native plants**: Non-native plant infestations were not observed during field visits, but the inaccessible parts of the sanctuary on the far side of the pond were not explored.
- **Combined change**: Overall, Tracy Brook has low vulnerability to the combined impact of climate change, diseases, and pests, browsing, and non-native plant invasions.

Management recommendations:

1. Beaver activity dominates the sanctuary ecology. When beavers abandon the pond, be prepared to respond to non-native plant invasions that may take advantage of the new terrestrial habitat when the beaver pond drains.

Native canopy tree species list:

- Benefit:
- Neutral: red maple, yellow birch, sugar maple, red oak, black birch, black cherry
- Decline: white pine, hemlock, white ash, American elm

Wachusett Meadow

Vulnerabilities:

- **Climate**: Most of Wachusett Meadow Wildlife Sanctuary forests are dominated by some combination of white pine, red oak, black oak, red maple, and birches. This species forest composition is not vulnerable to climate change, especially where oaks dominate. The relatively few stands where hemlock, which is vulnerable to warming, is dominant are mainly in the southwestern part of the sanctuary. A red pine planting in the north is also severely vulnerable.
- **Pests and diseases**: Eastern white pine, which is vulnerable to needle cast disease, is dominant or co-dominant in most forests at Wachusett Meadow. White ash is a prominent species in hardwood swamps and in the young forests that grew in abandoned fields in the southeastern part of the sanctuary. White ash mortality from emerald ash borer is expected imminently. Eastern hemlock, which is vulnerable to hemlock woolly adelgid and hemlock scale, is dominant in some of the lowlands in the southwestern part of the sanctuary. Beech was likely more abundant before the spread of beech bark disease. Although chestnut was not encountered during field exploration, the habitat appears suitable, and chestnut may well have occurred in the sanctuary prior to the spread of chestnut blight. The widespread oaks in the sanctuary may be thinned out by future spongy moth outbreaks, while maples could suffer some mortality in a conceivable future Asian longhorned beetle outbreak.
- **Browsing**: Deer browsing impact appears to be moderate at Wachusett Meadow.

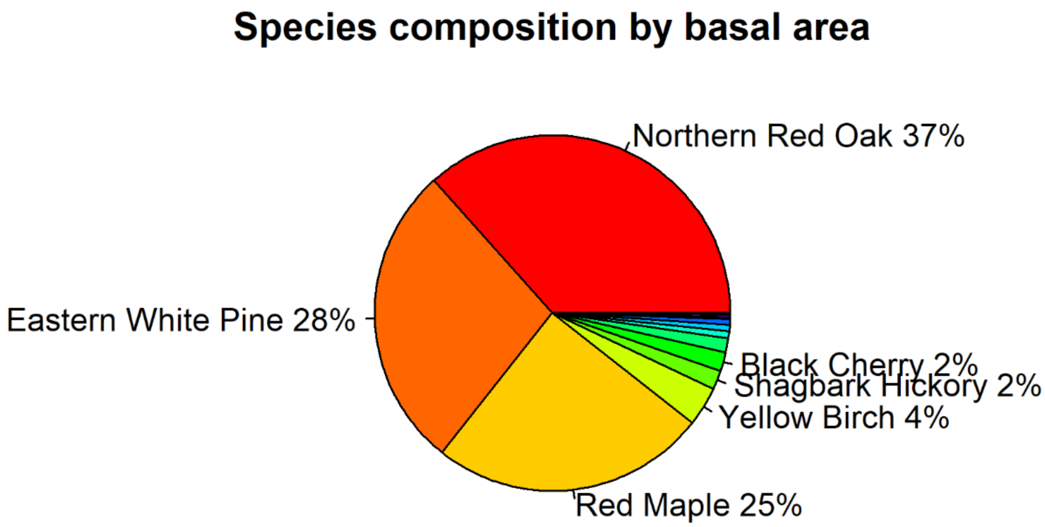
- **Non-native plants**: Non-native plants are few in the older forests, but in edge habitats around fields and wetlands, they are a severe threat, especially at lower elevations in the southeastern part of the sanctuary. The breaking and overtopping of trees and saplings by non-native lianas such as round-leaved bittersweet and porcelain berry is especially concerning.
- **Combined change**: Wachusett Meadow is moderately vulnerable to the combined impact of climate change, diseases, pests, browsing, and non-native plant invasions. There is little that managers can do to prevent future die-offs of the frequently dominant evergreen conifers. The widespread oaks, maples, and hickories at Wachusett Meadow could lead a subsequent recovery, provided that regeneration is not hindered by deer browsing and non-native plant competition.

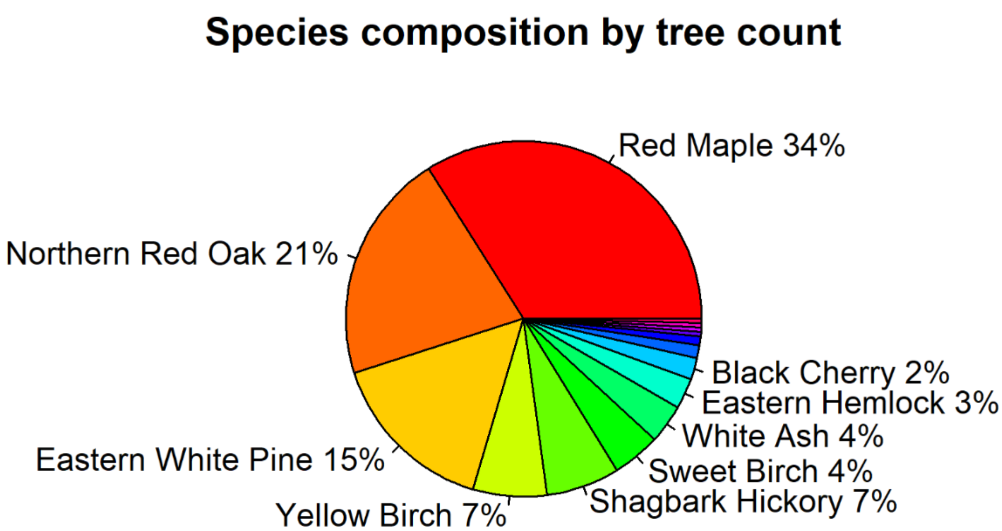
Management recommendations:

1. Open the wildlife sanctuary to an organized annual deer hunt to reduce the impact of deer browsing. Monitor the deer population and its browsing impact.
2. Suppress non-native plant infestations, especially round-leaved bittersweet, around all field edges and in hardwood swamps. Another high priority is to eradicate the localized porcelain berry infestation along Goodnow Road before is spreads further.
3. One could plant a few seed trees of species that are well-adapted to future climate conditions (e.g. tulip tree, chestnut oak, black gum, pignut & mockernut hickories, or disease resistant American chestnut) where there are adequate canopy openings at Wachusett Meadow such as in the abandoned field south of Goodnow Road or in the canopy gaps near Fieldstone Farm Trail.

Native canopy tree species list:

- Benefit: shagbark hickory, bitternut hickory, white oak, black oak, scarlet oak
- Neutral: red oak, black birch, black cherry, sugar maple, red maple, yellow birch, bigtooth aspen, basswood, trembling aspen
- Decline: white pine, hemlock, beech, red pine, white ash, American elm





Summary of forest composition in carbon inventory plots at Wachusett Meadow Wildlife Sanctuary in 2016.

Waseeka

Vulnerabilities:

- **Climate**: The oak dominated forests at Waseeka will likely benefit from a warmer climate because they are at the northern range edge of this forest type. Waseeka has a moderate tree species richness, many of which are adapted to a warmer climate. Waseeka also has a history of fires which could become more frequent with climate change, but the tree species are well adapted to fire.
- **Pests and diseases**: Chestnut was a co-dominant tree species in parts of Waseeka prior to the spread of chestnut blight. The now dominant oaks are not immediately threatened by pests and diseases, although some appear to have died from the 2015-2017 spongy moth outbreak. Among the dominant tree species at Waseeka, white pine is the most vulnerable to disease, particularly in dense stands.
- **Browsing**: The impact of deer browsing at Waseeka appears to be moderate to severe.
- **Non-native plants**: Non-native plants are highly dominant in the abandoned orchard and spreading into the adjacent forests in the north of the sanctuary. By contrast, the oak dominated forests in the west of the sanctuary are largely free of non-native plants. The top of the dam and areas east of the impoundment are intermediate.
- **Combined change**: Overall, Waseeka has low vulnerability to the combined impact of climate change, diseases, and pests. Succession away from oak dominance towards white pine could gradually increase these vulnerabilities. Browsing by deer and the proliferation of non-native plants are also eroding ecological resilience of the forest. The man-made dam is likely impairing ecological functioning of stream and riparian

ecosystems. But, these threats to ecological resilience can be reduced through active management.

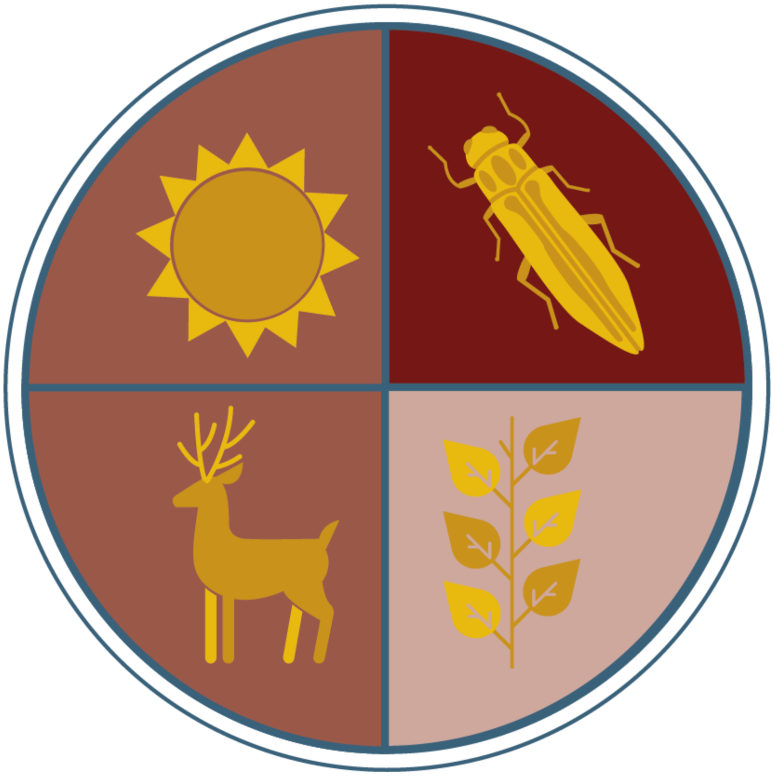
Management recommendations:

1. Continue to reduce deer population through a managed hunt. Monitor the deer population and their browsing impact.
2. Breach the man-made dam to restore a more natural hydrological and sediment regime in the stream and associated beaver wetlands.
3. Clear the mostly non-native vegetation in the abandoned orchard that is in the north of the sanctuary. Consider how to manage the clearing subsequently to prevent reinvasion such as with periodic mowing, or reforesting, or some combination of both. Reforestation would be an opportunity to implement a climate change adaptation planting. The soils of the orchard appear to have been enriched by cultivation which supports different species than the nutrient poor soils of the forested part of the sanctuary. Warm climate adapted species that one could plant in the former orchard could include tulip tree (*Liriodendron tulipifera*), chestnut oak (*Quercus prinus*), black gum (*Nyssa sylvatica*), mockernut and shagbark hickories (*Carya tomentosa, C. ovata*). The native trees in the orchard should be preserved as much as feasible during clearing of non-native vegetation if the goal is reforestation.
4. Suppress non-native plants that are spreading into the forest around the edges of the abandoned orchard. Priority should be on the bittersweet lianas that are expanding canopy openings by breaking branches and entire trees.
5. The oak forests that dominate much of the sanctuary are adapted to occasional ground fires which are likely to become more frequent with climate change. Indeed, much of the southwest of the sanctuary was burned by a ground fire in 2022. One could explore if managing these habitats with prescribed ground fires could be beneficial both from a fire hazard reduction and ecological perspective. The pond is a potential fire break.
6. Consider restoring an oak and pitch pine barren in the area burned in 2022. A first step could be to thin the stand with a harvest of generalist tree species such as white pine and red maple. Allowing succession to continue towards increased white pine and red maple dominance would reduce the resilience of the forest to climate change, diseases, and fires. A more diverse size structure following a partial harvest would also have bird habitat benefits and increase tree vigor.

Native canopy tree species list:

- Benefit: pignut hickory, scarlet oak, white oak, black oak, American holly
- Neutral: red oak, red maple, bigtooth aspen, sassafras, pitch pine, black birch, yellow birch, black walnut, black cherry
- Decline: white pine, chestnut, white ash, American elm, butternut

West Branch



Vulnerabilities:

- **Climate**: Some of the stands of trees at West Branch are dominated by eastern hemlock, a species that is vulnerable to climate warming. Paper birch, which is also vulnerable to climate change, is a minor species at West Branch. Unfortunately, there are few tree species at West Branch that would benefit from a warmer climate.
- **Pests and diseases**: Beech was likely more abundant at West Branch before the spread of beech bark disease. The remaining beech trees are now imminently threatened by beech leaf disease. Likewise, emerald ash borer is an imminent threat to white ash, a minor species at West Branch. Eastern white pine is threatened by needle cast disease.
- **Browsing**: Deer browsing impact is moderate at West Branch.
- **Non-native plants**: Non-native plants are exceptionally few in the sanctuary, except for some Japanese knotweed in the West Branch River floodplain.
- **Combined change**: West Branch Wildlife Sanctuary is moderately vulnerable to the combined impact of climate change, diseases, and pests. There is little that managers can do to prevent a die-off of the dominant hemlock and minor canopy species that are vulnerable to climate change and/or pests or diseases. However, the low incidence of non-native plants and deer browse should allow the forest to recover well from canopy disturbances.

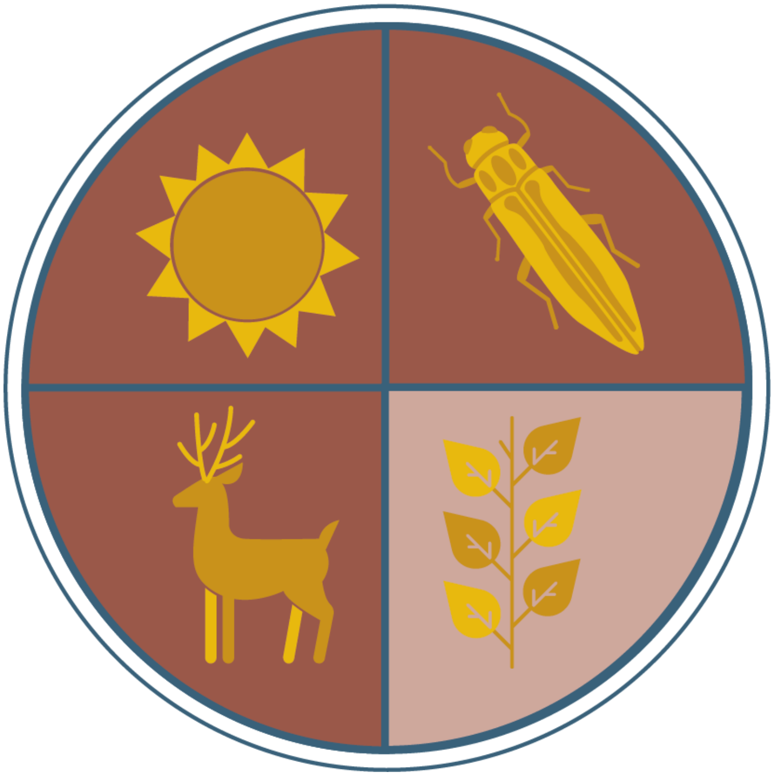
Management recommendations:

1. Open West Branch to deer hunting (subject to all applicable state regulations).

Native canopy tree species list:

- Benefit: basswood, black birch, bitternut hickory, black cherry
- Neutral: sugar maple, red maple, yellow birch,
- Decline: white pine, white ash, beech, paper birch, hemlock

West Mountain



Vulnerabilities:

- **Climate**: West Mountain has extensive stands of red spruce (on hilltops) and some stands of eastern hemlock (on north-facing slopes), two northern conifer species that are highly vulnerable to climate change. Paper birch and balsam fir, which are vulnerable to climate change, also frequently occur in hilltop stands. However, the currently still relatively cold local climate may delay these impacts until after 2050.
- **Pests and diseases**: Hemlock stands will become vulnerable to hemlock woolly adelgid outbreaks as the climate warms. Beech was likely more abundant before the spread of beech bark disease and is now also threatened by beech leaf disease. White ash, which is now threatened by emerald ash borer, is common in the hardwood stands, especially in coves and on east-facing slopes. The dominant maples at West Mountain would be vulnerable to Asian longhorned beetle if an outbreak were to reach this sanctuary.
- **Browsing**: Browsing by deer is moderate at West Mountain.
- **Non-native plants**: Abundance of non-native plants is generally low at West Mountain, except for some of the abandoned fields.
- **Combined change**: Overall, West Mountain Wildlife Sanctuary is moderately vulnerable to the combined impact of climate change, diseases, pests, browsing, and non-native plant invasion threats until 2050, but would become increasingly vulnerable with more extreme climate change longer term. Diverse tree species that are adapted to future conditions are present in parts of the sanctuary and could lead

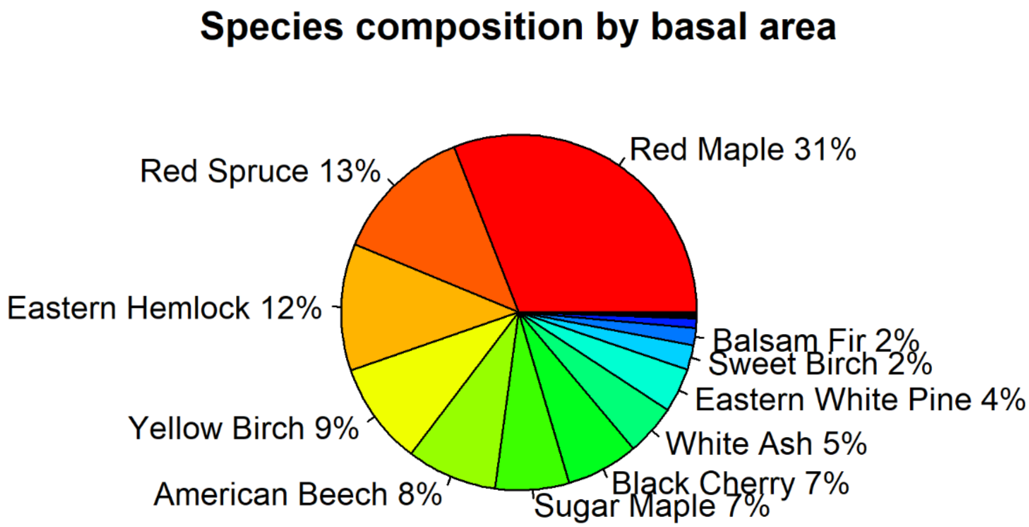
a recovery following die-offs of canopy trees, if tree regeneration does not become impaired by deer browsing or non-native plant competition.

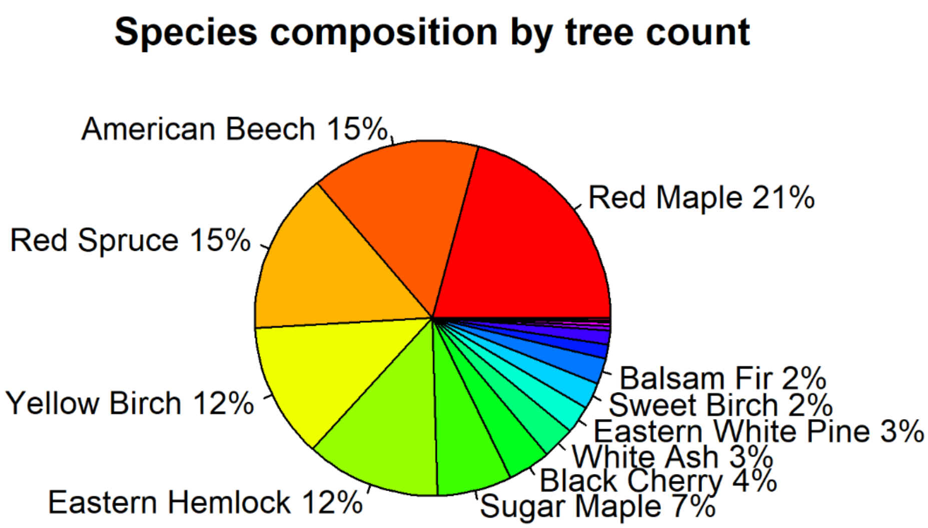
Management recommendations:

1. Open the wildlife sanctuary to an organized annual deer hunt to reduce the impact of deer browsing. Monitor the deer and moose populations and their browsing impacts.
2. Plant tree species that are better adapted to future climate conditions in the abandoned field on West Main Street. Planted species could include the following: black oak, white oak, shagbark hickory, and tulip tree, in the well drained areas, and black gum, sweetgum, sycamore, swamp white oak, pin oak, or disease resistant selections of American elm (e.g. Valley Forge, Prairie Expedition, Saint Croix, Princeton) in wetter areas.
3. Explore the possibility of removing defunct dams in the sanctuary.
4. Release biological controls for emerald ash borer in ash stands on east facing slopes near trails, if any biological controls were to become available again for release in Massachusetts (currently production of biological controls is prioritized for states that have not yet had releases).

Native canopy tree species list:

- Benefit: basswood, red oak, black birch, black cherry, bitternut hickory
- Neutral: sugar maple, red maple, paper birch, yellow birch, trembling aspen, bigtooth aspen, hemlock, white pine
- Decline: white ash, beech, red spruce, balsam fir





Summary of forest composition in carbon inventory plots at West Mountain Wildlife Sanctuary in 2016.

Whetstone Wood

Vulnerabilities:

- **Climate**: Eastern hemlock, which is highly vulnerable to climate change, is either the dominant or a co-dominant tree species in most of Whetstone Wood. Paper birch and red spruce are minor species that are also vulnerable to climate change. Unfortunately, tree species that would benefit from a warmer climate are absent in most of the sanctuary.
- **Pests and diseases**: Extensive hemlock and eastern white pine stands are threatened by hemlock woolly adelgid and needle cast disease, respectively. A warmer future climate will exacerbate the hemlock woolly adelgid threat. Chestnut sprouts occur on Orcutt Hill and along New Salem Road suggesting that this species was more common in this part of the sanctuary prior to the spread of chestnut blight. The hill named "Chestnut Hill" in the northeast of the sanctuary provides further evidence of former chestnut dominance in parts of the sanctuary. Beech is common at Whetstone Wood and was likely more abundant before the spread of beech bark disease. The remaining beech is imminently threatened by beech leaf disease. White ash, which is vulnerable to emerald ash borer, is another minor tree species, mostly occurring in hardwood swamps and along streams. The abundant red oak and red maple would suffer some mortality if there were a future outbreak of spongy moth or Asian longhorned beetle, respectively.
- **Browsing**: Browsing by deer is relatively slight. Indeed, moose may be a more important browser than deer at Whetstone Wood.
- **Non-native plants**: Abundance of non-native plants is generally low in the mature forests in Whetstone Wood, except for glossy buckthorn which occurs in many parts

of the sanctuary, especially around the fringes of beaver marshes. There is also a common reed infestation in the marsh on Morse Village Road.

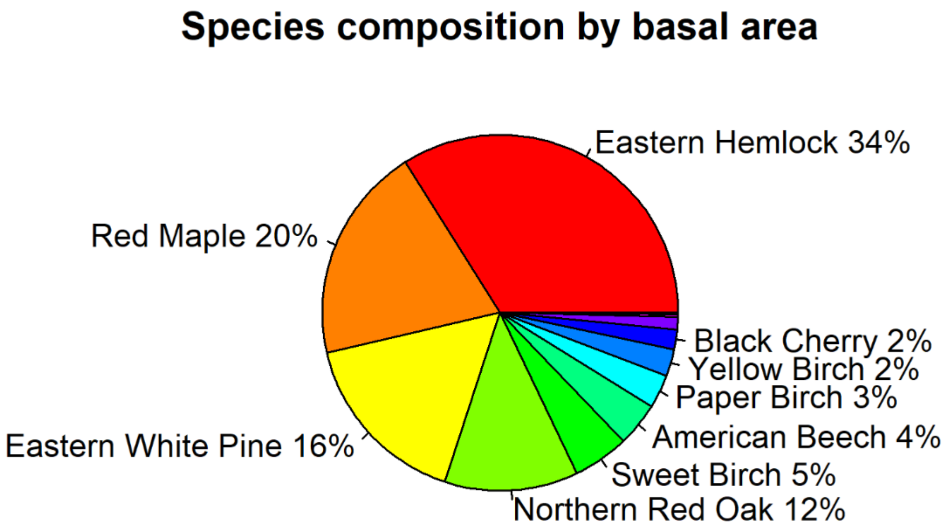
- **Combined change**: Whetstone Wood is moderately vulnerable to the combined impact of climate change, diseases, and pests. There is little that managers can do to prevent a die-off of the dominant conifers. However, the low incidence of non-native plants and deer browsing should allow the forest to recover from such a major disturbance.

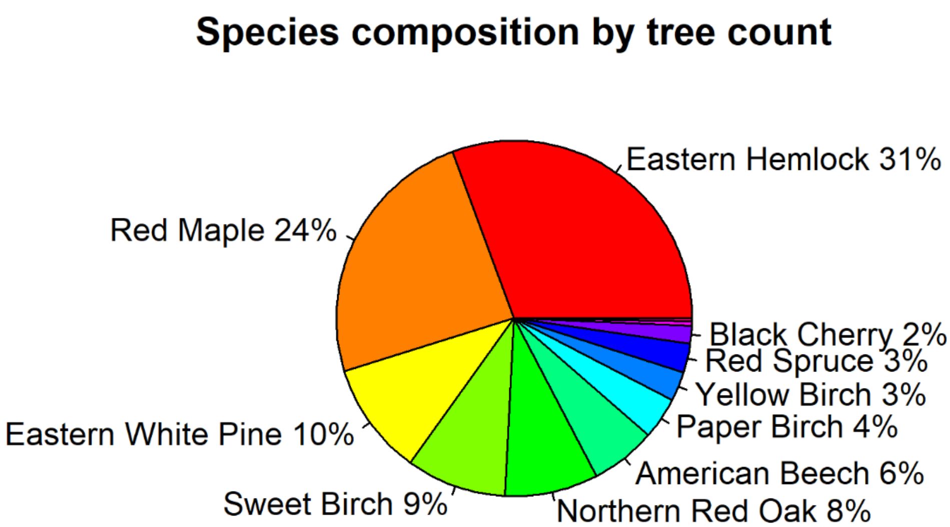
Management recommendations:

1. Seek permits and funding to eradicate the common reed infestation in the beaver marsh on Morse Village Road as well as the non-native woody plants in the abandoned field on New Salem Road.
2. Plant canopy openings with tree species that could benefit from a warmer future climate. Appropriate species choices might include the following: white oak, black oak, scarlet oak, chestnut oak, shagbark, pignut & mockernut hickories, black gum, pitch pine. Potential planting locations could include the following:
    - the abandoned field on New Salem Road after invasive plant suppression,
    - the abandoned cleared land at the intersection of New Salem and Morse Village Roads,
    - the canopy gaps created by the partial harvest on the recently acquired Killay property on Gate Lane,
    - possibly, properties with cleared land that get added to the sanctuary in the future.
3. If permissible by the restrictions on management activities at Whetstone Wood, cut competing neighbors from around the few individuals of white oak and pitch pine at Whetstone Wood to preserve these trees as warm climate adapted seed trees that might otherwise die from increasing competition by more shade tolerant species.

Native canopy tree species list:

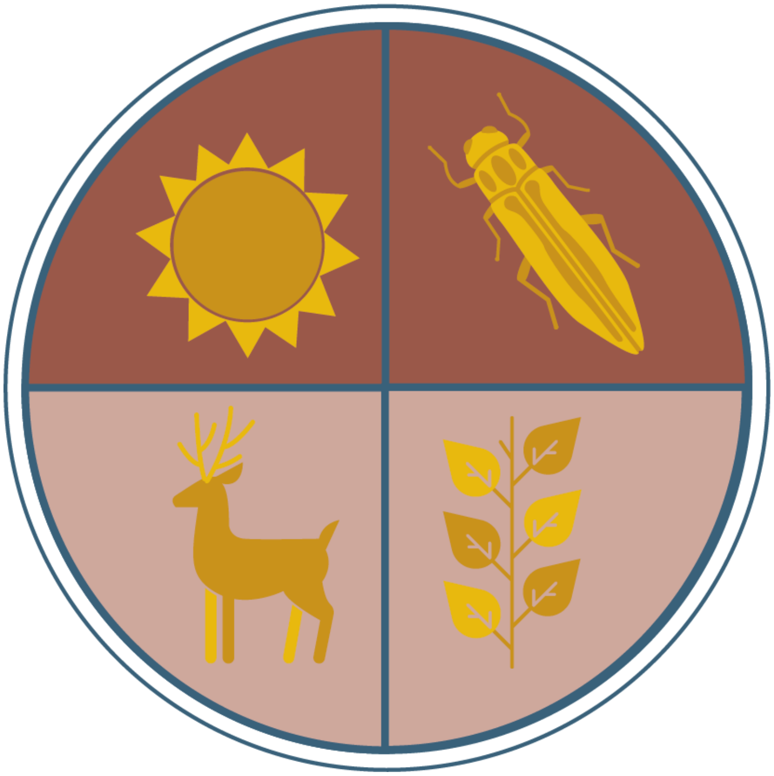
- Benefit: white oak, shagbark hickory
- Neutral: black birch, red oak, yellow birch, red maple, sugar maple, black cherry, bigtooth aspen, pitch pine, black gum
- Decline: white pine, beech, paper birch, white ash, hemlock, chestnut, red pine, red spruce





Summary of forest composition in carbon inventory plots at Whetstone Wood Wildlife Sanctuary in 2016.

Wildwood Camp



Vulnerabilities:

- **Climate**: The forests at Wildwood Camp are dominated by northern evergreen conifers such as red spruce, red pine, and hemlock that are doomed by climate warming in the long term. However, the currently still relatively cold local climate may delay much of this impact until after 2050. There are few tree species presently at Wildwood Camp that are adapted to a warmer climate.
- **Pests and diseases**: The extensive stands of eastern hemlock and eastern white pine are vulnerable to pests and diseases such as hemlock woolly adelgid and needle cast disease, respectively. However, relatively cold winter temperatures may limit hemlock woolly adelgid populations until after 2050.
- **Browsing**: Browsing impact by deer is slight at Wildwood Camp.
- **Non-native plants**: Non-native plants are extremely few at Wildwood Camp except for a tree-of-heaven that is growing in a brush pile.
- **Combined change**: The forests and wetlands at Wildwood Camp are moderately vulnerable to the combined impact of climate change, pests, and diseases until 2050 but will likely become severely vulnerable as warming becomes more extreme later this century. The low intensity of deer browsing, and the absence of non-native plants should facilitate regeneration after major losses of canopy trees. Recovery of the forest may become limited by the availability of seed trees that belong to species that are better adapted to a warmer climate.

Management recommendations:

1. Cut the tree-of-heaven before it has a chance to spread.
2. Plant tree species that are better adapted to future climate conditions in some of the abandoned gravel pits while this cleared land is still open. Currently, these abandoned pits are being colonized by eastern white pine and birches, tree species that are vulnerable to climate change and disease. Potentially site appropriate tree species that are adapted to a slightly warmer climate and that do not yet occur at Wildwood Camp include oaks, hickories, and black gum.
3. Consider implementing an ecological harvest in the pine stands south of Old New Ipswich Road. The purpose would be to increase the vigor of white pines by thinning stands and to release the warm-climate-adapted red oaks from competition.
4. Monitor the deer population and their browsing impact on understory vegetation.

Native canopy tree species list:

- Benefit: red oak, black birch, black cherry
- Neutral: yellow birch, red maple, sugar maple, trembling aspen, bigtooth aspen, paper birch, white pine, hemlock
- Decline: beech, white ash, red pine, red spruce

Detailed Methods

Climate Change

A score of climate change vulnerability of forests was assessed as follows:

- Severe: >25% of the current forest basal area or trees is comprised of species that are likely to die due to climate change[1].
- Moderate: 5-25% of the current forest basal area or trees is comprised of species that are likely to die due to climate change.
- Slight: <5% of the current forest basal area or trees is comprised of species that are likely to die due to climate change[2].

If a forest is comprised of vulnerable species but has a sufficiently cold climate currently that a climate change induced die-off is likely not going to happen until after 2050, the vulnerability score would be reduced by one level (i.e. moderate instead of severe for stands with >25% of trees being of vulnerable species) because the hazard is less immediate and management action is less urgent. This rule was applied in the following example: white pine dominated stands because, according to the climate change tree atlas, white pine becomes vulnerable only under the more severe warming scenarios that are not expected until after 2050.

Which species are likely to benefit from a warmer climate also differs among sites depending on the current local climate. For example, black birch may benefit from warming at the coldest Mass Audubon wildlife sanctuaries but be relatively unaffected or even suffer from warming at the warmest sanctuaries, especially on dry soils. The likely climate change responses of individual species at each wildlife sanctuary were assessed by considering the regional model predictions for the species (Appendix 1).

Pests and Diseases

A score of pest and disease vulnerability of forests was assessed as follows:

- Severe: >25% of the current forest basal area or trees is comprised of species that are likely to die due to a pest or disease outbreak[1].
- Moderate: 5-25% of the current forest basal area or trees is comprised of species that are likely to die due to a pest or disease outbreak.
- Slight: <5% of the current forest basal area or trees is comprised of species that are likely to die due to a pest or disease outbreak[2].

If a forest is comprised of vulnerable species but has a sufficiently cold climate currently that a pest outbreak induced die-off is likely not going to happen until after 2050, the vulnerability score would be reduced by one level (i.e. moderate instead of severe for stands

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[1] Stand thinning experiments have shown that removing up to around a quarter of the tree basal area in a partial harvest can stimulate growth of the remaining trees sufficiently to compensate for the productivity lost from the harvested trees.

[2] In the absence of a disturbance, the normal background tree mortality rate in forests is between 1 and 4% per year, with early successional stands typically being at the higher end of this range and late successional stands at the lower end.

with >25% of trees being of vulnerable species) because the hazard is less immediate and management action is less urgent. This rule was applied in the following example: hemlock dominated stands at sites where abundant red spruce indicates substantially colder winters than at the sites where hemlock woolly adelgid outbreaks have already caused hemlock mortality.

This assessment considers only the serious pests and diseases that are already causing tree die-offs in New England (Appendix 2). Pests that only cause local damage periodically such as spongy moth outbreaks are not included among serious pests. Similarly, pests such as Asian longhorned beetle that are currently suppressed by management efforts that are preventing outbreaks are noted but are not included in assessing vulnerability scores. Furthermore, the vulnerability to new pests and diseases cannot be estimated because we cannot predict which new pests or diseases might arrive in the coming decades, which host trees they might attack, or how severe their impact might be on their hosts. We should, however, be aware that new pests and diseases are likely to continue being introduced into eastern North America (Appendix 2). In this sense, the assessments of vulnerability to pests and diseases are a best-case scenario.

Browsing

The severity of deer browsing damage on tree regeneration was assessed in canopy gaps. Gaps have enough sunlight for tree seedlings of all species to grow vigorously enough to become saplings in the absence of browsing, whereas seedlings of many species may not survive in a shady understory. If seedlings in a gap showed little or no evidence of browsing, the browsing was classified as slight. The browsing was classified as severe if most shoots on seedlings were browsed and only individuals of the least palatable species such as white pine grew into the sapling height where deer could no longer reach the top shoots. If there were lots of browsed shoots but a wider range of species still reached the sapling height, the browsing was classified as moderate. A sanctuary average of the severity of browsing observed in gaps was approximated (summary map 6). One value was used for the entire sanctuary because deer herds move across a large area. For example, when a new canopy gap opens in a stand that previously had few seedlings and therefore little deer activity, deer may shift more of their activity to the gap and begin to browse in this new food patch. Similarly, efforts to cull the deer herd with hunting would be done at a larger spatial scale than a single stand of trees. However, field observations of locations where deer spend much of their time were noted under field comments in the attribute tables of ArcGIS maps associated with this assessment to help guide hunters if that management option is pursued.

Non-native Plants

Vulnerability to invasion by non-native plants was assessed based on the current level of invasion in and around a forest, wetland, or field. The vulnerability was classified as severe if non-native plants were already among the dominant species in either the herb, shrub, subcanopy tree, or canopy tree layers. If non-native plants were dominant only in the edges around a stand of trees or around an abandoned field, vulnerability was also classified as severe. If edges were invaded around a field that is still mowed regularly, the vulnerability was reduced to moderate because mowing slows the invasion but does not stop it entirely from advancing. Stands of trees adjacent to habitats that were classified as severely vulnerable were classified as moderately vulnerable because they are likely to be invaded next as the invasion front advances. Abandoned fields where non-native invasive plants were still absent, were classified as moderately vulnerable because invasion is not imminent but abandoned fields are easily invaded if non-native invasive plants arrived at the site. By contrast, mature forests where non-native plants are absent or rare were classified as slightly vulnerable because subcanopy shade and less nutrient rich soils in mature forests offer greater resistance to invasion than agricultural fields. These classifications of vulnerability to non-native plant invasion reflect what the likely composition of the vegetation by 2050 in the absence of management action. On-going and future efforts to suppress non-native invasive plants can alter this trajectory.

Combined Change

The assessment of combined change vulnerability considers the likely combined impacts of climate change, pests, diseases, deer browsing, non-native plant invasions, and their interactions by 2050. The combined change vulnerability is not an average of the vulnerability scores for climate change, deer browsing, non-native plant invasions, and pests and diseases because that would misjudge the great importance of interactions among these factors. Examples of important interactions include the following:

- A warmer climate can increase the winter survival of pests such as hemlock woolly adelgid or southern pine beetle, thereby allowing outbreaks in places where host trees were previously spared from attack.
- Invasion of Japanese barberry (*Berberis thunbergii*) or of Japanese stiltgrass (*Microstegium vimineum*) into forests is facilitated by deer browsing most other understory vegetation but avoiding these unpalatable species.
- Non-native lianas such as round-leaf bittersweet (*Celastrus orbiculatus*), porcelainberry (*Ampelopsis glandulosa*), and hardy kiwi (*Actinidia arguta*) thrive along sunny forest edges where there are shrubs and saplings that they can climb over to get into the forest canopy. Disturbances that open canopy gaps such as a tree die-off induced by climate change, disease, or pest thus greatly expands the opportunity for lianas to proliferate by creating sunny forest edges.
- A forest may recover after a die-off of a dominant canopy tree species when browsing by deer is slight and non-native plants are largely absent. Indeed, the new generation of trees may be better adapted to climate change. Alternatively, intense browsing by deer or invasion by non-native lianas could interfere with recovery of a closed-canopy forest.
- The climate change may stress northern tree species, thereby reducing their resistance to pests and diseases.

The likely state of forests in 2050 based on the severity of these factors and their interactions was projected, assuming no management action. As for the individual factors, the vulnerability was classified as either slight, moderate, or severe depending on the percentage of trees or basal area that is likely to be affected. Management recommendations aim to alter this trajectory towards a more desirable state, if necessary.

Tree Species Diversity

The richness of tree species that currently occur was calculated for each wildlife sanctuary (Summary map 1). Only native tree species that grow sufficiently large to be part of the forest canopy at the sanctuary were included in the diversity assessment. Trees were defined as native if they occurred in eastern North America before the beginning of trans-Atlantic trade during the colonial period. Thus, for the purposes of this assessment, tree of heaven and Norway maple are considered non-native, but black locust and northern catalpa are considered native even though they are weedy tree species that are not locally native to Massachusetts. Black locust and northern catalpa are both native elsewhere in eastern North America. The decision for that regional definition of native is based on the observation that the eastern North American flora has been migrating latitudinally in response to climate change for millennia. Not too long ago, geologically speaking, all of Massachusetts was covered in a thick ice cap. The flora and associated fauna of eastern North America have encountered each other many times over the glacial and interglacial cycles of the last 800,000 years, even if they do not co-occur everywhere now. That long period of co-existence has allowed them to co-evolve. By contrast, species from overseas do not have this shared history of co-evolution, which increases risks of detrimental ecological impacts, especially with respect to trophic interactions. For example, non-native plants support far fewer native insects such as the caterpillars that are an essential source of protein for breeding songbirds (Tallamy 2009).

The diversity of native canopy trees that are unlikely to be impacted negatively by climate change, pests, and diseases was assessed for each wildlife sanctuary (summary maps 2&3) Species were classified as either benefitting from climate change, neutral in their response to climate change, or likely to suffer a decline due to climate change and/or pests and diseases at the sanctuary. Species that might benefit from a warmer climate but are unlikely to expand their population for other reasons such as the predominant soils in the sanctuary were included in the neutral category because they have little opportunity for expanding their population at the sanctuary. A weighted diversity score of future-adapted genera was calculated with the following formula:

$$Score = 2 * (\#genera\ that\ benefit) + 1 * (\#genera\ that\ are\ neutral)$$

The score is based on genera because pests and diseases tend to attack an entire genus rather than only an individual species. Sites with a low score for future adapted genera have little buffer if new pests or diseases arrive in the future. This score helps assess if there is a lack of future-adapted diversity that would call for introducing new tree species from elsewhere in eastern North America that are adapted to warmer climates than the species that are already present in the sanctuary.

Wetlands

Non-native species invasions in wetlands were assessed in a manner analogous to forests. Additionally, for streams and associated riparian wetlands, hydrological alteration was considered. Specifically, man-made dam impoundments were classified as severely vulnerable to climate change, as are stream reaches and associated wetlands immediately downstream of a highly urbanized watershed.

Mapping

Converting field notes describing forests and other landcover types into detailed wildlife sanctuary maps was aided by several datasets in ArcGIS, as follows:

- Aerial photos provided insight into the extend of landcover types such as fields, wetlands, water bodies, and forests. Winter photos revealed the extent of evergreen tree cover. In forests where there is a deciduous overstory with an evergreen midstory or understory, that evergreen cover would be hidden in summer photos. Late fall photos can be used to distinguish deciduous species that drop their leaves early (e.g. birches, ashes, red maple) from deciduous species that retain their leaves longer (e.g. oaks, Norway maple). In some cases, fall colors could further distinguish rust-colored oaks from bright yellow aspens, for example. The extend of common reed infestations in wetlands could sometimes also be made out in aerial photos by a distinct texture.
- Local moisture conditions interact with broader climatic variation in shaping distributions of forest types and vegetation types more generally. To gain insights into local moisture conditions, an integrated soil moisture index (IMI) was computed for a 10x10m raster over the entire state of Massachusetts. The IMI was modified from earlier versions of IMI by other researchers who showed that IMI correlates well with moisture availability in the field (Iverson et al. 2004). Specifically, we modified the IMI methods to be more easily implemented with tools available in newer version of ArcGIS (Pro 3.1, in this case). Our version of the IMI combined the following three components that contribute to moisture availability: 1) the effect of slope and aspect on the amount of insolation at different times of day, 2) accumulation of surface flow downslope, 3) available water storage in soils. Each of these three components was scaled from 1-100 (dry – wet) before summing the three components into the integrated moisture index. The effect of slope and aspect was modeled with the Hillshade raster tool using a digital elevation model (DEM). An azimuth of 240^{o} and an elevation of 56 ^{o} was used in the Hillshade tool. These values were representative of mid-summer around July 15 at 2pm. The 2pm time was a compromise between temperature which peaks around 4pm in Massachusetts and solar radiation which peaks at noon. Flow accumulation was modeled with the Flow Direction tool in Spatial Analyst using the MFD algorithm and a DEM (Qin et al. 2007). Downslope flow accumulation has a highly skewed distribution of values. Therefore, we log transformed (base 10) these values. Available water storage soils came from a publicly available soils map (MassGIS Soils SSURGO-Certified NRCS). Available water storage (AWS) is the volume of water that the soil, to a depth of 100 centimeters, can store that is available to plants. The model of accumulation of moisture from surface flow worked well in steep topography but did poorly in some flat areas, especially wetlands and water bodies. To avoid that problem the IMI was used only for uplands, and the wettest part of the landscape was mapped with the Massachusetts State Wetlands shape file instead.

Landcover type and moisture index are often but not always related. Sometimes, vegetation is more closely related with disturbance history than with the physical conditions of the site. In particular, the history of clearing land for agriculture and subsequent abandonment of fields has left long-lasting legacies on soils and on vegetation composition.

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Appendix 1: Climate change tree atlas species prediction tables

Table A1: Species abundance change predictions for two climate change scenarios from the USDA Forest Service climate change atlas model (Prasad, AM; Iverson, LR; Peters, MP; Matthews 2014). The model is based on empirical relationships among species abundances in FIA plots, climate, and other site factors such as soils. Species are arranged in descending order of current abundance Species that do not already occur in the FIA forest monitoring plots in central and western Massachusetts are ordered based on their prospects for migrating into the region. MR = model reliability. FIAsum = The area-weighted sum of the importance values (IV) per 100 sq km for the FIA plots in the 1 x 1-degree grid cell centered on the Connecticut River Valley. Tree species that were in the predictions for the neighboring 1 x 1-degree grid cells immediately to the West or East but were not listed for this grid cell were added into the table. ChngCl45 or ChngCl85 = Class of potential change in habitat suitability by 2100 according to the ratios of future (2070-2099) suitable habitat for an average of 3 GCMs to FIA actual (2001-2016) suitable habitat, using either lower (RCP 4.5) or higher (RCP 8.5) emission scenarios. Adap = Adaptability score for the species, according to a literature review of 12 disturbance and 9 biological characteristics, or modification factors. Capabil45 or Capabil85 = The overall estimate of capability for the species to cope with the changing climate within the region. Abundance is used to modify classes so that if the species is Abundant, we increase capability by one class (e.g., poor to fair, or good to very good); if species is Rare, we decrease capability by one class (e.g., poor to very poor); if species is Common, there is no change in capability. The idea is that common species are more likely to find refugia into the future, and rare species are less likely. SHIFT45 or SHIFT85 = A combined classification, for RCP 4.5 or 8.5, separating out those species that may (1) infill, where a species is currently recorded to be present by FIA and likely to spread out within the region; (2) be likely, where a species was not reported by FIA but models suggest it is likely to have suitable habitat under current conditions; and (3) migrate, where a species is not reported or modeled in the region, but has some potential to migrate to suitable habitat within 100 years - and could be considered as a high candidate for translocation.

Common Name	***Scientific Name***	**MR**	**FIAsum**	**ChngCl45**	**ChngCl85**	**Adap**	**Capabil45**	**Capabil85**	**SHIFT45**	**SHIFT85**
red maple	*Acer rubrum*	High	2149.63	No change	Sm. dec.	High	Very Good	Good		
eastern hemlock	*Tsuga canadensis*	High	1665.56	Lg. dec.	Lg. dec.	Low	Poor	Poor		
eastern white pine	*Pinus strobus*	High	1608.26	Sm. dec.	Lg. dec.	Low	Fair	Poor		
northern red oak	*Quercus rubra*	Medium	1091.54	No change	No change	High	Very Good	Very Good		
sugar maple	*Acer saccharum*	High	716.91	Sm. inc.	Sm. inc.	High	Very Good	Very Good		
black birch	*Betula lenta*	High	622.38	No change	Sm. dec.	Low	Fair	Fair		
American beech	*Fagus grandifolia*	High	609.27	No change	No change	Medium	Good	Good		
yellow birch	*Betula alleghaniensis*	High	471.1	No change	Sm. dec.	Medium	Fair	Poor		
white ash	*Fraxinus americana*	Medium	369	Sm. inc.	Sm. inc.	Low	Fair	Fair		
black cherry	*Prunus serotina*	Medium	325.75	Sm. inc.	Sm. inc.	Low	Fair	Fair		
paper birch	*Betula papyrifera*	High	265.73	Lg. dec.	Lg. dec.	Medium	Poor	Poor		
white oak	*Quercus alba*	Medium	257.42	Lg. inc.	Lg. inc.	High	Very Good	Very Good		
black oak	*Quercus velutina*	High	226.22	Lg. inc.	Lg. inc.	Medium	Very Good	Very Good		
red spruce	*Picea rubens*	High	217.36	Lg. dec.	Lg. dec.	Low	Very Poor	Very Poor		
quaking aspen	*Populus tremuloides*	High	125.54	No change	No change	Medium	Fair	Fair		
scarlet oak	*Quercus coccinea*	Medium	121.1	Lg. inc.	Lg. inc.	Medium	Very Good	Very Good		
American elm	*Ulmus americana*	Medium	98.82	Sm. dec.	No change	Medium	Poor	Fair		
balsam fir	*Abies balsamea*	High	89.31	Lg. dec.	Lg. dec.	Low	Very Poor	Very Poor		
bigtooth aspen	*Populus grandidentata*	Medium	87.93	Sm. inc.	No change	Medium	Good	Fair		

Common Name	*Scientific Name*	MR	FIAsum	ChngCl45	ChngCl85	Adap	Capabil45	Capabil85	SHIFT45	SHIFT85
pignut hickory	*Carya glabra*	Medium	82.75	Lg. inc.	Lg. inc.	Medium	Very Good	Very Good		
shagbark hickory	*Carya ovata*	Medium	52.03	Lg. inc.	Lg. inc.	Medium	Very Good	Very Good		
chestnut oak	*Quercus montana*	High	51.3	Lg. inc.	Lg. inc.	High	Very Good	Very Good	Infill ++	Infill ++
silver maple	*Acer saccharinum*	Low	49.65	Sm. dec.	No change	High	Poor	Fair		Infill +
gray birch	*Betula populifolia*	Low	37.17	Sm. dec.	No change	Medium	Very Poor	Poor		
Siberian elm	*Ulmus pumila*	FIA	36.61	Unknown	Unknown	NA	NNIS	NNIS		
striped maple	*Acer pensylvanicum*	Medium	35.97	Sm. dec.	Lg. dec.	Medium	Very Poor	Very Poor		
hophornbeam	*Ostrya virginiana*	Low	35.64	No change	Lg. inc.	High	Fair	Good		
Scots pine	*Pinus sylvestris*	FIA	26.85	Unknown	Unknown	NA	NNIS	NNIS		
red pine	*Pinus resinosa*	Medium	23.27	Very Lg. dec.	Very Lg. dec.	Low	Lost	Lost		
Norway spruce	*Picea abies*	FIA	22.85	Unknown	Unknown	NA	NNIS	NNIS		
black willow	*Salix nigra*	Low	19.57	Sm. dec.	Sm. dec.	Low	Very Poor	Very Poor		
pin cherry	*Prunus pensylvanica*	Low	17.19	Sm. dec.	Lg. dec.	Medium	Very Poor	Very Poor		
Norway spruce	*Picea abies*	FIA	17.12	Unknown	Unknown	NA	NNIS	NNIS		
Atlantic white-cedar	*Chamaecyparis thyoides*	Low	14.08	Sm. dec.	Sm. dec.	Low	Very Poor	Very Poor		
musclewood	*Carpinus caroliniana*	Low	13.72	Sm. dec.	Lg. inc.	Medium	Very Poor	Good		
eastern redcedar	*Juniperus virginiana*	Medium	13.23	Lg. inc.	Lg. inc.	Medium	Good	Good	Infill ++	Infill ++
American chestnut	*Castanea dentata*	FIA	12.98	Unknown	Unknown	Medium	FIA Only	FIA Only		
river birch	*Betula nigra*	Low	11.75	Sm. dec.	Sm. dec.	Medium	Very Poor	Very Poor		
butternut	*Juglans cinerea*	FIA	10.56	Unknown	Unknown	Low	FIA Only	FIA Only		
American basswood	*Tilia americana*	Medium	10.52	Lg. inc.	Lg. inc.	Medium	Good	Good	Infill ++	Infill ++
serviceberry	*Amelanchier spp.*	Low	10.23	No change	No change	Medium	Poor	Poor		
black locust	*Robinia pseudoacacia*	Low	9.5	Lg. inc.	Lg. inc.	Medium	Good	Good	Infill ++	Infill ++
yellow-poplar	*Liriodendron tulipifera*	High	9.09	Lg. inc.	Lg. inc.	High	Good	Good		
blackgum	*Nyssa sylvatica*	Medium	8.9	Lg. inc.	Lg. inc.	High	Good	Good	Infill ++	Infill ++
eastern cottonwood	*Populus deltoides*	Low	8.65	Sm. dec.	Sm. dec.	Medium	Very Poor	Very Poor		
scrub oak	*Quercus ilicifolia*	FIA	7.45	Unknown	Unknown	Medium	FIA Only	FIA Only		
bur oak	*Quercus macrocarpa*	Medium	7.34	Sm. dec.	Sm. dec.	High	Poor	Poor		

Common Name	***Scientific Name***	**MR**	**FIAsum**	**ChngCl45**	**ChngCl85**	**Adap**	**Capabil45**	**Capabil85**	**SHIFT45**	**SHIFT85**
black walnut	*Juglans nigra*	Low	7.04	Sm. dec.	No change	Medium	Very Poor	Poor		Infill +
sassafras	*Sassafras albidum*	Low	6.68	Lg. inc.	Lg. inc.	Medium	Good	Good	Infill ++	Infill ++
tree-of-heaven	*Ailanthus altissima*	FIA	6.52	Unknown	Unknown	NA	NNIS	NNIS		
green ash	*Fraxinus pennsylvanica*	Low	6.3	No change	Lg. inc.	Medium	Poor	Good	Infill +	Infill ++
pitch pine	*Pinus rigida*	High	5.53	No change	Sm. inc.	Medium	Poor	Fair	Infill +	Infill +
bitternut hickory	*Carya cordiformis*	Low	5.11	No change	Lg. inc.	High	Fair	Good	Infill +	Infill ++
slippery elm	*Ulmus rubra*	Low	4.71	Sm. dec.	Sm. dec.	Medium	Very Poor	Very Poor		
mockernut hickory	*Carya alba*	Medium	3.03	Lg. inc.	Lg. inc.	High	Good	Good	Infill ++	Infill ++
mountain maple	*Acer spicatum*	Low	2.32	Lg. dec.	Lg. dec.	High	Poor	Poor		
swamp chestnut oak	*Quercus michauxii*	Low	2.27	Sm. dec.	Sm. dec.	Medium	Very Poor	Very Poor		
black ash	*Fraxinus nigra*	Medium	2.11	Sm. dec.	Very Lg. dec.	Low	Very Poor	Lost		
white spruce	*Picea glauca*	Medium	1.13	Very Lg. dec.	Very Lg. dec.	Medium	Lost	Lost		
swamp white oak	*Quercus bicolor*	Low	0.99	Sm. inc.	Lg. inc.	Medium	Fair	Good	Infill +	
Norway maple	*Acer platanoides*	FIA	0.99	Unknown	Unknown	NA	NNIS	NNIS		
boxelder	*Acer negundo*	Low	0.82	Very Lg. dec.	No change	High	Lost	Fair		Infill +
black spruce	*Picea mariana*	High	0.8	Very Lg. dec.	Very Lg. dec.	Medium	Lost	Lost		
tamarack (native)	*Larix laricina*	High	0.38	Lg. dec.	Lg. dec.	Low	Very Poor	Very Poor		
American mountain-ash	*Sorbus americana*	Low	0.31	Lg. dec.	Sm. dec.	Low	Very Poor	Very Poor		
sweetgum	*Liquidambar styraciflua*	High	0	New Habitat	New Habitat	Medium	New Habitat	New Habitat	Migrate +	Migrate ++
northern hackberry	*Celtis occidentalis*	Medium	0	New Habitat	New Habitat	High	New Habitat	New Habitat	Migrate +	Migrate +
sycamore	*Platanus occidentalis*	Low	0	New Habitat	New Habitat	Medium	New Habitat	New Habitat	Migrate +	Migrate +
pawpaw	*Asimina triloba*	Low	0	New Habitat	New Habitat	Medium	New Habitat	New Habitat	Migrate +	Migrate +
post oak	*Quercus stellata*	High	0	New Habitat	New Habitat	High	New Habitat	New Habitat		Migrate ++
shortleaf pine	*Pinus echinata*	High	0	New Habitat	New Habitat	Medium	New Habitat	New Habitat		Migrate ++
loblolly pine	*Pinus taeda*	High	0	New Habitat	New Habitat	Medium	New Habitat	New Habitat		Migrate ++
Virginia pine	*Pinus virginiana*	High	0	New Habitat	New Habitat	Medium	New Habitat	New Habitat		Migrate ++

Common Name	*Scientific Name*	MR	FIAsum	ChngCl45	ChngCl85	Adap	Capabil45	Capabil85	SHIFT45	SHIFT85
common persimmon	*Diospyros virginiana*	Low	0	New Habitat	New Habitat	High	New Habitat	New Habitat		Migrate +
southern red oak	*Quercus falcata*	Medium	0	New Habitat	New Habitat	High	New Habitat	New Habitat		Migrate +
Table Mountain pine	*Pinus pungens*	Low	0	New Habitat	New Habitat	High	New Habitat	New Habitat		Migrate +
eastern redbud	*Cercis canadensis*	Low	0	New Habitat	New Habitat	Medium	New Habitat	New Habitat		Migrate +
American holly	*Ilex opaca*	Medium	0	New Habitat	New Habitat	Medium	New Habitat	New Habitat		Migrate +
chinkapin oak	*Quercus muehlenbergii*	Medium	0	Unknown	New Habitat	Medium	Unknown	New Habitat		Migrate +
willow oak	*Quercus phellos*	Low	0	New Habitat	New Habitat	Medium	New Habitat	New Habitat		Migrate +
flowering dogwood	*Cornus florida*	Medium	0	Unknown	New Habitat	Medium	Unknown	New Habitat		Likely +
cittamwood	*Sideroxylon lanuginosum*	Low	0	Unknown	Unknown	High	Unknown	Unknown		
sourwood	*Oxydendrum arboreum*	High	0	New Habitat	New Habitat	High	New Habitat	New Habitat		
blackjack oak	*Quercus marilandica*	Medium	0	New Habitat	New Habitat	High	New Habitat	New Habitat		
Shumard oak	*Quercus shumardii*	Low	0	New Habitat	New Habitat	High	New Habitat	New Habitat		
redbay	*Persea borbonia*	Low	0	Unknown	Unknown	High	Unknown	Unknown		
black hickory	*Carya texana*	High	0	New Habitat	New Habitat	Medium	New Habitat	New Habitat		
sugarberry	*Celtis laevigata*	Medium	0	Unknown	New Habitat	Medium	Unknown	New Habitat		
bigleaf magnolia	*Magnolia macrophylla*	Low	0	Unknown	Unknown	Medium	Unknown	Unknown		
cherrybark oak	*Quercus pagoda*	Medium	0	New Habitat	New Habitat	Medium	New Habitat	New Habitat		
water oak	*Quercus nigra*	High	0	New Habitat	New Habitat	Medium	New Habitat	New Habitat		
winged elm	*Ulmus alata*	Medium	0	New Habitat	New Habitat	Medium	New Habitat	New Habitat		
Ohio buckeye	*Aesculus glabra*	Low	0	Unknown	Unknown	Medium	Unknown	Unknown		
pecan	*Carya illinoinensis*	Low	0	Unknown	New Habitat	Low	Unknown	New Habitat		
mountain magnolia	*Magnolia fraseri*	Low	0	Unknown	New Habitat	Low	Unknown	New Habitat		
yellow buckeye	*Aesculus flava*	Low	0	Unknown	New Habitat	Low	Unknown	New Habitat		

Appendix 2: Non-native pest and disease threats summary

Table A2.1: Non-native pests and diseases that are substantially reducing the life span of one or more genera of canopy trees in northeastern North America. There are many non-native pests and pathogens in the region that are not listed in this table because they rarely cause tree mortality. Understory trees such as flowering dogwood are not included in the summary. Year is the approximate year when the pest or disease was first discovered causing damage in northeastern North America. In some cases, such as spongy moth, the year of first detection is the same as when it arrived in Massachusetts; whereas in other cases, such as beech bark disease, some decades passed before it spread to Massachusetts from elsewhere in northeastern North America. Taxa lists the genera/subgenera/species that are the preferred host that is most affected, but in many cases secondary hosts are also affected, although less so. For example, spotted lanternfly's preferred host is the non-native tree of heaven, but in places with outbreaks other taxa are also impacted, in this case, most notable vineyards and orchards, but also to a lesser degree various native trees. Control summarizes the current state of management actions and natural controls on the spread and impact of the pest or disease.

Pest or disease	**Year**	**Taxa**	**Control**
Spongy moth	1869	Oaks (genus *Quercus*)	Biological controls that were released over a century ago have reduced duration and frequency of outbreaks since the 1990s, but substantial mortality still accompanies outbreaks.
Chestnut blight	1904	Chestnut (genus *Castanea*)	Genetic engineering is being used to introduce resistance into trees and to improve biological controls of the pathogen.
Elongate hemlock scale	1908	Hemlock (genus *Tsuga*)	May be limited by cold winters in northern New England. Mainly causes mortality in trees that are already stressed by hemlock woolly adelgid.
White pine blister rust	Early 1900's	soft pines (subgenus *Strobus* of genus *Pinus*)	Eradication of the alternate host in the early decades of the 20th century has largely eliminated this disease from New England.
Beech bark disease	1929	Beech (genus *Fagus*)	A few percent of trees have naturally occurring resistance to the insects that spread the disease.
Dutch elm disease	1930	Elms (genus *Ulmus*)	A few American elms have been identified that demonstrate elevated resistance to the disease, but fully resistant native elm trees have never been found. Hybrids of native slippery elm and non-native

			Siberian elm have elevated disease resistance and are spreading in the wild.
Winter moth	1931	Oaks (genus *Quercus*), maples (genus *Acer*), birches (genus *Betula*)	Effective biological control was achieved in the 1950s in Nova Scotia; a success that researchers are currently attempting to replicate in New England.
Hemlock woolly adelgid	1951	Hemlock (genus *Tsuga*)	Limited by cold winter temperatures in Massachusetts. Biological controls are under development but have not yet been effective.
Butternut canker disease	1967	Butternut (*Juglans cinerea*)	No native butternuts with resistance have been found, but hybrids between butternut and Japanese walnut have some resistance and have spread to the wild.
Asian longhorned beetle	1996	Maples (genus *Acer*)	The eradication program in Worcester County has not fully eradicated this pest but reduced its numbers to the point of having no significant impact on tree populations in the early 2020s.
White pine needle cast disease	1998	soft pines (subgenus *Strobus* of genus *Pinus*)	Vigorous individuals are able to survive greater damage.
Emerald ash borer	2002	Ashes (genus *Fraxinus*)	A few native ash trees may have elevated resistance to this pest, but it is still too early in the outbreak to tell. Biological controls are actively being developed and released. Preliminary results provide hope that some of the biological controls could become effective at suppressing this pest.
Beech leaf disease	2012	Beech (genus *Fagus*)	Researchers are only beginning to learn about this new disease, to which native beech trees appear to be highly susceptible.
Southern pine beetle	2013	hard pines (subgenus *Pinus* of genus *Pinus*)	Vigorous individuals in stands with lower tree density are less likely to be attacked. Until recently, cold winters limited this pest from spreading in New England.
Spotted lanternfly	2014	grape vines (genus *Vitis*), and (non-native) tree of heaven (*Ailanthus altissima*)	Biological controls are being developed for this pest, but these biological controls are still in the testing stages.

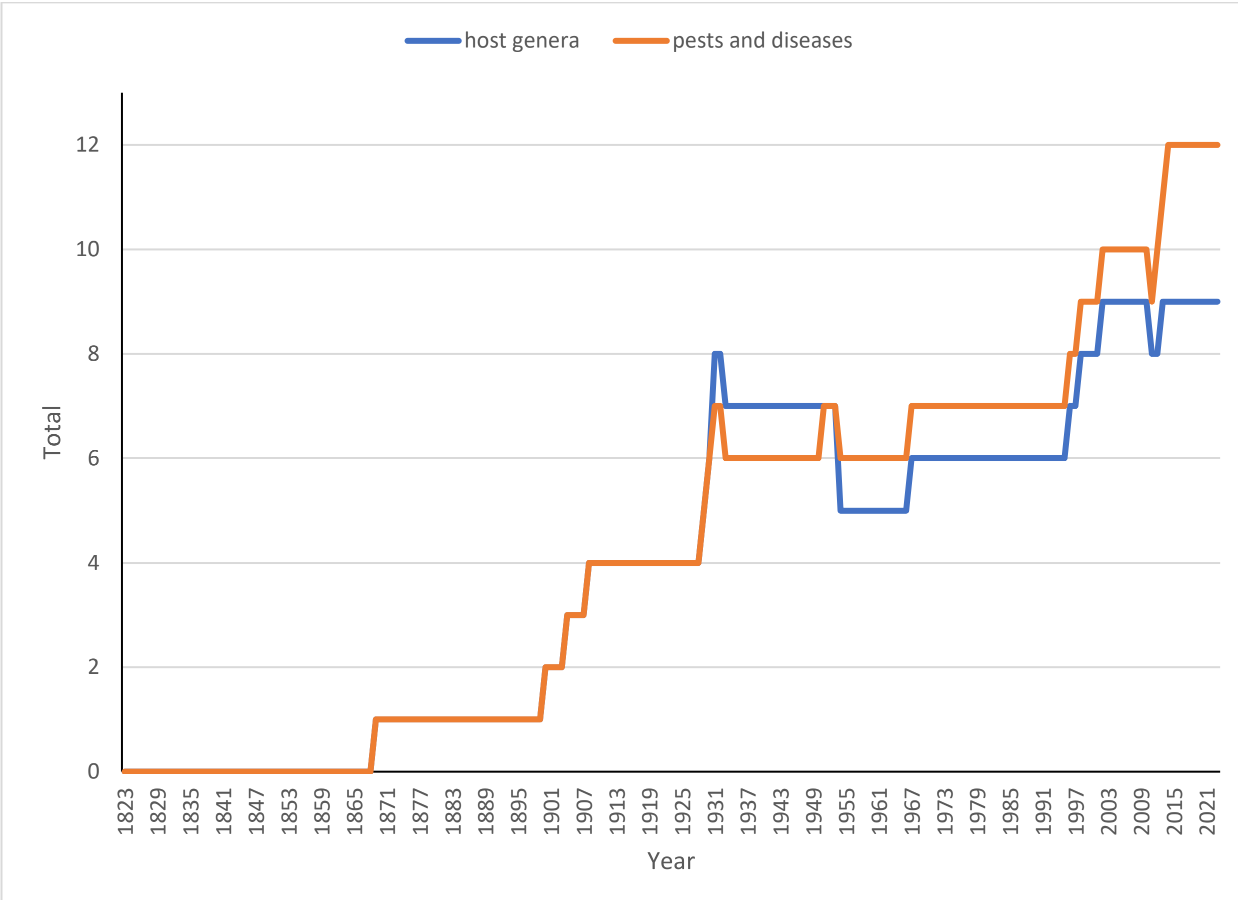

Figure A2.1: Accumulation of economically important non-native pest insects and diseases of trees in northeastern North America over the past two centuries. Note that pests and diseases have increased more rapidly than the affected number of hosts because the new pest or disease is often affecting taxa that were already severely impacted by a pest or disease that arrived earlier. Reversals are cases where management actions have greatly reduced the impact of a non-native pest or disease.

Appendix 3: Biological control programs in northeastern North America

Biological control is often the only feasible solution to limit the impact of the most widespread and damaging non-native plant and insect pest species at the regional scale. Ecological resilience to disturbances could be augmented if safe and effective biological controls for the most damaging non-native plants and pests. Biological control programs do not always succeed because there may not be a species that can effectively control the pest, or if there is that species is not sufficiently specialized to avoid damage to non-target species. However, many biological control programs have been successful, in North America and elsewhere. The status of biological control programs for important non-native plants and pests as of summer 2023 is as follows:

- Species with biological controls that were already widely released in the past:
  - Purple loosestrife (*Lythrum salicaria*)
  - Spongy moth (*Lymantria dispar*)
  - Winter moth (*Operophtera brumata*)
- Species with biological control programs in various stages of development:
  - Non-native subspecies of common reed (*Phragmites australis*)
  - Non-native knotweeds (*Reynoutria japonica, R. sachalinensis, R. x bohemica*)
  - Water chestnut (*Trapa natans*)
  - Non-native swallow-worts (*Vincetoxicum rossicum, V. nigrum*)
  - Garlic mustard (*Alliaria petiolata*)
  - Mile-a-minute weed (*Persicaria perfoliata*)
  - Tree of heaven (*Ailanthus altissima*)
  - Hemlock woolly adelgid (*Adelges tsugae*)
  - Emerald ash borer (*Agrilus planipennis*)
  - Asian longhorned beetle (*Anoplophora glabripennis*)
  - Spotted lanternfly (*Lycorma delicatula*)
- Species that do not yet have a biological control program:
  - Round-leaved bittersweet (*Celastrus orbiculatus*)
- Species where the search for effective biological controls was given up:
  - Glossy buckthorn (*Rhamnus frangula*)
  - Common buckthorn (*Rhamnus cathartica*)
  - Kudzu (*Pueraria montana*)