Non-native Tree Pest Assessment for Marsh-Billings-Rockefeller National Historical Park

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September 2020

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Introduction

This report assesses the stand-level susceptibility and management options for 10 non-native invasive tree pest species at Marsh-Billings-Rockefeller National Historical Park (MABI). The Mount Tom Forest in MABI is the oldest planned and continuously managed forest in the United States. MABI is mandated by its enabling legislation to preserve the forest and continue progressive stewardship. Existing populations and potential introductions of non-native tree pests can alter the health, composition, and viability of the Mount Tom Forest's historic character and natural communities.

The park's forest management plant (NPS 2006a) outlines the values of forests within the park and the objectives of management: "The Mount Tom Forest is a key component of the cultural landscape of the 555-acre Marsh-Billings-Rockefeller National Historical Park and plays an important role in the Park's interpretation and demonstration of stewardship. The Forest Management Plan provides a strategy for managing the Mount Tom Forest that will:

- perpetuate the tradition of sustainable forest management on the property,
- incorporate a long-term perspective on the changing composition and character of the Forest,
- value the Forest as both a natural and cultural resource,
- emphasize the relationship of the Park's forest management to broader community well-being and sustainability, and
- strengthen civic engagement and stewardship"

The Mount Tom Forest includes plantations of North American and European species as well as native forest types common to the region. Active forest management within the park includes thinning, regeneration harvests, timber stand improvement, and planting, as well as non-native species management.

Non-native invasive species present a serious and growing threat to forest ecosystems in the northeastern United States due to climate change and increasing global trade, travel, and tourism. Tree pests, including insects and pathogens, are a problem of growing concern that public forest managers must address. For MABI, tree pests threaten the preservation and character of a nationally significant historic forest. A changing climate further complicates the dynamic relationships between tree pests and the forest; many species such as red pine scale and hemlock woolly adelgid are cold sensitive and a warming climate can lead to expansion of their ranges in the northeast.

NPS Management Policies (2006b; section 4.4.4.2) specifically guide park managers to develop response strategies to non-native invasive species "that have, or potentially could have, a substantial impact on park resources, and that can reasonably be expected to be successfully controllable." All parks in the northeast face the challenge of dealing with similar tree pest issues. Integrated Pest Management plans have been developed individually for many parks throughout the Northeast, including MABI, but did not consider many forest pests. Subsequently, the NPS developed a rapid response plan for forest pests of concern in the eastern NPS regions (Ackerson and Millington 2010). This project builds upon this rapid response plan by including pests that are new or have increased their proximity to the Marsh-Billings-Rockefeller forest, such as red pine scale and emerald ash borer. MABI is unique to the NPS in that it can implement a wider array of forest management options than most other parks typically use to help combat forest pests. Silvicultural treatments can be utilized to reduce the frequency of outbreak occurrence and minimize severity of outbreaks. They can be used to alter species composition, diameter distribution and stocking to help mitigate susceptibility, and sanitation and salvage treatments can mitigate hazard levels in stands.

The report is divided into two parts. The first section is a spatial assessment of forest susceptibility to 10 currently present and proximate forest pest species. The stand-level assessment is based on the current range of tree pests, rate of spread (and thus pest arrival date in MABI), and host tree abundance in the park. The second part of the report provides background information on each pest and detection, control, and management options. The report is not intended to be prescriptive of which management actions to take but rather lays out a suite of available options. Managers should weigh benefits and side effects of all control options, for example, neonicotinoid pesticide harm to non-target insects or the consequences of taking no management action, and follow local, state, and NPS guidance.

Pest species were selected based on current proximity to the park, host tree abundance, and manager concerns (Table 1). The selected species have high potential impact to the park's forests, though other nearby pests and species not presently found within 350 km of the park could impact park resources in the future, for example sudden oak death now found only on the west coast of the U.S. Continued monitoring within the park and staying informed on pest infestations in the region are necessary for effective stewardship.

Table 1. Non-native tree pest species of management concern for Marsh-Billings-Rockefeller National Historical Park. All pest species are within 400 km and have host tree species present within the park.

Common Name	**Scientific Name**	**Forest susceptible (%)**	**Proximity (km)**
Asian longhorned beetle	*Anoplophora glabripennis*	43%	~150
Beech bark disease	*Cryptococcus fagisuga*; *Neonectria* spp.	4%	Present
Elongate hemlock scale	*Fiorinia externa*	28%	<50
Emerald ash borer	*Agrilus planipennis*	8%	<50
European gypsy moth	*Lymantria dispar dispar*	92%	Present
Hemlock woolly adelgid	*Adelges tsugae*	18%	<20
Oak wilt	*Ceratocystis fagacearum*	2%	~150
Red pine scale (pine bast scale)	*Matsucoccus matsumarae*	6%	<100
Spotted lanternfly	*Lycorma delicatula*	28%	~350
Winter moth	*Operophtera brumata*	41%	<100

This report looks out over the next 5-30 years at the potential rate of spread and presence of pests in the park, uses current forest composition information, and assesses current management options. Many factors in addition to pests are changing on the landscape and will affect the

Mount Tom forest. These changes will interact with tree pests and alter pest virulence. Climate change is ongoing and the region encompassing the park has become significantly warmer and wetter over the past three decades (USGCRP 2017). Future projections are for continued warming and higher total annual precipitation, though altered precipitation regimes including shifts in seasonal amounts and episodic drier periods may become more frequent (USGCRP 2017). A warming climate may accelerate the life cycle of tree pests and increase the rates of pest population growth. Drought, ice storms, heat waves, winter thaws, flooding, and other climate-related events may stress trees and make them more susceptible to damage and mortality from tree pests. The effectiveness of management options may change as well, for example dry springs reduce *Entomophaga* fungal control of gypsy moth.

Climate suitability will continue to change for existing trees within the park and future shifts in forest composition, whether through mortality events and natural range expansion or through management actions (e.g., managed relocation), will alter the susceptibility of the forest to tree pests. Many tree species are projected to gain suitable habitat, such as some oaks, hickories, and yellow-poplar, while other species may lose habitat, including maples, birches, and northern conifers (Fisichelli et al. 2014). Changes in forest composition mean changes in host tree species presence and abundance, and thus susceptibility to tree pests. Looking out into the future inherently brings many uncertainties and management strategies will need to adapt to emerging conditions and changes in the park forest.

References

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Part 1: Spatial Assessment of Forest Susceptibility

Introduction

Assessing the potential range expansion of non-native invasive insects and pathogens and their impact on native tree species is key for informing management options. This spatial analysis focused on 10 species of insects and disease-causing pathogens that may have the highest impact on Marsh-Billings-Rockefeller National Historical Park: Asian longhorned beetle, beech bark disease, emerald ash borer, European gypsy moth, elongate hemlock scale, hemlock woolly adelgid, oak wilt, red pine scale, spotted lanternfly, and winter moth. Some of these species are already present in the Park, such as beech bark disease and gypsy moth, and are already having significant impact on forest dynamics. The remaining species may expand into the park in the coming decades.

Although impossible to predict precisely, understanding rates of spread and approximate arrival dates of insects and pathogens is critical for management planning. In a study comparing 79 species of damaging non-native forest insect and pathogen species in the US, the average radial rate of range expansion was 5.2 km/year (Liebhold et al., 2013). This average rate did not differ between damage groups of pests (foliage feeders, sap-feeders, woodborers, and plant pathogens) indicating that human-assisted movement of pests is likely to be an important driver of range expansion, regardless of pest group. This average provides a baseline assumption for assessing a range of spread rates, resultant arrival dates, and implications for forest.

The objective of this map analysis was 1) to estimate arrival dates for major pest species to inform planning and prioritization and 2) to estimate stand-level susceptibility to each species. Since there are many factors that drive pest movement, a matrix of nine maps was created to display a range of forest susceptibility based on year and rate of spread. The susceptibility is based on known tree host species for each pest species.

Methods

Data sources

This analysis required four main inputs: current pest ranges, US counties, spatial stand-level tree composition data for Marsh-Billings-Rockefeller, and a list of host tree species for each pest.

> **Pest ranges** were downloaded from the Alien Forest Pest Explorer (AFPE). Created by the United States Forest Service (USFS) Northern Research Station, AFPE is an interactive portal containing range information for damaging non-native forest insect and pathogen species in the US. Pest range maps current to March 2019 were downloaded.
>
> A **US county shapefile** was used to display the pest ranges spatially. The US county shapefile was downloaded from the US Census Bureau as a 2017 cartographic boundary file, a simplified representation of the TIGER database.
>
> **Marsh-Billings-Rockefeller NHP stand-level composition data** was acquired from Redstart, Inc. This is an inventory database based on a permanent plot system established in 2000, and includes stand-level percent basal area of overstory trees (DBH > 4 in. (10.2 cm)) (2017 data).

Pest host species were compiled as part of the pest profile research featured in the latter half of this report. For the spatial analyses, the host species lists included only the overstory tree species from the stand-level data in the park (Table A3).

Rate of spread

The rates of spread used in this analysis were based on the Liebhold et al. (2013) study that determined the average radial rate of range expansion to be 5.2 km/year across all groups of pests. This may reflect human-aided spread as the dominant pathway by which many pests expand across the landscape. Due to the level of uncertainty in estimating rate of spread on a species-specific basis, we used three different rates of spread to display a range of outcomes: 1 km/year (low), 5 km/year (average in continental US), and 20 km/year (high).

Marsh-Billings-Rockefeller NHP is embedded in a matrix of private lands, with approximately 2/3rds of these properties being second homes (C. Marts personal communication). Many of these property owners have their primary residences to the south, within the current range limit of several tree pest species, including emerald ash borer and red pine scale. Unintentional movement of tree pests onto the landscape around the park is possible and thus even the high rate of spread used in this analysis may ultimately underestimate the arrival date for some pests.

Process

The data downloaded from AFPE included tabular data for the counties in which each pest was present. To create the pest range maps, the tabular data on presence were joined with the US county shapefile using ArcGIS Pro (2018).

Next, a model was created in Model Builder to automate the estimation of pest arrival date. This allows the user to repeat the process with multiple different pests by varying the input shapefile. The final model, 'Pest_Arrival_Model_centroid,' receives the Park stand and pest range shapefiles as inputs and creates an output table with estimated arrival years at three different rates of spread (1, 5, and 20 km/yr). The model first finds the centroids of the Park and each county in the pest range. Then, the distance between the Park centroid and the closest county centroid is calculated. This is the 'minimum distance to centroid.' This distance is the input for a custom Python script tool that estimates the arrival date assuming each rate of spread, and creates an output table with these dates. The script tool accepts four custom parameters: the minimum distance to centroid, the common name of the pest (which is used to populate the output table), the year of the input data, and the name of the output table.

The ten pest arrival tables, the table of host species, and the stand-level composition data were queried in Microsoft Access to calculate the susceptibility of each stand. In this analysis, susceptibility is the percent basal area of host tree species in the stand based on the pests that are present in each time period. The table from Microsoft Access with susceptibility information for each stand was used to create the final maps.

The impact of each pest species varies with many factors, including climate, drought, tree size and age, and the duration, intensity, and frequency of pest infestations. Furthermore, many of these pests have not yet reached Vermont and thus it is not known how they will interact with local factors and impact forest health. Given these many factors and uncertainties, assigning a likelihood of mortality or other pest impact value was deemed challenging. The susceptibility metric used here is thus based on basal area of the host tree species and number of pests per host species.

Results

Of the ten insect and pathogen species selected for analyses, two are already present in the park. The remaining seven arrive within 1-367 years, depending on species and rate of spread. The closest occurrence pest to the park is hemlock woolly adelgid (~7 km) and the furthest species in the analysis is spotted lanternfly (367 km). The rate of spread had a larger influence on the total number of pests in the park than the time scale used in the analysis (Table 1).

Table 1. The total number of pest species (out of 10 study species) present in Marsh-Billings-Rockefeller at three future times based on three assumed rates of spread. *2019 pests already present in park.

Year	1 km/yr	5 km/yr	20 km/yr
2019*	2	2	2
2025	3	3	7
2035	3	7	9
2050	3	9	10

The 10 insect and pathogen species impact all 15 of the most common overstory tree species presently found in Marsh-Billings-Rockefeller (Table 2). These 15 host species are 98.8% of the basal area found in the park. The tree species with the most insect and pathogen species are red maple (*Acer rubrum*), sugar maple (*Acer saccharum*), black cherry (*Prunus serotina),* and northern red oak *(Quercus rubra*), all with 4 out of 10 studied pests. However, this only occurs for the final period (2050) in the 20 km/yr scenario, and spotted lanternfly is the species that brings the total to four. Comparing the three rate of spread scenarios, pests per species is affected more by rate of spread than by year. Furthermore, deciduous species support a higher diversity of pest species in this study scenario than coniferous species.

Table 2. Host tree species and the number of associated insect and pathogen species (of 10 study species) based on year and rate of spread.

	1 km/yr			5 km/yr			20 km/yr		
Tree species	2025	2035	2050	2025	2035	2050	2025	2035	2050
Acer rubrum	1	1	1	1	2	3	2	3	4
Acer saccharum	1	1	1	1	2	3	2	3	4
Betula alleghaniensis	1	1	1	1	2	3	2	3	3
Fagus grandifolia	2	2	2	2	2	3	2	3	3
Fraxinus americana	0	0	0	0	2	3	2	3	3
Larix decidua	1	1	1	1	1	1	1	1	1
Ostrya virginiana	1	1	1	1	1	1	1	1	1
Picea abies	1	1	1	1	2	2	2	2	2
Pinus resinosa	1	1	1	1	2	2	2	2	2

Pinus strobus	1	1	1	1	1	1	1	1	1
Pinus sylvestris	1	1	1	1	1	1	1	1	1
Prunus serotina	1	1	1	1	2	3	2	3	4
Quercus rubra	1	1	1	1	2	3	2	3	4
Tilia americana	1	1	1	1	2	3	2	3	3
Tsuga canadensis	2	2	2	2	3	3	3	3	3

The matrix of maps (Figure 1) summarizes stand susceptibility based on the range expansion of the 10 target pest species using three different rates of spread over the next three decades. The stands are symbolized by the sum total percent basal area of overstory host species affected by pests and pathogens. For example, if emerald ash borer and beech bark disease are predicted to be present, the value symbolized is the sum of the percent composition of ash and beech in that stand. Because multiple different pests and pathogens can affect a host species, the maximum stand value is greater than one (highlighted in Table A1). The 1 km/yr maps are identical across years because hemlock woolly adelgid is projected to arrive by 2025, and the remaining pest and pathogen species arrive after 2050.

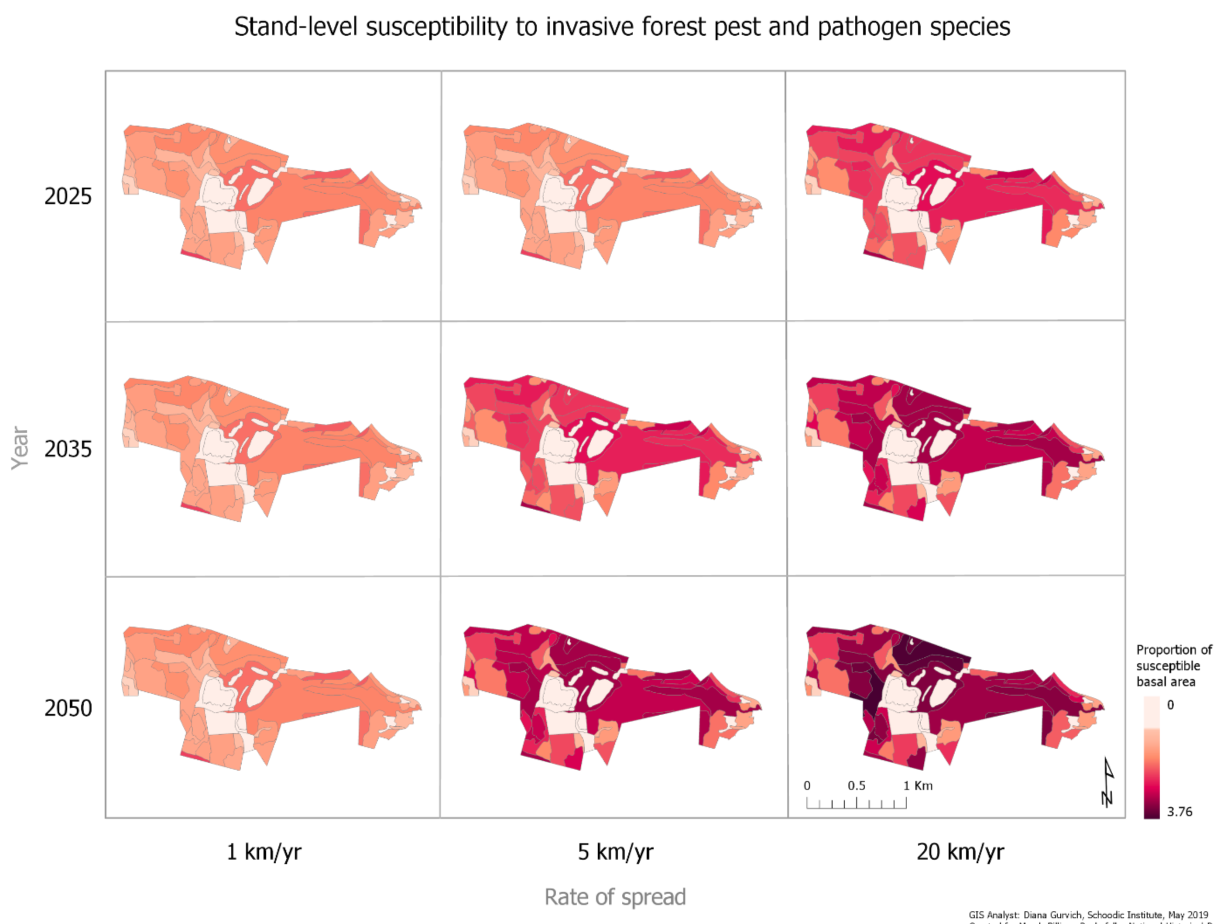


Figure 1. Stand-level susceptibility of Marsh-Billings-Rockefeller NHP forest stands to non-native pest and pathogen species, with susceptibility symbolized by proportion of host species

basal area affected. The scale maximum (3.76) is the maximum value across all scenarios shown (table A1).

Individual tree pests have different abundances of hosts and distributions of hosts across the park (Table 3). The pests with the most abundant host tree species in the stands of Marsh-Billings-Rockefeller are European gypsy moth (14), Asian longhorned beetle (7), and winter moth (7). These pests also affect the most basal area and the highest number of stands in the park. European gypsy moth is by far the most potentially impactful pest species in the park—in that it could affect 92% of the park basal area and 77% of stands. However, impacts to host tree species will vary within and across pest species and this assessment provides an initial assessment of potential impact. Asian longhorned beetle and winter moth are similar in impact, both affecting around 40% of park basal area and 72% of stands. While spotted lanternfly's impact on park basal area is less pronounced relative to other multi-host species, it could have a broad impact across the park at 69% of stands affected. Of the single-host pest species, hemlock woolly adelgid could have the most impact on the park at 18% basal area affected. Individual pest species results are shown below (Figs. 2-12 and Tables 4-11).

Table 3. Host tree and stand summaries for tree pests at Marsh-Billings-Rockefeller.

Pest species	No. of host species	Host basal area (m^2/ha, %)		Susceptible stands (n, %)	
Asian longhorned beetle	7	13.3	43%	47	72%
Beech bark disease	1	1.3	4%	14	22%
Elongate hemlock scale	2	8.6	28%	21	32%
Emerald ash borer	1	2.6	8%	37	57%
European gypsy moth	14	28.5	92%	50	77%
Hemlock woolly adelgid	1	5.7	18%	21	32%
Oak wilt	1	0.6	2%	12	19%
Red pine scale	1	1.9	6%	4	6%
Spotted lanternfly	4	8.7	28%	45	69%
Winter moth	7	12.6	41%	47	72%

Asian longhorned beetle

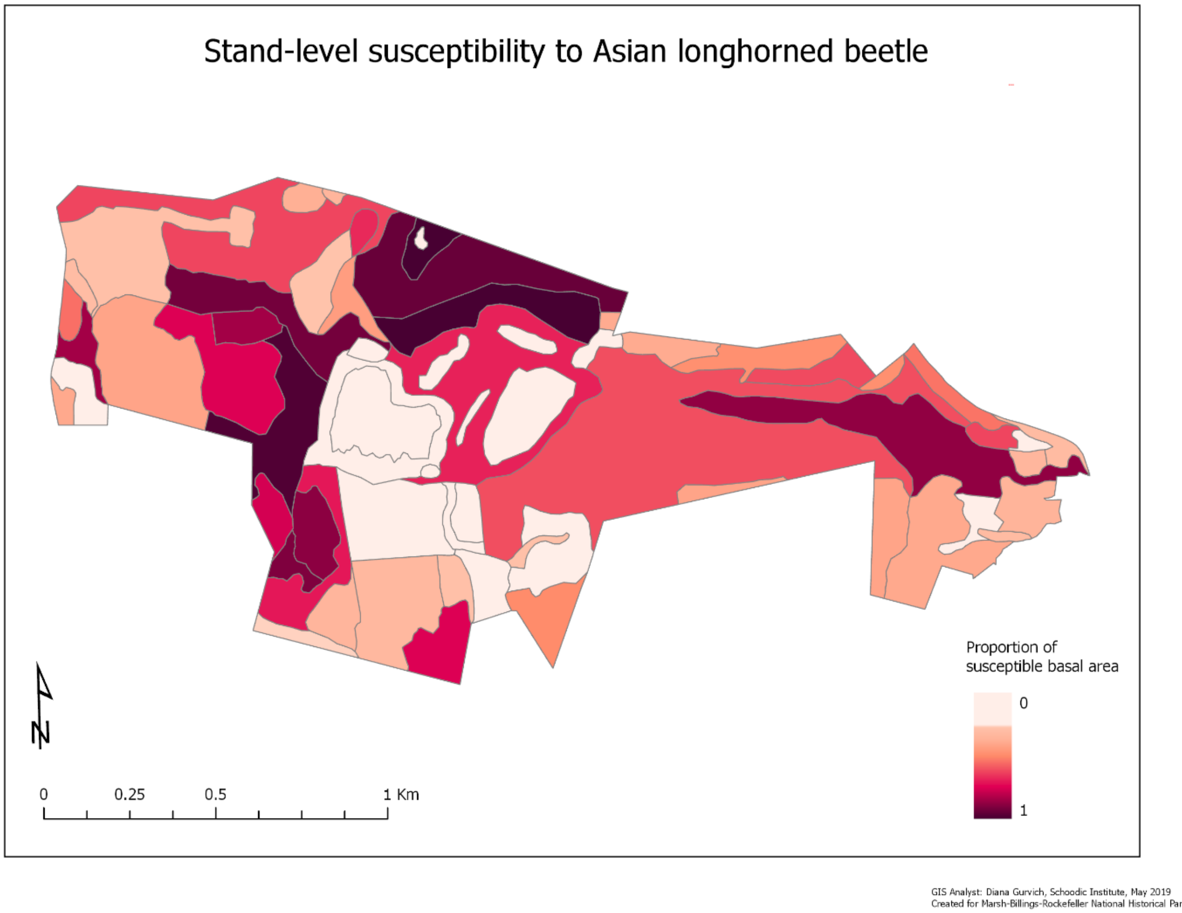


Figure 2. Stand-level susceptibility of Marsh-Billings-Rockefeller NHP forest stands to Asian longhorned beetle, with susceptibility symbolized by proportion of host species basal area.

Table 4. Asian longhorned beetle arrival times (start year is 2018). Closest occurrence is ~151 km from Marsh-Billing-Rockefeller.

Rate of spread (km/yr)	No. of years until arrival	Arrival year
1	151	2169
5	30	2048
20	8	2026

Beech bark disease

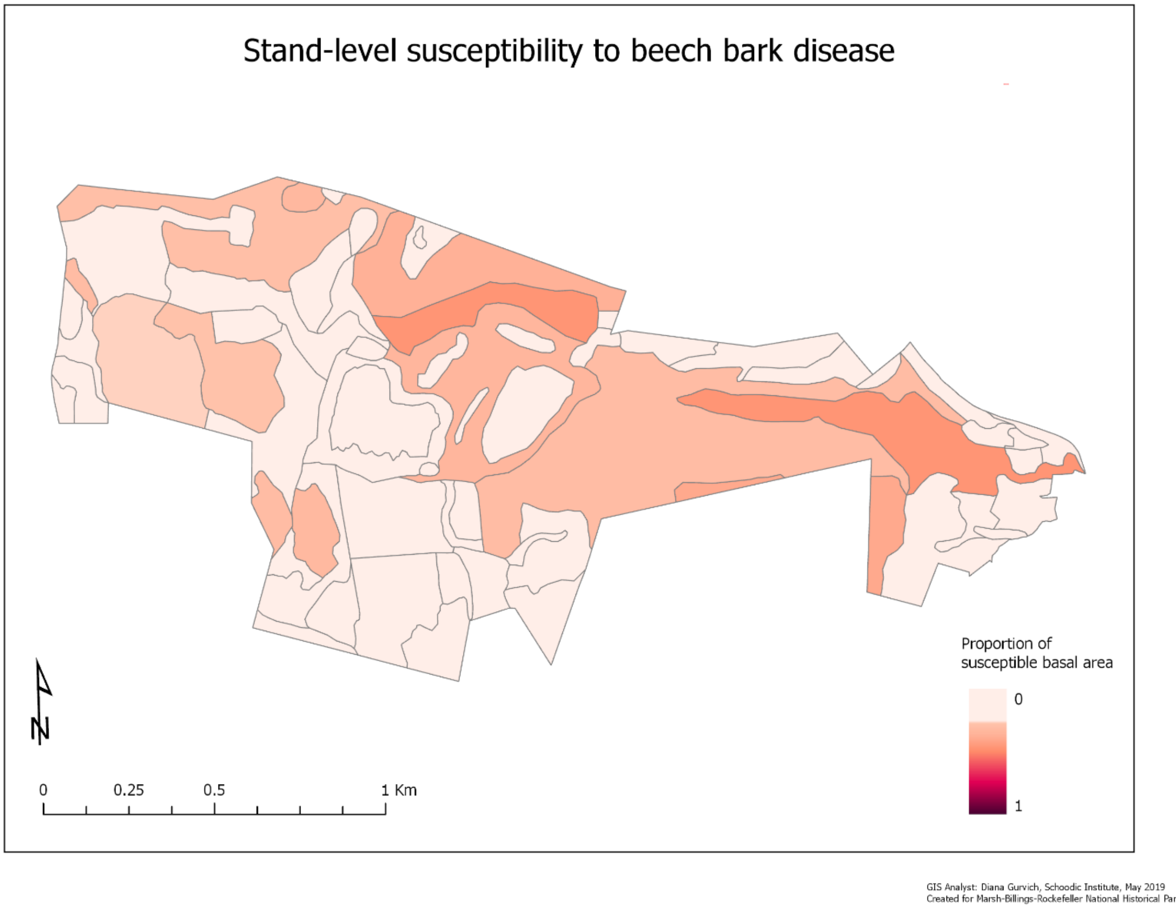


Figure 3. Stand-level susceptibility of Marsh-Billings-Rockefeller NHP forest stands to beech bark disease, with susceptibility symbolized by proportion of host species basal area.

Beech bark disease is already present in Marsh-Billings-Rockefeller.

Elongate hemlock scale

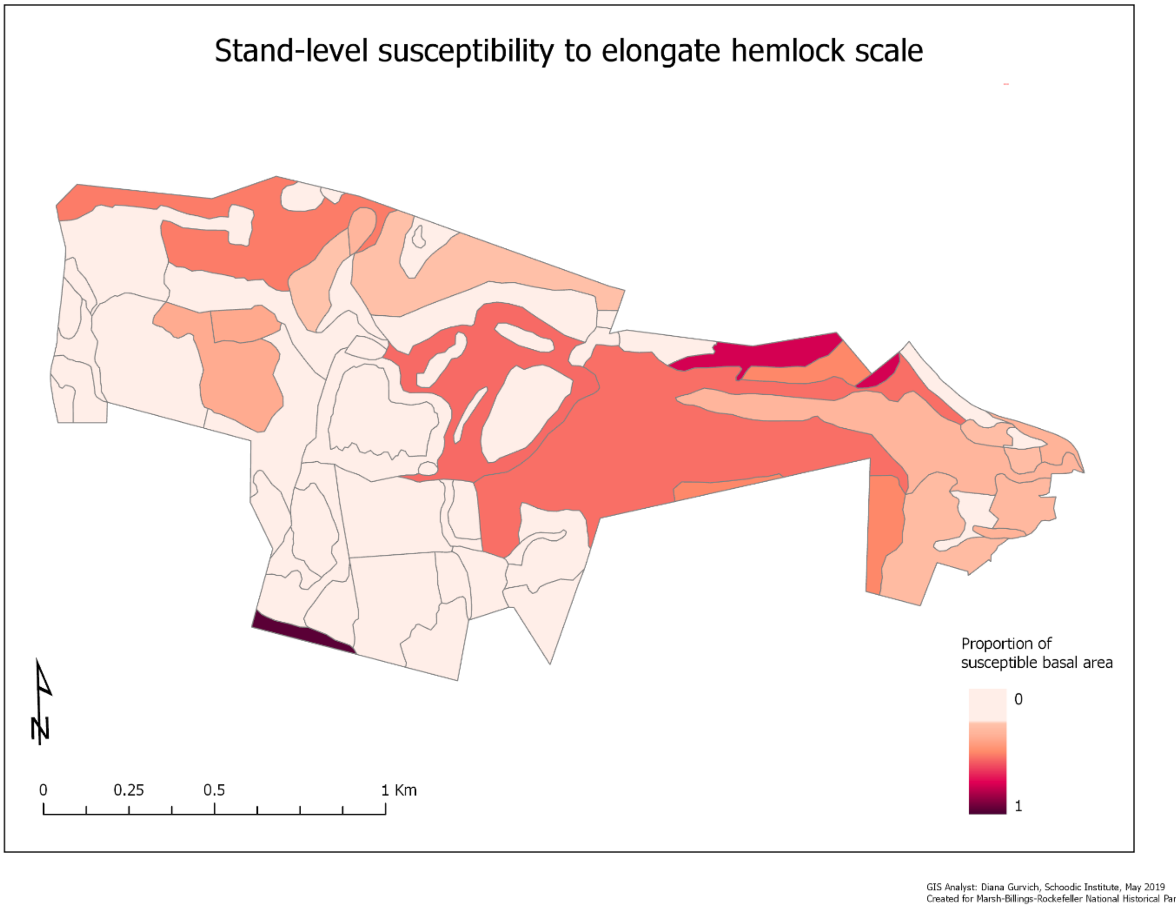


Figure 6. Stand-level susceptibility of Marsh-Billings-Rockefeller NHP forest stands to elongate hemlock scale, with susceptibility symbolized by proportion of host species basal area.

Table 6. Elongate hemlock scale arrival times (start year is 2018). Closest occurrence is ~40 km from Marsh-Billing-Rockefeller.

Rate of spread (km/yr)	No. of years until arrival	Arrival year
1	40	2058
5	8	2026
20	2	2020

Emerald ash borer

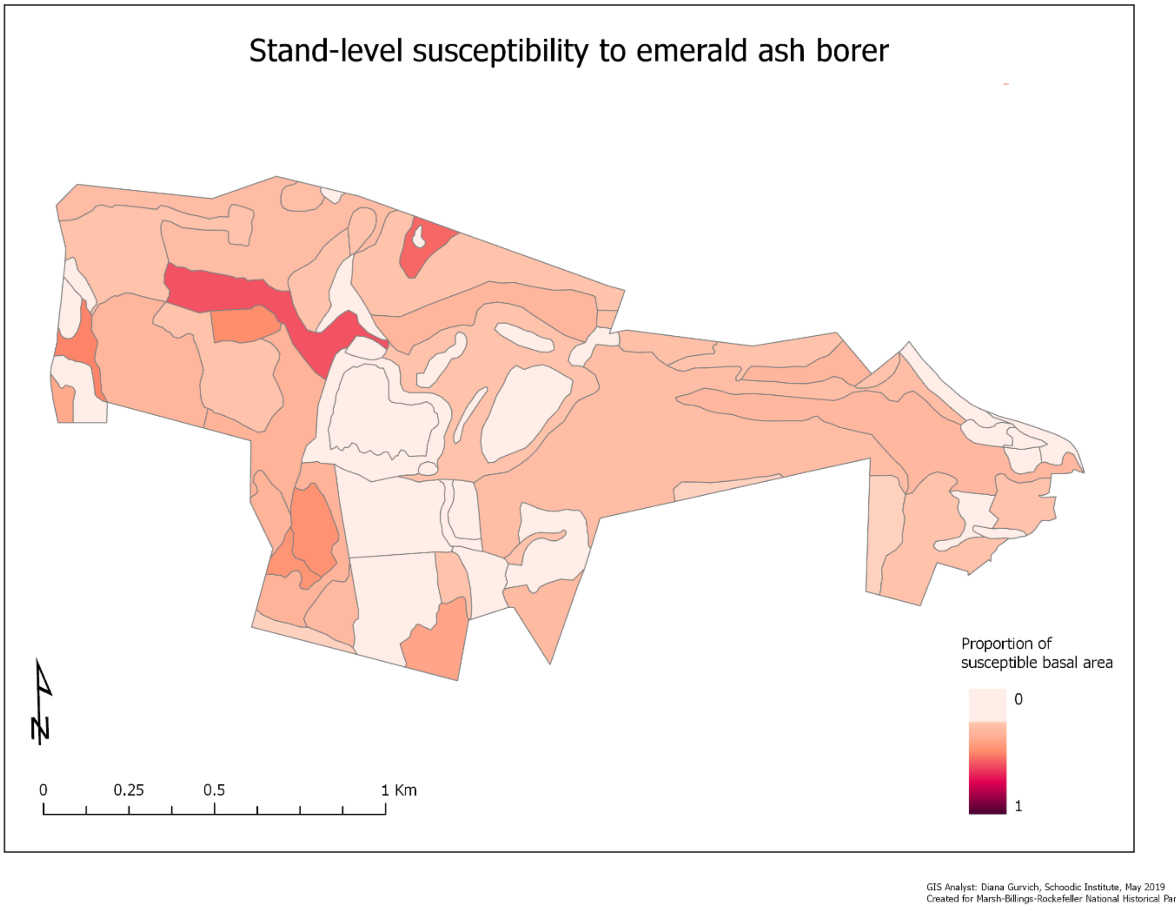


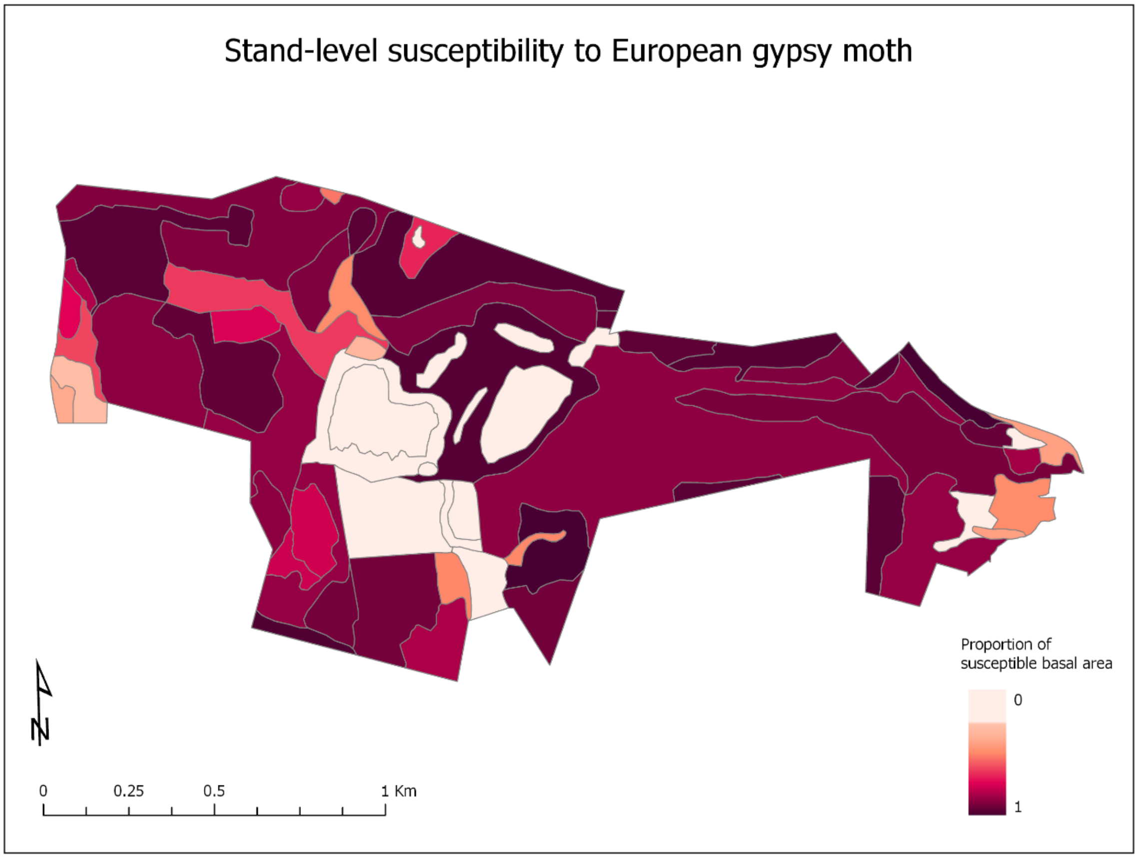
Figure 4. Stand-level susceptibility of Marsh-Billings-Rockefeller NHP forest stands to emerald ash borer, with susceptibility symbolized by proportion of host species basal area.

Table 5. Emerald ash borer arrival times (start year is 2018). Closest occurrence is ~43 km from Marsh-Billing-Rockefeller.

Rate of spread (km/yr)	No. of years until arrival	Arrival year
1	43	2061
5	9	2027
20	2	2020

Ash is present in low levels across the park, including along roads and trails, so emerald ash borer impact will not be concentrated in only a few stands.

European gypsy moth



GIS Analyst: Diana Gurvich, Schoodic Institute, May 2019
Created for Marsh-Billings-Rockefeller National Historical Park

Figure 5. Stand-level susceptibility of Marsh-Billings-Rockefeller NHP forest stands European gypsy moth, with susceptibility symbolized by proportion of host species basal area.

European gypsy moth is already present in Marsh-Billings-Rockefeller and the high potential susceptibility values in Figure 5 reflect the high number of host species in the park. Actual susceptibility will vary among species.

Hemlock woolly adelgid

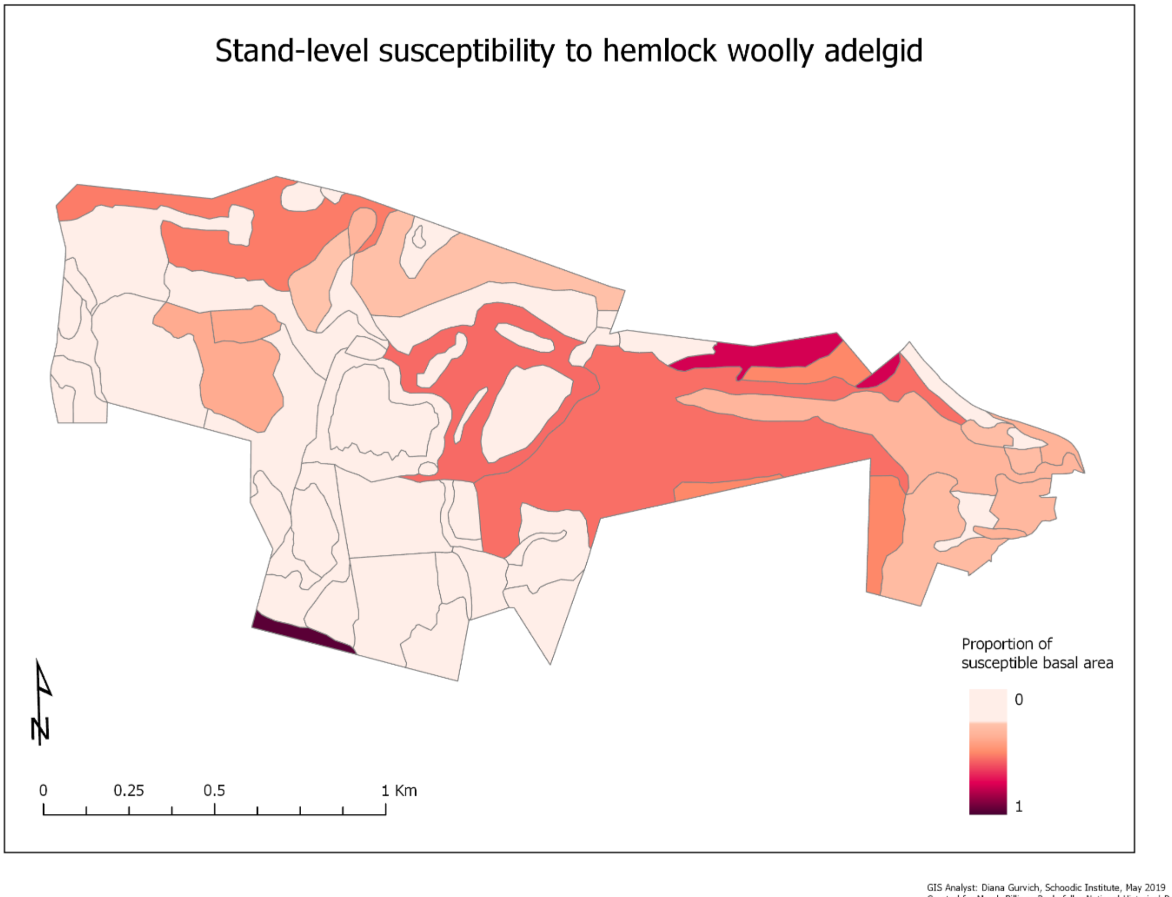


Figure 7. Stand-level susceptibility of Marsh-Billings-Rockefeller NHP forest stands to hemlock woolly adelgid, with susceptibility symbolized by proportion of host species basal area.

Table 7. Hemlock woolly adelgid arrival times (start year is 2018). Closest occurrence is ~7 km from Marsh-Billing-Rockefeller.

Rate of spread (km/yr)	No. of years until arrival	Arrival year
1	7	2025
5	1	2019
20	0	2018

Because hemlock woolly adelgid has been detected in Windsor County, the distance to the closest occurrence is the distance from the center of Marsh-Billings-Rockefeller to the center of the county.

Oak wilt

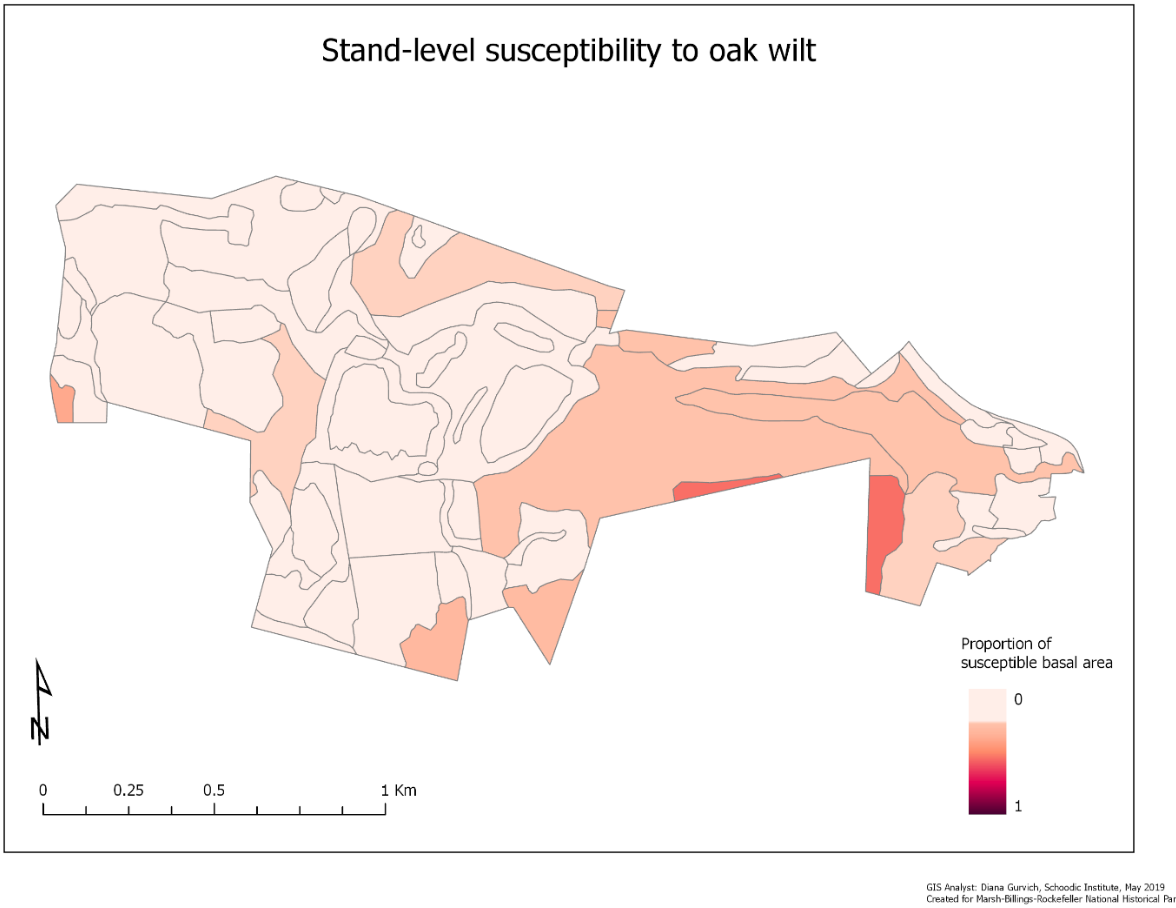


Figure 8. Stand-level susceptibility of Marsh-Billings-Rockefeller NHP forest stands to oak wilt, with susceptibility symbolized by proportion of host species basal area.

Table 8. Oak wilt arrival times (start year is 2018). Closest occurrence is ~153 km from Marsh-Billing-Rockefeller.

Rate of spread (km/yr)	No. of years until arrival	Arrival year
1	153	2171
5	31	2049
20	8	2026

Red pine scale

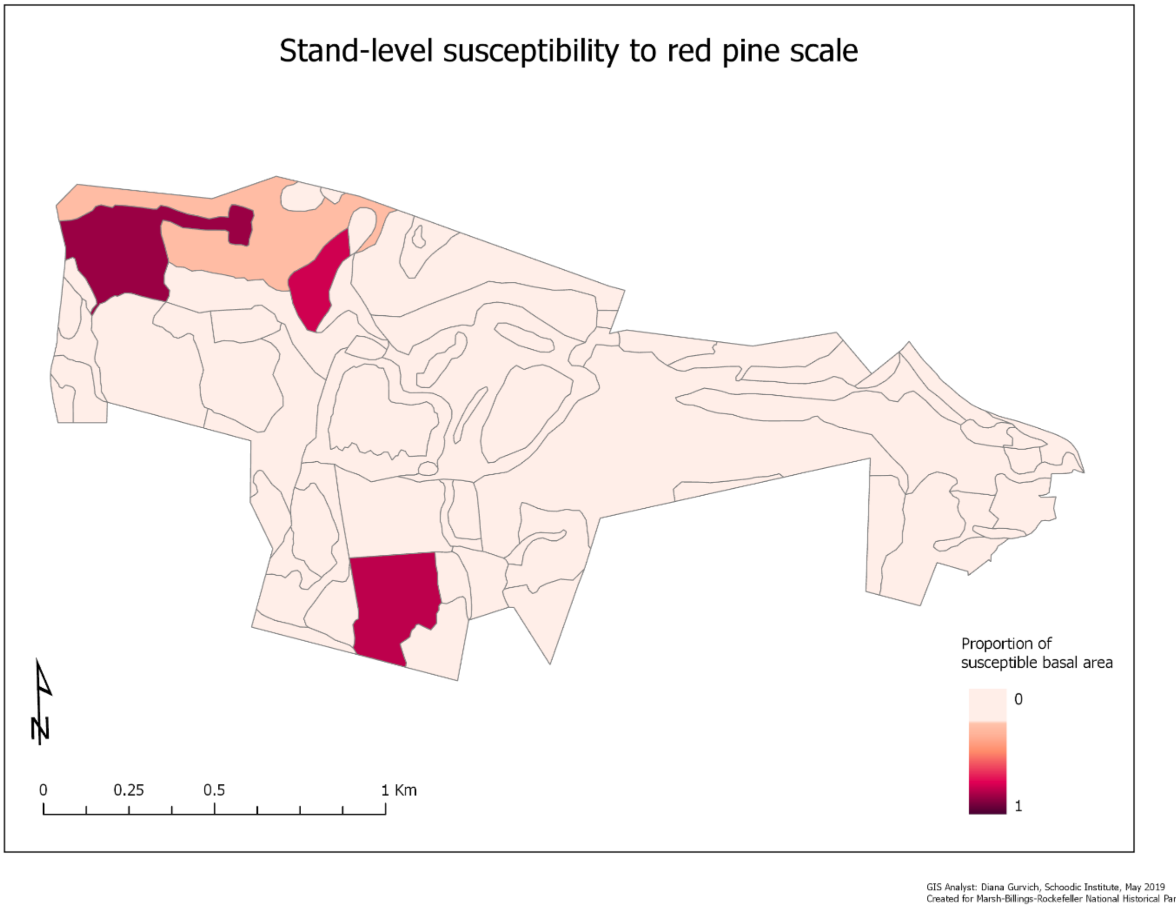


Figure 9. Stand-level susceptibility of Marsh-Billings-Rockefeller NHP forest stands to red pine scale, with susceptibility symbolized by proportion of host species basal area.

Table 9. Red pine scale arrival times (start year is 2018). Closest occurrence is ~79 km from Marsh-Billing-Rockefeller.

Rate of spread (km/yr)	No. of years until arrival	Arrival year
1	79	2097
5	16	2034
20	4	2022

Red pine scale is very concentrated where it is projected to be found in Marsh-Billings-Rockefeller because red pine almost exclusively grows in plantations in the park.

Spotted lanternfly

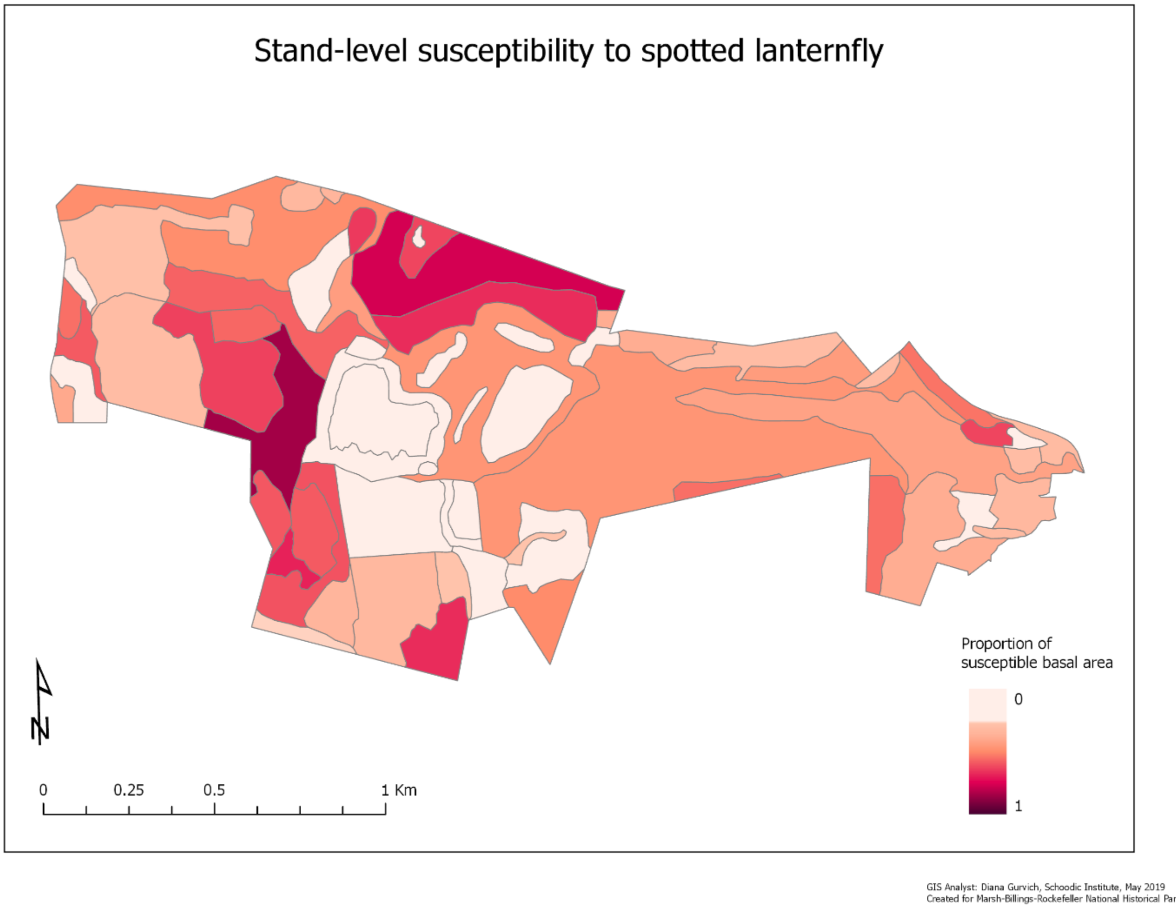


Figure 10. Stand-level susceptibility of Marsh-Billings-Rockefeller NHP forest stands to spotted lanternfly, with susceptibility symbolized by proportion of host species basal area.

Table 10. Spotted lanternfly arrival times (start year is 2018). Closest occurrence is ~367 km from Marsh-Billing-Rockefeller.

Rate of spread (km/yr)	No. of years until arrival	Arrival year
1	367	2385
5	73	2091
20	18	2036

Winter moth

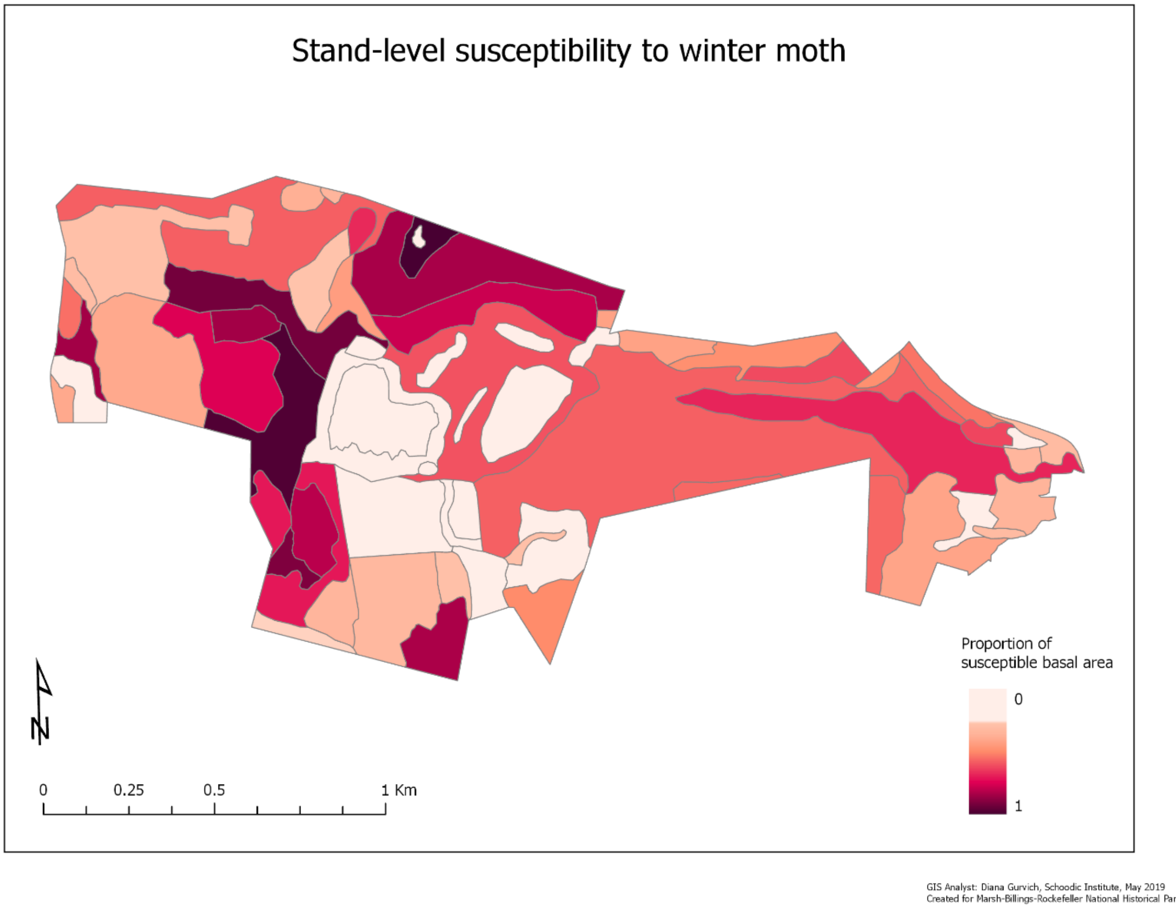


Figure 11. Stand-level susceptibility of Marsh-Billings-Rockefeller NHP forest stands to winter moth, with susceptibility symbolized by proportion of host species basal area affected.

Table 11. Winter moth arrival times (start year is 2018). Closest occurrence is ~83 km from Marsh-Billing-Rockefeller.

Rate of spread (km/yr)	No. of years until arrival	Arrival year
1	83	2101
5	17	2035
20	4	2022

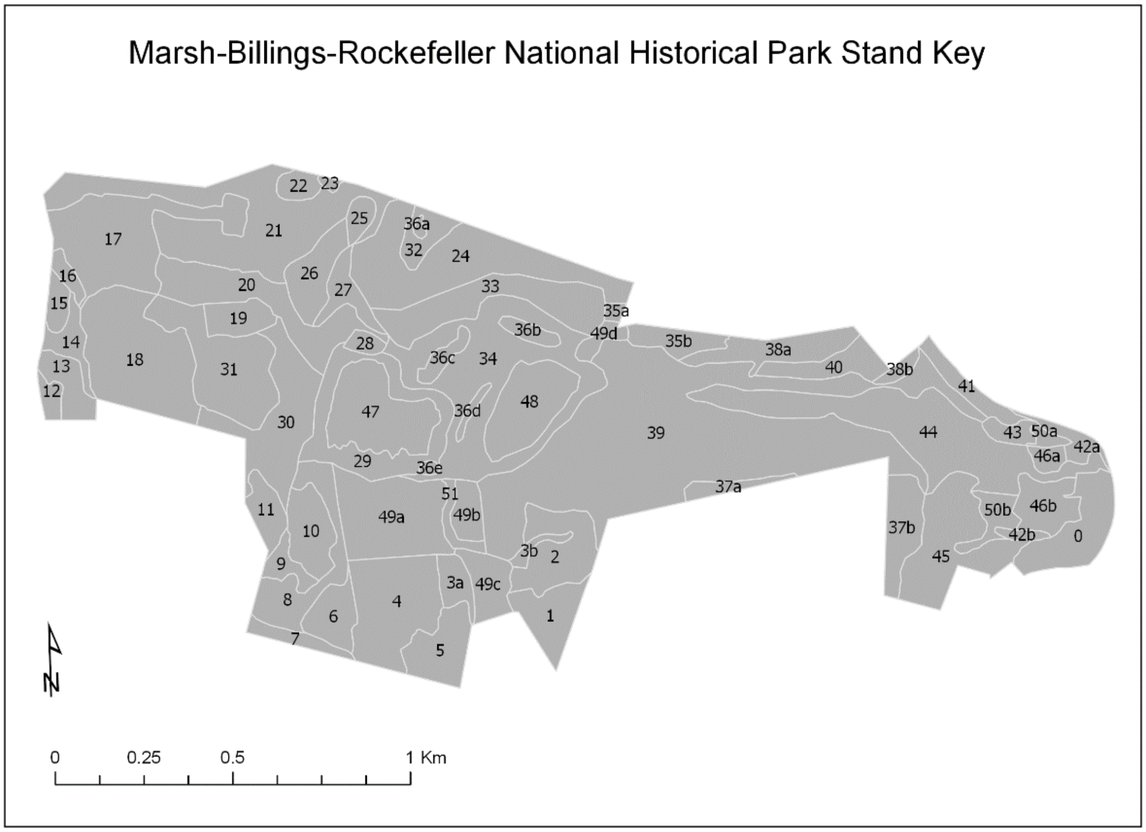


Figure 12. Stand key for Marsh-Billings-Rockefeller NHP (corresponds with Appendix A tables).

Discussion

The main goal of this spatial analysis was to help managers prioritize stand management based on estimated susceptibility to non-native pests and pathogens, and the maps above provide a perspective on management priorities based on proportion of host tree basal area. Using basal area as the metric for susceptibility highlights areas of the park that may experience the most impact after the introduction of an invasive organism, and this may be especially useful for species with more than one host, such as Asian longhorned beetle, gypsy moth, spotted lanternfly, and winter moth. For example, stand 30 appears particularly susceptible to winter moth, spotted lanternfly, gypsy moth, and Asian longhorned beetle compared to other stands in the park because over 80% of its overstory composition consists of host species, mainly sugar maple (*Acer saccharum)* and white ash (*Fraxinus americana)* (Fig. 2, 5, 10, 11; Table A2).

However, considering life history and mortality rates is an important aspect of interpreting these maps—while gypsy moth may appear to have the highest impact on the park, its cyclical nature of attack and low level of healthy host mortality make it less of a potential threat than single-host species such as emerald ash borer and hemlock woolly adelgid. This map shows that gypsy moth could cause widespread mortality over repeated outbreaks if not treated successfully. This was one of the challenges that we experienced—life history and mortality rates vary greatly based on environment, and because most of these species have not yet reached Vermont, it is difficult to report on their effects quantitatively.

A few non-native species appear to have relatively minimal potential effect on the park. This includes beech bark disease; however, but this map does not reflect smaller stems in the understory (<10.2 cm dbh). Since Marsh-Billings-Rockefeller is in the 'Aftermath' forest stage of beach bark disease (Keeton, 2005), there are fewer large overstory beech remaining per stand. Oak wilt is also projected to have low levels of impact across most of the park because of the low number of red oaks (*Quercus rubra*). The rate of spread of oak wilt depends largely on the spatial arrangement of these oaks: if they are found in close proximity to each other, the disease may spread rapidly through the area. If red oaks are widely scattered, the disease spreads much more slowly.

Opportunities for future work

There are a number of opportunities for more detailed future work. A more sophisticated analysis could create a vulnerability index that includes more factors than basal area of host trees, such as forest health, age, landscape position, soil characteristics, rate of mortality during infestation, and rate of population growth and establishment after introduction. The most important additional factor for improved model accuracy is likely rate of mortality, but in the literature review, quantitative data that could be used in a model was scarce. More research may be needed.

This spatial analysis used the assumption of a constant rate of spread across all species. Further analyses could include customized species-specific rates of spread, but this may not be valuable due to the level of uncertainty in modelling range expansion. However, a constant rate of spread also assumes no boundaries to movement (such as landscape barriers and availability of host species), which may be accurate if functioning on the assumption of mostly human-assisted long-range spread. A more sophisticated model could consider these barriers.

APPENDIX A

Table A1. Raw values for each scenario in the final map matrix of pests, categorized by rate of spread and year. Values the sum of percent composition of host species susceptible to non-native pests and pathogens. The maximum value (3.76) is highlighted in gray.

STAND ID	1km_2025	1km_2035	1km_2050	5km_2025	5km_2035	5km_2050	20km_2025	20km_2035	20km_2050
1	0.91	0.91	0.91	0.91	1.33	1.75	1.33	1.75	2.08
10	0.8	0.8	0.8	0.8	1.85	2.7	1.85	2.7	3.15
11	0.93	0.93	0.93	0.93	1.69	2.38	1.69	2.38	2.84
12	0.2	0.2	0.2	0.2	0.6	1	0.6	1	1.2
13	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
14	0.5	0.5	0.5	0.5	1.65	2.45	1.65	2.45	2.9
15	0.65	0.65	0.65	0.65	1.05	1.45	1.05	1.45	1.85
16	0.85	0.85	0.85	0.85	0.93	1.01	0.93	1.01	1.01
17	0.96	0.96	0.96	0.96	1.87	1.92	1.87	1.92	1.97
18	0.87	0.87	0.87	0.87	1.19	1.41	1.19	1.41	1.49
19	0.88	0.88	0.88	0.88	2.2	3	2.2	3	3.42
2	1	1	1	1	1	1	1	1	1
20	0.53	0.53	0.53	0.53	1.9	2.8	1.9	2.8	3.23
21	1.3	1.3	1.3	1.3	2.27	2.77	2.27	2.77	3.09
22	0.94	0.94	0.94	0.94	1.17	1.34	1.17	1.34	1.45
23	0.38	0.38	0.38	0.38	0.51	0.64	0.51	0.64	0.77
24	1.18	1.18	1.18	1.18	2.05	3	2.05	3	3.69
25	1.09	1.09	1.09	1.09	1.83	2.4	1.83	2.4	2.93
26	0.91	0.91	0.91	0.91	1.7	1.73	1.7	1.73	1.73
27	0.33	0.33	0.33	0.33	0.58	0.83	0.58	0.83	1.08
28	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
29	0	0	0	0	0	0	0	0	0
30	0.83	0.83	0.83	0.83	1.96	2.96	1.96	2.96	3.76
31	1.17	1.17	1.17	1.17	2.07	2.74	2.07	2.74	3.25
32	0.58	0.58	0.58	0.58	2	3	2	3	3.5
33	1.17	1.17	1.17	1.17	2	3	2	3	3.56
34	1.5	1.5	1.5	1.5	2.41	3	2.41	3	3.29
35a	0.95	0.95	0.95	0.95	1.23	1.46	1.23	1.46	1.64
35b	0.95	0.95	0.95	0.95	1.23	1.46	1.23	1.46	1.64
36a	0	0	0	0	0	0	0	0	0
36b	0	0	0	0	0	0	0	0	0
36c	0	0	0	0	0	0	0	0	0
36d	0	0	0	0	0	0	0	0	0
36e	0	0	0	0	0	0	0	0	0
37a	1.5	1.5	1.5	1.5	2.28	2.9	2.28	2.9	3.3
37b	1.5	1.5	1.5	1.5	2.28	2.9	2.28	2.9	3.3

STAND ID	1km_2025	1km_2035	1km_2050	5km_2025	5km_2035	5km_2050	20km_2025	20km_2035	20km_2050
38a	1.66	1.66	1.66	1.66	2.69	3	2.69	3	3.08
38b	1.66	1.66	1.66	1.66	2.69	3	2.69	3	3.08
39	1.325	1.325	1.325	1.325	2.23	2.745	2.23	2.745	3.035
3a	0.34	0.34	0.34	0.34	0.42	0.47	0.42	0.47	0.5
3b	0.34	0.34	0.34	0.34	0.42	0.47	0.42	0.47	0.5
4	0.9	0.9	0.9	0.9	1.75	1.86	1.75	1.86	1.97
40	1.22	1.22	1.22	1.22	2.17	2.66	2.17	2.66	2.92
41	1	1	1	1	1.39	1.78	1.39	1.78	2.17
42a	0.39	0.39	0.39	0.39	0.63	0.72	0.63	0.72	0.81
42b	0.39	0.39	0.39	0.39	0.63	0.72	0.63	0.72	0.81
43	1	1	1	1	1.57	2.07	1.57	2.07	2.57
44	1.31	1.31	1.31	1.31	2.13	3	2.13	3	3.23
45	0.92	0.92	0.92	0.92	1.27	1.49	1.27	1.49	1.67
46a	0.88	0.88	0.88	0.88	1.08	1.2	1.08	1.2	1.28
46b	0.44	0.44	0.44	0.44	0.72	0.86	0.72	0.86	0.97
47	0	0	0	0	0	0	0	0	0
48	0	0	0	0	0	0	0	0	0
49a	0	0	0	0	0	0	0	0	0
49b	0	0	0	0	0	0	0	0	0
49c	0	0	0	0	0	0	0	0	0
49d	0	0	0	0	0	0	0	0	0
5	0.78	0.78	0.78	0.78	1.78	2.56	1.78	2.56	3.12
50a	0	0	0	0	0	0	0	0	0
50b	0	0	0	0	0	0	0	0	0
51	0	0	0	0	0	0	0	0	0
6	0.9	0.9	0.9	0.9	1.13	1.26	1.13	1.26	1.39
7	1.94	1.94	1.94	1.94	2.94	2.96	2.94	2.96	2.98
8	0.83	0.83	0.83	0.83	1.58	2.19	1.58	2.19	2.66
9	0.71	0.71	0.71	0.71	1.88	2.76	1.88	2.76	3.35

Table A2. Raw values for each pest species, based on host tree relative basal area, used to make individual maps (fig. 2 – 12).

STAND ID	ALB	BBD	EAB	EHS	GM	HWA	OW	RPS	SLF	WM
1	0.33	0	0.09	0	0.91	0	0.09	0	0.33	0.33
10	0.85	0.1	0.3	0	0.7	0	0	0	0.45	0.75
11	0.69	0.08	0.15	0	0.85	0	0	0	0.46	0.61
12	0.2	0	0.2	0	0.2	0	0.2	0	0.2	0.2
13	0	0	0	0	0.07	0	0	0	0	0
14	0.8	0	0.35	0	0.5	0	0	0	0.45	0.8
15	0.4	0	0	0	0.65	0	0	0	0.4	0.4
16	0.08	0.08	0	0	0.77	0	0	0	0	0.08
17	0.05	0	0.04	0	0.96	0	0	0.82	0.05	0.05
18	0.22	0.02	0.12	0	0.85	0	0	0	0.08	0.2

STAND ID	ALB	BBD	EAB	EHS	GM	HWA	OW	RPS	SLF	WM
19	0.8	0	0.32	0.2	0.68	0.2	0	0	0.42	0.8
2	0	0	0	0	1	0	0	0	0	0
20	0.9	0	0.47	0	0.53	0	0	0	0.43	0.9
21	0.5	0.06	0.08	0.37	0.87	0.37	0	0.08	0.32	0.44
22	0.17	0.11	0.06	0	0.83	0	0	0	0.11	0.17
23	0.13	0	0	0	0.38	0	0	0	0.13	0.13
24	0.93	0.16	0.03	0.05	0.97	0.05	0.02	0	0.69	0.79
25	0.57	0	0.04	0.13	0.96	0.13	0	0	0.53	0.57
26	0.03	0	0.03	0.03	0.88	0.03	0	0.7	0	0.03
27	0.25	0	0	0	0.33	0	0	0	0.25	0.25
28	0	0	0	0	0.12	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0
30	0.98	0	0.15	0	0.83	0	0.02	0	0.8	0.98
31	0.67	0.04	0.04	0.19	0.94	0.19	0	0	0.51	0.67
32	1	0	0.42	0	0.58	0	0	0	0.5	1
33	1	0.29	0.12	0	0.88	0	0	0	0.56	0.71
34	0.59	0.12	0.03	0.41	0.97	0.41	0	0	0.29	0.47
35a	0.19	0	0.05	0	0.95	0	0.04	0	0.18	0.23
35b	0.19	0	0.05	0	0.95	0	0.04	0	0.18	0.23
36a	0	0	0	0	0	0	0	0	0	0
36b	0	0	0	0	0	0	0	0	0	0
36c	0	0	0	0	0	0	0	0	0	0
36d	0	0	0	0	0	0	0	0	0	0
36e	0	0	0	0	0	0	0	0	0	0
37a	0.22	0.2	0.02	0.34	0.96	0.34	0.4	0	0.4	0.42
37b	0.22	0.2	0.02	0.34	0.96	0.34	0.4	0	0.4	0.42
38a	0.31	0	0.03	0.69	0.97	0.69	0	0	0.08	0.31
38b	0.31	0	0.03	0.69	0.97	0.69	0	0	0.08	0.31
39	0.48	0.08	0.07	0.4	0.845	0.4	0.035	0	0.29	0.435
3a	0.05	0	0.03	0	0.34	0	0	0	0.03	0.05
3b	0.05	0	0.03	0	0.34	0	0	0	0.03	0.05
4	0.11	0	0	0	0.9	0	0	0.74	0.11	0.11
40	0.49	0	0.12	0.34	0.88	0.34	0	0	0.26	0.49
41	0.39	0	0	0	1	0	0	0	0.39	0.39
42a	0.09	0	0	0.15	0.24	0.15	0	0	0.09	0.09
42b	0.09	0	0	0.15	0.24	0.15	0	0	0.09	0.09
43	0.5	0	0	0.07	0.93	0.07	0	0	0.5	0.5
44	0.84	0.29	0.11	0.13	0.89	0.13	0.03	0	0.23	0.58
45	0.2	0	0.04	0.09	0.83	0.09	0.02	0	0.18	0.22
46a	0.12	0	0	0.08	0.8	0.08	0	0	0.08	0.12
46b	0.14	0	0.03	0.11	0.33	0.11	0	0	0.11	0.14
47	0	0	0	0	0	0	0	0	0	0
48	0	0	0	0	0	0	0	0	0	0

STAND ID	ALB	BBD	EAB	EHS	GM	HWA	OW	RPS	SLF	WM
49a	0	0	0	0	0	0	0	0	0	0
49b	0	0	0	0	0	0	0	0	0	0
49c	0	0	0	0	0	0	0	0	0	0
49d	0	0	0	0	0	0	0	0	0	0
5	0.67	0	0.22	0	0.78	0	0.11	0	0.56	0.78
50a	0	0	0	0	0	0	0	0	0	0
50b	0	0	0	0	0	0	0	0	0	0
51	0	0	0	0	0	0	0	0	0	0
6	0.13	0	0.1	0	0.9	0	0	0	0.13	0.13
7	0.02	0	0.02	0.96	0.98	0.96	0	0	0.02	0.02
8	0.61	0	0.14	0	0.83	0	0	0	0.47	0.61
9	0.88	0	0.29	0	0.71	0	0	0	0.59	0.88

Table A3. Host tree species present in Marsh-Billings-Rockefeller. Pest codes: ALB-Asian longhorned beetle; BBD-beech bark disease; EAB-emerald ash borer; EGM-European gypsy moth; HWA-hemlock woolly adelgid; WM-winter moth; OW-oak wilt; RPS-red pine scale; EHS-elongate hemlock scale; SLF-spotted lantern fly. Tree species codes are first three letters of the genus and species (e.g., ACERUB is *Acer rubrum*).

Pest code	ACERUB	ACESAC	BETALL	FAGGRA	FRAAME	LARDEC	OSTVIR	PICABI	PINRES	PINSTR	PINSYL	PRUSER	QUERUB	TILAME	TSUCAN	Sum
ALB	1	1	1	1	1							1		1		7
BBD				1												1
EAB					1											1
EGM	1	1	1	1		1	1	1	1	1	1	1	1	1	1	14
HWA															1	1
WM	1	1	1		1							1	1	1		7
OW													1			1
RPS									1							1
EHS								1							1	2
SLF	1	1										1	1			4
Sum of pests	4	4	3	3	3	1	1	2	2	1	1	4	4	3	3	

References

Keeton, W. S. (2005). *Forest Monitoring at the Marsh-Billings-Rockefeller National Historical Park.* https://doi.org/10.13140/2.1.2456.4808

Liebhold, A. M., McCullough, D. G., Blackburn, L. M., Frankel, S. J., Holle, B. von, & Aukema, J. E. (2013). A highly aggregated geographical distribution of forest pest invasions in the USA. *Diversity and Distributions*, *19*(9), 1208–1216. https://doi.org/10.1111/ddi.12112

Part 2: Non-native tree pest profiles

Introduction

The non-native tree pest profiles cover each of the 10 pest species included in the forest stand susceptibility assessment in the first part of this report. Each profile is intended to provide background information about the pest and management-relevant information on detection, control methods, and management scenarios.

This report is intended to provide managers with an easy to navigate summary of pest impacts and potential management responses. The information in the profiles was pulled from peer-reviewed scientific literature, federal agency reports and websites, and state-level reports and websites (a small number of key references can be found in Table 1).

Methods of control examined for each pest typically include biological, chemical, and mechanical options. The pest profiles below are not prescriptive as to which treatment to use but rather introduce available options and current understanding of application method, effectiveness, timing, life stage of pest, and non-target effects. All methods carry risks, both for the manager applying the treatment (e.g., spraying pesticides) and to the park resources (e.g., non-target pollinator species and host trees). Rapidly range-expanding tree pests, emerging control methods, and local conditions and context create many uncertainties that managers must navigate in the decision-making process. These pest profiles are intended to aid in the decision-making process for managers.

For many tree pest and pathogen species, biological and chemical controls are considered to be the most effective options for population control and eradication. However, it is important to emphasize that chemical and biological controls that are not specific to the target pest can have widespread non-target effects, and careful consideration of these effects is recommended before using any pest control. For example, Btk (Bacillus thuringiensis var. kurstaki), a group of bacteria recommended as a biological control agent against European gypsy moth, also targets native butterfly and moth species. Propiconazole is a systemic fungicide with broad use in agriculture that could potentially kill other beneficial soil fungi if used to control oak wilt. Research on biological controls is ongoing with an emphasis on identifying species with high host specificity. Managers are encouraged to consult with experts on the most up-to-date information on efficacy and risks of biological controls.

Neonicotinoids, such as imidacloprid and dinotefuran, are listed as a chemical management option for Asian longhorned beetle, beech bark disease, emerald ash borer, hemlock woolly adelgid, and spotted lanternfly. While the decline of insect populations has not been definitively linked to neonicotinoids, there is a growing body of evidence suggesting that existing levels of neonicotinoid pollution could lead to large-scale ecological impacts on a range of invertebrate species (Fairbrother et al., 2014, Lundin et al. 2015, Pisa et al., 2015). Furthermore, long-term low-level exposure to neonicotinoids could also impact invertebrate populations (Wood & Goulson, 2017).

Table 1. Key references, websites, and authorities on non-native tree pests and diseases. Pest abbreviations are ALB: Asian longhorned beetle; BBD: beech bark disease ; EAB: emerald ash borer; EGM: European gypsy moth; EHS: elongate hemlock scale; HWA: hemlock woolly adelgid; OW: oak wilt; RPS: red pine scale; SLF: spotted lantern fly; WM: winter moth.

Pest(s)	Authors	Title	Notes	Link
All	Contact: AFPE specialist Laura Blackburn	Alien Forest Pest Explorer	This site has range maps for 74 species of forest insects and 15 species of forest pathogens. Currently being ported to ESRI story map format.	https://www.nrs.fs.fed.us/tools/afpe/
All	Forest Ecosystem Monitoring Cooperative (FEMC)	Forest Ecosystem Monitoring Cooperative Long-Term Monitoring Update	The FEMC releases reports on long-term forest trends, including forest health and invasive species in Vermont and throughout the Northeast region	https://www.uvm.edu/femc/products/reports
ALB, BBD, EAB, EGM, HWA, SLF	-	USDA National Invasive Species Information Center - Terrestrial Invasives	Collection of links and up-to-date sources	https://www.invasivespeciesinfo.gov/terrestrial-invasives
ALB, EAB, EGM, HWA, OW	-	Centre for Agriculture and Bioscience International (CABI) Invasive Species Compendium	Non-profit international compendium of invasive species; only 5 species in this report have full datasheets, but search results also include papers for other species	https://www.cabi.org/isc/
ALB	Meng et al. 2015	Asian Longhorned Beetle (Coleoptera: Cerambycidae), an Introduced Pest of Maple and Other Hardwood Trees in North America and Europe	Review of management methods and recommendations	https://academic.oup.com/jipm/article/6/1/4/788453

Pest(s)	Authors	Title	Notes	Link
ALB	Dodds and Orwig 2011	An invasive urban forest pest invades natural environments — Asian longhorned beetle in northeastern US hardwood forests	Documenting potential impacts on northeastern forests based on the infestation in Worcester, MA	https://www.nrcresearchpress.com/doi/full/10.1139/x11-097#.XywfFyhKiUl
BBD	McCullough et al. 2005	Biology and Management of Beech Bark Disease		https://www.canr.msu.edu/uploads/files/e2746.pdf
BBD	Cale et al. 2017	Beech bark disease in North America: Over a century of research revisited	Comprehensive report covering BBD history and management strategies	https://www.sciencedirect.com/science/article/abs/pii/S0378112717301470#
EHS	Rajotte 2017	Elongate hemlock scales	PennState and PennState Extension are both important resources for EHS information	https://extension.psu.edu/elongate-hemlock-scales
EAB	Cappaert et al. 2005	Emerald ash borer in North America: a research and regulatory challenge	An older article with comprehensive background information on EAB	https://www.fs.usda.gov/treesearch/pubs/13648
EAB	FHTET	Biology and Control of Emerald Ash Borer		https://www.fs.fed.us/foresthealth/technology/pdfs/FHTET-2014-09_Biology_Control_EAB.pdf
EAB	USDA Forest Service, Michigan State University	Emerald Ash Borer Information Network	Collaboration between USDA Forest Service and Michigan State University to provide up-to-date info on EAB	http://www.emeraldashborer.info/resources.php
HWA	New York State Hemlock Initiative	Website	Organization that compiles HWA research and management in New York State	https://blogs.cornell.edu/nyshemlockinitiative/
HWA	Limbu et al. 2018	Hemlock woolly adelgid (Hemiptera: Adelgidae): A non-native pest of hemlocks in eastern North America	Article describing combination of HWA control options	https://www.nrs.fs.fed.us/pubs/57510

Pest(s)	Authors	Title	Notes	Link
OW	Koch et al. 2010	A review of oak wilt management: A summary of treatment options and their efficacy		https://www.nrs.fs.fed.us/pubs/jrnl/2010/nrs_2010_koch-k_001.pdf
OW	Juzwik et al. 2011	Challenges and successes in managing oak wilt in the United States		https://apsjournals.apsnet.org/doi/pdf/10.1094/PDIS-12-10-0944
OW	USDA Forest Service	How to identify, prevent, and control oak wilt		https://www.fs.usda.gov/naspf/sites/default/files/publications/identify_prevent_and_control_oak_wilt_print.pdf
RPS	Maine Forest Service	Red pine scale	Brief Forest Service fact sheet	https://www.maine.gov/dacf/mfs/forest_health/insects/red_pine_scale.htm
RPS	McClure et al. 1983	World forestry: Control of pine bast scale in China	This older study of RPS in China describes potential management strategies.	https://academic.oup.com/jof/article-abstract/81/7/440/4647917?redirectedFrom=fulltext
SLF	PennState Extension	Spotted Lanternfly		https://extension.psu.edu/spotted-lanternfly
SLF	Pennsylvania Department of Agriculture	Spotted Lanternfly		https://www.agriculture.pa.gov/Plants_Land_Water/PlantIndustry/Entomology/spotted_lanternfly/Pages/default.aspx
WM	FHTET (Elkinton et al. 2015)	Biology, spread, and biological control of winter moth in the eastern United States		https://www.fs.usda.gov/treesearch/pubs/50542
WM	O'Donnell 2015	The relationship between the winter moth and its host plants in coastal Maine		https://digitalcommons.library.umaine.edu/etd/2338/

To assess the range of intensities of management response, three potential management scenarios were created. In the 'do nothing' scenario, no management actions, beyond monitoring, are carried out. The 'single-tree protection' scenario includes management options to protect individual trees, e.g., culturally significant landscape trees or wildlife habitat trees. Finally, the 'stand-level protection' assesses options for protecting large stands of the host tree species for each pest.

Each profile uses the following structure of sections:

COMMON NAME
Latin name

Background
 Current range
 Host trees
 Historical impact
 Life history
 (Dispersal)

Detection
 Signs and symptoms
  >Sub-heading
 Monitoring
  >Sub-heading

Methods of control
 (*Preventive actions)*
  >Sub-heading

 Biological
  >Sub-heading

 Chemical
  >Sub-heading

 Mechanical
  >Sub-heading

 Resistance

 Silvicultural

 Etc. in alphabetical order

Management scenarios
 'Do nothing'
 Single-tree protection
 Stand-level protection

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Asian longhorned beetle

Anoplophora glabripennis

Background

Asian longhorned beetle (ALB) is a significant threat to hardwood trees in North America. It has the potential to destroy millions of acres of hardwoods and could be more destructive than Dutch elm disease, chestnut blight, and gypsy moth combined if left unchecked (U.S. Department of Agriculture, Animal and Plant Health Inspection Service [USDA-APHIS], n.d.)). It is capable of destroying 30.3% of urban trees in the United States, worth $669 billion collectively (Meng, Hoover, & Keena, 2015).

Current range

ALB was first discovered in Brooklyn, New York in 1996. Since then, it has spread to other urban centers in New Jersey, Massachusetts, Ohio, and Illinois, but has since been successfully eradicated from Illinois and New Jersey. While models show that most of the eastern US is at risk, locations close to transportation corridors are especially vulnerable because of the insect's main vector of spread—movement of wood materials (Meng et al., 2015).

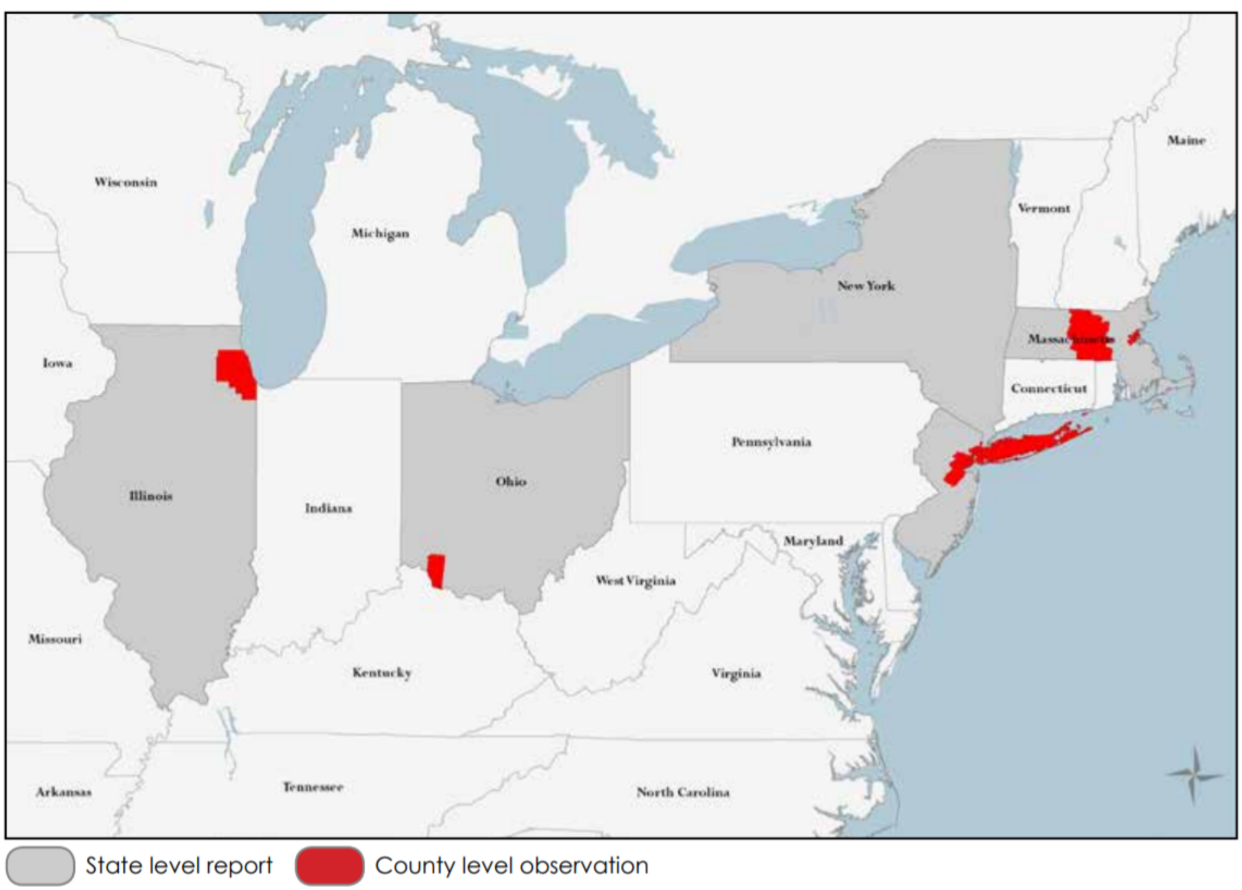

Figure 1. Asian longhorned beetle range; last updated March 25, 2019 (U.S. Department of Agriculture, Forest Service, Northern Research Station and Forest Health Protection [USDA-FS], 2019).

The states in which ALB is currently present have been able to mitigate the number of active infestations (e.g. the Boston population was eradicated in May 2014) (USDA-APHIS, 2018a). The closest active ALB infestation to MABI is in Worcester, MA and covers 110 square miles as of 2015 (Meng et al., 2015; USDA-APHIS, 2018a). Other active populations are found in Ohio and New York (USDA-APHIS, n.d.). While ALB has not spread beyond New York City, 137 square miles are regulated for ALB in New York (USDA-APHIS, 2017). ALB was first detected in Ohio in 2011, and 57 square miles are regulated across multiple locations in Clermont County (USDA-APHIS, 2018b).

Host trees
ALB feeds on over 100 tree species across the world, but it prefers maples*,* poplars*,* willows*,* and elms*.* In the US, it has also been known to attack buckeyes and birches.(Meng et al., 2015; USDA-APHIS, n.d.)).

The following is an extended list of native host genera (Meng et al., 2015):

Latin name	Common name
Acer	Maple
Aesculus	Buckeye and horse chestnut
Betula	Birch
Carpinus	Hornbeam
Carya	Hickory
Crataegus	Hawthorn
Fagus	Beech
Fraxinus	Ash
Malus	Apple
Platanus	Sycamore
Populus	Poplar
Prunus	Cherry
Salix	Willow
Sorbus	Mountain-ash
Tilia	Linden, basswood
Ulmus	Elm

Historical impact
Although ALB exists in the forests of eastern China, there has been no significant mortality (Culin, 2017). Significant numbers of trees in western China began to die in the 1980's when ALB was first reported outside of its native range. This occurred following the large-scale planting of poplar trees in China beginning in the 1960's, part of a program intended to prevent soil erosion, slow desertification, enhance urban spaces, and increase pulpwood production. Since poplars are a preferred host of ALB, this dramatic increase in preferred host trees spurred the population growth of ALB in western China (Culin, 2017).

In 1992, ALB was first detected on the east coast of North America in both American and Canadian ports, but it was eradicated before it could become established (Culin, 2017). The first established population was found in New York City in 1996. Since its discovery in the United

States, eradication efforts have cost the US more than $373 million and more than 110,000 trees have been removed leading up to 2010 (Culin, 2017).

Life history
Adults are relatively visible due to their size and coloring. They are 0.75-1.5 in. (1.9-3.8 cm) long with antennae longer than the length of their bodies, and have shiny black bodies speckled with white spots and long striped antennae (fig. 1) (USDA-APHIS, n.d.).

Figure 2. Asian longhorned beetle adult. *Photo credit: Joe Boggs, The Ohio State University.*

The following life history information is from Meng et al. (2015). In summer/early fall, adult females chew under bark and make oviposition pits in the phloem of host trees. Each oviposition pit receives a single egg. Egg development is highly dependent on temperature, with the highest percentage of egg hatch occurring at 25°C. Egg hatch may be delayed until the following year if eggs are laid too late and experience temperatures above or below the optimum. ALB is most vulnerable during this stage and experiences the most mortality.

Once larvae emerge, they require 1-2 years of development before pupating. During this time, larvae feed extensively on sapwood and heartwood and can cause significant decreases to diameter and height growth of host trees. Like egg hatch, adult emergence is also dependent on temperature and can take up to two months to occur. Peak emergence in New York is between late June and late July, similar to the timing in China. Determining how the timing of emergence would compare in Vermont requires further research. Once adults emerge, they spend most of their time resting and usually reinfest the tree on which they hatched instead of flying to find a new host. Adults feed on the bark of fine twigs. They are least active during the early morning and late afternoon.

Dispersal

Multiple studies have been conducted on the dispersal abilities of ALB (Meng et al., 2015). The most recent study that measured the flight of released ALB showed that while 98% of recaptured beetles traveled within 920 m of the release point, maximum dispersal potential for males and females was 2,394 m and 2,644 m, respectively). To capture this dispersal ability, USDA APHIS requires quarantine boundaries to be placed 2,400 m from infected trees (Meng et al., 2015).

Detection

Signs and symptoms

Because an Asian longhorned beetle spends most of its development inside of its host tree, detection of low density populations is challenging (Ric et al., 2007). A single sign or symptom is often not a reliable way to detect all infested trees. The following is a list of possible signs and symptoms. A collection of high-quality diverse images of each sign and symptom is available in the training guide ‘Asian longhorned beetle injury’ (Ric et al., 2007). It is highly recommended to view these as they show signs and symptoms as they vary in appearance over time and on different tree genera.

>Signs

>>External signs

- Oviposition pit
- Frass
- Hollow bark
- Exposed feeding gallery
- Exit (emergence) hole
- Adult feeding

>>Internal signs

- Feeding gallery under bark
- Tunnel in wood

>Symptoms

- Oviposition stain
- Crack in bark
- Missing bark
- Foamy or frothy sap
- Callus tissue around injuries
- Branch dieback
- Tree death

Monitoring

Because ALB larvae can take up to two years to pupate, early detection of an infestation is often difficult. This is compounded by early infestations beginning in the higher branches of a tree—adults lay eggs on the lower trunk once the tree is heavily infested (Meng et al., 2015). While early detection methods do not currently exist, there is a strong need for their development. The active infestation in Worcester, MA was not discovered until 8-10 years after ALB had become established and now spans 110 square miles. It is crucial to detect ALB early to eradicate it (Meng et al., 2015).

>Person surveys

Person surveys are the most common method of survey for ALB. Surveyors use binoculars to look for signs of ALB in all stems greater than 2.5 cm. The detection accuracy of ground surveys is 30%. Tree climbers can detect ALB with higher accuracy (60-75%), but this accuracy comes at a higher labor cost and takes more time to complete. In urban areas, hydraulic lifts can be used (Meng et al., 2015).

>Traps

Traps have also shown success in monitoring ALB populations. Studies have shown that the most successful traps for catching female ALB were those baited with both male-produced pheromones and a plant kairomone mixture (rather than just using pheromones or kairomones alone) (Meng et al., 2015).

>Acoustic

Acoustic detection was investigated, and although sensors are capable of detecting ALB, they must be attached to each individual tree and the recordings must be identified with specialized software (Meng et al., 2015).

>Dogs

Trained sniffer dogs were able to detect EAB frass 80-90% of the time, but it is unclear how accessible this option is (Meng et al., 2015).

Methods of control

Summary of control options

The most important aspects of ALB eradication are:

1). Early detection of infestation

- Ground and tree-climbing surveys
- Lure and trap combination

2). Killing beetles in infested trees

- Control options are limited beyond mechanical control (removing infested trees).
- Biological control:
    - Predators and parasitoids are unlikely to be approved for release in US.
    - More research is needed on application methods of entomopathogenic fungi.
- Chemical control:

- Use of systemic generalist insecticides and potential harm to non-target organisms is widely debated. Ability of systemic insecticides to spread throughout the entire tree and kill target insects is in question.
- Widespread chemical treatments are likely to be prohibitively expensive.

3). Preventing spread of beetles
- The best current option is to harvest an infested tree before adults can emerge.
- Harvested trees should be completely removed from the site and chipped or burned.

Control methods for ALB are currently very limited, due to either inadequate effectiveness or lack of feasibility to apply in a field setting (Table 1). As described in the introduction, all pest control methods may have side effects that need to be considered in the decision-making process.

Table 1. Summary of control methods for Asian longhorned beetle.

Category	Treatment	Application method	Effectiveness	Timing	Life stage	Non-target effects
Biological	Biological control agents have been identified, but are not promising candidates for eradication.					
Chemical	Unrealistic for forest applications due to high cost of treatment.					
Mechanical	Removing host species	-	Effective in urban areas.	-	All	-
Mechanical	Trap trees	-	Limited to use in China. More research needed.	-	Larvae	-

Note: a hyphen signifies that either data was not readily available and more research is necessary, or the cell is not applicable to the treatment.

The following information on methods of control is based on Meng et al. (2015).

Preventive actions
Public outreach is still an important method of prevention to limit movement of infested wood because many ALB detections have been discovered by members of the public.

Biological
Biological control is typically more environmentally safe than using pesticides. However, it is not the preferred option because the goal of ALB management in North America is eradication, not population control. Furthermore, the current biological control options are either unfit for use in the US, ineffective, or do not currently have a viable method of application.

>Entomopathogens
None of the entomopathogens evaluated have shown promising results for release in North America. There is still some possibility in using the fungus, *Metarhizium brunneum*, as it slightly

decreases adult beetle survival, but it is unlikely to be highly effective in high temperature and low humidity environments. *Bacillus thuringiensis* was ineffective against ALB when ingested.

>Nematodes
Of the nematodes tested, only *Steinernema feltiae* and *Steinernema carpocapsae* were effective. However, effectiveness was limited as they only affected mid- to late-instars and there is currently no method of application for infested trees.

>Predators and parasitoids
The non-native predators and parasitoids investigated were unfit for use in the US because of their wide range of hosts, including honeybees. Ongoing studies are attempting to identify effectiveness of other options. Woodpeckers may provide some control, but not at a level high enough to eradicate ALB on their own.

Chemical
While imidacloprid and other neonicotinoids have been shown to be effective against ALB, they are slow to reach full potential in treated trees and harm non-target organisms like pollinators. Furthermore, a small percentage of beetles can escape the effects of imidacloprid, and with the high costs associated with treating trees to eradicate ALB, using large-scale imidacloprid treatments in natural forests is not considered financially feasible.

Mechanical
There is potential to use trap trees to lure adults and remove and destroy the host tree before eggs hatch and new adults emerge. However, these methods are limited to research presented in China, so it is unclear which species should be used as trap trees. In the eastern US, maple may be an option.

Eradication in urban areas has been achieved by removing all potential host trees from an area. Harvested trees must be disposed of properly, whether by chipping or burning, to ensure that ALB cannot develop further within the infested tree.

Resistance
If planting new species is a desired goal, certain species are better options for replanting in the US than others. A full list was compiled by the U.S. Forest Service in 2014. However, the link provided is now broken and the original PDF cannot be located (U.S. Department of Agriculture, Forest Service [USDA-FS], 2014).

Management Scenarios

'Do Nothing'
The majority of ALB infestations are in urban forests, so it is difficult to predict its behavior in natural forests. When ALB was detected in Worcester, MA in 2008, it was found in small forested stands adjacent to urban areas. Researchers took this unique opportunity to investigate stand conditions, host selection, and impact on tree growth, and the results of the study offer an important insight into the behavior of ALB (Dodds & Orwig, 2011).

Two closed-canopy forests infested with ALB were sampled between the years 2008 and 2010. In the stand that contained three maple host species, it was found that red maple was infested with ALB more often than sugar and Norway maple (Dodds & Orwig, 2011). This contrasts with laboratory studies in which sugar maple and Norway maple were preferred (Morewood, Neiner, McNeil, Sellmer, & Hoover, 2003; Smith, Bancroft, & Tropp, 2002). As a result, host choice of ALB may not depend primarily on species. Red maple was more abundant in codominant and dominant size classes in the study stand, suggesting that beetles may be attracted to larger trees (Dodds & Orwig, 2011). ALB also dispersed readily throughout the stand and did not remain at edges as previously suggested (Williams, Lee, & Kim, 2004). This indicates that it may continue to spread throughout northeastern forests if not eradicated.

Furthermore, Dodds and Orwig (2011) suggest that ALB may not kill trees as quickly as expected. ALB had existed in the stands for at least 10 years, but there are no signs suggesting that ALB was the primary factor in tree mortality (Dodds & Orwig, 2011). Impact on diameter growth of infested trees in both stands was minimal. ALB may also persist longer in a stand before severe stand decline occurs. However, it is difficult to measure population density of ALB accurately—even presence/absence tree climber surveys can miss infested trees. In addition,

If ALB invades Marsh-Billings-Rockefeller NHP, it will likely decrease the vigor of host trees (especially maples) over decades. Unless an alternative management method is developed, the damage it does can only be mitigated by eradication.

Single-tree protection
There is currently no way to eliminate ALB from an individual tree without also killing the tree. Infested trees that are harvested must be removed from the site and properly treated to prevent further spread of ALB (e.g. chipping or burning).

Stand-level protection
Stand-level control may be possible through complete eradication of ALB. Infestations have successfully been eradicated from urban forests, but minimal information exists on eradication from natural forests. However, it is clear that early detection of an ALB infestation is key to successful eradication of the population—the Worcester infestation was discovered in 2008, 8-10 years after estimated introduction, and newly infested trees are still found within the county as of January 2018 (USDA-APHIS, 2018c).

For stand-level protection to be successful, public outreach must be implemented to raise awareness of signs and symptoms, potential host species, and status of the closest infestation. As a result, if ALB is found in Vermont, it can be detected quickly and swiftly eradicated. Upon detection, it is suggested that preferred hosts are removed from the infested area (in northeastern forests, this is mainly maple). However, as mentioned above, host removal has only been successful in urban areas. It is currently unknown if removing host trees from a natural forest could eradicate an ALB population. Furthermore, maple is a significant component of northeastern forests and its removal will result in drastic long-term changes in stand structure, and without its calcium-rich foliage, soil composition may shift depending on which species remain after the harvest. Decisions regarding the removal of host trees within a stand should carefully weigh the potential residual effects.

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Beech bark disease

Cryptococcus fagisuga
Neonectria spp.

Background

Beech bark disease (beech bark disease) is a deadly complex that attacks American beech (*Fagus americana*), consisting of two exotic organisms—beech scale (*Cryptococcus fagisuga*) and fungus species in the genus *Neonectria.* First introduced to North America in 1890, it quickly spread from Nova Scotia and was found throughout eastern Canada and Maine by the 1930s. By 1960, beech bark disease had reached most of New England and New York and has continued to steadily spread west (Keeton, 2005; McCullough, Heyd, O'Brien, & Marquette, 2005).

Current range

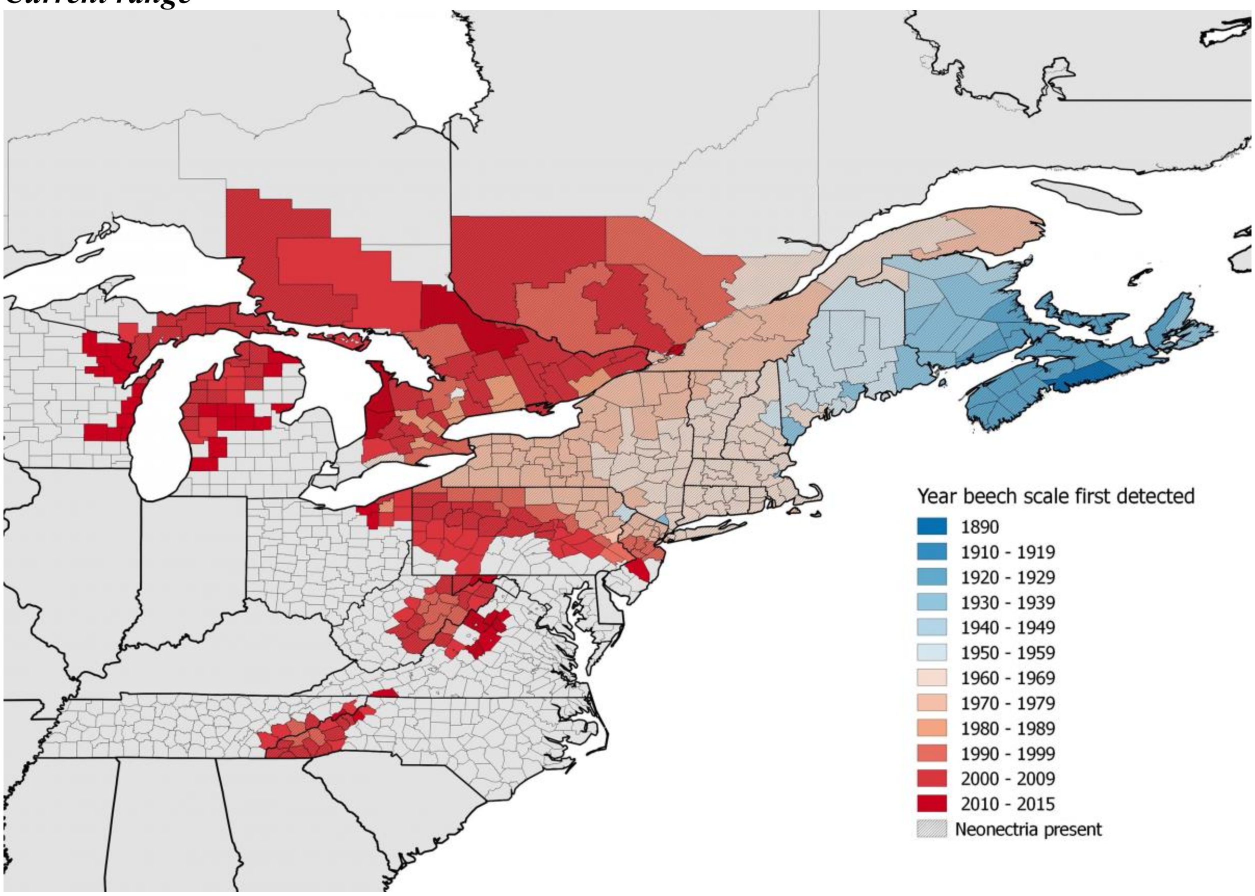

Figure 1. First detection of beech scale by county in the United States and Canada (from (Cale, Garrison-Johnston, Teale, & Castello, 2017)).

Host trees

American beech (*Fagus grandifolia*) and European beech (*Fagus sylvatica*) are affected by beech bark disease. Factors contributing to the likelihood of invasion by *Neonectria* are age (older trees are more likely to succumb), crown damage, severe drought, severe defoliation, and bark roughness. Beech scale prefers to invade trees with rough bark. Once *Neonectria* invasion begins, large trees and trees with heavy scale infestation are the most likely to die (McCullough et al., 2005).

Historical impact

Beech bark disease has caused widespread mortality and deterioration of beech across the northeastern United States and Canada. Its decimation of beech populations has redefined forest dynamics in the Northeast. Following an outbreak, McCullough et al. (2005) describes that while most beech are killed, those that are left behind either survive *Neonectria* infection with poor vigor or are resistant. In northern Pennsylvania, the first wave of beech bark disease killed about half of the beech larger than 10 in. (25.4 cm) DBH. The same phenomenon occurred in Maine, where beech bark disease has been present for over 70 years. The remaining large-diameter trees are severely damaged.

The functional loss of beech on the landscape has had both predictable and unexpected effects on the landscape that are still being revealed, exemplified in part by a 14-year study of a 250-year-old northern hardwood stand in the central Adirondack Mountains (McNulty & Masters, 2005). Large beech were lost from the forest over the course of the study, but beechnut production did not suffer as expected and actually increased during two different periods in a cyclical fashion. The number of medium-sized beech remained stable. Beech sapling abundance increased, but saplings displayed advanced symptoms of beech bark disease. Overall species richness and abundance in the understory layer increased, likely due to gaps created by dead canopy trees.

Life history

McCullough et al. (2005) provides a detailed description of the life history of beech scale and *Neonectria* fungi. Beech scale is a small, yellow, soft-bodied insect that precedes *Neonectria* invasion of beech. Adults are 0.5-1.0 mm in length and have no legs or wings. Their bodies are covered in white, woolly wax. Reproduction is asexual (through parthenogenesis) and one generation of scale matures per year. Adults lay 4-7 eggs mid-summer, which hatch from late summer to early winter. The immature scale nymphs (also known as crawlers) move around their host tree until they find a suitable location to feed, at which point they insert their mouthparts into the bark to feed on sap. After feeding enough, they molt into second-stage crawlers which overwinter and molt into adults the following spring.

Heavy scale infestation is followed by *Neonectria* fungi. There are three species that are known to be associated with beech scale in the beech bark disease complex—*Neonectria galligena* (a native pathogen), *Neonectria coccinea* var. *faginata* (an exotic pathogen from Europe), and *Neonectria ochroleuca* (found in Pennsylvania, West Virginia, and Ontario, Canada).

Beech bark disease invasion can be described in three stages: the Advancing Front, the Killing Front, and the Aftermath Forest (Cale & McNulty, 2017).

Advancing Front

Stands in the Advancing Front exhibit beech scale but have not yet been infested with the *Neonectria* fungus. Forests can survive in this stage for years depending on how far away they are from other areas affected by beech bark disease. Beech scale and the Advancing Front have been estimated to spread about 6 mi (1.6 km) per year.

Killing Front

Stands in the Killing Front contain high numbers of both beech scale and *Neonectria* infection, and experience high levels of mortality. Neonectria invasion of trees generally occurs 3-6 years after scale infestation.

Aftermath Forest

Stands in the Aftermath Forest have experienced the first wave of beech mortality, leaving behind residual trees with generally poor vigor that escaped the infestation through chance or through resistance. Beech scale numbers are lower than in previous stages, beech mortality is slowed, and understory beech prevalence increases.

Dispersal

Crawlers are able to disperse around the tree on which they hatched and wind and birds can sometimes move them to other trees. However, humans likely play a significant role in beech scale dispersal as new infestations in Michigan, West Virginia, and Ohio were located around human-frequented areas such as campgrounds (McCullough et al., 2005).

Detection

Signs and symptoms

Old branch stubs, the undersides of large branches, and other rough areas of bark are generally the first places on a tree to become infested with beech scale. Later, as the infestation grows, the whole trunk and branches may be covered with the white wool of the scale (McCullough et al., 2005).

Symptoms of *Neonectria* infection include tarry spots on the bark, with bright red perithecia (fruiting bodies) sometimes forming around the spots. These open cankers can become infected with other fungi, and this can lead to injury to the sapwood of the tree. If damage to a tree is great enough, *Neonectria* fungi can eventually girdle and kill it as more areas around the tree become infected. The tree is sometimes able to compartmentalize this damage if it is not extensive. A tree dying of *Neonectria* has a crown that appears "thin and raggedy" because its new leaves do not mature and turn yellow over the course of the summer (McCullough et al., 2005).

Monitoring

Beech bark disease has been present in Vermont since the 1960's (Figure 1).

Methods of control

According to analysis by Keeton (2005), MABI is in the "Aftermath Forest" stage of beech bark disease invasion, characterized by the presence of beech thickets and loss of large diameter beech. The control methods (Table 1) and management methods suggested are built on this assumption. As described in the introduction, all pest control methods may have side effects that need to be considered in the decision-making process.

Table 1. Summary of control methods for beech bark disease.

Category	Treatment	Application method	Effectiveness	Timing	Life stage	Non-target effects
Biological	Biological control agents have been identified, but are not promising candidates for stand-level control.					
Chemical	Horticultural oil and insecticidal soap	Spray	Low	November to March	Crawlers	During growing season
Chemical	Systemic insecticides (e.g. neonicotonoids) are not a feasible option for beech bark disease control in forests.					
Genetic resistance	Breeding trials are in progress.					
Mechanical	Unrealistic for forest applications due to labor-intensive nature and high costs.					
Silvicultural	Selection cut	-	May improve resistance in remaining beech.	Winter	All	-

Note: a hyphen signifies that either data was not readily available and more research is necessary, or the cell is not applicable to the treatment.

Biological

>Predators

Multiple mite genera are known to prey on beech scale, but most are generalists. The large red velvet mite *Allothrombium mitchelli* has been known to feed on beech scale at low to moderate densities (Cale et al., 2017). *Chilocorus stigma,* a ladybird beetle, was identified in Michigan as a predator of beech scale. It is the only non-mite predator to be examined as a potential biological control agent. However, it is not capable of controlling infestations at the stand level (Cale et al., 2017; McCullough et al., 2005).

>Fungi

Entomopathogenic fungi (*Beauveria bassiana* and *Lacanicillium muscarium*) have reduced beech scale populations in laboratory trials, but effects under field conditions remain unclear (Cale et al., 2017). A parasitic fungus, *Nematogonum ferrugineum*, parasitizes both species of fungus involved in beech bark disease and slows development of *Neonectria* spp. in the field, but it has minimal impact on development of beech bark disease (Cale et al., 2017).

Chemical

>Horticultural oils and insecticidal soaps

Oils and soaps can be used on both stages of crawlers to reduce overwintering. While they do not provide preventive protection, they can reduce the existing scale population on a tree. It is recommended to apply oils outside of the growing season (November through March) since contact with leaves may cause leaf burn (Hale, Wiggins, Lambdin, & Grant, 2006; Wisconsin

Department of Natural Resources [Wisconsin DNR], 2014). Horticultural oils and insecticidal soaps should be applied at temperatures 45-90 °F (7-32 °C) on clear, sunny days with low humidity. A high-pressure spray is often used to achieve the complete coverage necessary for maximum effectiveness. Scales should be checked for status to determine if trees should be sprayed a second time. Dead scales will appear "shriveled or flattened and darker" than live scales (Hale et al., 2006).

>Neonicotinoids
While neonicotinoid insecticides (e.g. imidacloprid, dinotefuran) have been shown to be effective against scale insects, their effects on beech scale specifically are unclear (Hale et al., 2006). As a result, there are concerns regarding non-target effects on native insects. Imidacloprid cannot control beech scale on its own via systemic treatment, but a 2013 preliminary study showed that annual imidacloprid injections combined with buprofezin spraying prevented beech scale infestation (Roberts, 2013). However, these treatments should exclude phosphoric acid, which led to infestations developing when the acid caused bark wounding to develop. Because of the high costs associated with applying chemical treatments, chemical control is not a feasible option for beech bark disease control in forest settings, whether applied to beech scale or *Neonectria* fungi. It is a better fit for high-value ornamental trees (Cale et al., 2017).

Mechanical
Mechanical methods for beech scale control are highly labor-intensive. It is possible to physically remove scale insects from a tree using a brush or a strong stream of water, but because of the high associated costs, it is only feasible for high-value ornamental or yard trees (Wisconsin DNR, 2014).

Resistance
Cale et al. (2017) reports that new propagation methods have expedited the rate at which seed-bearing, scale-resistant beech trees can be created, and field trials are in progress. It is unclear yet if planting resistant trees in aftermath forests can disrupt beech bark disease development in the stand. Scale-resistant plantings may be most effective in the early stages of beech bark disease invasion, before beech scale becomes strongly established.

Silvicultural
Salvaging damaged beech has been recommended by some to retain profit (McCullough et al., 2005). This argument is supported by the idea that damaged saplings may respond positively to canopy openings by growing more vigorously, but ultimately, saplings remain weak and grow slowly if they remain afflicted with beech bark disease. However, retaining large beech as wildlife trees or as a source of beech nuts is an option that should be considered in silvicultural prescriptions, especially when beech is a minor component (<20% of total basal area) of a stand (Wisconsin DNR, 2014).

If beech is a greater component of a stand (>20% of total basal area), large beech that are at least partially resistant to beech bark disease should be identified and retained. Resistance to beech bark disease can range from a tree hosting no scales to fewer scales, and the absence of *Neonectria* can also signify resistance (Wisconsin DNR, 2014). Trees with potential resistance to beech bark disease must be at least 9 in. (22.9 cm) DBH and near other trees that have been heavily infested without attracting scales (or attracting a relatively low number of scales) for over a year (McCullough et al., 2005). About 1-3% of American beech have resistance to the beech scale (Stephanson & Coe, 2017).

Long-term selection cuts of infested and infected trees may improve beech bark disease resistance in remaining trees, which was a successful management method in New Hampshire (Leak, 2006). However, thinning, salvage cutting, and removing diseased beech may not actually inhibit beech bark disease development or spread since it may not be associated with host density.

Root sprout management

Root sprouting can be managed with chemical and mechanical treatments. Glyphosate and triclopyr are effective herbicides at controlling understory beech for two growing seasons post-harvest. The application methods currently available are mist-blown, hack-and-squirt glyphosate, and triclopyr basal spray. While they are all effective, they range widely in cost and application rate (Table 2).

Table 2. Average chemical and labor costs for treatment of beech root sprouts in West Virginia (Kochenderfer, Kochenderfer, Warner, & Miller, 2004).

Treatment	Num. stems (stems/ac)	DBH class	Cost (dollars/ac)
Glyphosate injection	159	≥ 6 in. (15.2 cm)	39.28
Triclopyr basal spray	396	1.0-5.9 (2.5-15.0 cm)	80.32
Triclopyr basal spray	3,473	2 ft. tall to 0.9 in. (2.3 cm)	230.09

Stem girdling is effective but labor intensive. Brush saw treatments are a better management technique for thick beech understory. Clearing understory beech lets more light through to the understory with the goal of increasing species diversity and health. While harvesting large beech does not control beech regeneration, it was found to contribute to improved establishment of more desirable species like yellow birch (*Betula alleghaniensis*) and sugar maple (*Acer saccharum*) (Dracup & MacLean, 2018).

However, studies show that the connection between root sprouts and beech bark disease may not be as clear as previously thought. A study that compared stands affected and unaffected by beech bark disease, measuring both seedlings and root suckers, found no correlation between beech bark disease and suckers (Roy & Nolet, 2018). Beech seedling density was found to be higher in beech bark disease-affected stands, suggesting that beech bark disease may not necessarily trigger root sucker establishment in beech but may favor advance regeneration.

Management scenarios

'Do nothing'

Studies have shown that unlike other exotic species that damage forests, beech scale and *Neonectria* populations persist in an area even after the "killing front" stage of beech bark disease is over (Cale & McNulty, 2017). Cale and McNulty (2017) found that while beech affected by beech bark disease can stay alive for up to 28 years, the presence of beech bark disease still increases chances of mortality on an annual basis. A tree's chances of surviving are mainly driven by the initial severity of beech bark disease in the affected stand, regardless of how it developed over time. Unlike other insects and pathogens that cause destructive disturbances in forests, beech bark disease is able to persist and continually cause tree mortality in an aftermath forest, albeit to a lesser degree than at its peak. Usually, once a mortality event passes, the density of the insect/pathogen drops and mortality slows, decreasing the need for management. This not being the case for beech bark disease, it is important to continue to manage beech bark disease to mitigate the mortality cycle.

As aftermath forests develop, recent studies have shown that older trees with beech bark disease can spread the infection to new stems as small as 2 in. (5 cm) in diameter (Cale et al., 2017). This suggests that aftermath forests may experience a second wave of mortality as younger trees mature, though it is currently unclear how these secondary killing fronts may function. They are predicted to be more "locally eruptive" in contrast with the primary killing front that functioned along a leading edge (Cale et al., 2017). If future management decisions do not consider this, stands may experience increased beech mortality.

The interaction of beech bark disease with climate change is another important consideration. The warmer temperatures and increased precipitation events that will come with climate change will favor the growth and spread of beech bark disease. This additional threat to the survival of American beech may complicate the past century of selection for beech bark disease resistance (Stephanson & Coe, 2017).

If no actions are taken to control beech bark disease in Marsh-Billings-Rockefeller, it will persist in the forest and infect healthy beech in the future.

Single-tree protection
The most reliable method of interrupting beech bark disease complex establishment is the physical removal of beech scale from a tree. As mentioned above, manual removal can be accomplished with a high-pressure hose or a brush (Wisconsin DNR, 2014). A high-pressure hose can also be used to apply horticultural oil or insecticidal soap to the tree (see chemical control). Both methods are labor-intensive and must be reapplied at least annually. Since insecticides and physical removal only address beech scale, their effectiveness in controlling beech bark disease in MABI is limited due to 1) accessibility issues in bringing large equipment into the forest, and 2) MABI being in the latest stage of beech bark disease infection. As a result, beech scale control may not be an appropriate management technique for beech bark disease in aftermath forests (Cale et al., 2017).

Stand-level protection
At this point, there is no existing method of stand-level control against beech bark disease, especially after *Neonectria* is well-established in a stand (Hale et al., 2006). As mentioned above in 'Silvicultural control,' the only management option for Aftermath Forests is harvesting BBD-affected beech while retaining beech that seem at least partially resistant to encourage future resistance of the population. However, management approaches should consider a more holistic approach to beech bark disease control that includes stand factors beyond beech scale and

Neonectria spp. density, such as species composition, beech bark disease resistance, and stand developmental trajectories.

Missing information

Houston documented a significant knowledge gap in the area of beech bark disease management that has yet to be filled more than a decade later (Evans, Lucas, & Twery, 2005; Houston, 2005). The same issues that were mentioned over a decade ago about lack of options for control and the mystery of beech resistance to both the beech scale and *Neonectria* fungi remain unanswered by literature today. Based on the lack of recent research addressing management directly, significant progress has not been made since 2005, around the time when many other beech bark disease articles were published. The recent literature review of beech bark disease written by Cale et al. (2017) mentions the same mysteries as suggestions for future research.

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Elongate hemlock scale

Fiorinia externa

Background

Current range

Elongate hemlock scale is an invasive scale insect native to Japan and China that was first detected in Queens, New York in 1908 (Hoover, 2009). As of 2019, its main range is in southern New England and New York, but it has also been found in Maryland, New Jersey, Ohio, Pennsylvania, North Carolina, and Virginia (U.S. Department of Agriculture, Forest Service, Northern Research Station and Forest Health Protection [USDA-FS], 2019).

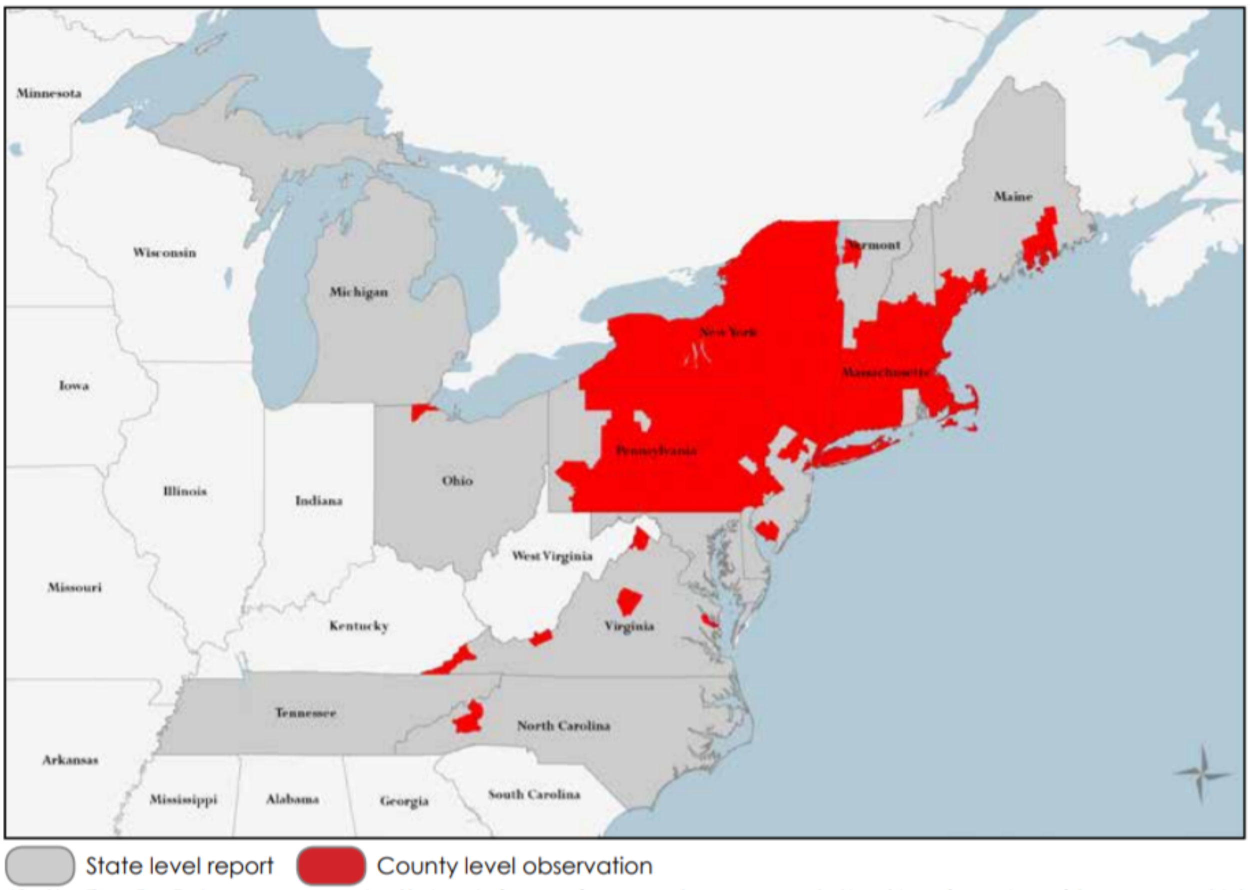

Figure 1. Elongate hemlock scale range (last updated March 25, 2019) (USDA-FS, 2019).

Host trees

The preferred hosts of elongate hemlock scale are eastern hemlock (*Tsuga canadensis*), Carolina hemlock (*Tsuga caroliniana*), northern Japanese hemlock (*Tsuga diversifolia*), fir (*Abies* spp.), and spruce (*Picea* spp.) (Hoover, 2009). As a result, it is often found with hemlock woolly adelgid. Other hosts include (*Cedrus* spp.), Douglas-fir (*Pseudotsuga menziesii*), pine (*Pinus* spp.), and yew (*Taxus* spp.) These less preferred hosts are usually attacked when in close proximity to preferred hosts (Hoover, 2009).

Historical impact
Despite being present in North America since 1908, there is very limited information available on elongate hemlock scale's historical impact on forests. Across its range, it has reduced the vigor of eastern and Carolina hemlock. Infestations first result in limb dieback and culminate in eventual death within ten years (U.S. Department of Agriculture, Forest Service [USDA-FS], 2007).

Life history
The number of generations of elongate hemlock scale per year depends on the region. In the Northeast, populations generally only have one generation and scales overwinter as eggs, while southern and Mid-Atlantic state populations can have overlapping generations in which fertilized females are able to overwinter (Rajotte, 2017).

The general life history pattern is as follows: in early spring, females lay eggs under a waxy covering and continue to lay eggs through early summer. A single female can lay up to 20 eggs during its lifetime. Like the eggs and crawlers, females are yellow and covered by a light yellow-brown to brown-orange waxy substance. Three to four weeks later, crawlers emerge from eggs and are dispersed by wind currents and foraging birds. Once crawlers find the underside of a needle, they attach to feed until they pass through all developmental stages (instars) to adulthood. Females have three instars before becoming adults, while males pass through five. Unlike females, the waxy covering of males is white. High scale populations can make the lower surface of infested needles appear completely white, often leading to confusion with hemlock woolly adelgid. Once winged males emerge and mate with females, females lay second-generation eggs 6-8 weeks after mating. These eggs overwinter until the next season, when the cycle begins anew (Hoover, 2009).

Dispersal
There are no accessible studies that directly address elongate hemlock scale dispersal. However, as it is functionally similar to hemlock woolly adelgid, dispersal mechanisms may be similar.

Detection

Signs and symptoms
Like other scale insects, elongate hemlock scale damages host plants by inserting its mouthparts into needles. Feeding on vital nutrients found in foliage reduces the vigor of the host and causes needles to develop yellow banding. Eventually, the crown appears thin as needles drop prematurely (Hoover, 2009). Limb dieback occurs and host trees tend to die within 10 years (USDA-FS, 2007).

Monitoring
Currently, the only method for early detection of elongate hemlock scale is person surveys (Rajotte, 2017). Surveyors should look for elongate hemlock scale on the underside of needles, where it can sometimes be found with hemlock woolly adelgid, Cryptomeria scale, and balsam woolly adelgid. If only a few infested trees are found, they should be removed and destroyed before the population can spread. However, if there are more than a few infested trees, a few should be tagged to track crawler emergence in the spring. Sticky cards placed on infested branches can trap adult males, whose emergence signals that females will soon be able to lay

eggs. Scouting of tagged trees should begin in mid-May to track the timing of crawler emergence. When adults are detected on trap cards, it can be reasonably estimated that crawlers will soon follow. Treatment is most effective when crawlers are abundant (Rajotte, 2017).

Methods of control

Because all developmental stages may be present during the growing season, management of elongate hemlock scale is a challenge (Hoover, 2009). Since hemlock woolly adelgid and elongate hemlock scale can often be found together on the same host trees, studies have compared their respective impacts on host trees and attempted to provide recommendations on management. Miller-Pierce et al. (2010) compared the effects of hemlock woolly adelgid and elongate hemlock scale on eastern hemlock saplings and found that hemlock woolly adelgid has a greater impact on hemlock over a 2-year period, significantly reducing the growth of saplings compared to elongate hemlock scale alone (Miller-Pierce, Orwig, & Preisser, 2010). Based on these results, the authors suggested focusing on hemlock woolly adelgid management in early stages of infestation.

However, other studies (Danoff-burg & Bird, 2002) recommend managing both species. A hemlock stand in New York was surveyed for levels of elongate hemlock scale and hemlock woolly adelgid infestation, and analyses showed that the abundance of both hemlock woolly adelgid and elongate hemlock scale was significantly correlated with early hemlock decline. In later, more advanced stages of decline, elongate hemlock scale abundance was significantly correlated with needle loss due to infestation, while hemlock woolly adelgid abundance was not. At a minimum, the authors suggest that both hemlock woolly adelgid and elongate hemlock scale contribute to the decline of hemlock at the field site and that managers should address both species in their work to slow hemlock decline (Danoff-burg & Bird, 2002).

Furthermore, though susceptibility to elongate hemlock scale varies significantly across its 14 coniferous host species, its abundance was positively correlated with foliar nitrogen and water content of young foliage, particularly in mid-June when nymphs are most abundant (McClure, 1980). Species with higher foliar nitrogen and water content are more susceptible to elongate hemlock scale infestation.

Unfortunately, the options for managing elongate hemlock scale are currently limited in comparison to hemlock woolly adelgid management (Table 1). As described in the introduction, all pest control methods may have side effects that need to be considered in the decision-making process.

Biological

While there are a few biological control agents that may provide some population control of elongate hemlock scale, they occur naturally and may not have high enough population numbers to control high elongate hemlock scale populations (Hoover, 2009; McClure, 2002). This includes a wasp parasitoid (*Aspidiotiphagus citrinus*), two lady beetles (*Chilocorus stigma* and *Microweisea misella*), and several lacewing species (Hoover, 2009; McClure, 2002). While the wasp parasitoid, *A. citrinus,* is extremely effective at controlling elongate hemlock scale populations in Japan, parasitism is too inconsistent to be effective in the northeastern US

(McClure, 2002). There are currently no recommendations for use of introduced species in biological control.

Table 1. Summary of control methods for elongate hemlock scale.

Category	Treatment	Application method	Effectiveness	Timing	Life stage	Non-target effects
Chemical	Dinotefuran	Foliar spray, basal bark spray	-	Late May to early June, retreat in early July	Crawlers	-
Chemical	Dinotefuran	Soil application	Ineffective	-	-	-

Note: a hyphen signifies that either data was not readily available and more research is necessary, or the cell is not applicable to the treatment.

Chemical

The best time to treat elongate hemlock scale with insecticide is when crawlers are most abundant in late May through early June (Rajotte, 2017). A second spray may be applied in early July if necessary. Applications may be repeated through mid-September for effective crawler management, but insecticides should not be used more than four times per season. The recommended application rate is 3-4 applications spaced over a 12-week period (Rajotte, 2017). However, it is unclear whether these recommendations are exclusive to nursery plants. Soil-injected systemic insecticides are not effective in managing elongate hemlock scale (Hoover 2009). Lower-rate horticultural oil (rate refers to the ratio of horticultural oil to water) can be applied during the growing season (Rajotte, 2017). The lower rate can prevent damage to new growth, or application can be delayed until new growth has hardened off. The exact recommended rate was not specified.

Because there are a few natural native predators (See “Biological” section below) that can provide some population control of elongate hemlock scale, use of broad-spectrum insecticides is discouraged (McClure, 2002; Rajotte, 2017).

Mechanical

Heavily infested trees should be removed and destroyed before bud break. To avoid transferring the scale to other trees during removal, trees can be wrapped in tarp or plastic as they are dragged. The lowest branches, which tend to be the most heavily infested, can also be pruned and removed, but this is typically only applicable to ornamental trees (Rajotte, 2017).

Silvicultural

There are no notable silvicultural recommendations for managing elongate hemlock scale. McClure notes that outbreaks intensify following other stressors that weaken hemlock, such as hemlock woolly adelgid infestations and drought (McClure, 2002). As a result, it is suggested that maintaining the health of hemlocks may mitigate the damage of elongate hemlock scale by preventing extreme population growth. Fertilization of soil should be avoided as nitrogen fertilization of hemlock actually increases elongate hemlock scale populations (Hoover, 2009).

Management scenarios

'Do nothing'

If elongate hemlock scale is not addressed, it is difficult to determine how it will affect eastern hemlock at Marsh-Billings-Rockefeller NHP due to a lack of consensus in the current literature. As mentioned above in 'Methods of control,' there are contrasting opinions on the need for elongate hemlock scale management. However, it is understood that elongate hemlock scale alone is less of a threat to hemlock than hemlock woolly adelgid. A study following eastern hemlocks over the course of five years found that hemlock regeneration and hemlock seedling density were inversely correlated with stand-level adelgid density (density of both hemlock woolly adelgid and elongate hemlock scale) (Preisser, Miller-Pierce, Vansant, & Orwig, 2011). However, there was no correlation between change in seedling density and stand-level density of elongate hemlock scale. This implies that hemlock forests may only experience long-term compositional changes if both hemlock woolly adelgid and elongate hemlock scale are present. This includes declining regeneration and decreased vigor of mature hemlocks (Hoover, 2009; Preisser et al., 2011; USDA-FS, 2007). In addition to compounding effects of hemlock woolly adelgid, elongate hemlock scale can also allow subsequent attack by other damaging organisms, such as the hemlock borer (*Melanophila fulvoguttata*) and *Armillaria* root rot (Hoover, 2009).

Single-tree protection

While broad-spectrum insecticides can be applied when crawlers are active, their use is discouraged to avoid unintentionally harming natural native predators of elongate hemlock scale and other non-target native species. If used improperly, the insecticides may fail to fully eliminate elongate hemlock scale while eliminating natural predators of elongate hemlock scale, causing elongate hemlock scale populations to quickly rebound (McClure, 2002).
Trees may be drenched with horticultural oil during early Spring when trees are dormant to control crawlers, but this is mainly a technique for ornamental plantings (McClure, 2002; Rajotte, 2017).

Stand-level protection

There is currently no accepted management technique for elongate hemlock scale control in forests (McClure, 2002). Maintaining the health of hemlock is recommended to reduce susceptibility to elongate hemlock scale infestation.

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Emerald ash borer

Agrilus planipennis

Background

In June 2002, a local extension agent in Detroit, Michigan submitted beetles he had reared from ash logs to the Michigan State University (MSU) Department of Entomology. With MSU entomologists unable to identify them past the genus *Agrilus*, they were sent to specialists in the US and Europe for further identification (Cappaert, McCullough, Poland, & Siegert, 2005). Eduard Jendek of Bratislava, Slovakia identified the mystery beetle as *A. planipennis*, a species native to northeastern China, Korea, Japan, Mongolia, Taiwan, and eastern Russia (Haack et al., 2002; Jendek, 1994).

Current range

Emerald ash borer has spread extensively since it was originally discovered in Michigan, and can now be found from Maine west to Minnesota and south to Arkansas and Georgia (Figure 1).

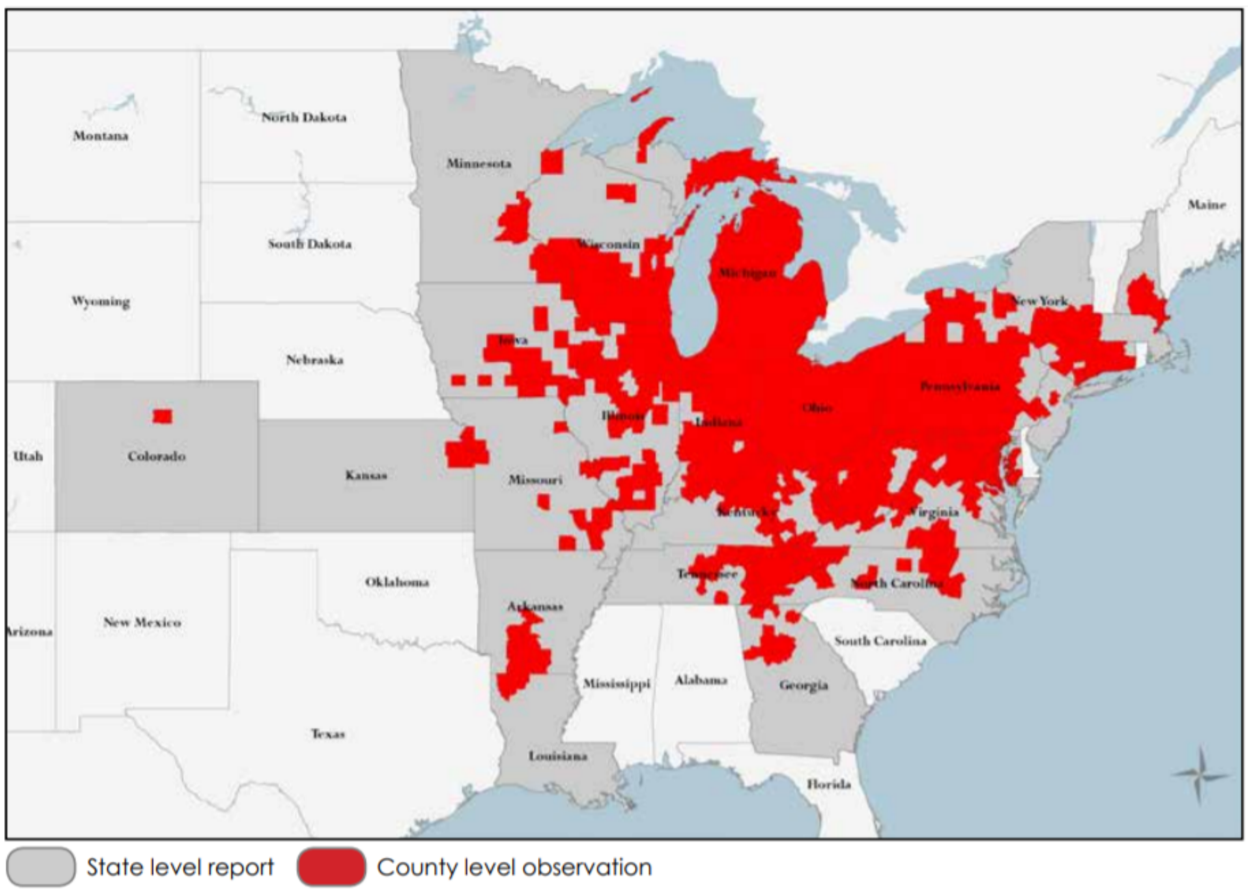

Figure 1. Emerald ash borer range (last updated March 25, 2019) (U.S. Department of Agriculture, Forest Service, Northern Research Station and Forest Health Protection [USDA-FS], 2019).

Host trees
All native *Fraxinus* species, including cultivars, are susceptible to emerald ash borer. However, where they occur in similar densities, green ash (*Fraxinus pennsylvanica)* has been attacked sooner than white ash (*Fraxinus americana)* (Cappaert et al., 2005). Where blue ash (*Fraxinus quadrangulata)* co-occurs with white ash, it is generally not attacked until white ash begins to succumb to emerald ash borer (Agius, McCullough, & Cappaert, 2005).

Other potential hosts have been studied with no indication of alternate hosts to ash. First instars may attempt to feed on the phloem of other species, such as black walnut (*Juglans nigra*) and Japanese tree lilac (*Syringa reticulata)*, but ultimately fail. Privet (*Ligustrum* spp.) allowed larvae to develop to their second instar in no-choice tests, but eventually died as phloem became too dry (Agius et al., 2005).

Diameter of trees does not appear to affect host selection at moderate-to-high densities as larval development can occur on stems and branches 0.8 – 60 in. (2 cm – 1.5 m) in diameter (Cappaert et al., 2005).

Historical impact
The ecological and economic impacts of emerald ash borer are projected to rival or exceed those of chestnut blight and Dutch elm disease (Herms, Stone, & Chatfield, 2004; Klooster et al., 2014). While wood-boring beetles tend to attack stressed trees (Muilenburg & Herms, 2012), emerald ash borer can kill healthy ash—both planted, residential ash that are cared for and naturally regenerated ash in forests. This has contributed to the decimation of ash across the eastern US. In the year following the discovery of emerald ash borer, 5-7 million infested ash trees were found in a six-county area of southeastern Michigan (Herms & McCullough, 2014).

Life history
Adult emergence of emerald ash borer is in mid- to late- May or early June depending on local conditions (Brown-Rytlewski & Wilson, 2005). Adults feed on foliage for 5-7 days before mating, and females feed for another 5-7 days before ovipositing (Bauer, Haack, Miller, Petrice, & Liu, 2004; Lyons & Jones, 2005). In laboratory settings, females lay 60-90 eggs (Lyons & Jones, 2005) which are laid individually under bark or in crevices. Adults are able to feed for another 3-6 weeks, the remainder of their life span (Cappaert et al., 2005), and are able to mate multiple times over the course of their lives (Bauer, Haack, Miller, Petrice et al., 2004; Lyons & Jones, 2005). Activity peaks in late June-early July and adults are rarely observed after early August (Cappaert et al., 2005).

Larvae emerge in late July-early August and begin a period of intensive feeding in ash phloem, creating galleries under bark and "scoring" outer xylem. By October-November, the larvae have passed through four instars and completed their feeding. In preparation for the winter, they excavate cells in sapwood and overwinter as pre-pupal larvae. Pupation begins in mid-April and continues into May. While most larvae develop within one year, there have been instances of delayed larval development in which larvae take 2 years to pupate. While it is unclear why exactly this occurs, it is thought that lower density populations may be one of the factors (Cappaert et al., 2005).

Dispersal
Flight ability of emerald ash borer adults is still being evaluated. They are highly capable of flying short distances and are able to fly several kilometers in lab conditions, but this may be a rare occurrence (Bauer, Haack, Miller, & Taylor, 2004; Taylor, Bauer, Miller, & Haack, 2005).

Despite the adults' ability to fly, the most likely agent for the long-range dispersal of emerald ash borer is human-assisted movement of wood materials (Cappaert et al., 2005).

Detection

Signs and symptoms
Detection of emerald ash borer is complicated by the fact that early attacks tend to occur in the canopy and move down the stem as colonization progresses, and on mature trees, exit holes are difficult to find amidst rough, furrowed bark. Furthermore, the symptoms of emerald ash borer can appear similar to those caused by ash yellows, a disease that affects the vascular system of ash and can cause substantial dieback and decline. In late stages, infestation is characterized by epicormic shoots, canopy dieback, and bark cracks over larval galleries (Cappaert et al., 2005). Larval galleries eventually girdle the tree, and once canopy decline is visible, trees tend to die within 2-4 years (Herms and McCullough 2013).

Monitoring
Early detection of emerald ash borer is difficult because external symptoms on trees are rarely visible when insect populations are at low density. Although emerald ash borer was first detected in 2002, dendrochronological evidence suggests that emerald ash borer was established in southeastern Michigan for at least 10 years before its discovery (Cappaert et al., 2005). Studies have shown that many non-native pests experience a lag phase lasting for several years after initial establishment until favorable conditions allow populations to increase rapidly (Crooks & Soulé, 1999; Shigesada & Kawasaki, 1997). This may have contributed to its ability to go undetected since its establishment.

As a result, successful monitoring efforts depend on the use of trap trees. Early studies show that stressed trees (i.e. trees that are girdled or treated with herbicide) hosted a marked increase of emerald ash borer—the number of adults and the density of larval galleries were significantly higher on stressed trees. After adults were attracted to a trap tree, the tree's bark was stripped to kill larvae before they could successfully pupate. While this is a very effective detection tool, particularly at the leading edge of emerald ash borer where population densities are low, it is very labor intensive and destructive (Cappaert et al., 2005; Hunt, Mastro, Lance, Reardon, & Parra, 2007; Rauscher, Mastro, Reardon, & Parra, 2005).

However, the discovery that the stress-induced volatiles of ash can be used to attract beetles led to another effective detection method—manufactured traps (Cappaert et al., 2005). While emerald ash borer adults do not produce long-range pheromones that could be used to bait traps, baiting traps with ash volatiles has been successful (Grant, Ryall, Lyons, & Abou-Zaid, 2010; Poland, Anulewicz, & McCullough, 2011). Emerald ash borer is also responsive to visual cues, depending on them to find suitable mates, and was found in early trials to be sensitive to specific wavelengths of red, violet, and green light. Purple hues were particularly attractive (Crook, Khrimian, Cossé, Fraser, & Mastro, 2012). Since 2008, sticky purple prism traps have been used to bait and capture emerald ash borer (Crook & Mastro, 2010). An alternative design consists of two purple prism traps baited with volatiles and is called a double-decker trap. Unlike the other traps, it can be placed in full sun near woodland edges to give beetles a more distinct point source (McCullough, Poland, Anulewicz, & Cappaert, 2009; Poland et al., 2011). Double-decker traps have been more effective at low densities, but both types are equally effective once populations are high (Marshall, Storer, Fraser, & Mastro, 2010; Poland et al., 2011).

Methods of control

Research on control methods for emerald ash borer is ongoing. Chemical treatments are currently most effective, while biological and mechanical controls have limited success (Table 1, 2). As described in the introduction, all pest control methods may have side effects that need to be considered in the decision-making process.

Table 1. Summary of emerald ash borer control methods.

Category	Treatment	Application method	Effectiveness	Timing	Life stage	Non-target effects
Biological	No promising biocontrol candidates have been identified.					
Chemical	Emamectin benzoate	Trunk injection	High (2-3 years)	April to September	Adults	-
Chemical	See Table 2 for other chemical treatments that are effective up to one year.					
Mechanical	Trap trees	Girdling ash	High	Spring	Larvae	-

Note: a hyphen signifies that either data was not readily available and more research is necessary, or the cell is not applicable to the treatment.

Biological

>North American natural enemies

North American enemies of emerald ash borer have been identified but no single enemy is a promising candidate for biological control. For example, native parasitoids, predators, and pathogenic fungi were identified on emerald ash borer, but their densities were too low to make a significant impact on populations observed (Cappaert et al., 2005; Liu et al., 2018). Woodpeckers have also been recorded preying on emerald ash borer in winter and early spring (Lindell, McCullough, Cappaert, Apostolou, & Roth, 2008), and while the population dynamics are still unclear, woodpeckers represent the single greatest mortality factor for emerald ash borer (Cappaert et al., 2005; Duan, Ulyshen, Bauer, Gould, & van Driesche, 2010). Parasitism by native wasps in the genus *Atanycolus* (primarily *A. cappaerti*) has been observed (Cappaert & McCullough, 2009; Marsh, Strazanac, & Laurusonis, 2018), with higher rates of parasitism found in areas with high densities of emerald ash borer (Duan, Bauer, Abell, & van Driesche, 2012).

>Classical biological control

Three species are currently being reared and released as biological control agents of emerald ash borer: *Oobius agrili,* an egg parasitoid; *Tetrastichus planipennisi*, a larval endoparasitoid; and *Spathius agrili*, a larval ectoparasitoid. However, there is not enough evidence to suggest that parasitoids are capable of controlling emerald ash borer populations and it is more likely that populations are controlled by host availability (Muilenburg & Herms, 2012). *Tetrastichus planipennisi* may have some success with young trees (Duan et al. 2012), but *O. agrili* and *S. agrili* have had limited establishment success overall (Duan et al., 2010; Duan et al., 2012). Lack of success in using parasitoids is supported by the fact that North American ash trees planted in China still experienced a high level of mortality due to emerald ash borer (Liu et al., 2018; Wei, Reardon, Wu, & Sun, 2004), suggesting that it's unlikely that introduced parasitoids will be successful in controlling high-density populations.

Chemical

Systemic insecticides can be applied as soil injections or drenches, injected into the base of the trunk, or sprayed on the basal 5' (1.5 m) of the trunk (Herms et al., 2009; Smitley, Doccola, & Cox, 2010). While most products provide up to one year of protection, emamectin benzoate can provide up to two years (see 'Emamectin benzoate' below) (Williamson & Liesch, 2019). However, research has shown that not all infested ash trees should be treated. Those that are in poor condition may be too expensive to treat and recover after a certain threshold—insecticide treatments were found to be significantly more effective on ash with less than 50% canopy thinning (Williamson & Liesch, 2019). It is recommended that trees with greater than 50% canopy thinning are removed and disposed of appropriately. Wood should be burned or chipped and dried properly to ensure that any remaining pests within the tree are killed.

Small trees that are less than 6 in. (15.24 cm) DBH are best treated with soil drenches or injections of imidacloprid (Williamson & Liesch, 2019). Treatment for larger trees can be preventive. Because larger trees can take up to two years of consecutive treatments before they are effectively protected, treatments can begin before the trees are infested.

Furthermore, timing of treatment can affect the success of the insecticide. Studies have shown that applying insecticides during spring has been more effective at control than treating during the fall (Williamson & Liesch, 2019).

>Emamectin benzoate

Emamectin benzoate has proven to be the most effective product in a range of insecticides including imidacloprid, azadirachtin, and dinotefuran. Trees treated with trunk-injected emamectin benzoate were protected for 2-3 years with near 100% control in multiple trials (Herms et al., 2010; McCullough & Mercader, 2012; McCullough, Poland, Anulewicz, Lewis, & Cappaert, 2011; Smitley et al., 2010). This treatment was 100% effective at killing emerald ash borer adults that fed on foliage from treated trees, reducing larval density by 99% (Poland, Ciaramitaro, & McCullough, 2016). However, these effects are limited to trees that are lightly to moderately infested—heavily infested trees generally declined, or died (Flower, Dalton, Knight, Brikha, & Gonzalez-Meler, 2015).

Table 2. Emerald ash borer insecticide treatments available to professionals (adapted from Williamson & Liesch, 2019).

Active Ingredient	Product(s)	Timing	Application Method
Acephate	ACE-Jet Acecap implants	Mid-May to mid-June	Trunk injection Trunk implant
Azadirachtin	AzaGuard, Treeazin	Early/mid-April to early September	Trunk injection
Bidrin	Inject-A-Cide B	Inject when infestation is evident	Trunk injection
Bifenthrin	Alpine, Onyx, OnyxPro	Apply prior to or just at the time of adult emergence. Multiple applications may be needed.	Preventative bark and foliage cover sprays
Cyfluthrin	Tempo		
Dinotefuran	Dinocide, Dinocide HP Safari, Transtect, Zylam	Late-April to late-May	Trunk injection Soil drench, trunk spray
Emamectin benzoate	ArborMectin, Boxer, Brandt enTREE EB, Tree-äge, Tree-äge G4, Tree-äge R10, TreeMec	April to September	Trunk injection
Imidacloprid	Merit 75 WP, Merit 75 WSP, Merit 2F, Xytect 2F, Xytect 75WSP, and others	Mid-April to late-May and/or early-September to mid-October	Soil injection or drench
	IMA-jet, IMA-jet 10, Imicide, Imicide HP, Pointer, Xytect 10%	Mid-April to mid-May	Trunk injection

Mechanical

Girdling trees to use as trap trees is not only an effective detection technique, but also a management option for reducing emerald ash borer populations. Trees can be girdled in the spring to attract adults, and then debarked before larvae can develop, though this technique is labor intensive and destructive (Hunt et al., 2007; McCullough, Poland, Anulewicz et al., 2009; McCullough, Poland, & Cappaert, 2009; Rauscher et al., 2005).

Silvicultural

Ash has experienced widespread and nearly complete mortality in study areas, seemingly regardless of site differences such as ash density, edaphic factors, stand health, and community composition (Klooster et al., 2014). This suggests that there is little opportunity to mitigate emerald ash borer damage with silvicultural practices (Knight, Brown, & Long, 2012; Smith, 2006). Nevertheless, harvesting ash to reduce available phloem for emerald ash borer, slow population growth, and provide economic benefits to landowners may be an option (Herms & McCullough, 2014).

Management scenarios

'Do nothing'

Increased mortality of ash in MABI will open up forest canopy gaps and allow light to reach understory vegetation. This provides opportunity for saplings to recruit into the new canopy space but may also favor invasive species establishment and expansion. With most MABI stands containing less than 15% ash, emerald ash borer infestation will likely create single-tree gaps across the park. Exceptions to this trend include stands 20 and 32, which both contain 40-50% ash. Losing ash in these stands will have a much greater impact on understory light availability and is likely to increase vulnerability to invasive species if they are present.

Because emerald ash borer was first detected less than 20 years ago, there is limited information available on long-term effects on ecosystem processes, but the following is known:

- Emerald ash borer can lead to tree mortality in as little as 2 years, and stand mortality in as little as 5 years (Flower et al., 2015).
- *Acer* and *Ulmus* respond positively to emerald ash borer disturbance (Flower et al., 2015).
- Widespread ash mortality causes reduced short-term regional forest productivity (Flower et al., 2015).
- Despite near 100% overstory ash mortality in areas heavily infested by emerald ash borer, ash seedlings and saplings have remained unaffected. In a Michigan study, ash regeneration was more abundant in upland forests than in lowland forests. New seedlings were less common than other size classes, but regeneration was sufficient to replenish overstory ash in upland forests. It remains unclear if ash will recover to pre-emerald ash borer levels (Kashian & Witter, 2011).

Single-tree protection

Trunk-injected emamectin benzoate is by far the most effective method of control for individual trees with emerald ash borer. (See 'Methods of control').

Stand-level protection

Integrated management efforts are not expected to eradicate emerald ash borer, but instead to provide time to plan a long-term approach and consider other options before reacting (Herms & McCullough, 2014). A pilot project called SLAM (SLow Ash Mortality) attempted to use a combination of chemical, mechanical, and silvicultural management tactics to slow emerald ash borer population growth: emamectin benzoate, debarking trap trees (McCullough, Poland, Anulewicz et al., 2009; McCullough, Poland, & Cappaert, 2009), and harvesting ash to reduce available phloem (Siegert, McCullough, Liebhold, & Telewski, 2007). This list was also the order of effectiveness from most to least at slowing emerald ash borer growth when each method was used in isolation (Mercader, Siegert, Liebhold, & McCullough, 2011a, 2011b). Insecticides are especially effective in residential areas where trees are readily accessible. However, even in forest settings, there is evidence that annually treating 20% of trees starting 4 years after emerald ash borer establishment could save 90% of trees after 10 years (Herms & McCullough, 2014). This is significantly less costly than having to remove and replace ash on the landscape and in residential areas.

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European gypsy moth

Lymantria dispar

Background

Current range

Gypsy moth is currently found across the east coast, from Maine to northern North Carolina, and west into Wisconsin (U.S. Department of Agriculture, Forest Service, Northern Research Station and Forest Health Protection [USDA-FS], 2019).

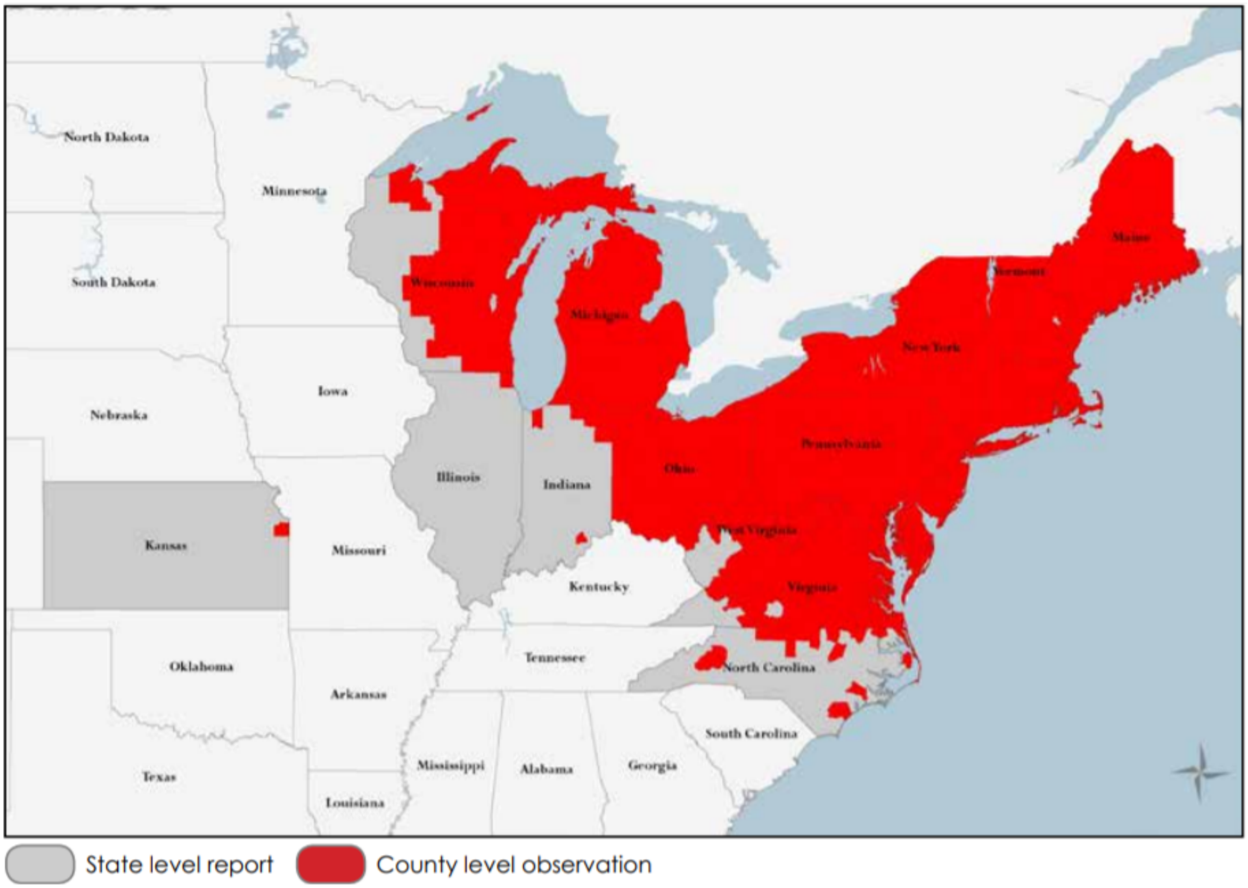

Figure 1. European gypsy moth range (last updated March 25, 2019) (USDA-FS, 2019).

Host trees

European gypsy moth has over 300 known host species and around 150 favored species. Softwoods like hemlock, pine, and spruce are less preferred as hosts than hardwoods, but are significantly more susceptible to gypsy moth damage because they cannot refoliate after early season defoliation like deciduous trees. A full list of host species was compiled by Bartlett Tree Experts (Fite, n.d.), but the main preferred species are oak (*Quercus* spp.), maple (*Acer* spp.), birch (*Betula* spp.), alder (*Alnus* spp.), and hawthorn (*Crataegus* spp.) (Forest Invasives Canada).

Historical impact

European gypsy moth was first introduced to North America in 1869 when it escaped from a home near Boston, Massachusetts (Hoover, 2000). By 1902, it had spread to the rest of New England, eastern New York, and New Jersey. Because it can survive in such a wide range of conditions, successfully feeding on over 300 species of trees and shrubs, it has been incredibly successful in North America (University of Wisconsin-Madison, Division of Extension [UW-Madison Extension]). Its cyclical heavy defoliation of hosts leads to increased host stress, invasion by other organisms, and eventual mortality of the host (Forest Invasives Canada; Hoover, 2000).

Life history

Eggs are the overwintering stage for European gypsy moth (Forest Invasives Canada; Mass Audubon, 2016). In May, larvae hatch from tan, hair-covered egg masses that are laid on trees and other nearby sheltered surfaces (including items such as cars, garden decor, and houses), and climb up to feed on fresh foliage. Larvae are easily identifiable by their distinct coloration—five pairs of blue spots followed by six pairs of red spots along the back. They are able to wind disperse until they find a suitable host tree by spinning silken threads, which older instars also use to descend to the ground and seek shelter during the day under loose bark or in leaf litter. Larvae climb back up into the canopy and continue to feed at night. As they feed, they grow and molt several times. Once larvae are about 1 in. (2.5 cm) in length, the defoliation caused by infestation is usually noticeable. By July, or about 40 days after hatching, larvae reach a length of 1.5-2.5 in. (3.81-6.35 cm) and begin to pupate. Adults emerge about two weeks later in early-to-mid-summer. In July and August, adult females have a window of two weeks to mate and lay eggs. They use pheromones to attract males because unlike their male counterparts, they are unable to fly. After mating, each female lays an egg mass containing 75 to 1,000 eggs (Forest Invasives Canada; Mass Audubon, 2016).

Dispersal

European gypsy moth has a few different methods of dispersal that have facilitated its rapid spread south and west of its original point of introduction. Male moths are capable of flying to disperse, but their ability to spread the population is limited since they must seek out females to reproduce successfully (Mass Audubon, 2016). Since females cannot fly, larvae rely on wind dispersal to reach host trees by ballooning on strands of silk. Furthermore, humans can unintentionally move egg masses to previously unaffected areas when females lay egg masses on cars, firewood, or other items left outdoors during an infestation.

Detection

Signs and symptoms

European gypsy moth infestations range in severity. Normal outbreak patterns are cyclical: there may be 2 years of light infestation with minimal damage, followed by 2 years of moderate-to-heavy infestation and the consequent population collapse (Hoover, 2000).

Light defoliation: 0-30% loss of foliage
This level of defoliation is barely detectable and does not cause serious damage.

Moderate defoliation: 31-50% loss of foliage

Larvae may be a nuisance if not managed. Mortality is rare and trees have enough remaining foliage to stay green.

Heavy defoliation: 51% or more loss of foliage
Hemlock, pine, and spruce may die after one year of heavy defoliation. Two or more years of heavy defoliation can kill deciduous trees. At this level of defoliation, deciduous trees refoliate by mid-August.

Monitoring
Pheromone-based trapping of males can inform managers about the status of current gypsy moth populations (Forest Invasives Canada; Mass Audubon, 2016; Thorpe, Reardon, Tcheslavskaia, & Leonard, 2006).

Methods of control

Due to its long-term presence in the eastern U.S. several control methods for European gypsy moth have been developed and assessed (Table 1). As described in the introduction, all pest control methods may have side effects that need to be considered in the decision-making process.

Table 1. Summary of European gypsy moth control methods.

Category	Treatment	Application method	Effectiveness	Timing	Life stage	Non-target effects
Biological	*Bacillus thuringiensis* var. *kurstaki* (*Btk*)	Foliar application	Very effective	During active feeding	Larvae	Other caterpillar species
Chemical	Disparlure	Mating disruption (pheromone traps)	Effective against low density populations	July/August	Adult male emergence	None
Mechanical	Destroying egg masses	-	Unrealistic for forest applications	May to July	Larvae	-
Mechanical	Disrupting daily movement of larvae	Burlap, sticky strips	Unrealistic for forest applications	May to July	Larvae	Very low

Note: a hyphen signifies that either data was not readily available and more research is necessary, or the cell is not applicable to the treatment.

Biological
Bacillus thuringiensis var. *kurstaki* (*Btk*) is a strain of bacterium that is used to control caterpillar pests, including gypsy moth. It is more advantageous for gypsy moth control than chemical pesticides because it has less non-target effects on the animals that feed on gypsy moth, it does not persist in the foliage for more than five days following application, and has no known human

health threats. After *Btk* is applied to leaves, gypsy moth caterpillars ingest it and an endotoxin is released by the bacterium into the stomach of the caterpillar that poisons its digestive system. Once the *Btk* spores enter the caterpillar's bloodstream, it causes a fatal infection that kills the caterpillar within a few days (Ellis). It is known to be extremely effective at both controlling outbreaks and eradicating new populations (Solter & Hajek, 2009). However, although *Btk* is more specific than general pesticides, it is still capable of killing a number of native butterfly and moth species, and may interfere with the natural factors that contribute to gypsy moth control at high densities (Mass Audubon, 2016).

Other biological control agents include a species-specific fungal pathogen found in the native range of gypsy moth in Japan, *Entomophaga maimaiga*, that has caused high levels of mortality in US gypsy moth populations since 1989 (Forest Invasives Canada; Nielsen, Keena, & Hajek, 2005; Solter & Hajek, 2009). It is an epizootic pathogen (capable of causing epidemic outbreaks in animal populations) and can control both low and high gypsy moth populations (Solter & Hajek, 2009). However, it is highly dependent on environmental conditions—it is most effective during wet springs. The nucleopolyhedrosis virus (NPV), a virus that primarily affects butterflies and moths, occurs naturally in large populations and can greatly debilitate and kill gypsy moths (Forest Invasives Canada). Another virus, Baculovirus *Ld*MNPV, is only applied in environmentally sensitive areas because of its limited commercial availability. However, it is also epizootic and capable of crashing high-density populations (Solter & Hajek, 2009).

Native birds and mammals feed on gypsy moth larvae, but not enough to control populations. This includes cuckoos, woodpeckers, catbirds, grackles, white-footed mice, and gray squirrels. Native parasitic insects and fungi also attack larvae.

Chemical

European gypsy moth populations that are isolated or that have a relatively low population density (defined as less than 30 male moths caught per season in pheromone traps) can be controlled using the mating disruption technique. Thorpe (2006) provides the criteria for population levels (derived from operational experience):

> "1. Traps should capture no greater than 30 male moths per trap, and average capture should be less than 15 per trap in the year before treatment
> 2. Populations should be well delimited (i.e., at least nine traps per square mile)
> 3. The treated area should be at least 5 miles from a source of large numbers of migrating male moths
> 4. The treated area should be large enough to offset anticipated male moth migration (e.g., at least 2,500 ft. on a side)."

The mating disruption technique involves saturating the air with the synthetic pheromone, disparlure, to confuse males in their search for a female (Thorpe et al., 2006). This is only effective in low-density populations by virtue of probability—the fewer males per unit of area, the less likely they are to bump into a female by chance. The traps used to track populations are not an effective control on their own, and can only be used to estimate population sizes and predict outbreaks.

Mechanical
While there are a few different methods of mechanical control available that focus on killing eggs and larvae, their effectiveness at controlling an outbreak is not dependable and is oftentimes unrealistic in forest management.

One technique takes advantage of daily larval movement between the canopy and the ground. Since larvae feed at night and seek shelter at the base of trees during the day, 14-18 in. wide burlap material can be used to cover the bole at about chest height (Hoover, 2000). To capture larvae, a string may be secured around the middle of the band and the top material can be folded down over the string. Larvae that seek shelter under this burlap apron can be destroyed during daily checks. According to Hoover (2000), this is an effective technique during light-to-moderate infestations, and is effective at minimizing defoliation to below 50%. It is not, however, feasible for infested forests. Horticultural sticky tape can also be wrapped around trees to catch larvae as they climb to the canopy (Mass Audubon, 2016). However, because larvae often use silk to move around trees, this may only be effective when larvae first hatch. The overall effectiveness of these mechanical methods is questionable since they do not address the full scope of the infestation, especially once larvae hatch (Mass Audubon, 2016).

In fall and winter, mechanical control can also include scraping and killing egg masses with ethanol or boiling water (Forest Invasives Canada; Mass Audubon, 2016). This may be more cost-effective than attempting to capture and kill larvae, but in high levels of infestation, many well-hidden egg masses can go undetected as females attempt to lay eggs in sheltered locations.

Silvicultural treatment guidelines exist for gypsy moth and include reducing the abundance of host tree species and increasing stand vigor (Gottschalk 1993). Favoring non-host tree species and/or a greater diversity of host species, as well as removing damaged or suppressed trees through harvesting could reduce the extent and severity of future outbreaks.

Management scenarios

'Do nothing'
If no management is implemented, stands composed mainly of species that are susceptible to gypsy moth are more likely to experience mortality than diverse stands with a mix of favored, intermediately susceptible, and unfavored species (Davidson, Gottschalk, & Johnson, 1999). Based on data collected from long-term forest monitoring plots (NETN), the common tree species in Marsh-Billings-Rockefeller favored by gypsy moth are American beech, northern red oak, bigtooth aspen, Tilia spp., and paper birch. Intermediate species in the park include yellow birch, black cherry, eastern hemlock, hophornbeam, maples, pines, and spruce. Ash is unfavored. Intermediately favored species are only attacked if favored species are nearby and populations are at outbreak level. However, because the park's forest composition mainly consists of favored and intermediate species, gypsy moth could be a threat at outbreak levels.

Gypsy moth infestations provide opportunities for some native species (Mass Audubon, 2016). Increased light to the understory because of defoliation may encourage greater diversity and forest health in the long-term. For example, ash seedlings may recruit into larger size classes due to increases in understory light levels. Furthermore, larvae are an abundant source of food for mammals and birds, and the snags created by repeat outbreaks can function as wildlife trees.

Frass, though nitrogen-rich, does not appear to be as available to plants as expected and therefore the excessive frass addition to the soil may not actually increase plant biomass (Christenson, Lovett, Mitchell, & Groffman, 2002).

Single-tree

The mechanical methods that are available for protecting individual trees, such as wrapping with sticky tape or burlap, are likely ineffective when the full scope of the infestation is considered. Each egg mass can contain up to 1,000 eggs, and once they hatch, attempting to eradicate gypsy moth by trapping and killing larvae is unrealistic. While egg masses can be destroyed on an individual tree, it will not prevent the tree from being colonized by larvae from other sources.

Without any systemic chemical control options available that are specific to gypsy moth, single-tree protection does not currently seem feasible.

Stand-level

For eradication of stand-level outbreaks, early detection of populations is critical. There is currently a great need for monitoring tools to be sensitive enough to detect very low-density gypsy moth populations (Hajek & Tobin, 2009). The best current solution to early detection is using pheromone-baited traps followed by egg mass surveys.

Once gypsy moth is detected, *Btk* is the primary method for eradication (see 'Biological control'). It can be applied aerially 2-3 times during early instar presence to kill larvae as they feed on leaves (Hajek & Tobin, 2009). Because leaves must be expanded to use *Btk*, buds may already be damaged by early instars. However, it is imperative that the non-target effects of *Btk* are considered before deciding on its use. Btk is just as effective at killing the young larvae of some native moths and butterflies as it is at killing gypsy moth and other pest larvae.

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Hemlock woolly adelgid

Adelges tsugae

Background

Hemlock woolly adelgid (HWA) is an aphid-like invasive insect that has decimated hemlock populations on the east coast of the United States since its introduction in the 1950s. It poses a significant threat to eastern hemlock (*Tsuga canadensis),* "one of the most abundant, long-lived, shade tolerant species across its range" (Orwig, Foster, & Mausel, 2002).

Historical impact

HWA is native to Japan and the first description of HWA in the United States was on western hemlock (*Tsuga heterophylla)* in the Pacific Northwest in 1922 (Chrystal & Story, 1922). A few decades later in 1951, HWA was discovered on eastern hemlock in Richmond, Virginia (R. A. Evans et al., 1996; Souto, Luther, & Chianese, 1996). However, the individuals found in Richmond originated from the insect's native range in Japan and not from the population on the west coast of the US (Foottit, Maw, Havill, Ahern, & Montgomery, 2009; Havill & Foottit, 2007; Havill, Montgomery, Yu, Shiyake, & Caccone, 2006). By 1980, HWA had spread to Pennsylvania, causing significant damage to eastern hemlocks in its established range (McClure & Cheah, 1999).

Current range

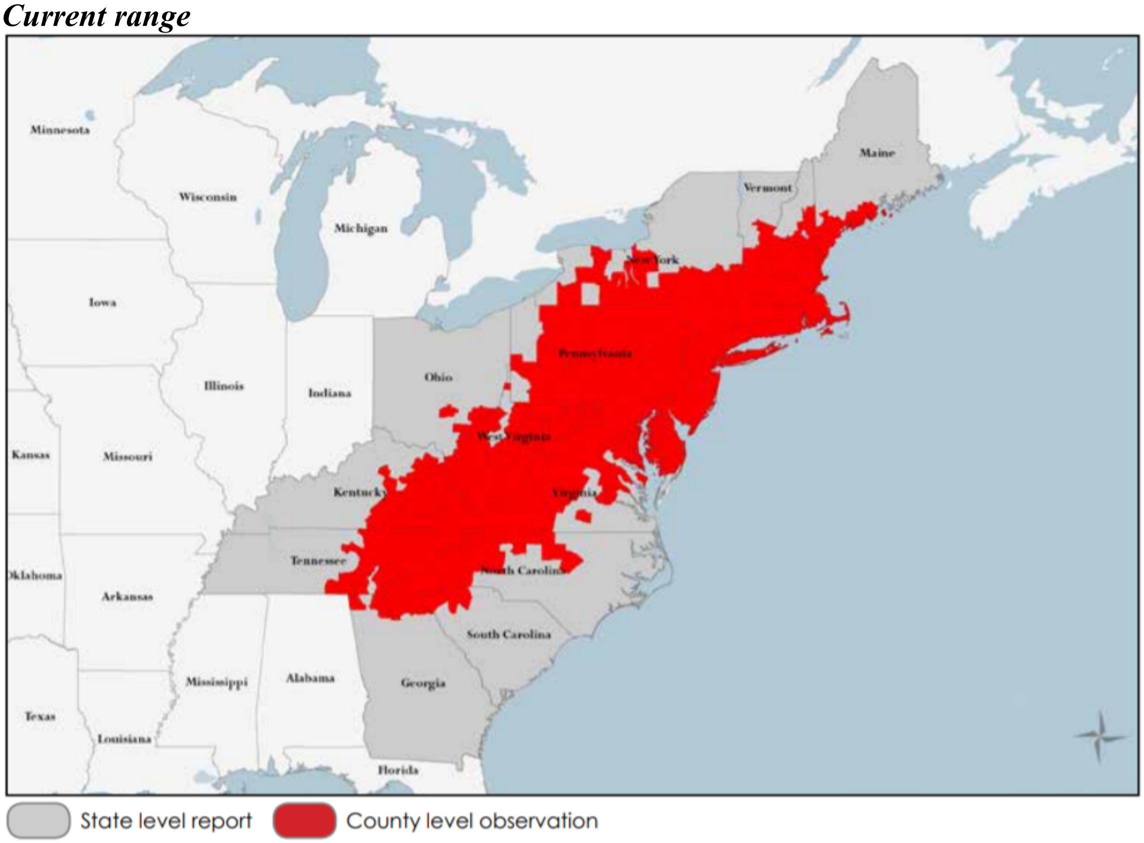

Figure 1. Hemlock woolly adelgid range in eastern US (last updated March 25, 2019) (U.S. Department of Agriculture, Forest Service, Northern Research Station and Forest Health Protection [USDA-FS], 2019).

Since its discovery on the east coast, HWA has spread throughout the native ranges of eastern hemlock and Carolina hemlock (*Tsuga caroliniana)*. As of 2017, it was established in 19 states—from Georgia to southern Maine and west into Ohio (Ellison, Orwig, Fitzpatrick, & Preisser, 2018).

Host trees
All species in the Tsuga genus are vulnerable to HWA, including the two eastern North American species: eastern hemlock (*Tsuga canadensis*) and Carolina hemlock (*Tsuga caroliniana*).

Life history
HWA produces two generations every year which overlap in the spring—an overwintering generation (sistens) and a spring generation (progrediens)—and both generations go through six stages of development (McClure, 1989). Four juvenile (nymph) stages are bookended by the egg and adult stages.

Throughout the spring (March-May), overwintering adult females lay eggs in woolly masses. These eggs hatch in early summer (April-June), depending on spring temperatures, and the first instar nymphs settle on needles for summer dormancy (aestivation). During October, the nymphs break dormancy and begin developing through the remaining three instars. In their final fourth instar, they develop the woolly mass above their bodies that is their namesake (McClure, 1989).

During late winter and early spring, the nymphs become adults and lay eggs, which will become the progrediens generation. This second generation of adelgids has no dormancy period and develops from egg to adult much more rapidly than the overwintering generation. By mid-summer, the progrediens individuals are adults (McClure, 1989).

In its native range in Japan, HWA completes sexual development on its primary host, tigertail spruce (*Picea torano).* Some of the progrediens adults develop wings to fly to the primary host while the remaining adults stay to lay more eggs on the host tree. North American spruce species are not suitable substitute primary hosts, so the winged adults die before they can reproduce sexually (McClure, 1989).

Dispersal
Despite its mostly sessile lifestyle in North America, HWA has spread rapidly across the range of eastern hemlock. Its rate of spread on average is around 7.8 mi/yr (12.5 km/yr), and county-based data have shown a faster rate of range expansion in the south 9.7 mi/yr (15.6 km/yr) and a slower rate in the northern part of its range 5.1 mi/yr (8.13 km/yr) (A. M. Evans & Gregoire, 2007).

Birds are likely the primary local and long-distance agent of HWA dispersal, along with wind, deer, and humans. Birds moving northward during spring migration can carry eggs, first instar crawlers, and adults that attach while they feed in infested trees. With peak crawler emergence in May, its coincidence with peak migration for many Neotropical bird species makes birds the most common culprit for dispersal of HWA (McClure, 1990; Russo, Cheah, & Tingley, 2016; Russo, Elphick, Havill, & Tingley, 2019).

Detection

Signs and symptoms

Since both generations of HWA feed on new needles, early signs of attack are often observed as needle loss in the lower and central portions of a tree's crown. Needle loss progresses throughout the crown as HWA density increases. From the lower parts of the crown, it moves to the interior branches, exterior branch tips, and the top of the crown (Orwig et al., 2002). After HWA becomes established in an area, it can kill the host tree within 4 years if there is no chemical, biological, or silvicultural intervention (Cheah et al., 2004).

Methods of control

Many control methods for hemlock woolly adelgid have been developed in recent decades (Table 1). As described in the introduction, all pest control methods may have side effects that need to be considered in the decision-making process.

Table 1. Summary of hemlock woolly adelgid control methods.

Category	Treatment	Application method	Effectiveness	Timing	Life stage	Non-target effects
Biological	*Laricobius* spp.	Predator	Investigation in progress	November to May	All	Low
Biological	*Leucopis* spp. (silver flies)	Predator	Investigation in progress	Released early spring; effective late spring and summer	Egg	Low
Chemical	Dinotefuran	Basal bark spray	High (can take 2-3 weeks to reach canopy, and effective up to one year)	Spring, Fall	Adult and nymphs	Low
Chemical	Imidacloprid	Soil application (drench, injection, time-release tablets)	High (can take up to one year to reach canopy, effective up to two years)	After rain event (except time-release tablets)	Adults and nymphs	High; Within 75 ft. of water

Category	Treatment	Application method	Effectiveness	Timing	Life stage	Non-target effects
Chemical	Imidacloprid	Trunk injection	High (can take up to one year to reach canopy, effective up to two years)	Spring, Fall	All	Low
Chemical	Imidacloprid	Basal bark spray	High (can take up to one year to reach canopy, effective up to two years)	Spring, Fall	Adults and nymphs	Low
Silvicultural	Allowing direct sunlight to reach infested trees by creating canopy gaps	Harvest	Investigation in progress	Winter	Adults and nymphs	-

Note: a hyphen signifies that either data was not readily available and more research is necessary, or the cell is not applicable to the treatment.

Biological

Biological control has been thought to be the most promising solution to HWA control, and consequently has attracted the most attention and funding for research (Onken & Reardon, 2011; Sumpter, McAvoy, Brewster, Mayfield III, & Salom, 2018). While there are no known parasitoids, there are multiple predators of HWA that have been investigated as potential biological control agents (Cheah et al., 2004; Foley, Salom, & Minteer, 2018). One single species is unlikely to be successful on its own, and the ideal biological control solution for HWA would be combining multiple different predators that differ in temporal and spatial patterns to provide greater coverage (Letheren, Hill, Salie, Parkman, & Chen, 2017).

Biological control agents

Leucopis spp. (silver flies)

- Promising control agent that is 1) capable of developing to adult stages on HWA and 2) able to survive at the northern and southern extent of HWA's range in the US (Motley, 2017).
- The New York State Hemlock Initiative (NYSHI) releases *Leucopis* flies annually in their work to develop an effective biocontrol program (Whitmore, Marschner, Bittner, Dietschler, & Malmborg, 2018).
- First released in eastern US in 2015 (Motley et al., 2017).
- Found on western hemlock in the west, pine bark adelgids in the east (not found on eastern hemlock) (Foley et al., 2018).
- Adults and larvae present in late spring and summer; could be used simultaneously with *Laricobius* beetles present during winter and spring for year-round control (Foley et al., 2018).

Laricobius nigrinus (Foley et al., 2018; Letheren et al., 2017)

- Viable candidate for biological control—evidence of substantial HWA mortality due to predation.
- Native to western temperate rainforests of US and Canada.
- Released in eastern US since 2003 and has been a focus of rearing efforts 2003-2018.
- Long-term effects are still being evaluated.

Laricobius osakensis (Foley et al., 2018; Letheren et al., 2017)

- Current focus of mass rearing efforts, but used together with *L. nigrinus*.
- Responds to hemlock volatiles when locating prey.
- Native to Japan and specific to HWA—may have coevolved with HWA in eastern US.
- Life cycle synchronous with HWA.
- Superior to *L. nigrinus* based on laboratory host range, performance, and phenology studies.

Laricobius rubidus (Foley et al., 2018; Letheren et al., 2017).

- Primary host is pine bark adelgid (host: white pine) but it has also been observed on balsam woolly adelgid and on HWA.
- The only *Laricobius* species native to the eastern US.
- Can hybridize with *L. nigrinus,* potentially causing complications.

Sasajiscymnus tsugae (Foley et al., 2018; Letheren et al., 2017)

- Over 2.5 million released in North America since 1995, but no proof of significant HWA control.
- Native to Japan.

Chemical

Systemic insecticides have been found to be an effective management technique against HWA, and the two most common insecticides are imidacloprid and dinotefuran. Both are systemic neuro-active insecticides modelled after nicotine, and are intended for the control of insects with piercing/sucking mouthparts (Kidd & James, 1991). As neonicotinoids, they function by interfering with the transmission of stimuli in the insect nervous system. They are selectively more toxic to insects than warm-blooded animals because they target a neuronal pathway that is more common in insects. Upon contact or ingestion, the insect is paralyzed and eventually killed (Kidd & James, 1991). While labor-intensive and potentially harmful to non-target invertebrates, insecticides have been shown to protect hemlock from HWA for up to two years.

>Imidacloprid

>>>Applications

Imidacloprid can be applied via soil drench, soil injection, time-release soil tablets, trunk injection, or basal bark spray. Soil drenching and soil injections may be limited by weather conditions and time of year as they should be done while soil is moist (i.e. after a rain event during the spring and fall), and should not be applied within 75 feet of a body of water. This can be disadvantageous in a natural setting where trees are more difficult to access, further complicating timing. As a result, time-release soil tablets may be a more convenient option for forest management because they can be inserted into the soil while it is still dry, and the dose of imidacloprid is released after rain events over a period of two years. Lastly, tree injections are thought to be less environmentally risky as their application does not come into direct contact with soil. However, since a small hole is drilled into the xylem, this method can be more harmful to the tree than soil-based methods (Whitmore, 2014).

>>>Effectiveness

Soil application of imidacloprid was found to be effective in suppressing HWA for up to two years following application (Cowles, Montgomery, & Cheah, 2006). Furthermore, imidacloprid therapy of residential hemlocks allowed damaged trees to recover post-infestation, even with significant damage. Trees with little new growth but no dieback recovered the quickest with the densest growth, while trees in the poorest condition recovered more slowly (Webb, Frank, & Raupp, 2003). However, imidacloprid moves relatively slowly through a tree and can take up to a year to reach the canopy (Whitmore, 2014).

>>>Risks

In a risk assessment of imidacloprid, the Forest Service did not identify any substantial risks to workers or members of the public when imidacloprid was used for tree injection, soil injection, or bark application. The same is true for vertebrate wildlife. Because of limited data on reptiles and amphibians, a risk characterization was not possible (Durkin, 2016).

On the other hand, risks can be substantial for phytophagous terrestrial insects, honeybees, and some groups of aquatic invertebrates. Tree injections may pose a threat to honeybees only if foraging occurs on the species of interest. Maple, for example, can be a potential threat if injected with imidacloprid, but it is still uncertain if the same is true for hemlock. Impacts to aquatic invertebrates are also currently unknown, and no studies have examined long-term interactions between treated trees and aquatic invertebrates. Direct spills into bodies of water, especially as a result of soil injections and drenches, pose a higher risk to certain groups of aquatic invertebrates (Ostracoda, Annelia, midges and other Diptera, Hemiptera, Amphipoda, Trichoptera, Mysida, Megaloptera, and one species of Cladocera, *Ceriodaphnia dubia*) (Durkin, 2016).

Imidacloprid also has the potential to have adverse interactions with HWA biological control agents. Eisenback (2010) examined two popular species for HWA biological control, *Laricobius nigrinus* and *Sasajiscymnus tsugae* (Eisenback, Salom, Kok, & Lagalante, 2010). In no-choice forage tests, they found that *L. nigrinus* had a significantly higher mortality rate when feeding on branches treated with imidacloprid.

>Dinotefuran

>>>Applications

Dinotefuran has similar methods of application to those of imidacloprid, but its behavior within treated trees differs in a few key ways.

Safari 20 SG is a formulation of dinotefuran that is more beneficial for use in forestry than other formulations because it can be used in soil drenches and injections and is not limited to broadcast granular application. Soil injections in particular could be advantageous in forestry applications because they do not require artificial irrigation (Whitmore, 2014). Bark sprays should be applied during the growing season when trees are actively transpiring (Gill & Shrewsbury, n.d.; Whitmore, 2014).

>>>Effectiveness

Dinotefuran differs from imidacloprid in the rate at which it becomes effective throughout the tree and the length of protection it provides. When used as a bark spray, it can reach the canopy within 2-3 weeks. However, it only stays viable for a year—half the protection that imidacloprid provides. Because of these differences, it has been suggested that imidacloprid and dinotefuran be used together to provide both short-term and long-term HWA suppression (Whitmore, 2014).

>>>Risks

Dinotefuran is a relatively new insecticide, and the Forest Service reviewed it in 2009 to assess its designation through the EPA as a Reduced Risk alternative to imidacloprid (Durkin, 2009). This assessment focused on the reduced risk for human health and non-target species.

Risks to humans are likely low—there is limited basis for health risks to workers, and the only exposure concern for the general public is through long-term consumption of vegetation after foliar application (Durkin, 2009). Since dinotefuran only remains effective for half the time duration of imidacloprid in HWA control, it is unlikely to be used for the purposes of invasive forest pest management.

Risks for vertebrate wildlife are similarly low. However, as a broad-spectrum insecticide, dinotefuran poses a higher risk to phytophagous terrestrial insects, honeybees, and aquatic invertebrates (Durkin, 2009).

Silvicultural

Silvicultural studies are currently in progress, but preliminary results show that opening the canopy and allowing direct sunlight to reach trees could contribute to increased mortality of HWA during the summer (Whittier, Mayfield III, & Jetton, 2017).

Management scenarios

'Do nothing'

While it is difficult to predict how hemlock will react to HWA on a stand-level basis due to the amount of landscape variation and variable environmental factors, hemlock health on average will decline once HWA reaches Marsh-Billings-Rockefeller NHP. While some hemlock may survive longer than 4 years, the majority could die within 3-4 years once infested and without treatment (Cheah et al., 2004).

Effects of HWA on hemlock and the surrounding landscape:

- Hemlock stands have not been impacted equally by HWA; risk varies geographically (Morin & Liebhold, 2015).
- Landscape-level impacts of HWA on hemlock have been slower to manifest than originally expected. In a 22-state study utilizing historical FIA data, hemlock net growth rates decreased and mortality rates increased for decades after initial HWA infestation (Morin & Liebhold, 2015).

- Black birch (*Betula lenta)* often replaces hemlock in stands with high levels of HWA disturbance (Cole, 2016). Other new understory species in a Connecticut study included red maple (*Acer rubrum*), Canada may flower (*Maianthemum canadense*), witch-hazel (*Hamamelis virginiana*), northern red oak (*Quercus rubra)*, and chestnut oak (*Quercus prinus)* (Letheren et al., 2017).
- Increased light availability in the understory from canopy dieback and mortality increases seedling regeneration (Jenkins, Aber, & Canham, 1999).
- Nitrate leaching is likely in regions with high levels of hemlock mortality (Jenkins et al., 1999).
- Hemlock saplings infested with HWA have significantly reduced growth and foliar %N (Miller-Pierce, Orwig, & Preisser, 2010).

Single-tree protection
Currently, the protection of individual hemlocks is likely only possible with chemical control. While insecticides and foliar sprays are the most immediate and effective treatment for HWA, they must be frequently reapplied for maximum effectiveness and their use is limited by accessibility to the treatment area. They are widely used in landscape and horticultural settings, but application in a forest setting is likely extremely limited due to the cost, time, and labor requirements. However, for highly valuable forest trees that are easily accessed from a road, insecticide treatments may be an option.

Stand-level protection
The most promising option for long-term, sustainable, and cost-effective control of HWA is integration of chemical and biological control with host-plant resistance methods. Treating infested trees periodically with insecticide while releasing predators of HWA will offer protection while the predator population becomes established.

Missing information
Research on applications of insecticide in forest settings is limited so it is difficult to estimate effectiveness based on studies looking at easily accessible landscape hemlock in a horticultural setting. Similarly, research is limited on the long-term effects of insecticide use on the ecosystem.

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Oak wilt

Bretziella fagacearum

Background

Oak wilt (*Bretziella fagacearum)* is a relatively slow spreading disease affecting all oaks in North America (Beer, Marincowitz, Duong, & Wingfield, 2017; Juzwik, Appel, MacDonald, & Burks, 2011). Its greatest impact is in the north-central states and Texas, but it is manageable in locations where it is detected early and actively managed (Juzwik et al., 2011). Due its recent discovery in New York in 2016, it poses a greater threat to the Northeast than previously expected (Hassett, Kotary, & Robert, 2018).

Current range

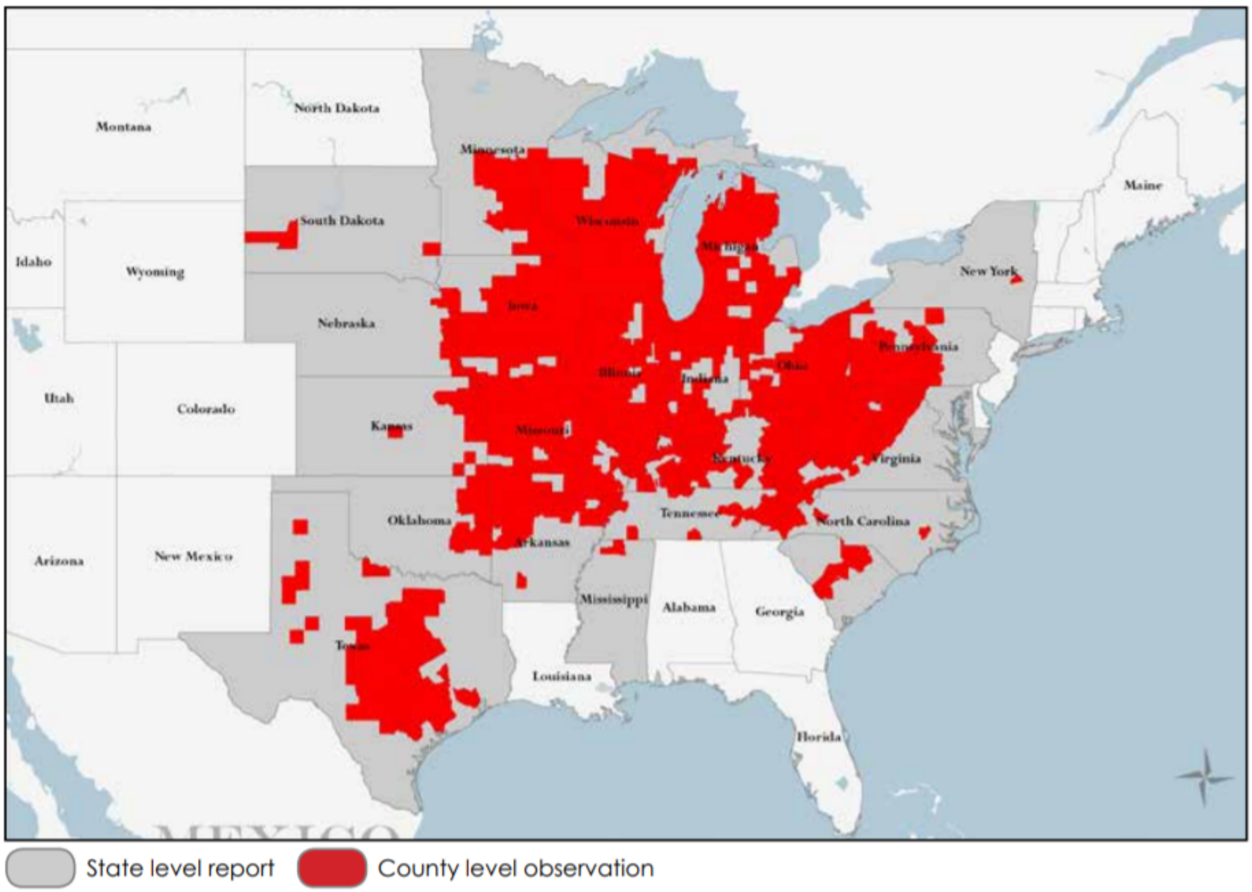

Figure 1. Oak wilt range (last updated March 27, 2019) (U.S. Department of Agriculture, Forest Service, Northern Research Station and Forest Health Protection [USDA-FS], 2019).

Host trees

While oak wilt attacks all oak species, oaks in the red oak group are significantly more susceptible than white oak group species and show more severe symptoms once infested

(Blaedow & Juzwik, 2010; Koch, Quiram, & Venette, 2010). See ‘Signs and symptoms’ for more information.

Table 1. Host species of oak wilt organized by oak group.

OAK GROUP	COMMON NAME	LATIN NAME
RED OAKS	Northern red oak	*Quercus rubra*
	Black oak	*Quercus velutina*
	Bear oak	*Quercus ilicifolia*
	Southern red oak	*Quercus falcata*
	Shumard oak	*Quercus shumardii*
WHITE OAKS	White oak	*Quercus alba*
	Bur oak	*Quercus macrocarpa*
	Chestnut oak	*Quercus prinus*
	Live oak	*Quercus fusiformis*
	Southern live oak	*Quercus virginiana*

White oak *(Q. alba)* is the least susceptible of the white oak group, with infection usually resulting in branch dieback, and can survive for decades after being infected. The other white oaks have moderate resistance and usually die several years after infection (Juzwik et al., 2011).

Historical impact

When oak wilt was officially described in 1944, its range included Wisconsin, Minnesota, Illinois, and Iowa. Oak wilt symptoms have been reported as early as 1881 in Wisconsin, but it is unknown when it first appeared in the United States or where it originated (Koch et al., 2010). Since then, it has spread throughout the Lake States and south to Texas. While it occurs sporadically in the Appalachian region, the environment is not as conducive to spread—factors such as higher species diversity, rich soils, and variable topography limit the size of disease centers. Sandy soils, on the other hand, have been positively correlated with higher oak wilt mortality in red oaks. Tens of thousands of oaks die annually in the Lake States, and millions of trees have died in Texas since oak wilt was detected there (Juzwik et al., 2011).

Life history

The oak wilt fungus grows on the outer sapwood of oaks and clogs xylem vessels with its hyphae, spores, and metabolic by-products (Koch et al., 2010). The tyloses (defensive structures of oaks) produced in response to stressors also contribute to the blockage of xylem. This restricts the movement of water and nutrients through the tree, eventually causing death. Fungal mats and insect vectors are most active from February to late June (Koch et al., 2010).

Dispersal
The spores of oak wilt can be spread to uninfected oaks via aboveground and underground vectors. Aboveground spread usually introduces new infection centers, while underground spread expands existing infection centers.

>Insects
Insects are known to be the main vector of aboveground oak wilt spread, with evidence pointing to nitidulid or sap beetles (Coleoptera: Nitidulidae) being the primary vectors. During peak fungal mat formation, insects are attracted to the fruit-like odor of the mats and carry oak wilt spores to open wounds of uninfected trees. Aboveground infection is not possible without the spore-carrying insect's visit to a "fresh" xylem-penetrating wound (Juzwik et al., 2011). In Minnesota, 1-3 day old wounds attracted higher numbers of beetles than 4-6 day old wounds, and beetles were most abundant on wounds created in May (Juzwik, Skalbeck, & Neuman, 2004). There is no evidence of spread via wind, precipitation, burning infected firewood, or tree pruning. However, movement of infected dead material does account for introduction to disease-free areas. This is most likely how oak wilt was introduced to New York and west Texas (Juzwik et al., 2011).

>Roots
Underground root grafting is the less predictable vector of oak wilt spread. Underground spread is more common in stands with high oak composition and is less of a threat in diverse hardwood forests where extensive common root systems are limited (Juzwik et al., 2011). Once crown symptoms are present on a tree, one can assume that oak wilt is present in roots extending outward in all directions around the tree. However, the actual spread of oak wilt via roots is sporadic and unpredictable (Blaedow & Juzwik, 2010).

Detection

Signs and symptoms
Symptoms of oak wilt manifest differently in red and white oaks.

>Red oaks
Red oaks may develop symptoms within weeks of infection (Juzwik et al., 2011). Leaf wilt begins soon after infection and begins at the top of the canopy with the tips of leaf lobes becoming discolored and deformed. This discoloration then moves from the tips towards the midrib. Defoliation progresses rapidly and red oaks are killed within a few months of symptoms appearing (Koch et al., 2010). Other symptoms include mature leaves appearing "water-soaked" and abscission of leaves that appear otherwise healthy (Juzwik et al., 2011).

A definitive sign of oak wilt on dead red oaks is the formation of fungal mats under the bark. While difficult to detect without debarking a tree, fungal mats often cause vertical cracks in bark that emit a sweet odor. Fungal mats can form on the stem or branches of a tree as long as it is greater than 3 in. (7.6 cm) in diameter (Juzwik et al., 2011). The timing of mat formation varies greatly depending on season and region, and since oak wilt is not well established in the Northeast, there is no research documenting the active period for mat formation in this region. Another sign that indicates oak wilt is an outwardly expanding circle of dying oaks, also known as a disease center.

>White oaks
Oak wilt symptoms on white oak are similar to those of red oak, but they are less predictable in progression and ultimate outcome. White oak, which is highly resistant to oak wilt, may experience some branch dieback but can live for decades after infection unlike other infected oaks. Foliar symptoms on scattered branches are more common in other white oaks with less resistance (Juzwik et al., 2011).

Monitoring
Early diagnosis is essential to successful control. For definitive identification, the pathogen must be isolated in a laboratory setting from xylem tissue and the branches or sapwood must be obtained before the tree has desiccated (Juzwik et al., 2011).

In Minnesota, wilted red oaks are inspected between November and March the year after wilt occurred. If the cambium has signs of infection, the tree is marked for removal prior to April 1. This includes burning, chipping, and other processes that encourage wood drying. Other options include debarking lower trunk and deep girdling to promote drying, and covering felled logs with plastic sealed at the ground line. Removal and proper disposal should occur before mat production occurs in late winter or spring of the following year (Juzwik et al., 2011).

Methods of control

Once oak wilt is established, disease control methods can be expensive (Table 2). The most cost-effective option is to mitigate spread as much as possible with preventive measures. As described in the introduction, all pest control methods may have side effects that need to be considered in the decision-making process.

Table 2. Summary of oak wilt control methods.

Method	Treatment	Application type	Effectiveness	Timing	Life stage	Non-target effects
Chemical	Propiconazole	Fungicide	High (white oak group); Low (red oak group)	Late spring to early fall	-	-
Mechanical	Harvest	Removing potential spore-producing trees	High	Winter	-	-
Mechanical	Trench/plow lines	Disrupting root grafts	High	ASAP	-	-

Note: a hyphen signifies that either data was not readily available and more research is necessary, or the cell is not applicable to the treatment.

Preventive actions
Infection of healthy trees only occurs when insect vectors transmit the pathogen through a fresh wound, so infection can be prevented by avoiding wounding uninfected oaks. Wounds caused by management activities with equipment should be avoided during the times when beetles are active. In the Lake States, this is between early April and mid-July. It is currently unknown when the active period could be in the Northeast but it is likely similar (Juzwik et al., 2011).

Chemical
Propiconazole is the primary fungicide for oak wilt control, and can be used both preventively and therapeutically. Applications should be species-specific due to the differences between red and white oaks. In white oaks, it is nearly always effective as a preventive treatment—in one study, only 1 out of 26 oaks showed symptoms five years after treatment (Koch et al., 2010). It is also an effective therapeutic treatment for white oaks and can decrease mortality. Preventive treatment of red oaks is more variable with a broad range of results, from significant improvement to relatively high mortality. Red oaks treated post-infection showed a delay in symptom development if treated early enough (less than 25% crown wilt), but the treatment must be repeated every 2 years for continued protection. Treatment is ineffective at protecting red oak in late stages of infection. However, propiconazole injection is effective at preventing fungal mat formation on oak wilt-killed red oaks. Treated red oaks killed by oak wilt did not develop fungal mats, while untreated red oaks did. In both oak groups, repeated treatments may increase treatment efficacy (Koch et al., 2010). Oaks are typically treated late spring to early fall, after full leaf out and before fall senescence (Gleason & Mueller, 2005).

Mechanical
To prevent underground spread of oak wilt, root grafting can be disrupted by installing trench or plow lines separating healthy and infected trees. This should be done as soon as possible to mitigate spread—healthy oaks within 50-60 ft of infected oaks are susceptible to oak wilt spread via root graft (Gleason & Mueller, 2005). At the very least, these trenches must contain all symptomatic trees, and often trees within root grafting distance of infected trees, in order to be effective (Figure 2). Secondary lines are trench inserts within the boundary of the primary line that increase the efficacy of barriers. Equipment used to install trench lines varies regionally, but vibratory plows, bulldozers with ripper blades, and backhoes are used (Koch et al., 2010).

There are different suggestions for choosing the placement of the primary lines. Since underground spread of deciduous oaks is typically less than 50 ft. (15.2 m) per year, some suggest placing the primary line between 50 and 60 ft. (15.2 and 18.3 m)—a fixed distance that accounts for annual advance. Others suggest that placement of the primary line should be a function of soil type and tree size (Koch et al., 2010). The depth of the trench is said to vary, but Koch (2010) did not elaborate on a suitable range.

Removing potential spore-producing trees is also an important aspect of regulating oak wilt spread. In Minnesota, at least 1/3 of infected red oaks have the potential to produce fungal mats the following spring, and sanitation can be used to reduce infected inoculum and prevent transmission by insect vectors. There are two options: 1) removal of all infected oaks and all oaks that develop symptoms, and 2) a cut-to-the-line treatment that involves removal of all oak trees that fall within an infection center (i.e. within the root graft barrier line). The second method has been found to be more effective at suppressing oak wilt than the first. However, root grafts must be broken before symptomatic oaks are removed to prevent oak wilt from spreading underground (Gleason & Mueller, 2005).

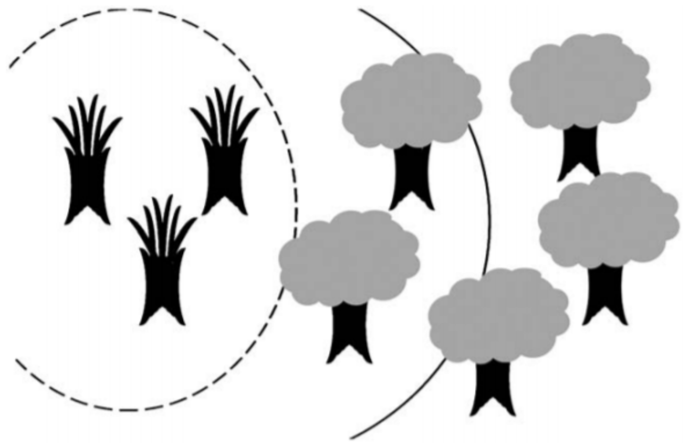

Figure 2. “An example of primary and secondary line placement. The primary line (solid) separates trees outside of the potential root grafting distance from the infection center and asymptomatic trees within root grafting distance. A secondary line (dashed) can be placed inside the primary line between symptomatic trees and apparently healthy trees inside root grafting distance” (Koch et al., 2010).

Once trees have been removed, infected wood must be sanitized since it still has the potential of fungal mat production. Examples of sanitation methods include burning, debarking, girdling, drying, chipping, covering with plastic and chemical treatment. All material greater than 3 in. (7.6 cm) in diameter should be treated. Girdling combined with chemical debarking has been 100% effective at suppressing mat formation in red oaks. It is important to remove an infected tree and complete sanitation by the following spring after it is found to prevent fungal mat formation.

Management Scenarios

’Do nothing’

It remains unclear how oak wilt may interact with northeastern forests, although some estimates can be made. Depending on the distribution of oaks in Marsh-Billings-Rockefeller, it may be a low-to-moderate threat. Red oak only composes 2% of the overstory of Marsh-Billings-Rockefeller. If these oaks are not found in clusters, oak wilt may not pose very much of a threat to the park. Furthermore, the way that oak wilt has interacted with oaks in the Appalachian region suggests that an outbreak in the Northeast, if it happens, may have less severe consequences on oak populations than the outbreaks in Texas and the Midwest. As mentioned earlier, sandy soils are positively correlated with red oak mortality due to oak wilt, while richer soils and more varied topography limits the size of disease centers. However, without region-specific oak wilt research, it is difficult to make an informed prediction about how oak wilt will affect Marsh-Billings-Rockefeller.

If oak wilt is detected in Marsh-Billings-Rockefeller and left unaddressed, the infected red oak will die and have the potential of spreading the fungus further through root grafting and fungal mat formation. Assuming underground spread is less than 50 ft. (15.2 m) per year on average, nearby oaks will become infected as the pathogen travels through the roots of the original host. Fungal mats may not always form on dead red oaks, but their presence will attract insect vectors that can spread the pathogen to disease-free areas in the park and local community from early April to mid-July. Left unchecked, oak wilt could slowly decimate the red oak population of Marsh-Billings-Rockefeller.

Single-tree protection

Protection from oak wilt on a single-tree basis is likely impractical in a forest setting. Very early detection of oak wilt is necessary for therapeutic fungicidal treatments to be effective in treating red oak (less than 25% crown wilt). A successful treatment will delay symptom development, but only temporarily—the treatment must be repeated every 2 years for continued protection. Preventive treatments for red oak have not been reliable and are therefore not a viable option for single-tree protection. Fungicide treatments may be a worthwhile investment for culturally valuable red oaks that are easily accessible, but are likely too labor-intensive for less valuable oaks.

Stand-level protection

Stand-level protection may be feasible if oak wilt is detected early. Since local spread of oak wilt is dependent on site characteristics, an oak wilt management plan should consider each infection center on an individual site basis. The management plan for the infection center should at least include information about soil type, root graft distance, tree density; these factors will inform the size of the removal buffer (e.g. if healthy trees need to be removed) and if root disruption will be used.

The most successful methods of slowing spread involve:

1.) Early diagnosis
2.) Root graft disruption (if necessary; depends on root grafting distance)
3.) Removal of all infected trees, in addition to any trees within the root graft zone
4.) Sanitation of infected wood (via burning, debarking, girdling, drying, chipping, covering with plastic, and/or chemical treatment)

If oak wilt is detected sufficiently early, it can be successfully managed and eradicated from a site using a combination of management techniques that address both aboveground and underground spread.

Table 3. Root grafting distances, based on a 99% confidence level (Bruhn & Heyd, 1992; Hassett et al., 2018).

COMBINED DBH (IN.)	INTER-TREE ROOT GRAFT DISTANCES FOR SOIL TYPES		
	Sandy soils (ft.)	Loamy-sand soil (ft.)	Sandy-loam/loam soil (ft.)
2	5.1	4.1	2.9
10	25.5	20.3	14.8
20	51.1	40.6	29.5
30	76.6	61.0	44.3
40	102.1	81.3	59.1
50	127.6	101.6	74.0

Table 4. Risk of oak wilt fungus spread by sap beetles and advisory comments by time of year (Hassett et al., 2018).

TIME OF YEAR	RISK OF INSECT SPREAD	ADVISORY NOTES
MARCH – JULY	High	Do not wound, prune, or fell oaks in oak wilt counties during this time. Immediately cover any unavoidable wounds with paint or shellac.
AUGUST – OCTOBER	Low	Depending on weather conditions and insect populations, infections are less likely. Immediately cover pruning wounds, stump surfaces of felled trees, and other wounds with paint.
NOVEMBER – FEBRUARY	Safe	Fungal pathogens and insect vectors are inactive.

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Red pine scale

Matsucoccus matsumurae (formerly known as *M. resinosae*)

Background

Red pine scale is considered to be one of the most significant pests of red pine in the United States, and is considered a serious pest in the rest of its introduced range (China, Korea, and Europe) (Maine Department of Agriculture, Conservation, and Forestry, Maine Forest Service [Maine-FS], 2014). Native to Japan, red pine scale was first found in the US in 1946 in Easton, Connecticut (Maine Department of Agriculture, Conservation, and Forestry, Maine Forest Service, Forest Health and Monitoring Division [Maine-FS FHM], 2014), likely after being introduced to the US through the New York World's Fair in 1939 (NH Bugs).

Current range

The northward expansion of red pine scale has been relatively slow, suggesting that it is limited by its intolerance for cold winter temperatures (Maine-FS, 2014). This is supported by McClure (1983), who suggests that the spread of red pine scale is inhibited by high overwintering mortality in the North and a lack of suitable hosts in the South (McClure, 1983). Updated information that considers interactions with warming temperatures is necessary.

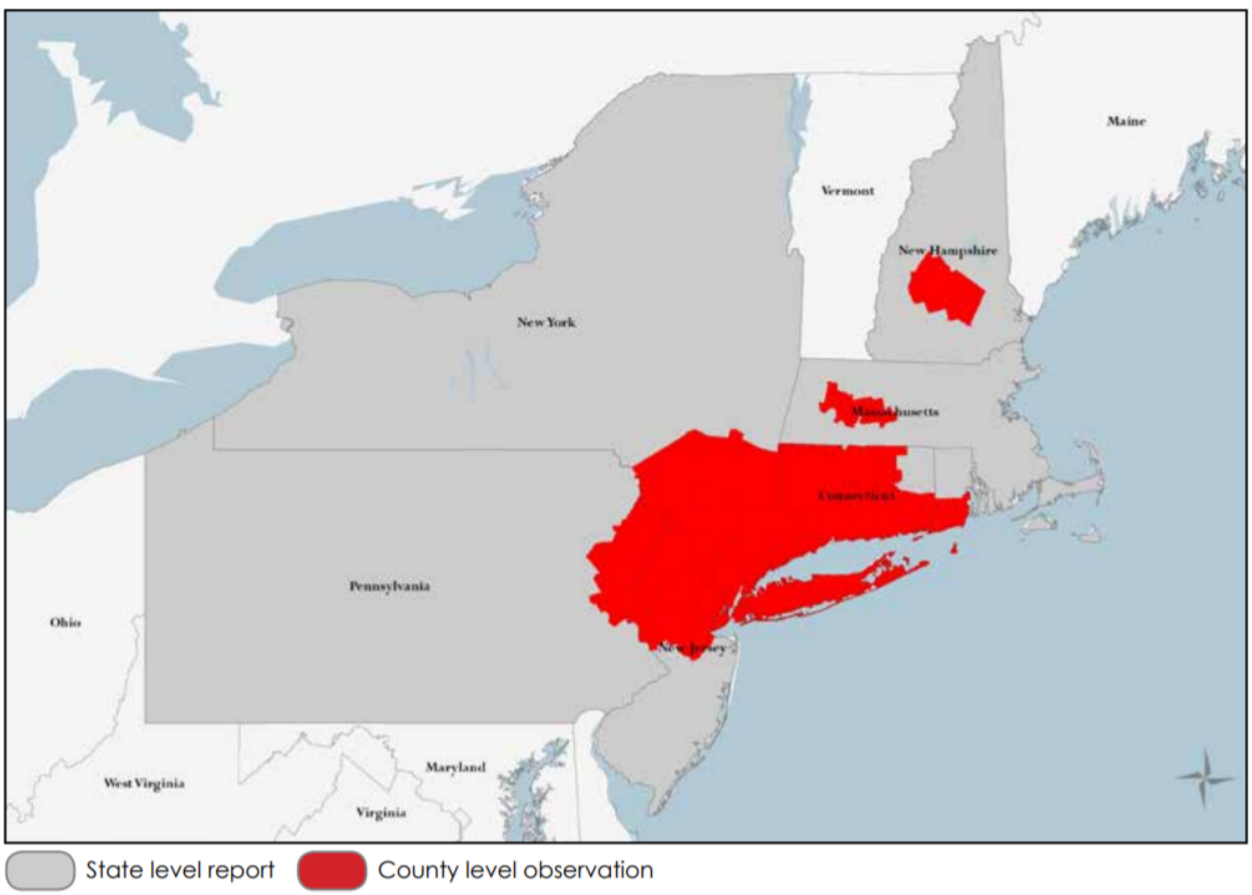

Figure 1. Red pine scale range (last updated March 25, 2019) (U.S. Department of Agriculture, Forest Service, Northern Research Station and Forest Health Protection [USDA-FS], 2019).

Nevertheless, red pine scale has steadily spread through the New England states in the past decade. It was first identified in New Hampshire in 2012 at Bear Brook State Park, at which point it was found throughout southern New England, New York, New Jersey, and eastern Pennsylvania (NH Bugs). In 2014, it was first identified in Mount Desert, Maine (Maine-FS, 2014), and light populations of red pine scale were confirmed in Rutland and Orange counties in Vermont in 2015 (Schultz et al., 2016). However, it has not been relocated in Vermont since then.

Host trees

The known hosts of red pine scale are red pine (*Pinus resinosa*), Japanese red pine (*P. densiflora*), Japanese black pine (*P. thunbergii*), and Chinese pine (*P. tabulaeformis*) (Maine-FS FHM, 2014).

Historical impact

Red pine has declined severely in the northeastern United States over the past decade, and one of the main culprits is thought to be red pine scale. The mass mortality of both natural red pine stands and plantations has led some towns to begin removal programs in an attempt to mitigate the damage both to trees and to residential areas (e.g. Northampton, MA, Rutland, VT) (Hongoltz-Hetling, 2017).

In Mount Desert, ME, red pine scale has contributed to red pine decline and mortality. It is still unclear exactly how much of Maine's red pine decline can be attributed to red pine scale because there are other threats to red pine health, the main agents being two shoot blights, *Sirococcus conigenus* and *Diplodia pinea* (Maine-FS, 2014).

In Vermont, red pine has experienced significant decline. As of 2018, 765 acres of red pine in Vermont were declining, with high levels of mortality in Washington and Rutland counties. However, there are no clear indicators that red pine scale is the cause of this decline, especially since it has not been relocated in Vermont since 2015. While it may simply be going undetected, there are also several shoot blight fungi present in Vermont that may be contributing to the state-wide decline (Schultz, Hanson, Halman, Spinney, & Parisio, 2018).

Life history

Red pine scale has two generations each year. The summer generation adult females, which are brownish-red and wingless, lay eggs in May and larvae hatch by early June (Esden, n.d.; Maine-FS FHM, 2014). These larvae settle down under the bark scales of red pine to feed. First stage larvae transform into intermediate stage larvae by mid-July. Pre-adult males emerge out of the intermediate stage in August and spin a loose cocoon in which they transform into winged true adults. Adult females, on the other hand, emerge from the intermediate stage and lay the fall generation eggs from August to September. The fall generation larvae hatch and move under bark scales to overwinter. Their development to adults is expedited—after breaking dormancy in April, they develop into intermediate stage larvae and morph into adults by late spring (Maine-FS FHM, 2014).

Dispersal
Similar to hemlock woolly adelgid, red pine scale can be dispersed via wind, birds, and mammals. Winter is the least likely time for scale dispersal because of it the dormant period, and any management activities that are planned should be completed in the winter to minimize risk of spreading the scale (Maine-FS, 2014).

Detection

Signs and symptoms
The first sign of red pine scale infestation in New Hampshire stands was "flagging"—when the foliage at the base of the crown turns orange-red (Guinn, 2014). This discoloration moves from the base of the crown to the top, changing in color from olive green, to orange, and finally red just before the death of the tree. Other signs include white woolly masses on fine branches. Secondary pests, particularly bark beetles, are common once a tree is infested with red pine scale. Pitch tubes are a significant sign calling for further examination for red pine scale. Decline is swift after detection, with mortality occurring 3-5 years after infestation. However, an infestation may go undetected for years (Guinn, 2014; Maine-FS, 2014; Maine-FS FHM, 2014).

However, red pine decline across the Northeast has multiple potential causes, and the symptoms listed above are not enough to identify red pine scale definitively. Examining host samples under a microscope will reveal the woolly larvae and adults under the bark scales, and fine branches may have "flocculence," the woolly structure covering the scales (Esden, n.d.).

Monitoring
Frequent monitoring of red pine stands with a focus on looking at any health issues is recommended. There is no protocol in place currently for surveying red pine for scale.

Methods of control

Unfortunately, there is scant evidence of effective control measures (Table 1). With limited evidence of chemical control for high-value trees, prevention and removal of infested trees are the best options for control. As described in the introduction, all pest control methods may have side effects that need to be considered in the decision-making process.

Table 1. Summary of red pine scale control methods.

Category	Treatment	Application method	Effectiveness	Timing	Life stage	Non-target effects
Biological	No effective options in the US.					
Chemical	Insecticides are not a practical option for stand-level infestations, especially in plantations.					
Mechanical	Harvesting infested trees with extra precautions	-	Mixed; see 'Mechanical'	Winter	Overwintering larvae	Low

Note: a hyphen signifies that either data was not readily available and more research is necessary, or the cell is not applicable to the treatment.

Biological
In east-central China, the Chinese Ministry of Forestry created an intensive control program against red pine scale that includes biological, chemical, regulatory, and silvicultural methods (McClure, Dahlsten, DeBarr, & Hedden, 1983). The most effective predators of red pine scale are several ladybird beetles, an anthocorid bug (Hemiptera: Anthocoridae), and a mite, but at the time of publishing, these biological control methods were still experimental. Insecticides were also used when population density is high enough to warrant their use, and they are applied via smoke, spray, and injection. Dense monocultures on northern slopes at low-to-middle elevations were the most likely to be attacked by red pine scale (Hanye, Weijun, Qingjie, & Xiangguo, 1983; McClure et al., 1983). More recently, an entomopathogenic fungus, *Lecanicillium lecanii,* was found to be a promising biocontrol agent of red pine in China and successfully caused disease and death of the scale (Liu et al., 2014). Male third instar nymphs and adult females, crucial points in the scale's life cycle, are most susceptible to the fungus.

However, none of the methods used in China have been effective when introduced to the US. Natural predators do exist in the northeastern US, but do not affect populations of red pine scale enough to be a successful method of control (Guinn, 2014). A 1983-1986 study in Connecticut attempted to rear Asian lady beetles, *Harmonia axyridis*, as potential predators of red pine scale. Predation was high during more conspicuous stages of the scale's life cycle (eggs and adults), but overwintering scales were concealed by bark and less likely to be preyed upon (McClure, 1987). However, these beetles were ultimately an unsuccessful control candidate as less than 10% of adults released into field cages were able to survive normal winter conditions in Connecticut.

Chemical
Information on chemical control of red pine scale is extremely limited, but the consensus is that insecticides are not a practical option for stand-level infestations (especially when stands are plantations). The Maine Forest Service suggests using 2% rate horticultural oil in early June and early September for single-tree control of ornamental individuals. Furthermore, they suggest avoiding fertilization (Maine-FS FHM, 2014). Repeated applications of insecticides may protect individual trees to some extent (Guinn, 2014).

Mechanical
While there are no silvicultural recommendations for mitigating red pine scale impact, extra precautions should be considered when harvesting in infested stands to reduce human-assisted spread. For example, stands should be harvested during the winter when the scale is dormant, and plant material should be removed from equipment before leaving a site (Guinn, 2014). If red pine is harvested, tops should be chipped to allow dead material to dry out faster. Removing infested red pines has been said to be the "only effective means of control" of red pine scale (Guinn, 2014), but removing all trees susceptible to an invasive pest could accelerate their premature disappearance from the landscape before an effective management technique is developed.

Management scenarios

’Do nothing’

Red pine scale has the potential to decimate the historic red pine plantations of Marsh-Billings-Rockefeller NHP if it is not detected and treated. While the loss of the overstory in red pine plantations would be a significant cultural loss, the rapid development of gaps and eventual complete loss of overstory trees could also create the opportunity for invasive species and beech to proliferate if no native regeneration is established.

Red pine scale is one of the causes of red pine decline across the Northeast, but the extent of its contribution is unclear (see ‘Historical impact’). If conditions in Vermont are similar to those in Maine, where red pines have died within three to five years of becoming infested, loss of canopy may be swift and significant.

Single-tree protection

The short timeframe in which red pine scale causes total red pine mortality makes early detection especially important, but detection is complicated by the difficulty of accurate identification. Red pine scale should be identified under a microscope since its symptoms overlap with other causes of red pine decline.

Horticultural oil may be an option for protection of individual trees, but more information is needed for this to be a feasible technique. The Maine Forest Service briefly mentioned this as an option on their management page with no details regarding application (Maine-FS FHM, 2014).

Stand-level protection

Stand-level protection post-infestation is not currently possible. The best option for future stand-level protection is an effective prevention plan that involves taking precautions to slow spread, especially during harvests (see ‘Mechanical’).

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Spotted lanternfly

Lycorma delicatula

Background

The spotted lanternfly is a newly emerging invasive threat to agricultural crops, such as grapes and hops, and native hardwoods in the US (Pennsylvania Department of Agriculture, n.d.a). Since its discovery in Pennsylvania in 2014, Penn State University has led a bulk of the research addressing its life history and potential management options, collaborating with the Pennsylvania Department of Agriculture and APHIS to provide educational materials (Penn State Extension, n.d.; Pennsylvania Department of Agriculture, n.d.a).

Current range

Spotted lanternfly is native to China, India, and Vietnam. Although it has spread to neighboring states, there are no confirmed infestations north of New Jersey and Pennsylvania (Figure 1).

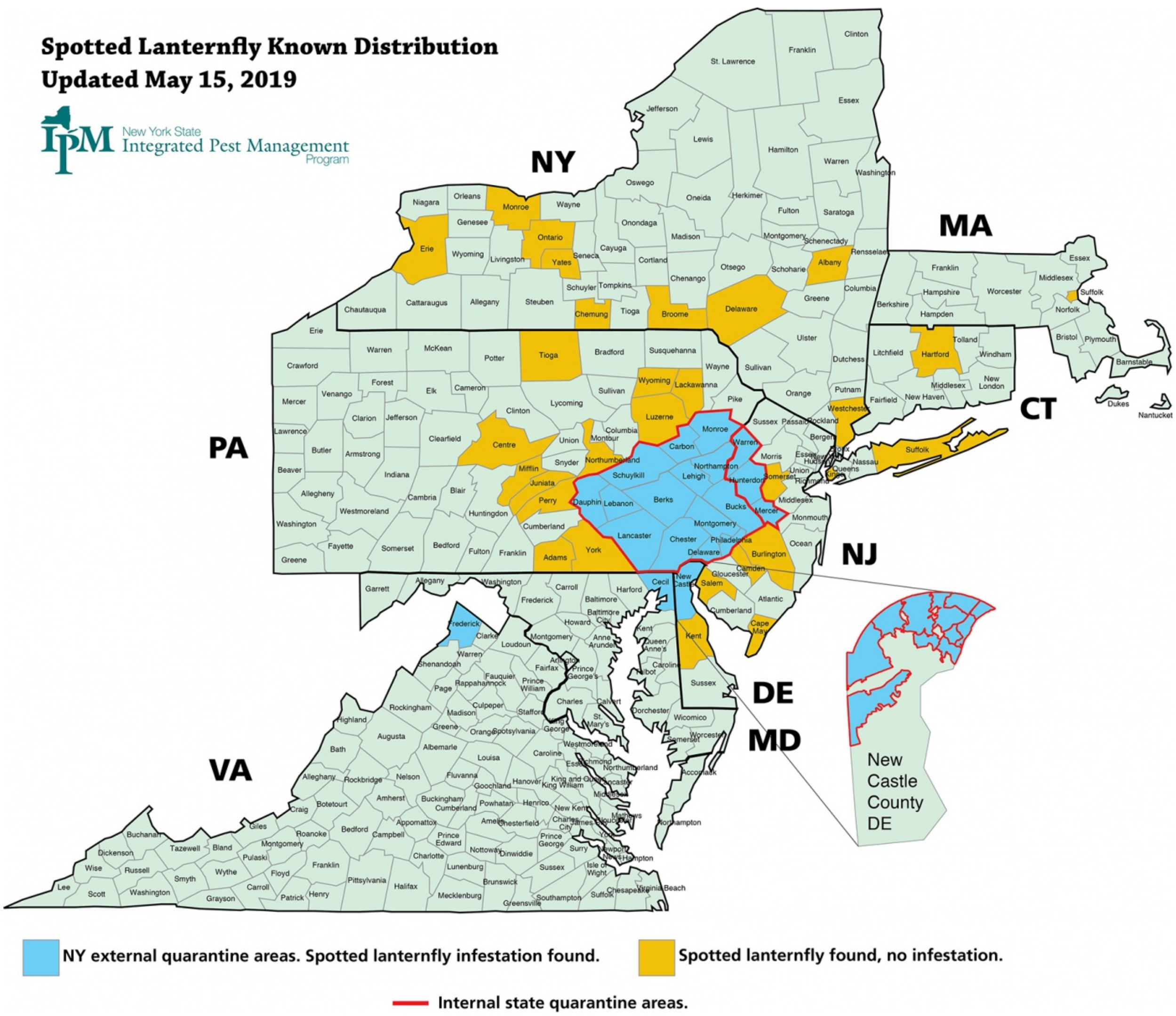

Figure 1. Spotted lanternfly range (last updated May 15, 2019) (New York State Integrated Pest Management Program [NY-IPM], 2019).

Host trees
While spotted lanternfly has a wide range of host plants, it has a strong preference for the invasive tree-of-heaven (*Ailanthus altissima)* (Swackhamer, Jackson, & Gover, 2017). Host trees that are most relevant to Marsh-Billings-Rockefeller include cherry (*Prunus spp.)*, maple (*Acer spp.)*, oak (*Quercus spp.*), and poplar (*Populus spp.)*. Spotted lanternfly also affects agricultural and nursery crops including: almonds, apples, apricots, grapes, hops, nectarines, peaches, and plums.

Historical impact
Since it was discovered very recently (2014), little is known about its potential long-term impact. It has spread through southeastern Pennsylvania, with some sightings in neighboring states, and a quarantine has been imposed in counties in which it is present. Movement of plants, plant-based materials, and outdoor items is strictly regulated to prevent human-assisted spread (Penn State Extension, n.d.).

Life history
There is one generation of spotted lanternfly per year (Figure 2). Eggs are laid in the fall and hatch in the spring, with 30-50 eggs per egg mass (Leach, Biddinger, & Krawczyk, 2019). Spotted lanternfly then goes through four nymph stages (instars) after hatching before becoming an adult. The first three stages are black in color with white spots, while the last stage before adulthood is red with white dots and black stripes. Adults emerge in July and are active until winter—during this time, they are most detectable due to their large size (1 in. (2.5 cm) long and ½ in. (3.8 cm) wide at rest) and mobility (Leach et al., 2019; Simisky, 2018). However, their colorful wings are not usually visible because they jump more than they fly (Leach et al., 2019; Pennsylvania Department of Agriculture, n.d.b).

Dispersal
Long-distance dispersal of spotted lanternfly is thought to be a result of moving outdoor items containing egg masses, leading to the restriction of movement of plants, plant-based materials, and outdoor items in counties in which it is present. Adults disperse widely to lay eggs on a variety of surfaces (Simisky, 2018). Additional studies on dispersal mechanics are needed.

Detection

Signs and symptoms
Spotted lanternfly uses its piercing-sucking mouthparts to feed on the sap in trunks, branches, twigs, and leaves, which leaves weeping wounds with grayish-black trails on the trunk of a tree (Penn State Extension, n.d.; Pennsylvania Department of Agriculture, n.d.b).

The excretions of "honeydew" as lanternflies feed can attract other insects such as ants, bees, and wasps (Penn State Extension, n.d.; Pennsylvania Department of Agriculture, n.d.b). This honeydew can cover the host tree and the ground around it and encourage fungal growth (e.g. sooty mold), increasing the host tree's chances of mortality (Penn State Extension, n.d.).

Egg masses can be seen in late fall on host trees and smooth surfaces (stone, outdoor furniture, vehicles, and other structures) (Figure 3). Egg masses appear gray, resembling mud, and can become dry and cracked over time (Leach et al., 2019; Pennsylvania Department of Agriculture, n.d.b).

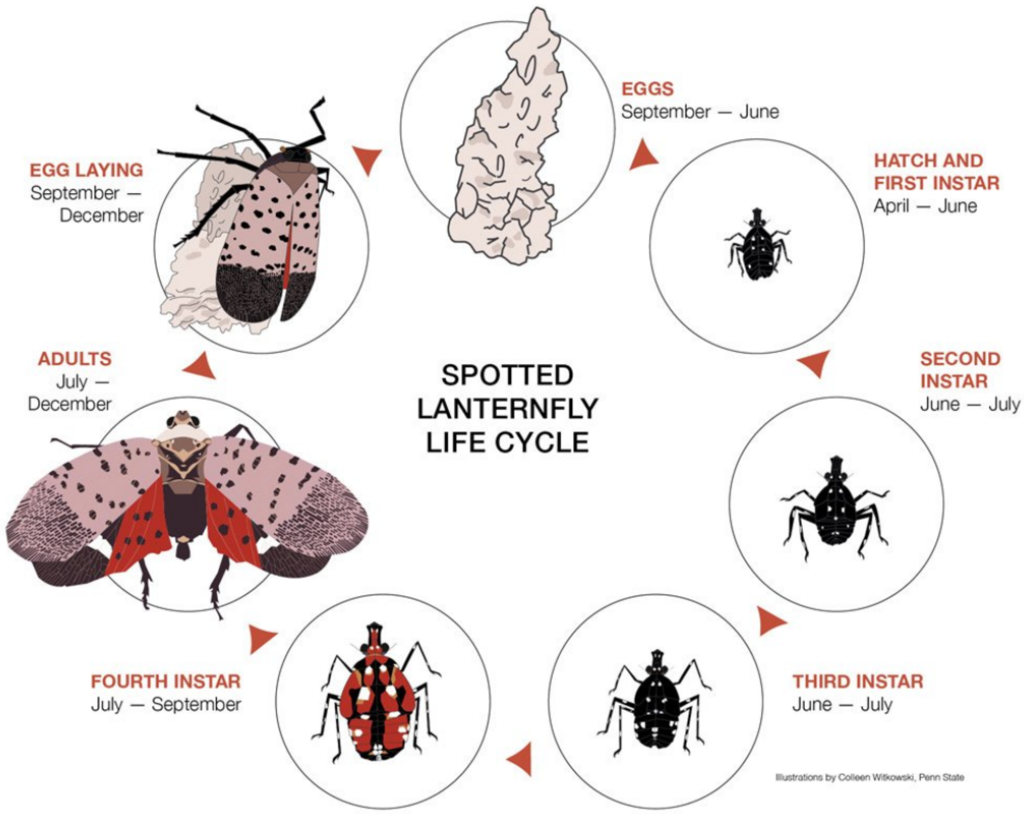

Figure 2. Spotted lanternfly life cycle, illustrated by Colleen Witkowski (Penn State Extension, n.d.).

Figure 3. Spotted lanternfly egg mass (Pennsylvania Department of Agriculture, n.d.b).

Monitoring

Egg mass surveys should be conducted in late fall to early spring on host trees and nearby smooth surfaces (Leach et al., 2019; Pennsylvania Department of Agriculture, n.d.b). See 'Signs and symptoms' and 'Life history' for more information on egg masses.

Methods of control

The best management options currently available for spotted lanternfly are mechanical and chemical treatment, but no species-specific options exist (Table 1). Egg masses and nymphs may be removed and destroyed for population control. A range of general insecticides is available, though further study is needed. See the calendar of management options below for guidance on timing management actions (Figure 4). As described in the introduction, all pest control methods may have side effects that need to be considered in the decision-making process.

Table 1. Summary of spotted lanternfly control methods.

Category	Treatment	Application method	Effectiveness	Timing	Life stage	Non-target effects
Chemical	See Table X1.					
Mechanical	Destroying egg masses	N/A	Low	Late Fall to early Spring	Egg	None
Mechanical	Removing host species (tree-of-heaven)	Harvest	High	-	All	None
Mechanical	Sticky tape	Trap	Low	Before May (when nymphs emerge)	Nymph	Low

Note: a hyphen signifies that either data was not readily available and more research is necessary, or the cell is not applicable to the treatment.

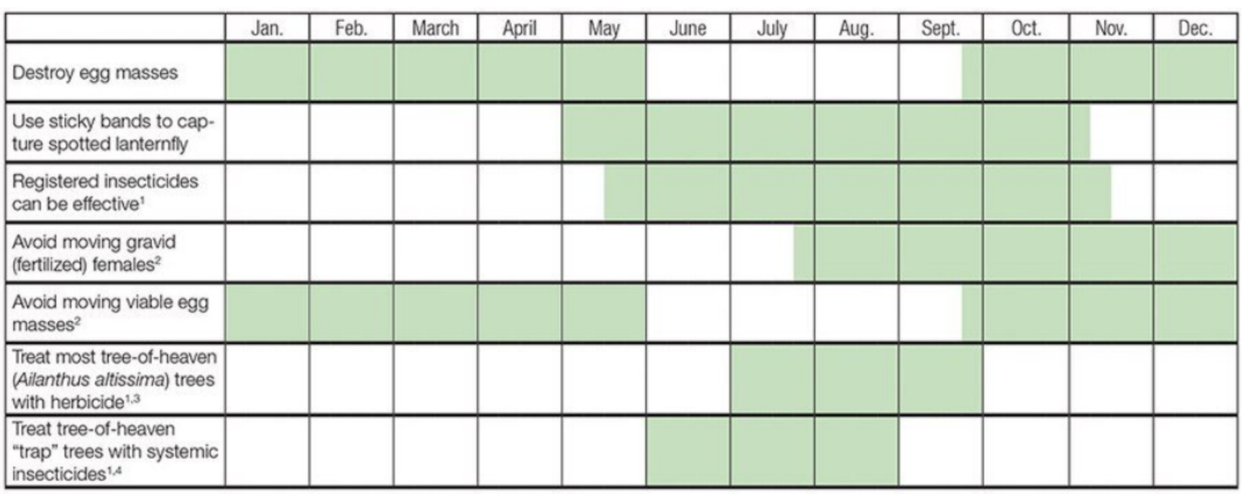

Figure 4. Best times to use management practices for spotted lanternfly in Pennsylvania (Swackhamer et al., 2017).

Chemical

Research is ongoing to identify which insecticides are most effective for use against spotted lanternfly. The insecticides listed below in Table 2 are not specific to spotted lanternfly and should be used only on trees with a heavy infestation. Systemic insecticides are most effective in early summer (July) before adult emergence but can also be applied later in the season to kill adults. They should always be applied during the growing period (Leach et al., 2019).

Table 2. Insecticides effective against spotted lanternfly (adapted from Leach et al., 2019).

Active Ingredient	Mode of Exposure	Available Products	Legal Use	Activity Against SLF	Residual Activity
Bifenthrin	Contact	Talstar P	Ornamental and landscape plants and trees	Excellent	Excellent
Carbaryl	Contact	Garden Tech Sevin Ready-to-Spray Bug Killer (note: new formulation is sold with zeta-cypermethrin)	Vegetable and ornamental plants and trees under 10 feet tall	Excellent	Good
Dinotefuran	Systemic/contact	Safari 20SG, Transect 70 WSP, Zylam Liquid	Ornamental and landscape plants and trees	Excellent	Excellent
Imidacloprid	Systemic/contact	Bayer Advanced 3 in 1 Insect Disease Mite Control, Bonide Annual Tree & Shrub Insect Control	Ornamental and landscape plants and trees	Excellent	Good
Insecticidal soaps*	Contact	Garden Safe Insecticidal Soap	Vegetables, fruit trees, ornamentals, shrubs, flowers, and gardens	Good	Poor
Malathion	Contact	Spectracide Malathion Insect Spray	Flowers and bushes, fruit, and vegetables	Excellent	Poor
Natural pyrethrins	Contact	Garden Safe Multi-Purpose Garden Insect Killer, Natria Insect Mite and Disease Control	Vegetables, ornamentals, trees, shrubs, and flowers	Excellent	Poor
Neem oil*	Contact	Bonide Neem Oil	Flowers, ornamental trees and shrubs, fruit, nuts, and vegetables	Good	Poor
Spinosad*	Systemic	Bonide Captain Jack's Deadbug Brew	Outdoor ornamentals, fruit, and vegetables	Fair	Poor

Active Ingredient	Mode of Exposure	Available Products	Legal Use	Activity Against SLF	Residual Activity
Tau-fluvalinate, tebuconazole	Contact/systemic	BioAdvance 3 in 1, Insect, Disease and Mite Control	Nonedible plants only, groundcovers, vines, ornamentals, shrubs, and trees	Excellent	Good
Zeta-cypermethrin	Contact	Amdro Quick Kill Outdoor Insect Killer Concentrate	Lawns, trees and shrubs, roses, and flowers	Excellent	Excellent

*Recommended for organic production.

Note: The listing of products in this table is not an endorsement or specific recommendation of the product or the company. Other products with the same active ingredient should also work in the same way, but they may have different rates or formulations.

Application methods of insecticides include tree injection, bark spray, soil drench, and direct spray (Leach et al., 2019). The USDA uses dinotefuran tree injections and bark spray on tree-of-heaven to manage spotted lanternfly, but both methods have residual activity lasting from several weeks to several months. While bark spray works well for spotted lanternfly control, it must be mixed with a bark penetrant to be effective and its effects are delayed—it can take from several days to several weeks to be effective. Soil drenches work best in early summer on trees that have had high spotted lanternfly populations in the past. To protect native pollinators, they should be applied after flowers have faded. Like bark sprays, their effects are also delayed up to several weeks. If immediate results are desired, direct sprays are applied to surfaces where the insect could be found or directly on nymphs and adults (Leach et al., 2019).

Mechanical

Mechanical methods of control include killing egg masses, using sticky tape to catch newly hatched nymphs, and removing tree-of-heaven (preferred host). Egg mass surveys should be done in late fall to early spring and should include nearby smooth surfaces as well as host trees. If egg masses are found, they can be scraped off and killed. Options for disposal include double bagging in plastic bags and throwing away, burning, or placing the egg masses in alcohol or hand sanitizer (Leach et al., 2019; Pennsylvania Department of Agriculture, n.d.b). Sticky tape acquired from horticultural centers can be placed around heavily infested trees (Leach et al., 2019). As nymphs hatch and travel up the tree to feed on new growth, the tape will catch them and prevent further development. It can also sometimes catch adults, but it is most effective against nymphs. The easiest way to avoid accidentally trapping birds and small mammals is to reduce the width of the tape (an exact width is not listed), which maintains effectiveness against spotted lanternfly. Another more intensive option is setting up a cage around the diameter of the tape. Tape should be checked and replaced at least every other week. The best time to place sticky tape is before nymphs hatch in May (Penn State Extension, n.d.). As of 2019, the invasive preferred host of spotted lanternfly, tree-of-heaven, is not established in Vermont. In areas with heavy spotted lanternfly infestations, removing tree-of-heaven is necessary to manage the pest population (Leach et al., 2019). It is still unclear if there are benefits to removing other potential host trees.

Management scenarios

'Do nothing'

Tree-of-heaven, the preferred host of spotted lanternfly, is not currently established in Vermont or New Hampshire. However, the introduction of spotted lanternfly to the park could still cause damage to the lanternfly's other hosts: cherry, maple, oak, and poplar. As mentioned above in 'Historical impact', very little is known about the long-term impacts of spotted lanternfly on host trees and on forests. It is also unknown if the pest can invade non-urban settings and how native tree species would respond if this occurred.

Single-tree protection

General insecticides are currently available for protection of individual trees against spotted lanternfly, and their use should be limited to trees with current or prior heavy infestations. Please see the section above on chemical control for further detail on treatment strategies. In areas with established tree-of-heaven, removal of host trees is an important management technique. Removal of other host trees has not been investigated yet and is not a current option for single-tree protection (see 'Mechanical').

Stand-level protection

There is no research currently available on stand-level protection. Since use of insecticides is limited to heavy infestations, there is no reliable method for spotted lanternfly control in its early stages. Egg masses and host trees may be removed and killed, but it is unclear if this would control stand-level populations.

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Winter moth

Operophtera brumata

Background

Current range

Winter moth, a destructive defoliator with a wide range of host species, was first recorded outside of its European native range when it was found in Nova Scotia in the 1930's (Maine Department of Agriculture, Conservation & Forestry, Maine Forest Service [Maine-FS], 2013; O'Donnell, 2015). Later, it was also detected in the Pacific Northwest in the 1970's (Maine-FS, 2013; O'Donnell, 2015). It was not identified in the northeastern US until 2003, and within two years, the population rapidly expanded to Long Island, Connecticut, Massachusetts, Rhode Island, New Hampshire, and Maine (Elkinton, Boettner, Liebhold, & Gwiazdowski, 2015).

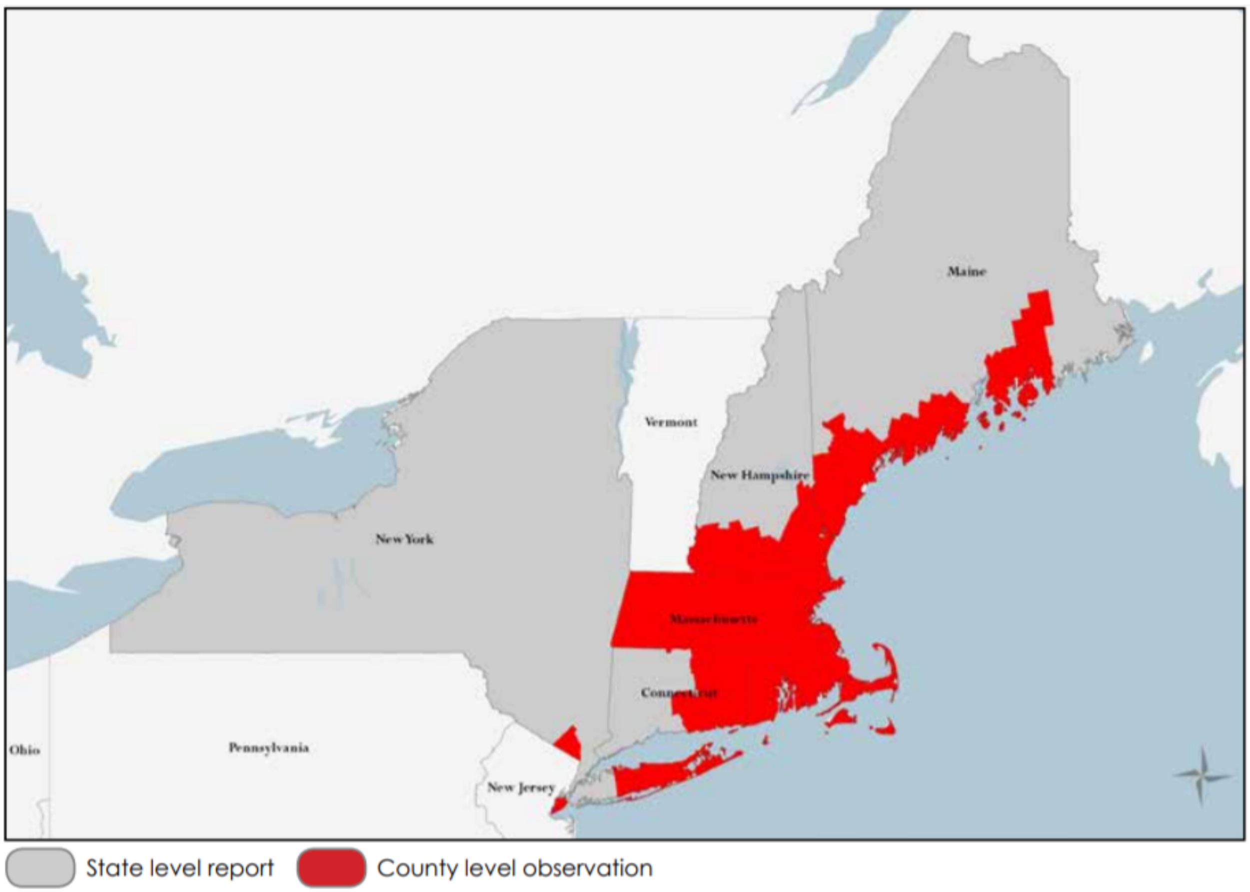

Figure 1. Winter moth range as of March 25, 2019 (U.S. Department of Agriculture, Forest Service, Northern Research Station and Forest Health Protection [USDA-FS], 2019).

Host trees

Winter moth attacks a wide range of hosts, with few trees going untouched in high-density outbreaks (table 1).

Table 1. Selection of common North American host species of winter moth (Cuming, 1961; Gillespie, Finlayson, Tonks, & Ross, 1978; Nestby, Percival, Martinussen, Opstad, & Rohloff, 2011; Tikkanen, Niemala, & Keranen, 2000; Vanbergen et al., 2003; Wint, 1983).

COMMON NAME	LATIN NAME
Maple	*Acer* spp.
Birch	*Betula* spp.
Common hawthorn	*Crataegus monogyna*
Ash	*Fraxinus* spp.
Apple*	*Malus* spp.
Quaking aspen	*Populus tremuloides*
Cherry*	*Prunus* spp.
Oak*	*Quercus* spp.

**Preferred hosts*

More recently, larval feeding has also been observed on lowbush blueberry (*Vaccinium angustifolium*) (O'Donnell, 2015). However, oak species have commonly been found to be the preferred host for winter moth, with many studies showing increased larval survival and density on oaks (Feeny, 1970; O'Donnell, 2015; Varley & Gradwell, 1958; Varley, Gradwell, & Southwood, 1968; Wint, 1983). Apples and most cherries are also popular hosts—pin cherry (*Prunus pensylvanica)* supports very low numbers of larvae (O'Donnell, 2015). Since winter moth readily changes hosts during its lifetime, a large number of plant species are at risk during outbreaks (O'Donnell, 2015).

Historical impact
After winter moth was discovered in Nova Scotia, areas with repeated outbreaks (>60% defoliation) experienced increased red oak mortality (Embree, 1967), with no oaks escaping without damage (Cuming, 1961). Similarly, outbreaks in Massachusetts killed many oaks and stunted the growth of many more. Over time, this actually led to a change in forest composition and an increase in woody understory plants (Simmons, Lee, Ducey, & Dodds, 2014).

Life history
Adult winter moths emerge in November-December, but only males can fly (Elkinton, Lance, Boettner, Khrimian, & Leva, 2011). Males emerge several days before females and fly in search of mates (Cuming, 1961; Tikkanen et al., 2000). The flightless females climb to the bases of trees or buildings and release pheromones to attract males (O'Donnell, 2015), which can be detected at temperatures 4-15°C (Roelofs & Brown, 1982). Females then lay about 150 eggs under tree bark or in a crevice (Mass Audubon, n.d.). In late spring, when temperatures reach about 13°C, the eggs hatch and the larvae disperse by "ballooning"—catching wind currents with

silk threads that they create (Cuming, 1961; Maine-FS, 2013; O'Donnell, 2015). Since females cannot fly, the natural spread of winter moth depends on larval ballooning. They can be carried significant distances under the right conditions—larvae have been recorded traveling up to several hundred meters on silk and being able to survive up to 5 days without feeding gives them greater opportunity to disperse (Cuming, 1961; Edland, 1971; Holliday, 1977).

Larvae balloon into tree canopies to find buds to feed on, but larval survival greatly depends on the synchrony between egg hatch and bud burst (O'Donnell, 2015). If bud burst is late and buds are too tightly closed, larvae will move on in search of opening buds. In England, it was found that oaks with earlier bud burst were damaged more severely than oaks with later bud burst (Varley & Gradwell, 1958). Larvae feed until June and then drop from tree canopies to pupate in the soil (Maine-FS, 2013).

Cyclical outbreaks of winter moth are common in its native range and have been observed in its introduced range. However, while outbreaks in winter moth's native range happen on a 9-10 year cycle (Ims, Yoccoz, & Hagen, 2004; Varley et al., 1968; Varley & Gradwell, 1960), they have been much more frequent in its introduced range and occur about every two years (O'Donnell, 2015).

Detection

Signs and symptoms

The most visible sign of damage is defoliation of trees and shrubs in the spring. While healthy trees can endure a defoliation event, trees that are stressed or defoliated repeatedly can experience branch dieback and mortality (Maine-FS, 2013).

Identification of winter moth is complicated by the fact that it is extremely difficult to tell apart from the native Bruce spanworm (*Operophtera bruceata)* in a lab setting, and impossible to do in the field (Maine-FS, 2013; O'Donnell, 2015). This is a major reason why outbreaks in the introduced range of winter moth were not readily recognized as the work of a non-native pest (O'Donnell, 2015).

Methods of control

Several biological and chemical treatments exist to control winter moth (Table 2), and active research is expanding understanding of these methods. As described in the introduction, all pest control methods may have side effects that need to be considered in the decision-making process.

Biological

Currently, the highly specialized parasitic fly, *Cyzenis albicans*, is the most promising biological control agent of winter moth. *Cyzenis albicans* was highly successful at controlling winter moth in Nova Scotia and in the Pacific Northwest after a few years of lag time, but was not tested in the northeastern US until 2005. A study led by an entomologist at UMass Amherst released a few hundred flies in eastern Massachusetts in 2005 and 2006 (Elkinton et al., 2011). After *C. albicans* was found successfully parasitizing winter moth at study sites, Elkinton released 700 more at 9 new sites in 2011 (UMass Amherst, 2011). They believe the lag time in the establishment of *C. albicans* is similar to patterns in the Pacific Northwest, and that populations should begin to increase in the northeastern US.

Table 2. Summary of winter moth control methods.

Category	Treatment	Application method	Effectiveness	Timing	Life stage	Non-target effects
Biological	*Bacillus thuringiensis (kurstaki)*	Bacterium	High	Early-mid April to late May/early June	Larvae	Low
Biological	*Cyzenis albicans*	Parasitoid	High	-	Larvae	None
Chemical	Horticultural oil	Spray	Low	November to late March	Egg	Low
Chemical	Pyrethroids	Spray	High	Late March to early-mid April	Egg hatch	High
Chemical	Spinosad	Spray, systemic insecticide	High	Early-mid April to late May/early June	Larvae	Low
Mechanical	Sticky tape	Trap	Low	November	Adult females	Very low

Note: a hyphen signifies that either data was not readily available and more research is necessary, or the cell is not applicable to the treatment.

However, parasitoids were not a constant cause of mortality in the native range of winter moth despite being a significant factor. Winter moth populations are generally too low to sustain *C. albicans* annually, naturally causing the fly population to decrease (Varley et al., 1968). While this means that there is little concern for *C. albicans* growing to uncontrollably high population levels, winter moth populations in the northeastern US must also be high enough for it to be an effective management technique.

Other alternative methods of control include a number of generalist parasitoids (Vindstad et al., 2013; Wylie, 1960), pathogens (Burand, Kim, Welch, & Elkinton, 2011; Raymond et al., 2002), and parasitic nematodes (Tomalak, 2003). However, generalist parasitoids have far underperformed *C. albicans* in establishment and winter moth control, and nematodes and pathogens have not been fully explored as methods of control.

Bacillus thuringiensis (kurstaki), or B.t.k., must be ingested by winter moth larvae to be effective (Childs et al., 2017). After entering the gut, the bacterium multiplies and kills the larvae within 1-3 days. Because B.t.k. is not specific to winter moth, there is some concern about affecting native Lepidopteran species. However, because the area of treatment is usually relatively small (an individual tree vs. the whole forest), non-target effects are usually limited (Childs et al., 2017).

Chemical

Horticultural oil spray can be used on trunks and branches in early April to kill eggs, but this is not completely effective as some eggs may be protected by bark (Childs, Swanson, Elkinton, Simisky, & Boettner, 2017; Maine-FS, 2013).

Spinosad is a biorational insecticide (derived from a bacterium) that attacks the nervous system (Childs et al., 2017). It can be used both as a contact spray and as a systemic insecticide, and is effective against all larvae instars. While its non-target effects are generally low, it should not be sprayed when flowering trees are in bloom to minimize effects on foraging bees.

The best chemical insecticide option is the pyrethroid group, but effects are much harsher on non-target organisms (Childs et al., 2017). They are generally applied at egg hatch, but pyrethroids range in toxicity and timing application may be difficult because of their ability to persist in the environment.

Mechanical

Products that act as barriers to the movement of adults are available, such as sticky strips that are attached at the base of a tree. These can be used in November when females are climbing trees to signal to males, but it is not always effective method as females can crawl under sticky traps or find a different uncovered vantage point (Maine-FS, 2013).

Management scenarios

'Do nothing'

Little is known about the individual tree impacts of winter moth defoliation in New England. Based on historical impacts, allowing outbreaks to occur repeatedly could eventually lead to stunted growth and mortality of oak. A recent study looking at effects of winter moth defoliation on oak growth determined that annual radial growth could be reduced by as much as 47% in association with defoliation, with earlywood production the following year reduced by up to 24% (Simmons, Lee, Ducey, Elkinton et al., 2014). The radial growth of maple species was not strongly associated with winter moth defoliation (Simmons, Lee, Ducey, Elkinton et al., 2014). Increased light levels due to oak mortality may also result in an increase in understory woody plant density (Simmons, Lee, Ducey, & Dodds, 2014).

Single-tree protection

There is currently no effective way to treat individual trees beyond horticultural oils. High-value trees may warrant the labor-intensive application, but rough bark that is able to conceal winter moth eggs may make it more difficult to treat mature trees.

Stand-level protection

Biological control using *C. albicans* is currently the best option for stand-level protection against winter moth, especially when populations reach outbreak-level. While studies are still tracking the effectiveness of *C. albicans* on the east coast, it has already been successful at controlling winter moth populations on the west coast and became established in Massachusetts in the past few years.

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