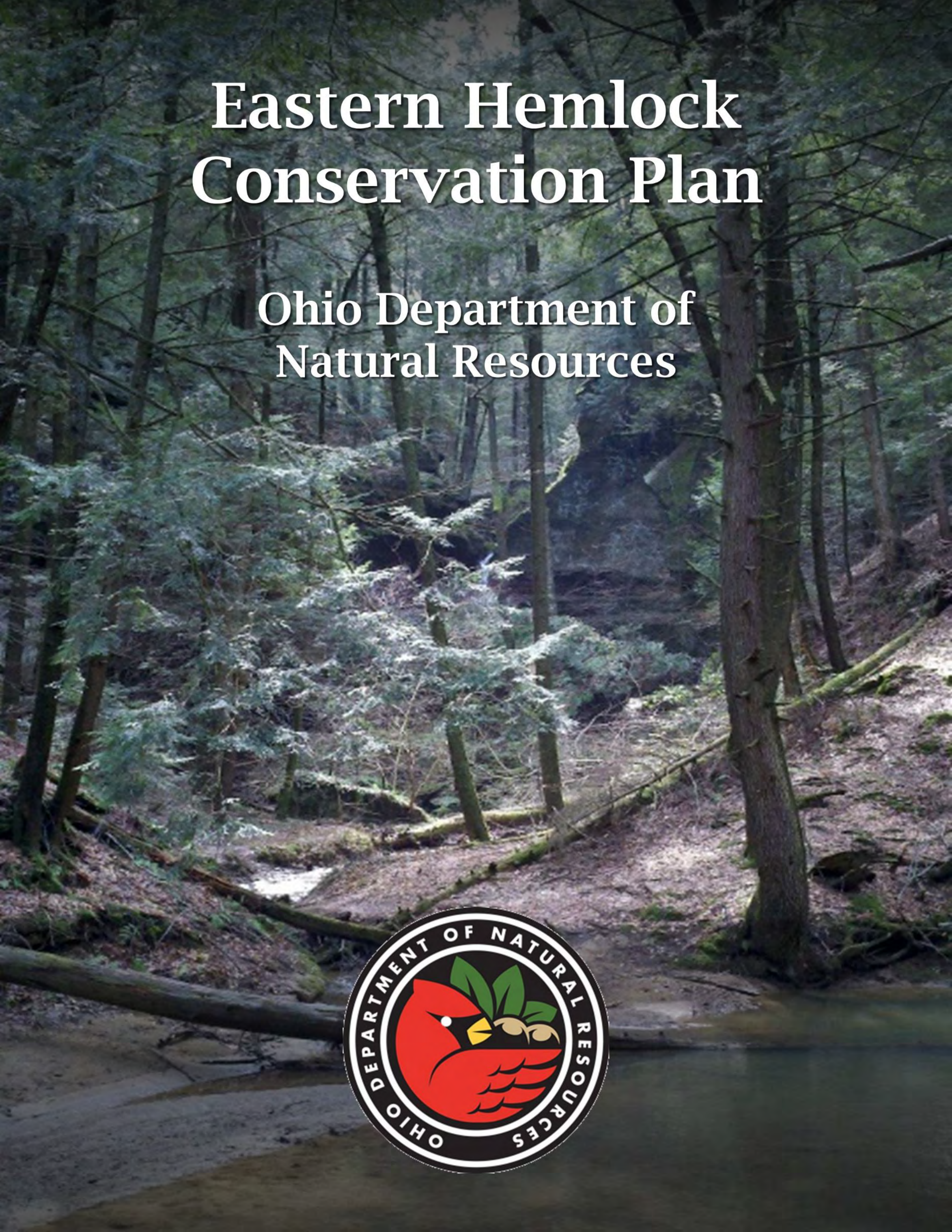
Eastern Hemlock Conservation Plan

Ohio Department of Natural Resources



EXECUTIVE SUMMARY

Eastern hemlock (*Tsuga canadensis*) is a very important evergreen coniferous tree species native to Ohio. It is commonly planted as a landscape tree throughout the state, and grows in natural forest stands, mainly in the eastern half of Ohio. These unique forests have significant ecological value as well as tourism value. The hemlock woolly adelgid (*Adelges tsugae*; HWA) is a non-native invasive insect that has caused widespread mortality of eastern and Carolina hemlock (*T. caroliniana*) since its accidental introduction to Virginia in the 1950s. This insect, along with several other pests and diseases, has the potential to functionally eliminate eastern and Carolina hemlock from their native ranges.

As a result of multiple findings of HWA in areas of southern Ohio since 2012, meetings were held starting in early 2014 to develop a hemlock conservation plan for lands owned and managed by the Ohio Department of Natural Resources (ODNR). At that time, grant funding provided to the ODNR Division of Forestry by the United States Department of Agriculture (USDA) Forest Service for survey and treatment of HWA allowed for quick and effective treatment of all HWA infestations found on ODNR lands. However, in the future, it may not be possible to manage all known HWA or other pest infestations individually. As such, it was clear that a plan identifying the "best" eastern hemlock forests in the state, on which to focus conservation efforts, was necessary. As directed by the Director of ODNR, personnel from the major land-managing ODNR Divisions (Forestry, Natural Areas & Preserves, State Parks & Watercraft, and Wildlife) have developed this plan for the purpose of identifying the highest quality eastern hemlock forests in the state, guiding survey for HWA and other eastern hemlock pests, and to establish protocols for the use of chemical and biological treatments for those pests on ODNR lands. Existing HWA management plans and strategies from other states were valuable tools in informing the creation of this plan. Input was also provided by partner groups through the Ohio HWA Task Force, a USDA Forest Service grant-funded collaboration, which includes participants from government agencies, non-governmental organizations (NGOs), and academic institutions that have an interest in, or manage, eastern hemlock forests in Ohio.

Various datasets were used to "rank" the conservation value of stands of eastern hemlock in Ohio. Those datasets included high-quality streams, records of rare and threatened plants and wildlife species, recreational trails, and roads. Eastern hemlock stands where a greater number of these attributes exist were ranked as having a higher conservation value than those stands in which fewer or none of these attributes exist. Stands with a higher conservation value will be surveyed more often for the presence of eastern hemlock pests and will receive more proactive treatment activities if an infestation is identified within them. This plan is intended as a guide for protocol to detect eastern hemlock pests and minimize their impacts. The recommendations within the plan can be modified and will be updated as needed based on new information or tools, funding levels, or by land managers based on their knowledge of local areas. The methodology and recommendations in this plan can be adapted and used by other land-managing organizations or private landowners for detecting and managing HWA on their lands.

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I. INTRODUCTION AND BACKGROUND

Eastern hemlock (*Tsuga canadensis*) is a coniferous evergreen tree species native to eastern North America. In Ohio, eastern hemlock occurs in pure and mixed-species forests mainly in the eastern half of the state on the Glaciated and Unglaciated Allegheny Plateaus (Figure 1). This tree species is also widely planted within and outside its native range as an ornamental landscape plant. Eastern hemlock forests are an uncommon forest type in Ohio and occupy approximately 33,000 acres; less than 0.5% of Ohio's forests (Stump 2009; Ellenwood et al. 2015). Eastern hemlock is a very important tree species in Ohio, with significant value to the ecology of the ecosystems where it occurs, in addition to the economy of those areas. This tree species is now threatened mainly due to the non-native invasive insect hemlock woolly adelgid (*Adelges tsugae*; HWA) as well as several other pests and diseases. Millions of eastern and Carolina (*T. caroliniana*) hemlocks have been killed by HWA from the southern Appalachian Mountains into New England (Figure 2). Significant changes in the composition, structure, and function of forests have occurred in areas where hemlock has been lost due to HWA (Orwig and Foster 1998; Jenkins et al. 1999; Ellison et al. 2005; Stadler et al. 2005; Eschtruth et al. 2006). Surveys to locate HWA and biological and chemical suppression of HWA in Ohio have been conducted by various agencies and organizations. Without intervention, this insect has the potential to cause significant mortality of eastern hemlock, resulting in the loss of the valuable ecosystem services the tree species provides, rendering it "functionally extinct" (Hessl and Pederson 2013).

Figure 1. Physiographic provinces and sections of Ohio (Brockman 1998).

Figure 2. Eastern hemlock trees killed by HWA in the southern Appalachian Mountains (Dave Apsley).

Biology of Eastern Hemlock

Eastern hemlock is one of the longest-lived and most shade-tolerant tree species in eastern North America. Eastern hemlock is a foundation species; one that has a strong influence on an ecosystem's processes as a result of its structural and functional attributes (Ellison et al. 2005). In the United States, eastern hemlock is the predominant species on over two million acres (McWilliams and Schmidt 2000). Its range extends from Nova Scotia south to Georgia and west to Minnesota (Figure 3). Eastern hemlock can live for over 800 years and can grow to 160 ft in height and over 6 ft in diameter. It can survive in the understory with as little as five percent of full sunlight and often develops very dense, nearly pure stands (Godman and Lancaster 1990). Eastern hemlock can be found on a wide variety of sites, though it is intolerant of drought and most often found growing in moist, well-drained, acidic soils. Eastern hemlock is a component of 25 forest cover types and a major component of the following eastern forest cover types: eastern white pine-hemlock, eastern hemlock, hemlock-yellow birch, and yellow-poplar-eastern hemlock (Godman and Lancaster 1990). Browsing by white-tailed deer (*Odocoileus virginianus*) can be a significant barrier for successful establishment and regeneration of eastern hemlock seedlings (Mladenoff and Stearns 1993; Goerlich and Nyland 2000). Eastern hemlock is a late-successional species that creates understory conditions conducive to its own regeneration and germination while excluding other tree species. Forest floor conditions beneath hemlock stands tend to be cooler and more acidic than those of hardwoods. It is possible for eastern hemlock to withstand decades or even centuries of suppression from overtopping trees. Because of this characteristic, saplings exhibit little direct relationship between stem diameter and age, and individuals up to 100 years old may have stem diameters of only a few inches (Brisbin 1970; Goerlich and Nyland 2000).

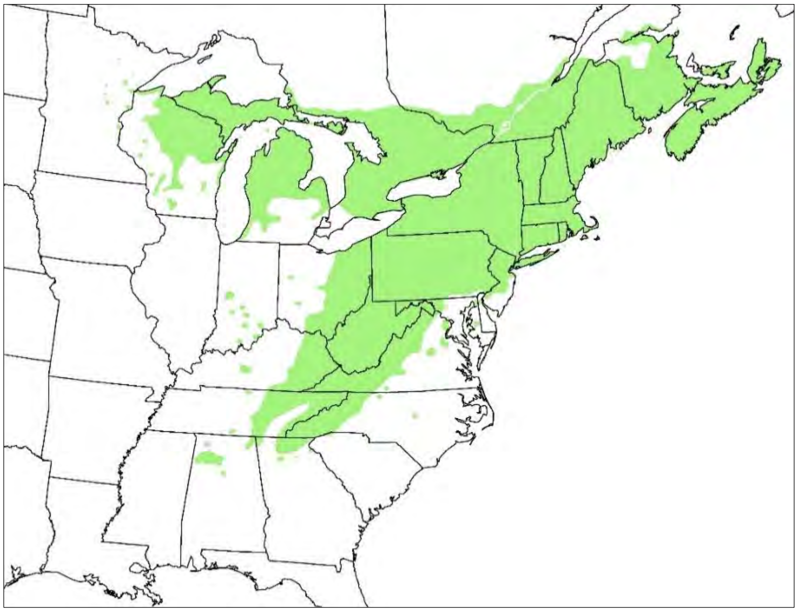

Figure 3. Native range of eastern hemlock (United States Geological Survey 1999).

Importance of Eastern Hemlock

Several unique characteristics of eastern hemlock make it a very important component of the ecosystems in which it occurs. Its dense evergreen canopy and high degree of shade-tolerance increases vertical and horizontal structural heterogeneity, creating the type of habitat required for many species of game and non-game wildlife (Ward et al. 2004). Nearly 100 bird species are associated with eastern hemlock in the eastern United States (Yamasaki et al. 2000). Unlike other conifers, eastern hemlock's shade-tolerance allows its lower branches to retain foliage, providing valuable foraging and nesting sites for mid-canopy bird species (Howe and Mossman 1996). Several avian species, including a few of conservation concern in Ohio (Ohio Division of Wildlife 2015), are strongly associated with eastern hemlock forest ecosystems (Yamasaki et al. 2000). Among these are black-throated green warbler (*Setophaga virens*), blackburnian warbler (*D. fusca*), and winter wren (*Troglodytes hiemalis*).

Eastern hemlock also has a major influence on aquatic systems. The heavy shade produced by the dense canopy of eastern hemlock moderates stream temperatures throughout the year. In the summer months, the cooler stream temperatures benefit cold water fish species. The dense shade and accumulation of organic litter beneath eastern hemlock stands creates a cool, moist microclimate, promoting habitat for wildlife species such as salamanders, fish, and freshwater invertebrates that are intolerant of seasonal drying (Havill et al. 2014). Aquatic macroinvertebrates are primary consumers of leaf litter inputs to streams and constitute a major food source for fish and birds as well as other terrestrial wildlife species. The chemical composition and timing of eastern hemlock litter inputs into streams differs from that of hardwoods and thus influences aquatic macroinvertebrate communities differently. Streams flowing through eastern hemlock forests have been shown to support more aquatic macroinvertebrate taxa than those flowing through hardwood forests (Snyder et al. 2002). The wood of eastern hemlock is very resistant to decay. This characteristic allows downed eastern hemlock wood to remain in streams as large wood jams much longer than associated hardwoods (Hedman et al. 1996;

Wallace et al. 2001; Morris et al. 2006). Ross et al. (2003) found that trout species were at least twice as abundant in eastern hemlock forests versus hardwood forests in headwater streams of the Delaware River basin. There are no other evergreen (or deciduous) tree species native to Ohio that influence the terrestrial and aquatic forest ecosystem processes in the way that eastern hemlock does. The loss of eastern hemlock would drastically change the structure and function of forests in Ohio where it currently exists.

Eastern hemlock has great aesthetic appeal (Quimby et al. 1996). It is a frequently used landscape tree, often planted as a screen or hedge. Hundreds of cultivated varieties of eastern hemlock have been developed (Swartley 1984). Several areas in Ohio, such as the Hocking Hills, Lake Katharine, and Mohican regions (Hocking, Jackson, and Ashland County, respectively) are very popular destinations for outdoor recreationists, due in large part to picturesque eastern hemlock forests. The Hocking Hills region attracts more than three million visitors annually. In 2015, Hocking County's tourism industry generated more than $134 million and supported one in seven jobs (Tourism Economics 2016).

While the value of eastern hemlock wood products is relatively low, there have been efforts to quantify the monetary value of the ecosystem services provided by eastern hemlock forests and how much people are willing to pay to protect eastern hemlock forests. Results of these typically show that the value attributed to these forests greatly exceeds the cost of invasive species control (Costanza et al. 1997; Moore and Holmes 2008). The loss of eastern hemlock due to HWA infestation has been shown to have a significant economic impact (Holmes et al. 2005). Eastern hemlock also has cultural value, as it was used for various purposes by Native Americans and early European settlers. Finally, eastern hemlock forests have educational value, providing opportunities to study many organisms and forest ecosystem processes.

Biology of Hemlock Woolly Adelgid

The hemlock woolly adelgid is an aphid-like insect that is native to hemlock forests of Asia and western North America. These insects are very small (less than 1/16 inch in length), and are easiest to identify on the undersides of hemlock foliage from October through June, when the developing nymphs and adults produce a white, woolly mass less than 1/8 inch in diameter that covers their bodies (Figure 4). HWA was first discovered in eastern North America in Virginia in the 1950s. Genetic analyses have revealed that there are several distinct lineages of HWA in their native ranges. The HWA introduced to eastern North America were likely accidentally imported on trees from Japan, as they are genetically identical to the lineage that is native to southern Japan (Havill et al. 2006). As of 2015, this insect is known to be present in 20 eastern North American states (Figure 5).

Figure 4. Eastern hemlock twig lightly infested with several HWA woolly masses (left) and eastern hemlock branch heavily infested with HWA (right).

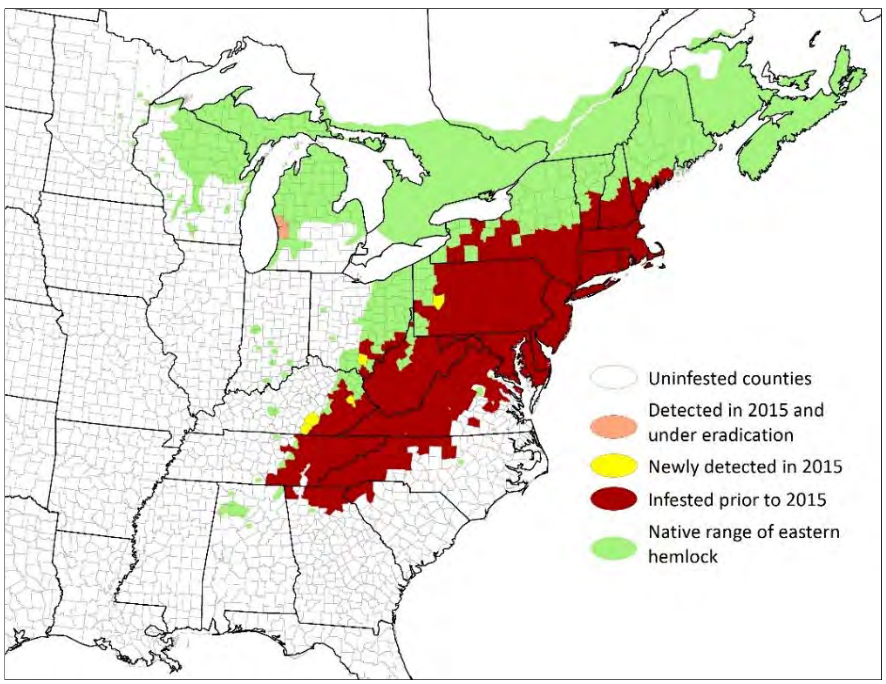

Figure 5. The distribution of HWA in the eastern United States as of 2015 (data provided by USDA Forest Service).

The lifecycle of HWA is somewhat complex and there are two generations annually (Figure 6). HWA can reproduce both sexually and asexually. In Japan, HWA survives and reproduces on a hemlock (*T. sieboldii*) and a spruce species (*Picea torano*). On the spruce species, there is a sexual generation. When the spruce species is absent, as in eastern North America, HWA reproduces only asexually on hemlock.

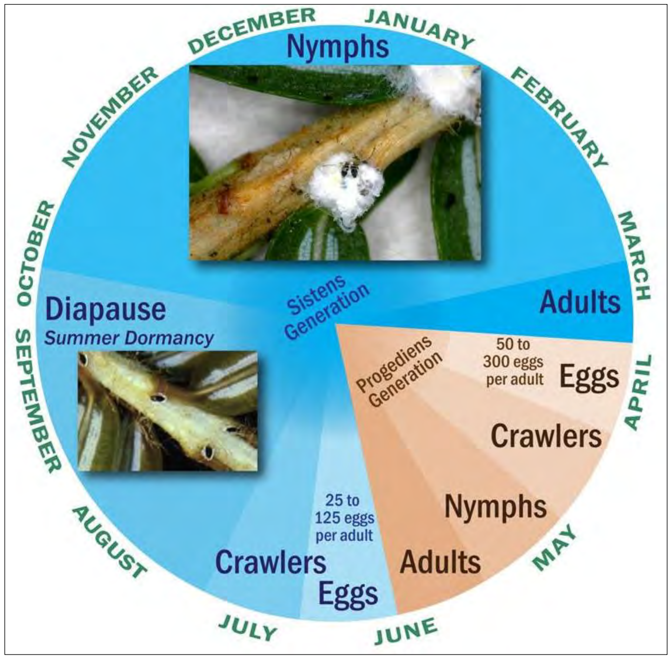

Figure 6. The annual lifecycle of HWA (adapted from Cheah et al. 2004).

One of the two generations, known as the "sistens" generation (from the Latin "to halt"), occurs from early-summer through the autumn and winter into early spring. After hatching from eggs, first instar nymphs, also known as "crawlers" (the only mobile stage of HWA that contributes to its spread in eastern North America), move to a suitable feeding site at the base of a hemlock needle where they attach by inserting their stylet mouthparts. Maturing nymphs and adults feed on stored carbohydrates in the xylem ray cells (Young et al. 1995). They will stay attached at the feeding site for the remainder of their lives. It is in this crawler stage that HWA can be transported short distances by wind or longer distances by wildlife (especially on birds) or human movement of infested plant material (McClure 1990). The nymphs then enter a stage of dormancy, or diapause, during the hot summer months. Feeding and development resume in the autumn, when maturing nymphs produce the characteristic white woolly covering.

By about March, HWA have matured into adults and each lays up to 300 eggs. By April the eggs hatch, marking the start of the "progrediens" generation (from the Latin "to proceed"). The individuals of this generation that are winged, fly away in search of a suitable spruce host, and in eastern North America, they fail to reproduce. This generation does not experience a diapause, and quickly develops from crawlers to adults by about June. These adults will lay up to 75 eggs, which will hatch to reinitiate the sistens generation.

Cold winter temperature is the major cause of HWA mortality in eastern North America (Havill et al. 2014). The lethal temperature for HWA varies depending on such factors as the time of year and duration of exposure to cold temperatures, but winter mortality upwards of 80% has been documented in certain regions (Struble et al. 2011), including in Ohio. Only the sistens generation, however, experiences the winter, and those individuals that do survive the winter lay eggs, initiating the progrediens generation, thus allowing populations to rebound rather quickly. Climate change and the possibility of HWA adapting to colder winter temperatures may lead to accelerated expansion of HWA's distribution (Butin et al. 2005).

The feeding behavior of HWA depletes nutrients stored in the needles and twigs of hemlock trees. There is also thought to be a hypersensitive response by the tree that inhibits water movement (Radville et al. 2011). Time from initial HWA infestation to tree death can vary widely, and initial tree health along with certain biotic and abiotic stressors, such as the presence of other insect or disease pests and climate, can be important factors. Eastern hemlock trees of any age and size can be infested, although the larger canopy trees tend to become more heavily infested and are killed faster than smaller understory trees and saplings. In the southern Appalachians, trees have been killed by HWA in as few as four years, while there are trees in the northern area of the HWA infestation that have survived for more than 15 years following initial infestation (Havill et al. 2014). This is likely the result of reduced HWA populations in the north due to cold-induced mortality in the winter.

History of Hemlock Woolly Adelgid Management in Ohio

Survey efforts focused on identifying infestations of HWA in Ohio began in 2002 by the Ohio Department of Natural Resources (ODNR) Division of Forestry and the Ohio Department of Agriculture (ODA). The ODA has typically focused their efforts on nurseries, while the ODNR Division of Forestry has focused on forested areas where eastern hemlock occurs. Much of the HWA survey work done by the ODNR has been funded through federal grants from the United States Department of Agriculture (USDA) Forest Service.

Since 2002, HWA has been detected in Ohio several times on nursery stock or in landscape settings, discovered by nursery inspectors with the ODA, or reported to state agencies by landowners. In each case, the infestations were promptly eradicated by ODA with assistance from ODNR either through destruction of the infested plant material or treatment with chemical insecticides. This rapid response to newly discovered infestations well ahead of the HWA "infestation front" is critical to slowing the spread of HWA to uninfested eastern hemlock forests. In 2012, HWA was found for the first time in a natural forested setting in southeastern Ohio within both Shade River State Forest and adjacent Forked Run State Park (Meigs County). This infestation differed from previous findings of HWA in Ohio, in that it was believed to have been the result of dispersal of HWA from nearby infested trees in West Virginia, via wind or wildlife, rather than arriving on infested landscape plants. Initial attempts to eradicate this infestation included the removal and burning of confirmed infested trees, but additional infested trees at this location were discovered soon after, necessitating a shift in management strategy. Since 2012, several additional HWA infestations have been found in Ohio.

All of the HWA infestations on state land discovered since 2012 have been or are being managed using chemical insecticides (via soil drench, trunk injection, or basal bark spray methods using imidacloprid or dinotefuran). These chemical treatments have been overseen by licensed pesticide applicators from the ODNR, ODA, and other partner organizations. These operations have been funded in large part by federal grants provided by the USDA Forest Service. Quarantines have been enacted by the ODA restricting the movement of any hemlock material from known infested counties into non-infested Ohio counties. The quarantine law also requires hemlock materials grown in non-infested counties in quarantined states to be inspected before being shipped and have a phytosanitary certificate verifying that the plant material is free of HWA when entering Ohio (State of Ohio 2015). The ODA has the authority to chemically treat or remove HWA-infested materials from private land (State of Ohio 1969).

Systemic insecticide treatments in Ohio have seemingly been very effective. Assessments are ongoing to determine reduction in HWA populations post-treatment. Imidacloprid has been the most commonly used systemic insecticide in Ohio. This chemical, while slow to take effect, has been shown to reduce the amount of HWA by greater than 99% three years after treatment (Cowles 2009). Dinotefuran is another systemic insecticide that has been used in Ohio and is taken up quicker into the foliage of the tree. The reduction of HWA populations at treatment sites in Ohio have ranged from 80% to 100%, although other factors, such as minimum winter temperatures (especially the colder than average winters of 2013-14 and 2014-15) could have played a role. Chemical control is critical in slowing the spread of HWA from small, newly established infestations out ahead of the generally-infested "advancing front" of HWA infestation. Success in limiting the spread and impacts of HWA at these sites is much more achievable than near the generally-infested zone, where re-infestation post-treatment is much more likely in the short-term. Chemical treatments are being used as a rapid response measure to reduce the population of HWA until a more sustainable, long-term solution can be employed, such as the establishment of biological control populations.

In addition to chemical suppression techniques, biological controls have been used in Ohio. As biological control agents become available, they are provided to forest health staff in states with HWA infestations through federal partnerships. In Ohio there have been several releases of two species of beetle (*Laricobius nigrinus* and *L. osakensis*) that prey on all of the life stages of HWA since 2013. Beetles released in Ohio have been shipped from the Virginia Tech University rearing facility as part of a multi-state collaborative effort and they have been field-collected from established populations in North Carolina and Washington. In Ohio, they have been released on private land, with landowner permission, at "field insectaries," in attempts to establish reproducing populations of predator beetles as sources for future releases in forested settings (Figure 7).

Figure 7. Row of planted eastern hemlock in southeastern Ohio being used as a HWA biological control field insectary (Dave Apsley).

Outreach and education efforts have been conducted by the ODNR, Ohio State University Extension (Apsley et al. 2014), Hocking Hills Conservation Association, Camp Oty'Okwa, Soil and Water Conservation Districts, Crane Hollow Nature Preserve, ODA, The Nature Conservancy, Ohio University, and various volunteer groups, among others, to raise awareness of HWA in Ohio. A webpage containing general info about HWA and its status in Ohio (ohiodnr.gov/HWA), including a HWA survey reporting tool, is hosted by the ODNR Division of Forestry for educational and data sharing purposes (Ohio Division of Forestry 2017).

Other Significant Pests and Diseases of Eastern Hemlock

In addition to HWA, there are several other pests of eastern hemlock that pose a significant threat to the health of Ohio's eastern hemlock resource. These pests include elongate hemlock scale (*Fiorinia externa*), cryptomeria scale (*Aspidiotus cryptomeriae*), spruce spider mite (*Oligonychus ununguis*), hemlock rust mite (*Nalepella tsugifoliae*), hemlock needle blight (*Fabrella tsugae*), and hemlock tip blight (*Sirococcus tsugae*). When one or more of these pests infests eastern hemlock trees simultaneously with HWA, they are especially devastating and can greatly exacerbate tree decline.

Elongate hemlock scale and cryptomeria scale are both invasive armored scale insects native to Japan, and both species have been found in Ohio. Both scales were first discovered in North America in New York; elongate hemlock scale in 1908, and cryptomeria scale in 1937 (Miller et al. 2005). In addition to hemlock species, hosts of these scales include other conifers such as firs (*Abies* spp.), pines (*Pinus* spp.), and spruces (*Picea* spp.). In heavy infestations, undersides of needles can be covered with the waxy scale covers (Figure 8). Feeding by these scales causes yellowing of needles and premature needle loss, resulting in general crown thinning and can lead to tree mortality. Armored scales feed on intracellular plant tissue (palisade and spongy mesophyll), rather than in the vascular tissue (phloem sap). As a result, the systemic insecticide imidacloprid, which is mainly transported in the phloem sap, is ineffective at controlling armored scales. However, dinotefuran, which is more water soluble and present in the intracellular tissue, is effective at controlling elongate hemlock scale and cryptomeria scale (Cowles 2010). Several biological control agents have been used for the control of elongate hemlock scale, including the predatory beetle *Cybocephalus nipponicus* (Blumenthal et al. 2005).

Figure 8. Elongate hemlock scale (left) and cryptomeria scale (right; Joe Boggs)

Spruce spider mites and hemlock rust mites are native to North America and are common pests of hemlocks and other coniferous species, including spruces, firs, pines, arborvitae (*Thuja* spp.), and junipers (*Juniperus* spp.). Hemlock rust mites feed on the upper and lower surfaces of needles, turning them yellowish brown and can cause needle drop. Spruce spider mites feed on individual cells of hemlock needles, producing characteristic yellow spots on the foliage, referred to as "stippling" (Figure 9). This stippling damage can result in yellowed or browned needles and premature needle drop, starting with needles towards the interior of the branch. Typically, natural biological controls, like predatory mites, keep populations of these mites in check in forested settings, but populations can occasionally build to damaging levels. Mite infestations alone rarely warrant treatment, but in combination with a more serious pest like HWA or elongate hemlock scale, treating for these mites using a registered miticide may be necessary.

Figure 9. Stippling damage caused by spruce spider mites on eastern hemlock foliage.

Hemlock needle blight and hemlock tip blight are fungal infections of the foliage and twigs of eastern hemlock. Fruiting bodies of hemlock needle blight can be observed as tiny dots on the underside of needles that appear white or tan early in the growing season, turning dark brown to black (Figure 10). This disease causes needles to turn brown, die, and drop prematurely, and can cause branch dieback, usually on lower or interior branches of the tree (Penn State Extension 2016). Hemlock tip blight infects the new growth of branch tips of hemlocks, usually on understory trees and saplings, or the lower branches of larger trees. Symptoms include twig dieback, resulting in brown foliage, and curled or drooping dead twig tips, which can remain on the branch for several months (Figure 10). Hemlock tip blight has been reported to be especially damaging, causing mortality of eastern hemlock regeneration in the northeastern United States (Miller-Weeks and Ostrofsky 2010). There are no known treatments for hemlock needle blight or hemlock tip blight, although cultural practices that increase air circulation, like pruning or thinning, may reduce their prevalence. It is not known if these fungal diseases are native to eastern North America. Both of these fungal diseases rarely cause significant damage, but in combination with other insect and disease pests or environmental stressors, can lead to decline and mortality of eastern hemlock.

Figure 10. Hemlock needle blight (left; Penn State Department of Plant Pathology & Environmental Microbiology Archives) and hemlock tip blight (right).

Scope and Purpose of this Conservation Plan

The threat of functional extinction of eastern hemlock, a foundation species in Ohio, by the non-native invasive insect HWA and other pests and diseases, has created the need for a plan of action to minimize the impact of these stressors and conserve as much of Ohio's eastern hemlock resource as possible. To date, the ODNR and its partners have had sufficient personnel and resources to proactively delineate and chemically treat every known HWA infestation on ODNR-owned and managed lands. These have mainly been small infestations, well ahead of the generally-infested advancing front of HWA infestation. Based on the impact and spread of HWA and other eastern hemlock pests in other states, however, it is expected that in the future, this level of response will become impossible. One component of this plan is a "scoring" of eastern hemlock stands based on the presence of certain natural and anthropogenic attributes. This scoring or ranking system will allow surveys and management efforts to be prioritized within those stands of higher conservation value. This plan is also intended to guide activities to detect and manage eastern hemlock pest infestations on ODNR-owned and managed land. The strategies used in this plan can be employed by other land managing entities as well as private landowners to locate high-priority eastern hemlock stands and target them for monitoring and treatment activities. As new research and management tools become available, this plan should be updated, and the protocols may be altered based on funding levels or special considerations at certain sites.

This conservation plan aims to further the mission of the Ohio Department of Natural Resources: *to ensure a balance between wise use and protection of our natural resources for the benefit of all*.

II. EASTERN HEMLOCK STAND PRIORITIZATION

Prioritization of eastern hemlock stands on ODNR lands is important for several reasons. First, ODNR and its partners do not have the means to survey all eastern hemlock stands thoroughly for significant pests and diseases on a timely basis. Prioritization of eastern hemlock stands will allow those stands with higher relative conservation value to be targeted for pest monitoring and suppression efforts. It is important to detect new infestations early, before the pest population size becomes too difficult to control. Prioritization will increase the likelihood of early detection of infestations in high-priority stands. Secondly, as the advancing front of HWA infestation moves through Ohio, a time will likely come when it will be impossible to manage all new HWA infestations on ODNR lands. Therefore, a prioritization of eastern hemlock stands using a geographic information system (GIS) will help guide decisions on which stands should receive more frequent monitoring and proactive management. Eastern hemlock stand prioritization was accomplished using ESRI's ArcGIS 10.3.1 (ESRI 2015).

Data Used in Eastern Hemlock Stand Prioritization

Eastern hemlock stands in Ohio are relatively small and widely scattered across the eastern half of the state with larger more contiguous stands found in the Hocking Hills, Lake Katharine, and Mohican regions (Figure 11). One outlying native population of eastern hemlock is known in the western half of the state; within Clifton Gorge State Nature Preserve in Greene County. Geospatial data from two previously created eastern hemlock stand spatial layers was used to prioritize Ohio's eastern hemlock stands.

One of the spatial layers used was originally created as part of a master's degree thesis project (Stump 2008). This effort initially focused on mapping eastern hemlock stands in the Hocking Hills region only. Work involved digitizing eastern hemlock stands using leaf-off, high-resolution satellite imagery based on visual features such as texture and color. This helped distinguish eastern hemlock from other evergreen species, such as eastern white pine (*Pinus strobus*), which often occur in rows in even-aged plantations in Ohio, making those stands appear relatively smooth in texture. Additionally, data such as topographic position, aspect, and soil type were used to more readily discern eastern hemlock stands. This work was later expanded, resulting in an eastern hemlock stand map of the entire state of Ohio (Stump 2009). This effort used information such as USDA Natural Resources Conservation Service (NRCS) soil survey data (Soil Survey Staff 2016), Ohio Breeding Bird Atlas II data (locations of eastern hemlock-dependent bird sightings; Rodewald et al. 2016), vegetation data from the Wayne National Forest, and ODNR's Natural Heritage Database (Ohio Division of Wildlife 2015) to better discern eastern hemlock stands. Some ground verification was completed.

The other spatial layer used in this analysis is an eastern hemlock stand layer developed by the USDA Forest Service's Forest Health Technology Enterprise Team (FHTET) remote sensing program. This layer was developed using such information as ground plot data measured by the USDA Forest Service's Forest Inventory & Analysis (FIA) program, as well as climate, terrain, soils, and satellite imagery and datamining software to model the occurrence of eastern hemlock stands (Ellenwood 2015).

Both of the above described layers were merged for a more complete delineation of Ohio's eastern hemlock stands (Figure 11). This combined eastern hemlock layer was used for prioritizing eastern hemlock stands on ODNR lands and across the state of Ohio.

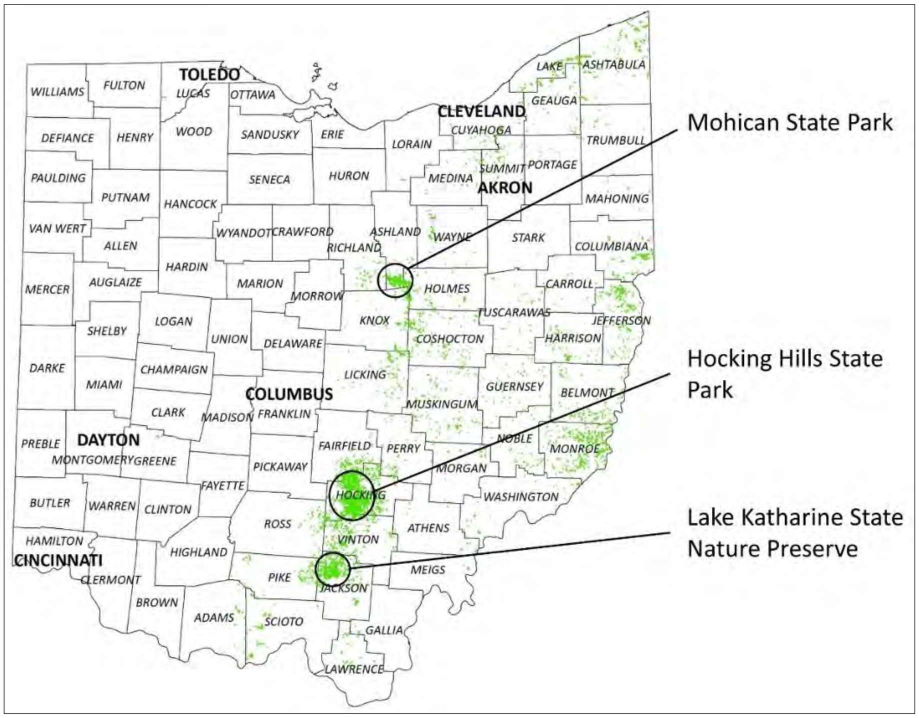

Figure 11. Mapped eastern hemlock forests in Ohio (shown in green) and popular ODNR recreation areas.

To prioritize Ohio's eastern hemlock stands based on their conservation value, the presence of certain biological, environmental, or anthropogenic features within those stands was examined. This analysis took into account spatial data for the presence of federally-listed (endangered, threatened, and species of concern) and state-listed (endangered, threatened, potentially threatened, species of concern, and species of special interest) rare plants and animals (Ohio Division of Wildlife 2015). It also used Ohio stream aquatic life designations (Ohio Environmental Protection Agency 2016), Ohio scenic rivers (Ohio Division of State Parks & Watercraft 2016), unique natural features (Ohio Division of Wildlife 2015), recreational trails (obtained from multiple ODNR divisions and the Buckeye Trail Association) and roadways (Ohio Geographically Referenced Information Program 2016). Additionally, several areas on ODNR land (state forest, nature preserve, or park property) were specifically chosen to be designated as high-priority hemlock forest due to high human recreational activity (Figure 12). This approach considers the biological value of these stands in providing important habitat for terrestrial and aquatic plant and wildlife species as well as the aesthetic and safety issues where there are high-levels of human activity. Additional details regarding the individual spatial datasets used in the prioritization analysis can be found in Appendix A.

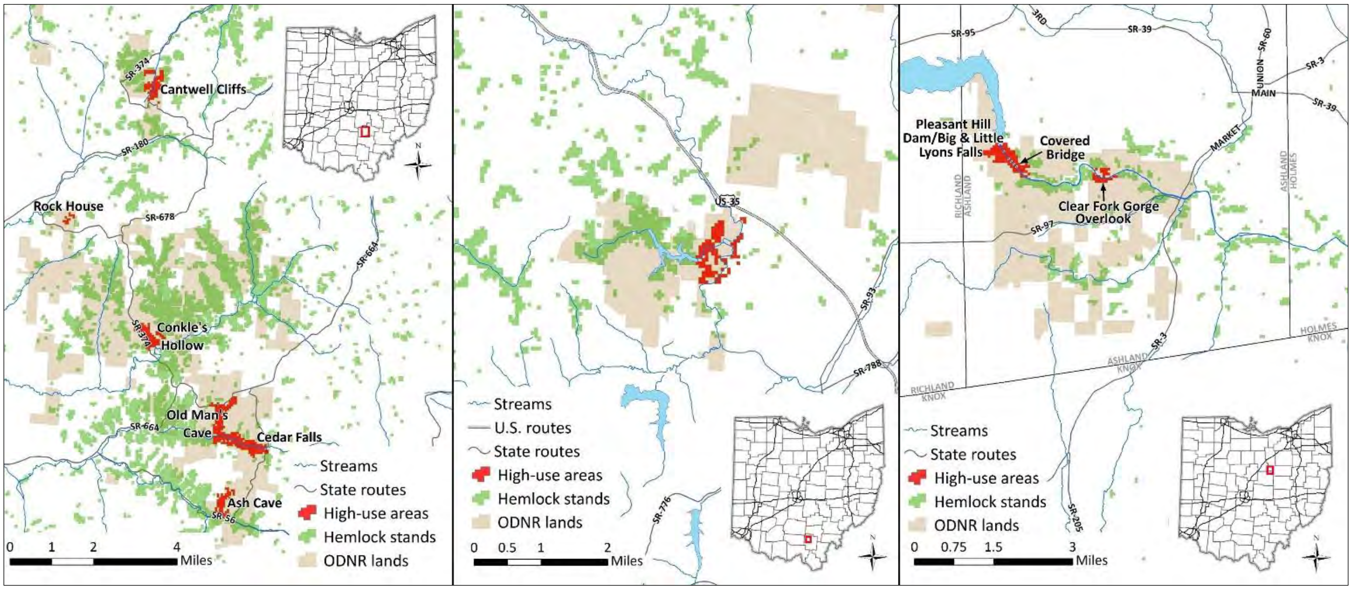

Figure 12. High-use hemlock areas in the Hocking Hills area (left), Lake Katharine area (center), and Mohican area (right) designated as high-priority.

Geographic Information System Methodology

In order to identify areas of high-priority eastern hemlock forest, it was necessary to buffer some of the feature data (points, lines, or polygons). The biological and stream features were buffered by a distance of 1,000 feet. This buffer size was used in order to encompass any hillsides or ravines that might border the streams, and would capture a fairly large area of habitat surrounding a data point (approximately 72 acres). Unique natural features and anthropogenic features were buffered by a distance of 500 feet. This buffer size was chosen mainly in respect to safety hazards that might be posed by falling dead limbs or trees and for aesthetic reasons (considering a hiker or driver's view from a trail or road). Each layer was united using the "union" geoprocessing tool with a vector layer of the state of Ohio to obtain a continuous spatial data layer, and converted to a raster file (250 ft x 250 ft pixels). In addition to buffering the features, they were also assigned a "conservation score" (Table 1). This allowed for certain features to have a higher conservation value than others. The "weighted sum" tool was used to overlay layers, assign conservation scores to each data layer, and calculate overlay weights. Where multiple data layers overlapped within a hemlock stand, their conservation scores were summed, resulting in an overall eastern hemlock stand conservation value. Eastern hemlock stand conservation values range from 0 (no features present) to 12 (highest-ranking conservation value). To simplify eastern hemlock stand rankings, stands with conservation values ranging from 0 to 3 were combined to form the low-priority stands, conservation values ranging from 4 to 7 were combined to form the medium-priority stands, and conservation values ranging from 8 to 12 were combined to form the high-priority stands (Figure 13). Additional information on the stand rankings, such as acreage of conservation scores by county and additional maps, is available in Appendix B.

Table 1. Groupings of spatial datasets and their buffer sizes and conservation scores used in eastern hemlock stand prioritization.

Feature type	Data group	Buffer size (ft)	Conservation score
Biological	Very rare species	1,000	3
	Rare species	1,000	2
	Uncommon species	1,000	1
Environmental	High-quality streams	1,000	3
	Medium-quality streams	1,000	2
	Low-quality streams	1,000	1
	Unique natural features	500	1
Anthropogenic	Recreational Trails	500	1
	Roads	500	1

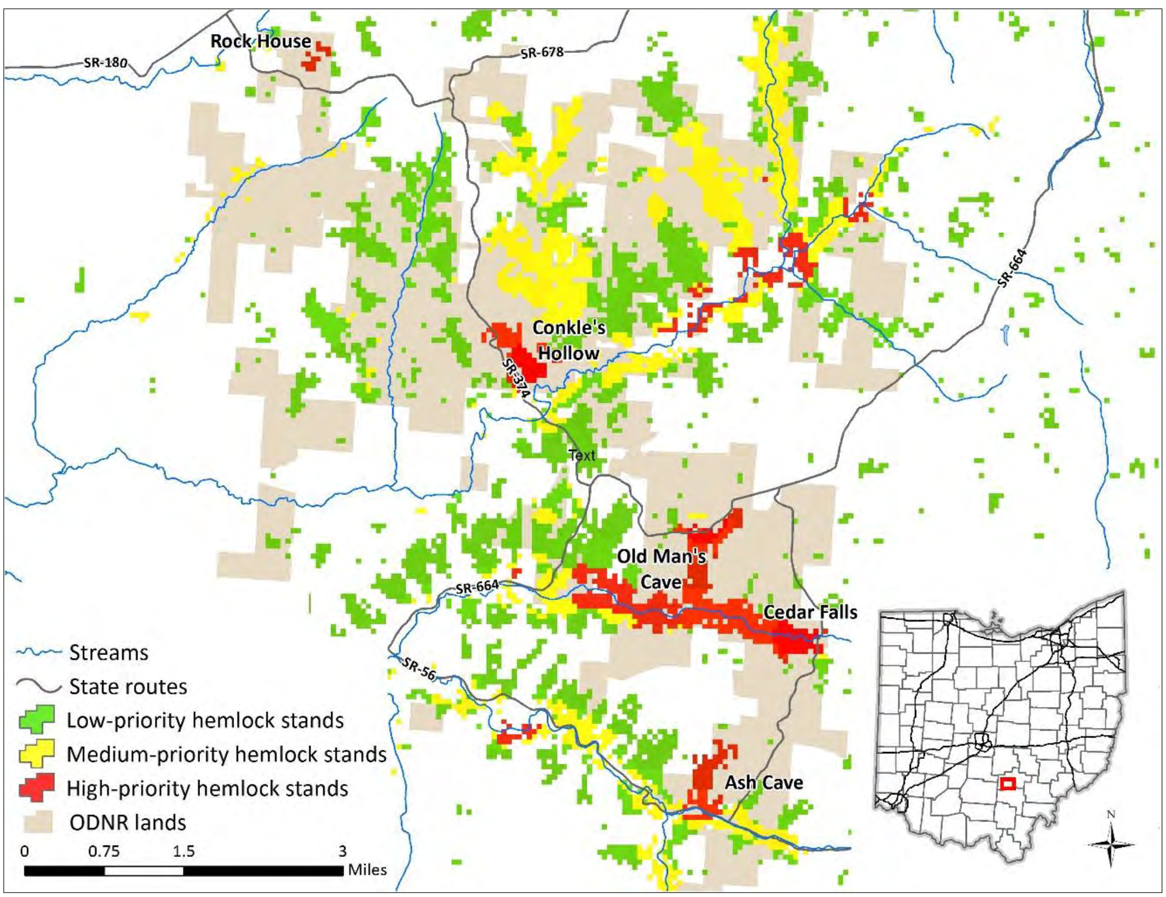

Figure 13. Eastern hemlock stand rankings in the Hocking Hills region (Hocking County).

III. EASTERN HEMLOCK CONSERVATION STRATEGY

In response to the rapid spread of HWA in the 1980s and 1990s, a national effort known as the Hemlock Woolly Adelgid Initiative began in 2003 and was renewed in 2008 and 2014 (Hemlock Woolly Adelgid Initiative 2014). This partnership of several federal and state agencies as well as universities and private industries, including the USDA Forest Service, Animal and Plant Health Inspection Service (APHIS), the National Association of State Foresters, and the National Plant Board, was formed to study HWA and develop strategies to slow its spread and reduce its impact. The efforts of the HWA Initiative have significantly improved the knowledge of the lifecycle and spread of HWA, biological controls of HWA, insecticidal management, silvicultural management, host resistance, and survey and monitoring of HWA. Much of the knowledge and tools developed through this initiative have been taken into consideration and are recommended in this conservation plan. The following sections describe the available tools and methods for monitoring and survey for HWA and other pests of eastern hemlock, chemical and biological suppression of eastern hemlock pests, eastern hemlock resistance to HWA, and preservation of eastern hemlock genetic material. Finally, several management scenarios are outlined, and the selected strategy for eastern hemlock conservation on ODNR lands is described.

Eastern Hemlock Pest Monitoring and Survey

Monitoring to detect the presence of an infestation of HWA or other pest is a critical initial step in any pest management strategy. Early detection of an infestation well in advance of symptoms of tree decline is critical to allow for time to plan appropriate suppression activities. Optimal timing for HWA survey is approximately October through June, when adelgids produce their characteristic white, woolly masses, although remnants of the woolly masses can be visible in mid- to late-summer (Costa and Onken 2006). Timing for detection of other eastern hemlock pests is less critical. It is important for those conducting pest surveys to be familiar with eastern hemlock pest identification, and be aware of other objects that can look similar to eastern hemlock pests. Because eastern hemlock is typically scattered within mixed hardwood forest stands in Ohio, or concentrated in small contiguous stands, attempts should be made to survey for pests throughout the stand in a semi-random fashion. A representative sample of trees distributed throughout the stand (not every tree, unless the stand is very small) should be examined based on personnel and time constraints. One to four living branches per tree should be examined, with special attention paid to the undersides of the terminal two feet. Within each surveyed stand, global positioning system (GPS) coordinates should be recorded. Any significant eastern hemlock pests should be noted. If needed, specimens will be collected for laboratory analysis and confirmation of identification. Data sheets for recording such attributes as site name, county, GPS coordinates, number of trees inspected, number of infested trees detected, and general eastern hemlock health should be kept. If HWA or EHS is detected, infested trees will be marked with flagging, a GPS point will be recorded, and the detection will be indicated on field data sheets.

Integrated Pest Management

Integrated pest management (IPM) is a sustainable strategy for controlling pests while minimizing risks to human and environmental health (State of Ohio 2004). The goal of an IPM approach is to effectively manage pest populations using all available and practical tools including physical, chemical, and biological methods, to maximize cost effectiveness and minimize negative environmental impact. While pest management using cultural, chemical, or biological methods can have environmental impacts, it is important to consider the risks and benefits of using these controls, versus the results of not managing the pest. Components of an IPM program include conducting an assessment of the pest population in the area of concern, determining effective suppression strategies, implementing management activities, and evaluating the results. In the case of HWA and other eastern hemlock pests, an IPM program would utilize detection survey, chemical insecticides, biological controls, host resistance, and treatment evaluation where appropriate.

Hemlock Woolly Adelgid Suppression

Several tools have been identified and developed for the purpose of controlling HWA and reducing its impact. Both chemical and biological controls are currently being used for the suppression of HWA. The use of a number of insecticides have been shown to be highly effective at controlling HWA when applied to individual trees both in the landscape and in forested settings (McClure 1991; Webb et al. 2003; Cowles et al. 2006). Biological controls, including insect predators and fungal pathogens, have been used to control HWA populations (Onken and Reardon 2011). Chemical and biological control options are crucial in attempting to slow the spread of HWA and limit its impacts.

Chemical Control

Several chemical insecticides are labeled for the control of hemlock woolly adelgid in forests and landscapes and have been shown to be effective (McClure 1991; Webb et al. 2003; Ward et al. 2004). Chemical treatments are not a permanent solution, and need to be re-applied at intervals ranging from several months to a few years. While not a long-term option, the use of chemical insecticides can be a valuable management tool to maintain the health of eastern hemlock trees, allowing them to continue to provide ecosystem services, until a more sustainable tool like biological controls or plant resistance can be established (Cowles and Lagalante 2009). In landscape settings, cover sprays with horticultural oils and insecticidal soaps can be effective, provided thorough coverage of all of the foliage is achieved (McClure 1995). Systemic insecticides, applied via soil drench or injection, soil tablets, bark spray, or trunk injection, are also viable options in the landscape (Steward and Horner 1994). Because of the difficulty in achieving thorough coverage of foliage with horticultural oils and insecticidal soaps on tall, difficult-to-access trees, and their short timeframe of residual effectiveness, the use of insecticides in forested settings is limited to systemic options.

The two systemic insecticides effective for control of HWA are imidacloprid and dinotefuran. These are included in a class of insecticides known as neonicotinoids, which have been used since 1985 in agricultural, pest control, and landscape pest management (Durkin 2015). Imidacloprid and dinotefuran are systemic, meaning they are moved throughout plant tissues within the sap. For control of HWA, imidacloprid is typically applied as a soil drench or injection, or in water-soluble tablets that are placed in the soil, and taken up by the tree's roots, or it is applied directly into the tree through trunk injection. It can also be applied via basal bark spray, where it is absorbed through the bark and transported within the tree. Dinotefuran can be applied through soil drench, soil injection, or basal bark spray. Sucking insects, like HWA, are killed when they feed on sap from a plant that has been treated. Studies have shown that dosage of imidacloprid is exponentially related to the diameter of the tree's trunk, and that minimum effective doses are often lower than the federally labeled rate (Cowles 2009). This minimum effective rate has been used in Ohio and in other states to maximize cost effectiveness and efficiency. More information on the minimum effective rates can be found in Appendix C. Certain insect pests, like adelgids, are extremely sensitive, and can be controlled with very low insecticide dosages.

Imidacloprid and dinotefuran can provide multiple years of control of HWA with a single treatment (Webb et al. 2003; Cowles et al. 2006; Dilling et al. 2010). Imidacloprid and the compound it is broken down into within plant tissues, known as olefin (which is also toxic to HWA), remains in hemlock foliage and is translocated to new growth, providing protection for at least seven years after a single treatment (Cowles and Lagalante 2009). Dinotefuran appears to provide effective control of HWA for two years (Cowles and Lagalante 2009). Dinotefuran is highly water soluble and is much more quickly moved into the foliage compared to imidacloprid (United States Environmental Protection Agency 2004). Research has shown that dinotefuran can begin to control HWA just two weeks after treatment, while imidacloprid may take several months before becoming effective (Cowles et al. 2006; Cowles and Lagalante 2009). Because dinotefuran is faster acting than imidacloprid, it is very valuable as a measure to save trees that are in severe decline from HWA infestation, while imidacloprid can be a very effective tool near or ahead of the infestation front of HWA infestation, where little to no decline from HWA has yet occurred.

Environmental Impact

The potential for imidacloprid and dinotefuran to impact non-target organisms, pollinators in particular, is an important issue that has been a major area of research in recent years. Neonicotinoids are toxic to insects and some other invertebrates and relatively non-toxic to humans and other vertebrates (Durkin 2015). In general, neonicotinoids break down quickly upon exposure to sunlight and are tightly bound to organic matter in the soil (Cowles 2014). Imidacloprid is labeled for broadcast application methods to many types of agricultural crops. The use of imidacloprid (and dinotefuran) for the suppression of HWA is limited to single tree applications, either to the soil immediately surrounding a tree's trunk, the bark, or injected into the trunk, limiting possible exposure to non-target organisms as well as applicators. As opposed to broadcast sprays and contact insecticides, systemic insecticides are contained within the tissues of the plant, and therefore only act upon insects that are feeding on the plant. Studies have shown that imidacloprid can reduce populations of non-target arthropod communities existing on treated hemlock trees (Dilling et al. 2009). This reduction may be temporary, however, as a rebound in predatory insects was noted one to one and a half years after treatment (Hakeem 2008). Additionally, eastern hemlocks are wind-, rather than insect-pollinated plants. Thus, there is a relatively low threat to pollinating insects when treating eastern hemlock trees.

Imidacloprid has rarely contaminated groundwater; where it has, they have been sites with very low soil organic matter (United States Environmental Protection Agency 2003). The high organic binding capacity of imidacloprid should prevent it from leaching through forest soils, especially in eastern hemlock forests, which are typically high in organic matter (Cowles 2009). A study from the southern Appalachian-region showed that soil applications of imidacloprid near streams had no significant negative effects on aquatic macroinvertebrates (Churchel et al. 2010). A more recent study (Benton et al. 2016) found that while imidacloprid was detected in water samples taken 30-300 feet downstream of areas where trees had been treated for HWA, the amount of the chemical detected was far less than

U.S. Environmental Protection Agency (EPA) chronic and acute aquatic life benchmarks for fish and aquatic macroinvertebrates (United State Environmental Protection Agency 2016). To reduce the likelihood of ground or surface water contamination, it is recommended (and has been the practice in Ohio), to avoid soil applications of imidacloprid within riparian or streamside buffer zones, and limit applications there to trunk injection methods only.

Biological Control

One key component of an IPM program is the use of biological controls; natural enemies (predators, parasitoids, or pathogens) that can reduce the population of the pest. Surveys in the 1980s and 1990s revealed that there are no parasitoids, and only a few generalist predators and non-host-specific pathogens of HWA, present in the eastern United States (Cheah et al. 2004). These native predators and pathogens have no evolutionary history with HWA, and therefore do not specialize on it, and cannot maintain HWA population densities sufficiently low to prevent tree damage and mortality. Investigations into biological controls of HWA outside of eastern North America began in the early-1990s, and was greatly expanded through the HWA Initiative (Onken and Reardon 2011). Biological control may offer a potential long-term control option for HWA in the eastern United States.

Several insect, mite, and pathogen species have been identified from parts of western North America, China, and Japan, and released as biological controls for HWA in eastern North America. One of the first mass-reared predator insects was the lady beetle *Sasajiscymnus tsugae*, native to Japan. Over 2.5 million of these insects were reared by five laboratories and released in 15 states (Onken and Reardon 2011). While some establishment of this insect has been documented, this biocontrol agent has been generally considered to be ineffective, although this species is still being explored as an option. Field explorations of HWA-infested hemlock in China and western North America have revealed several lady beetles in the genus *Scymnus* that might have potential as HWA biological controls and are currently being studied.

In 2000, *Laricobius nigrinus*, a small black beetle native to the Pacific Northwest, was approved for release (Figure 14). Since 2003, *L. nigrinus* has been reared at several lab colonies, and over 150,000 beetles have been released in 15 eastern states, including Ohio. *L. nigrinus* is the first biological control agent that has established large enough populations that beetles can be field-collected and redistributed. An inland biotype of *L. nigrinus* has been identified in northern Idaho and northwest Montana, which has greater cold-tolerance than the coastal biotype, and has been reared in lab colonies and released in New England (Onken and Reardon 2011). Both the adults and larvae of *L. nigrinus* feed on the eggs, nymphs, and adults of HWA. Females lay eggs in late winter and early spring. Larvae develop and drop to the forest floor to pupate. Adults are dormant in the soil during the summer months and emerge in the fall to feed on HWA sistens nymphs in the fall and winter (Zilahi-Balogh et al. 2003). In 2005, a new species of *Laricobius* (now *L. osakensis*) was discovered in Japan and studied to assess its feasibility as a biological control for HWA. It was found to consume more HWA and have a higher reproductive rate than *L. nigrinus*. Additionally, because this species is native to the same area in Japan as the source population of HWA present in eastern North America, it shares an evolutionary history with the HWA impacting eastern hemlocks, meaning it could be a highly effective predator. *L. osakensis* was approved for release in 2010, and has since been reared and released in eight states, including Ohio (Onken and Reardon 2011).

Figure 14. Vial containing *Laricobius nigrinus* beetles ready for release.

A fly species, *Leucopis argenticollis*, recovered from HWA-infested hemlocks in the Pacific Northwest, shows promise as a potential biological control and is currently being studied (Ross et al. 2011). *Scymnus coniferarum*, also native to western North America, is another potential predator of HWA. Both it and the *Leucopis* fly species could be important predators of the spring (progrediens) generation of HWA, while all of the other predators prey on the winter (sistens) generation.

Pathogens of HWA (entomopathogens) have been studied since the mid-2000s. While non-host specific native entomopathogens have been observed on HWA in North America and Asia, none have been found to be epizootic (causing a significant reduction in HWA populations). One particular fungus, *Lecanicillium muscarium*, recovered in the eastern United States, is currently being studied (Costa 2011). A commercially available formulation of this fungus has been tested in some small-scale forest studies and has been shown to be effective, although this control technique is still being developed (Havill et al. 2014).

While classical biological control principles have been initiated for control of HWA, there is still a long way to go. The use of HWA biological controls has not yet been definitively shown to be successful at limiting HWA populations below tree-damaging levels. However, in many areas, the release of biological control agents has only occurred for a few years, and their populations are still relatively small. Predators and pathogens of HWA have been studied in both North America and Asia, collected, screened, and in some cases, mass-released in the eastern United States. It will take time and many targeted releases to build up a suite of HWA biological control populations sufficient to keep eastern hemlock trees alive and providing their important ecosystem services.

Environmental Impact

The establishment of effective biological control agents has been viewed as a critical step in a successful IPM strategy for HWA. As with any biological control program, predicting the safety and success of HWA biological controls is difficult because the natural enemies exist within a complex system of multi-species, multi-trophic, and abiotic variables and interactions. Governmental regulations are in place to reduce the risk of non-target impacts and ensure that biological controls are host-specific, meaning they can only survive by feeding on the pest organism, or a narrow range of related species which includes the pest organism. Several potential HWA biological control agents were studied and found to have too broad a host range to be considered safe for use, including anthocorid bugs (*Tetraphleps galchanoides*, *Anthocoris nemoralis*, and *A. antevolens*) from China and western North America (Montgomery et al. 2011a). The introduction of biological controls can have unintended consequences such as impacts to non-target organisms, hybridization of the biological control agent with a related native species, ecological replacement, in which a native species that has become reliant on an invasive species is negatively impacted by the biological controls' reduction of the invasive species, or food web interactions, such as a biological control species becoming a food source for a native species, potentially changing community and trophic dynamics (United States Fish & Wildlife Service 2009). While there have been instances of biological controls becoming nuisance species or having unintended non-target effects, there have also been highly successful biological control programs (i.e., control of cottony cushion scale by the vedalia beetle *Rodolia cardinalis*, control of cassava mealybug by the parasitoid wasp *Apoanagyrus lopezi*, and control of Klamath weed by the beetle *Chrysolina quadrigemina*) (DeBach et al. 1971; Norgaard 1988; Louda et al. 1997). Before any biological control programs commence, in-depth risk analyses are performed to be sure that the benefits of the program outweigh the risks.

In 2000, Congress passed the Plant Protection Act, which gives the Secretary of the USDA authority to regulate the movement of any plant, plant product, biological control organism, noxious weed, and plant pest (United States Congress 2000). The authority has been delegated to USDA's Animal and Plant Health Inspection Service (APHIS), and the regulation of biological control agents has been assigned to APHIS's Plant Protection and Quarantine (PPQ) program. Additionally, compliance with the National Environmental Policy Act (NEPA) and the Endangered Species Act is required. The process for obtaining and introducing biological control organisms includes many steps. Initially, exhaustive literature reviews are performed to compile all known scientific data on the pest and known natural enemies. Climatic and habitat data is also collected for both the native range of the pest and the area in which the natural enemies will be introduced. Field surveys to identify potential natural enemies are then conducted both in the introduced range of the pest, and in the pest's native range. Once natural enemies are identified, they are brought into a containment facility (quarantine) approved by APHIS-PPQ and permits allowing the movement of the biocontrol agents must be obtained. The biology and host specificity of potential biocontrol agents is studied, both in quarantine and in its native habitat. Prior to releasing a biocontrol agent into the environment, permit applications are submitted to APHIS along with a report with information requested in the North American Plant Protection Organization (NAPPO) "Guidelines for Petition for First Release of Non-indigenous Entomophagous Biological Control Agents" (NAPPO 2008). If the review of these documents by NAPPO and APHIS is favorable, a draft environmental assessment (EA) is prepared by APHIS, and comments are solicited by any interested parties. If warranted, a finding of no significant impacts to the environment (FONSI) is issued along with a final EA. Only then may the permit to release the biocontrol agent from quarantine be issued (Montgomery 2011). These regulations help to ensure that the pertinent data is conscientiously collected, increasing the likelihood of success, and reducing the risk of impacts to non-target organisms.

One potential non-target impact of introducing biological controls is the dilution of the gene pool of a related native species, through hybridization. There are four *Laricobius* species known to occur in North

America; *L. nigrinus* and *L. laticollis* are native to western North America, and *L. rubidus* is native to eastern North America. *L. erichsonii*, native to Europe, was released on both coasts of North America for control of the balsam woolly adelgid (*Adelges piceae*), but the latest recorded recovery of that species was in 1978 (Havill et al. 2011a). Interestingly, a molecular study has shown that the two *Laricobius* species native to western North America are not the most closely related among the four species reported in North America. *L. nigrinus* was found to be very closely related to the eastern species, *L. rubidus* (Montgomery et al. 2011b). Recent work has shown that *L. nigrinus* and *L. rubidus* are interbreeding at sites in eastern North America where *L. nigrinus* has been released. The primary host of *L. rubidus* is the native pine bark adelgid (*Pineus strobi*), though it has been found to feed on balsam woolly adelgid and has been collected from eastern hemlock infested with HWA in the eastern United States (Montgomery and Lyon 1996; Wallace and Hain 2000; Mausel et al. 2008). Laboratory studies show that it can reproduce and complete its development on HWA, but it prefers to oviposit on pine bark adelgid (Zilahi-Balogh et al. 2005). Conversely, laboratory studies indicate that *L. nigrinus* is unable to successfully reproduce on pine bark adelgid. Hybridization between these two species has been confirmed, both in the field, where *L. nigrinus* had been released, and in the laboratory, where individuals of separate species interbred producing viable offspring (Havill et al. 2011a). Because *L. rubidus* prefers pine bark adelgid on white pine and *L. nigrinus* prefers HWA on hemlock, it may be most likely for these species to interbreed where eastern hemlock and eastern white pine (*Pinus strobus*) co-occur. The rate of hybridization of these species in the field has thus far been shown to be approximately 11-13 percent (Fischer et al. 2015). It appears that species separation is likely to be maintained with rare occurrences of hybridization. The implications of interbreeding for both species are not yet clear, and further research is needed. Hybridization between these species could have several outcomes, including a reduction in offspring fitness, an increase in reproductive isolation, or an increase in offspring fitness (Havill et al. 2011a). There is no indication yet, as to whether hybridization will negatively or positively affect the success of the biological control of HWA.

Resistance of Eastern Hemlock to Hemlock Woolly Adelgid

The hemlock woolly adelgid has caused widespread decline and mortality of eastern hemlock for two main reasons: there are no effective natural enemies of HWA established in the eastern United States to control its population and, because HWA and eastern hemlock share no evolutionary history, eastern hemlock cannot adequately resist or tolerate the impacts of HWA feeding. Although great progress has been made in the areas of chemical and biological control of HWA, eastern hemlock trees are still dying at an alarming rate. Manipulating hemlock resistance to HWA, through identifying naturally resistant trees or developing resistant crosses between eastern hemlock and other hemlock species, offers another potential solution to managing HWA. Unfortunately, developing and propagating resistant trees, and restoring them to natural and urban landscapes would require many decades to achieve. Even so, developing eastern hemlock resistance to HWA is an important area of research that is being pursued.

Interestingly, the two hemlock species native to eastern North America, eastern hemlock and Carolina hemlock, are not closely related (Havill et al. 2008). Carolina hemlock is more closely related to the Asian hemlock species than it is to eastern hemlock. This observation is consistent with Carolina hemlock's ability to hybridize with HWA tolerant Asian hemlock species, while attempts to cross eastern hemlock with other hemlock species have failed (Bentz et al. 2002). Hybrids between Carolina hemlock and

Chinese hemlock (*T. chinensis*) are resistant to HWA and could be a viable replacement for eastern hemlock (Montgomery et al. 2009). Additionally, Chinese hemlock grows well in the northeastern United States, while the two western North American species (*T. heterophylla* and *T. mertensiana*), though resistant to HWA, do not survive well in the eastern United States (Havill et al. 2011b).

There have been rare instances of individual eastern hemlocks growing vigorously within stands where the majority of the trees are in decline or have been killed by HWA infestation (Caswell et al. 2008; Ingwell and Preisser 2011). It has been shown that some of these trees have higher levels of certain chemicals that may make them resistant to HWA infestation (McKenzie et al. 2014), however further research is needed to determine if those chemicals are directly responsible for the resistance mechanism. Potentially resistant eastern or Carolina hemlocks can be reported to the Forest Restoration Alliance (a non-profit group of researchers, working to restore HWA-impacted forests) through its website (Forest Restoration Alliance 2016). The hybridization of Carolina hemlock and HWA tolerant Asian hemlock species and the identification and testing of possible naturally HWA resistant eastern or Carolina hemlocks are very important areas of work that need to be pursued as additional HWA management options.

Preservation of Eastern Hemlock Genetic Material

Eastern hemlock has low genetic variation relative to other hemlock species (Zabinsky 1992; Potter et al. 2008). This may translate into less natural variation in resistance to HWA, and make the search for resistant trees difficult. In response to the widespread mortality of eastern and Carolina hemlock due to HWA, Camcore (a private, non-profit, international tree breeding organization based at North Carolina State University), in cooperation with the USDA Forest Service and other organizations, has worked to conserve the genetic resources of these tree species (Jetton et al. 2011). Seeds are being collected throughout the ranges of both tree species and are being used to initiate plantings and breeding orchards within and outside of the United States, away from the threat of HWA, and are also being stored in seed banks using long-term cold storage. The objective is to maintain viable *ex situ* (off-site) populations and seed reserves of both hemlock species for breeding and restoration activities after effective HWA control strategies are established in the eastern United States. In 2009, the Ohio Division of Forestry collected and sent samples of eastern hemlock foliage from native stands in Ohio to Camcore in order to describe patterns of genetic diversity across the range of eastern hemlock. It will be important to continue to support this effort if future foliage or seed collections are requested from native stands of eastern hemlock in Ohio.

Management Options and Selected Strategy

No Management

Infestation by HWA has resulted in the mortality of millions of eastern and Carolina hemlock trees across the range of HWA distribution in eastern North America. Because of the susceptibility of eastern hemlock to HWA and lack of established effective natural predators of HWA, it is believed that HWA will have a similar impact on eastern hemlock stands in Ohio. HWA populations can increase exponentially, resulting in rapid mortality of eastern hemlock, especially following warm winters and drought conditions. As observed in the southern Appalachian Mountain-region and into New England, it is expected that drastic changes in forest composition, structure, and function will occur with the loss of eastern hemlock near the western edge of its range (Spaulding and Rieske 2010; Martin and Goebel 2011; Macy 2012). Should no HWA management actions occur, it is likely that eastern hemlock trees killed by HWA near heavily visited public areas (particularly at parks and nature preserves in the Hocking Hills, Lake Katharine, and Mohican regions) will require removal to mitigate human safety hazards. In some situations, the safe removal of these trees may be complicated by rugged topography including cliffs. These operations, which in themselves can be dangerous, would be more expensive than keeping trees alive using chemical treatments, and would result in lengthy trail or park closures, potentially reducing recreational visitation and negatively impacting local economies. Along with the eastern hemlock trees, the great aesthetic appeal of these unique forests that attract so many visitors would also be lost or permanently degraded. Additionally, the increased light reaching the forest floor after the mortality of eastern hemlock trees would likely stimulate dense growth of both native and non-native trees, shrubs, and vines. Invasive plants like tree-of-heaven (*Ailanthus altissima*), Japanese stiltgrass (*Microstegium vimineum*), and Asian bush honeysuckles (*Lonicera* spp.) can be difficult to manage and reduce native plant and wildlife diversity. Finally, the loss of eastern hemlock forests, an uncommon habitat in Ohio, would further threaten many rare and endangered plant and wildlife species that depend upon them. Without taking measures to suppress or manage infestations of HWA or other eastern hemlock pests, it is highly likely that eastern hemlock would be functionally removed as a component of the forests in which it occurs in Ohio. While a “hands off” strategy may seem to be the lowest cost option, expenses associated with the removal of hazard trees in high-use areas (i.e., parks and hiking trails), the impact of potentially reduced recreation on local economies, the potential for reduced property values, and management of dense vegetation regeneration and possible invasive plant colonization must be considered. For spot infestations well ahead of the generally-infested advancing front of HWA infestation and in high-priority eastern hemlock areas, a “no management” approach would be irresponsible in light of the comparatively low cost to protect trees via chemical means, and the potential economic, safety, ecological, aesthetic, and recreational consequences.

Chemical Control Only

Treatment with chemical insecticides is highly effective at protecting individual hemlock trees from HWA and other pests. The cost of chemicals used for the suppression of HWA and other eastern hemlock pests has decreased over time, and it is relatively inexpensive to treat landscape trees or small forest stands. Additional information regarding the costs of chemical control is available in Appendix C. Chemical treatment is a critical measure for managing relatively small, emerging infestations ahead of the advancing front of HWA and for saving high-value trees in special areas or in landscapes. However, it cannot be viewed as a stand-alone tool for HWA suppression at the landscape level due to the costs involved and potential environmental hazards. In a generally-infested situation, in which HWA is present throughout large tracts of eastern hemlock forest, chemical treatment on an individual tree basis becomes cost- and labor-prohibitive. Additionally, the potential for environmental hazards and risks to non-target organisms must be considered. In these situations, chemical control alone is not feasible; more sustainable methods of pest suppression, such as biological control or establishment of HWA-resistant hemlock trees, are needed.

Biological Control Only

There has been great progress in identifying, collecting, and rearing potential biological controls for HWA. Several predators and pathogens have been shown to reduce populations of HWA. Potential benefits of limiting HWA suppression tools to biological controls only, relative to chemical controls, includes the elimination of the risk of environmental hazard by chemical insecticides, as well as lower implementation costs. However, while several biological control agents do show promise in the suppression of HWA, none have yet been definitively shown to maintain HWA populations below tree-killing levels in forests of the eastern United States. Currently, the use of biological controls alone would likely not significantly slow the spread of HWA into and through Ohio and prevent eastern hemlock mortality. However, this does not mean that biological controls should not be pursued. The establishment of biological controls at field insectaries is an important step to ensure their availability for future use in generally-infested, large forest tracts. Given enough time for a suite of natural predators of HWA to establish healthy populations as well as further research, biological controls may prove to be the most important long-term suppression strategy for HWA. At this time, the use of biological controls alone would be ineffective at slowing the spread of HWA and maintaining eastern hemlock health in Ohio.

Selected Strategy: Integrated Pest Management

Based on years of research and knowledge gained from the HWA Initiative and other forest pest suppression efforts, it is clear that an integrated pest management (IPM) strategy that employs all available methods of pest detection, control, and evaluation offers the best chance of limiting HWA-caused damage, and conserving Ohio's eastern hemlock resource. Some recent research suggests that suppression of HWA and the health of eastern hemlock trees can be maximized through integrating the use of chemical and biological controls in the same forest stand (Mayfield et al. 2015). A possible effective strategy may include the chemical treatment of the larger canopy trees, which tend to decline and die faster than smaller understory trees, while simultaneously releasing predator beetles on nearby or understory trees. By the time the insecticide protection diminishes within the larger trees, the biological controls have established a larger population, providing a higher chance of protecting those trees. While acute toxicity from imidacloprid (the most commonly used insecticide for HWA control) has been demonstrated in the laboratory in *Laricobius nigrinus*, results in the field have been much less conclusive, and predator mortality and fitness impacts from feeding on HWA on previously treated trees were minimal (Eisenback et al. 2010). Additionally, because HWA is extremely sensitive to imidacloprid (Cowles et al. 2006), its presence on previously treated trees should indicate that concentrations of imidacloprid in those branches are low or absent. This integrated strategy could save more trees over time in a given area than either control measure (chemical or biological) would in isolation. ***It will be critical to continue surveying eastern hemlock stands for the presence of HWA and other pests, proactively treat early spot infestations using chemical controls, and continue to supplement and establish new biological control field insectaries.*** Should the number and scope of HWA infestations exceed the time and resources necessary for adequate management, the eastern hemlock stand prioritization will be critical for focusing limited resources on the highest value eastern hemlock areas. As new management tools are developed and strategies are refined, this plan should be updated and adapted in order to effectively conserve Ohio's important eastern hemlock forests.

APPENDIX A: Data Used for Eastern Hemlock Stand Prioritization

Table 2. Datasets used for eastern hemlock stand prioritization and their sources.

Data Group	Buffer Size (ft)	Conservation Score	Dataset	Source
Biological				
Very rare species	1,000	3	Federally-endangered species	ODNR Division of Wildlife Natural Heritage Database
			Federally-threatened species	
			State-endangered species	
Rare species	1,000	2	Federal species of concern	
			State-threatened species	
			State species of concern	
Uncommon species	1,000	1	State potentially threatened species	
			State species of interest	
Environmental				
Unique natural features	500	1	Unique natural features	ODNR Division of Wildlife Natural Heritage Database
High-quality streams	1,000	3	Scenic rivers	ODNR Division of State Parks & Watercraft
			Coldwater habitat (CWH)	Ohio EPA
			Exceptional warmwater habitat (EWH)	
			Outstanding state waters (OSW)	
			Superior high-quality waters (SHQW)	
Medium-quality streams	1,000	2	Warmwater habitat (WWH)	
			Seasonal salmonid habitat (SSH)	
Low-quality streams	1,000	1	Limited resource waters (LRW)	
			Limited warmwater habitat (LWH)	
			Modified warmwater habitat (MWH)	
Anthropogenic				
Recreational Trails	500	1	Recreational trails on ODNR lands	ODNR Divisions of Forestry, Natural Areas & Preserves, State Parks & Watercraft, and Wildlife
			Buckeye Trail	Buckeye Trail Association
Roads	500	1	Location Based Response System (LBRS) road data	Ohio Geographically Referenced Information Program (OGRIP)

Table 3. Descriptions of datasets used for eastern hemlock stand prioritization.

Dataset	Description
Biological	
Federally-endangered species	A species which is in danger of extinction throughout all or a significant portion of its range.
Federally-threatened species	A species which is likely to become an endangered species within the foreseeable future throughout all or a significant portion of its range.
State-endangered species	A native species or subspecies threatened with extirpation from the state. The danger may result from one or more causes, such as habitat loss, pollution, predation, interspecific competition, or disease.
Federal species of concern	A species believed to be in need of concentrated conservation actions. Such actions vary depending on the health of the populations and degree and types of threats.
State-threatened species	A species or subspecies whose survival in Ohio is not in immediate jeopardy, but to which a threat exists. Continued or increased stress will result in its becoming endangered.
State species of concern	A species or subspecies which might become threatened in Ohio under continued or increased stress. Also, a species or subspecies for which there is some concern, but for which information is insufficient to permit an adequate status evaluation. This category may contain species designated as a furbearer or game species, but whose statewide population is dependent on the quality and/or quantity of habitat and is not adversely impacted by regulated harvest.
State potentially threatened species	A native Ohio plant species that does not qualify as a state endangered or threatened species, but it is a proposed federal endangered or threatened species or a species listed in the Federal Register as under review for such proposal, or the natural populations of the species are imperiled to the extent that the species could conceivably become a threatened species in Ohio within the foreseeable future, or the natural populations of the species, even though they are not threatened in Ohio at the time of designation, are believed to be declining in abundance or vitality at a significant rate throughout all or large portions of the state.
State species of interest	A species that occurs periodically and is capable of breeding in Ohio. It is at the edge of a larger, contiguous range with viable population(s) within the core of its range. These species have no federal endangered or threatened status, are at low breeding densities in the state, and have not been recently released to enhance Ohio’s wildlife diversity. With the exception of efforts to conserve occupied areas, minimal management efforts will be directed for these species because it is unlikely to result in significant increases in their populations within the state.
Environmental	
Unique natural features	Interesting geologic formations (i.e., cliffs, waterfalls, caves, natural bridges, rock outcrops).
Scenic rivers	High-quality waters with natural character retained for the majority of its length.
Coldwater habitat (CWH)	Waters that support native cold water or cool water species and/or managed and stocked with trout.
Exceptional warmwater habitat (EWH)	Waters that support unique and diverse assemblage of fish and invertebrates.
Outstanding state waters (OSW)	Waters that have special significance for the state because of their exceptional ecological values or exceptional recreation values.
Superior high-quality waters (SHQW)	Waters that possess exceptional ecological values based upon a combination of the presence of threatened or endangered species and a high level of biological integrity.
Warmwater habitat (WWH)	Waters with typical assemblages of fish and invertebrates, similar to least impacted reference conditions.
Seasonal salmonid habitat (SSH)	Waters that support lake run steelhead trout fisheries.
Limited resource waters (LRW)	Waters in which fish and macroinvertebrates are severely limited by physical habitat or other irretrievable condition.
Limited warmwater habitat (LWH)	Waters incapable of meeting specific WWH criteria. This is a temporary designation based on 1978 Water Quality Standards and is being phased out. No new designations. Only acid mine drainage LWHs remain.
Modified warmwater habitat (MWH)	Waters that support tolerant assemblages of fish and macroinvertebrates, but otherwise similar to WWH; irretrievable condition precludes complete recovery to reference condition.
Anthropogenic	
Recreational trails on ODNR lands	All mapped recreational trails on ODNR lands (includes hiking, bridle, and multi-use trails).
Buckeye Trail	1,444-mile scenic hiking trail loop within the state of Ohio.
OGRIP Location Based Response System (LBRS) road data	Road centerline and addressing system collaboratively maintained between the state and county governments.

APPENDIX B: Results of Eastern Hemlock Stand Prioritization

Table 4. Acres of each conservation score for eastern hemlock stands of all land ownerships across Ohio.

County	Low-priority				Medium-priority				High-priority					Total acres
	0	1	2	3	4	5	6	7	8	9	10	11	12	
Adams	80.7	34.0	3.6	21.2	3.6	1.7								144.7
Ashland	178.4	266.8	192.6	169.7	63.7	74.3	30.1	84.2	265.1	190.8	1.7		228.0	1,745.3
Ashtabula	238.6	24.8	79.6	183.8	45.9	320.7	69.0	1.7	17.6	23.0				1,004.7
Athens	12.1	3.6	15.9	12.3						3.6				47.4
Belmont	127.2	67.1	88.3	77.7	15.9	23.0	1.7			1.7				402.8
Carroll	19.5	8.9	1.7	7.0										37.1
Columbiana	84.9	23.0	58.3	88.3	100.8	90.2	60.1	5.3		26.5	3.6			540.8
Coshocton	208.5	80.7	44.2	58.3	19.7	12.3		1.7	52.6	28.3	65.4	5.3		577.1
Cuyahoga	44.2	38.6	47.9	19.7	45.9	15.9	3.6		1.7					217.5
Fairfield	534.6	120.2	155.3	210.3	19.5	160.9	81.3	17.6	7.1					1,306.7
Gallia	5.3	3.6	3.6	3.6										16.0
Geauga	31.7	28.3	53.0	134.3	67.1	17.6	38.9	3.6			3.6			378.0
Greene	7.0								1.7					8.7
Guernsey	61.8	19.5	8.9	3.6										93.7
Harrison	148.4	45.9	17.6	5.3										217.3
Hocking	4,198.2	2,422.0	1,127.6	1,901.8	1,324.1	776.7	789.7	365.8	493.2	244.0	15.9		860.4	14,519.3
Holmes	341.2	85.6	169.6	69.0	8.9	107.7	10.6	20.0	10.6	8.9				831.9
Jackson	1,275.9	576.1	400.8	456.0	190.8	137.8	118.4	17.6	203.2	47.7	5.3		187.3	3,616.9
Jefferson	187.3	45.9	171.5	104.3	45.9	53.0	1.7							609.7
Knox	349.9	79.6	12.3	93.6	21.2	106.2	100.8	23.0	21.6	5.3	19.5			832.9
Lake	49.5	48.0	47.7	98.9	49.5	57.4	7.0	21.2	90.2	77.7	7.0	21.2		575.3
Lawrence	79.6	8.9	38.9	5.3	7.0	7.0								146.7
Licking	93.6	54.8	24.8	180.3	111.0	21.2	19.5							505.1
Lorain	8.9			1.7										10.6
Lucas	1.7								1.7	1.7				5.2
Mahoning	5.3	1.7	10.6	5.3	14.2									37.1
Medina	38.9	8.9	10.6	7.0	1.7									67.1
Meigs	3.6	5.3		5.3										14.2
Monroe	595.5	83.0	243.9	134.3	30.1	203.2	54.8							1,344.8
Morgan	60.1	7.0	28.3	21.2										116.6
Muskingum	167.9	63.7	84.1	56.5	12.3	1.7								386.3
Noble	52.8	14.2	17.6	12.3										96.9
Perry	70.7	23.0	36.1	19.5										149.3
Pickaway	1.0													1.0
Pike	177.4	52.6	56.9	30.1	8.9	3.6	1.7	5.3						336.4
Portage	10.6	3.6												14.2
Richland	56.5	35.4	30.1	30.1										152.0
Ross	110.5	68.1	5.3	37.1	15.9	3.6								240.4
Scioto	51.2	21.2	8.9	118.4	72.4	60.1	23.0	21.2	10.6	1.7		1.7		390.5
Stark	1.7													1.7
Summit	45.9	47.7	40.4	24.5	1.7	17.6	10.6	1.7						190.2
Trumbull	16.0	10.6	10.6	3.6	1.7			1.7		3.6	1.7			49.5
Tuscarawas	47.7	12.3	19.5	8.9										88.3
Vinton	344.5	168.0	93.6	157.2	70.2	106.9	32.1							972.6
Washington	32.3	14.2	33.6	28.3	1.7	15.9	15.9	3.6		1.7				147.2
Wayne	120.2	17.6	95.5	35.4	19.5	17.6								305.7
Total acres	10,379.0	4,743.8	3,589.1	4,640.6	2,390.8	2,413.8	1,470.4	595.3	1,176.9	666.2	123.7	28.2	1,275.7	33,493.5
	23,352.6				6,870.3				3,270.7					

Table 5. Acres of each conservation score for eastern hemlock stands on ODNR lands.

County	Low-priority				Medium-priority				High-priority					Total acres
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	
Adams	2.0	2.0	4.1		2.0									10.0
Ashland	8.0	98.8	54.4	90.8	34.3	42.3	28.3	12.1	195.7	115.0	2.0		229.9	911.5
Ashtabula	8.0	4.1	30.2	16.2		4.1								62.6
Athens		2.0												2.0
Belmont	12.1	4.1												16.2
Columbiana	24.2	2.0	6.0	24.2	52.4	38.4	42.3			30.2	4.1			223.8
Coshocton	36.3	10.1	14.1	6.0	6.0				17.7					90.3
Fairfield	117.4	20.1	22.2	127.1	4.1	104.9	54.4	12.1	6.0					468.3
Geauga			4.1											4.1
Greene	4.1													4.1
Guernsey		2.0	2.0											3.9
Harrison	54.4	2.0	0.0											56.4
Hocking	1,233.8	1,287.9	449.9	788.8	845.2	526.5	639.5	320.8	355.1	179.7	2.0		925.5	7,554.5
Jackson	127.2	36.3	96.9	96.9	40.3	50.5	107.0	2.0	153.2	14.2			157.2	881.6
Jefferson	10.1		26.3	10.1	10.1	4.1								60.7
Knox			4.1						0.4					4.5
Lake				4.1	2.0									6.0
Lawrence		2.0												2.0
Licking			2.0	4.1										6.0
Lorain	8.0			2.0										10.0
Meigs	2.0	6.0		6.0										14.1
Monroe	34.3		6.0			26.3								66.6
Muskingum	32.3	20.1	28.3	34.3	12.1									127.1
Noble	6.0	2.0												8.0
Perry		2.0												2.0
Pike	4.1	18.1	8.0											30.2
Ross	80.8	65.1		28.3	14.1	4.1								192.3
Scioto	24.2	14.1	4.1	26.3	44.4	28.3	18.1	20.1	10.1	2.0		2.0		193.6
Trumbull	16.2	8.0						2.0			2.0			28.1
Tuscarawas	4.1													4.1
Vinton	18.1	24.3	16.2	4.1	10.1	2.0	2.0							76.8
Washington		4.1				2.0	2.0							8.0
Total acres	1,867.6	1,636.9	778.7	1,269.2	1,077.1	833.2	893.5	369.0	738.3	341.1	10.0	2.0	1,312.5	11,129.2
	5,754.0				3,771.7				1,603.5					

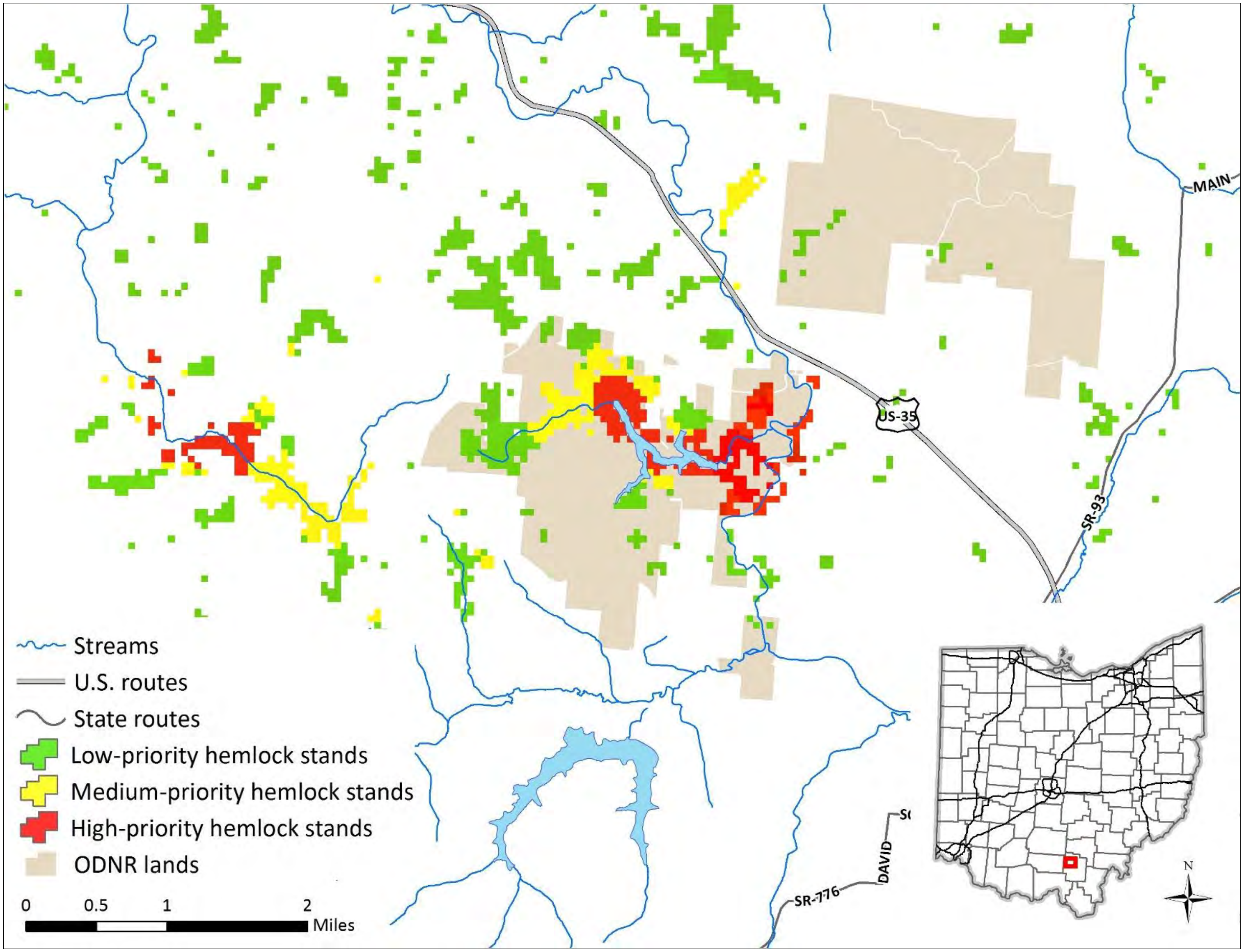

Figure 15. Eastern hemlock stand rankings in the Lake Katharine area (Jackson County).

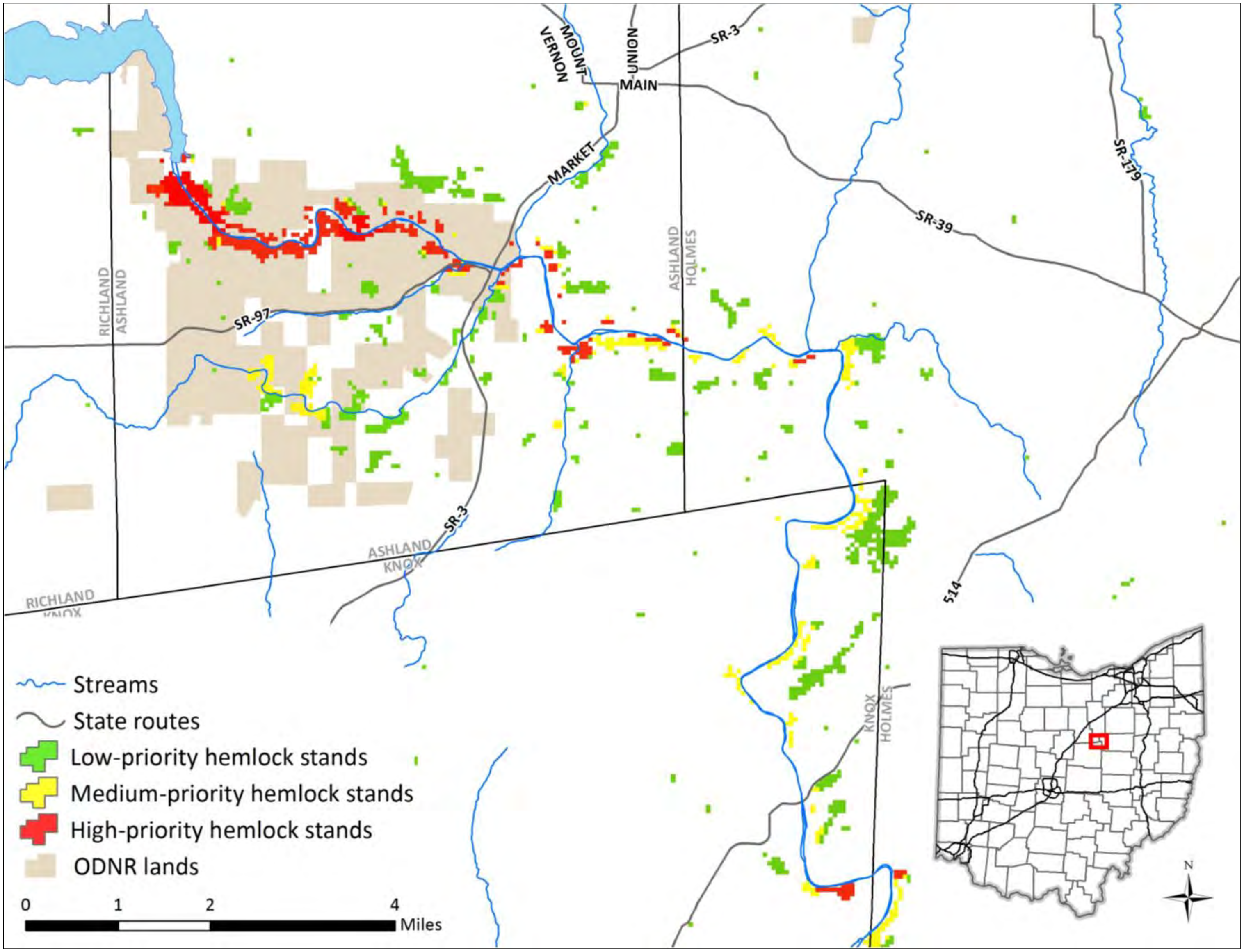

Figure 16. Eastern hemlock stand rankings in the Mohican area (Ashland County).

APPENDIX C: Chemical Treatment Costs

Table 6. Estimated costs of chemical for imidacloprid soil drench and basal bark spray treatments based on current commercial pricing.

Diameter at breast height (DBH) in inches	EPA active ingredient per acre limit	Grams active ingredient per inch of DBH		Max. inches DBH treated per acre per year	Chemical cost per inch DBH
		Label rate	Min. effective rate		
<7.9	0.4 lbs (181 g)	0.7-1.4	0.5	362	$0.13
8.0-14.9	0.4 lbs (181 g)	0.7-1.4	0.75	241.3	$0.19
15.0-20.9	0.4 lbs (181 g)	0.7-1.4	1.0	181	$0.25
>21.0	0.4 lbs (181 g)	0.7-1.4	1.4	129.3	$0.35

Table 7. Estimated costs of chemical for imidacloprid trunk injection and soil tablets and dinotefuran basal bark spray based on current commercial pricing.

	Imidacloprid		Dinotefuran
	Trunk injection	Soil tablets	Basal bark spray
EPA active ingredient per acre limit	None	0.5 lbs (226 g)	0.54 lbs (244 g)
Grams active ingredient per inch of DBH	2.0-4.0	1-1.5 (2-3 tablets)	1.0-2.0
Max. inches DBH treated per acre per year	Unlimited	150-226	122-244
Chemical cost per inch DBH	$0.60-$1.20	$0.72-$1.08	$1.56-$3.12

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