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Integrating Chemical and Biological Control of the Hemlock Woolly Adelgid:

A Resource Manager's Guide

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FOREST HEALTH ASSESSMENT AND APPLIED SCIENCES TEAM

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Cover Photos: (a) making visual crown rating estimates of hemlock health; (b) hemlock branch with a high density of HWA; (c) adult *Laricobius* beetle; (d) tablet formulation delivery method for treating hemlock trees with imidacloprid (Credits: a. A. Mayfield, USDA Forest Service; b. S. Salom, Virginia Tech; c,d. Elizabeth McCarty, University of Georgia, Bugwood.org)

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Integrating Chemical and Biological Control of the Hemlock Woolly Adelgid:

A Resource Manager's Guide

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ABSTRACT

A non-native invasive insect, the hemlock woolly adelgid (HWA), threatens the ability of natural resource managers to maintain eastern and Carolina hemlocks as critical components of unique forest ecosystems in eastern North America. Although substantial progress has been made in both chemical and biological control of HWA, neither of these tactics applied alone are expected to provide adequate control of HWA throughout its introduced range. This guide presents a methodological strategy for integrating biological and chemical control together in the same forest stands. The goal of the strategy is to prolong hemlock health on certain hemlock trees through temporary insecticide protection, while simultaneously establishing predators on nearby untreated trees. Temporarily-protected hemlocks are expected to eventually support predators after their chemical treatment wears off. Guidelines for site selection, treatment timing, spatial considerations, monitoring, and assessment are included. The guide is intended as a starting point for a more sustainable approach to HWA management that reduces the amount of insecticide applied, and that can be integrated with additional management tools as they are developed.

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INTRODUCTION

Eastern hemlock (*Tsuga canadensis*) is a highly valued, ecologically important native tree species widely distributed throughout the eastern United States (U.S.) and Canada. It is long-living, slow growing, highly shade-tolerant, and adaptable to growth under many types of site conditions (Godman and Lancaster 1990). Eastern hemlock often occurs as a component of mixed hardwood forests (Figure 1a) or as the dominant conifer in the later stages of ecological succession. It is also considered a foundation species in critical riparian habitats (Figure 1b) and other systems where it has a strong influence on biodiversity and ecological processes (Ellison et al. 2005). Another hemlock species found in the eastern U.S. is the relatively rare Carolina hemlock (*Tsuga caroliniana*), which is limited to small pockets of forest in the southern Appalachian Mountains (Jetton et al. 2008).

The hemlock woolly adelgid (*Adelges tsugae,* or HWA) is found on hemlock species (*Tsuga* spp.) worldwide but is not native to eastern North America (Havill and Foottit 2007). In its native ranges, HWA rarely reaches population levels that are injurious to hemlocks, because it is likely suppressed through a combination of evolved host resistance and a complex of native predators (Havill et al. 2006). HWA was discovered in the eastern U.S. in the early 1950s near Richmond, VA, and the origin of this population was traced back to the southern region of the Japanese island of Honshu, near the city of Osaka (Havill et al. 2006, Havill et al. 2016a). Since then, HWA has become a serious pest on both eastern and Carolina hemlocks (Havill et al. 2016b). The range of HWA continues to expand, and it has become established throughout much of the eastern U.S. from Maine to Georgia, as far west as Michigan, and as far north as Nova Scotia (Figure 2). Since the 1980s, HWA has caused extensive decline and mortality of eastern and Carolina hemlocks (Orwig et al. 2002, Vose et al. 2013; Figure 3). HWA is capable of killing hemlocks of any age and size class.

Figure 1. Eastern hemlock grows in a variety of habitats, including mixed confer-hardwood stands (a) and along stream corridors (b). (Credits: a. A. Mayfield, USDA Forest Service; b. N. Schneeberger, USDA Forest Service).

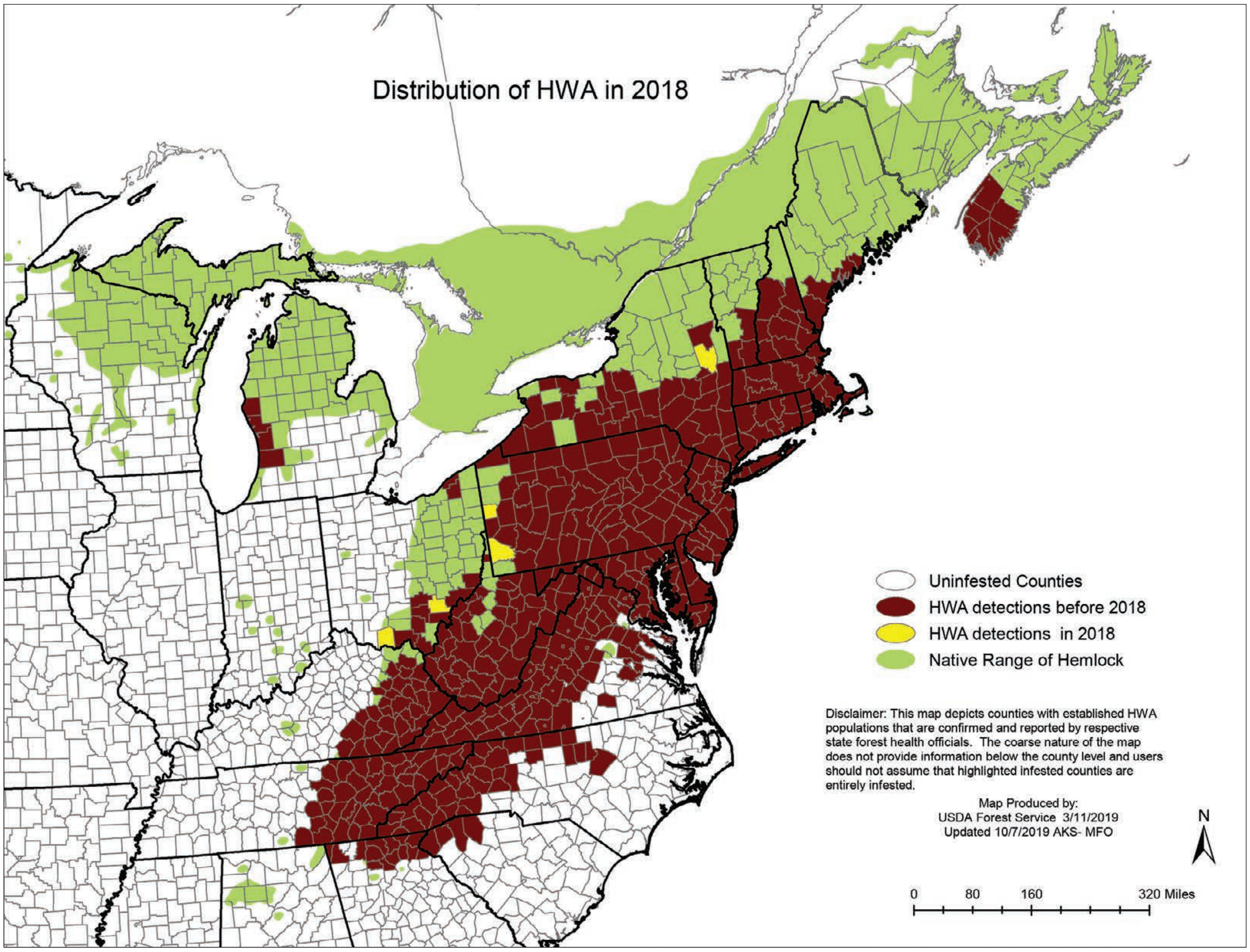

Figure 2. Distribution of the hemlock woolly adelgid in eastern North America as of 2018. (Maps archived at http://hiro.ento.vt.edu/hwa/index.php/distribution-maps/)

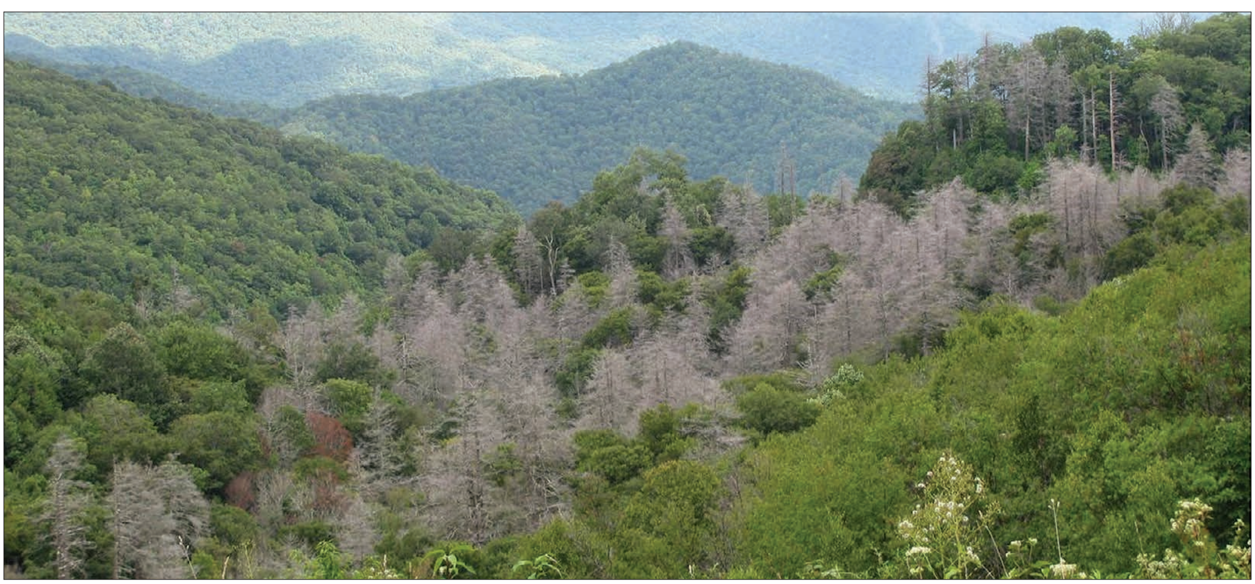

Figure 3. Eastern hemlocks killed by the hemlock woolly adelgid in the southern Appalachian Mountains. (Credit: D. Casey, USDA Forest Service)

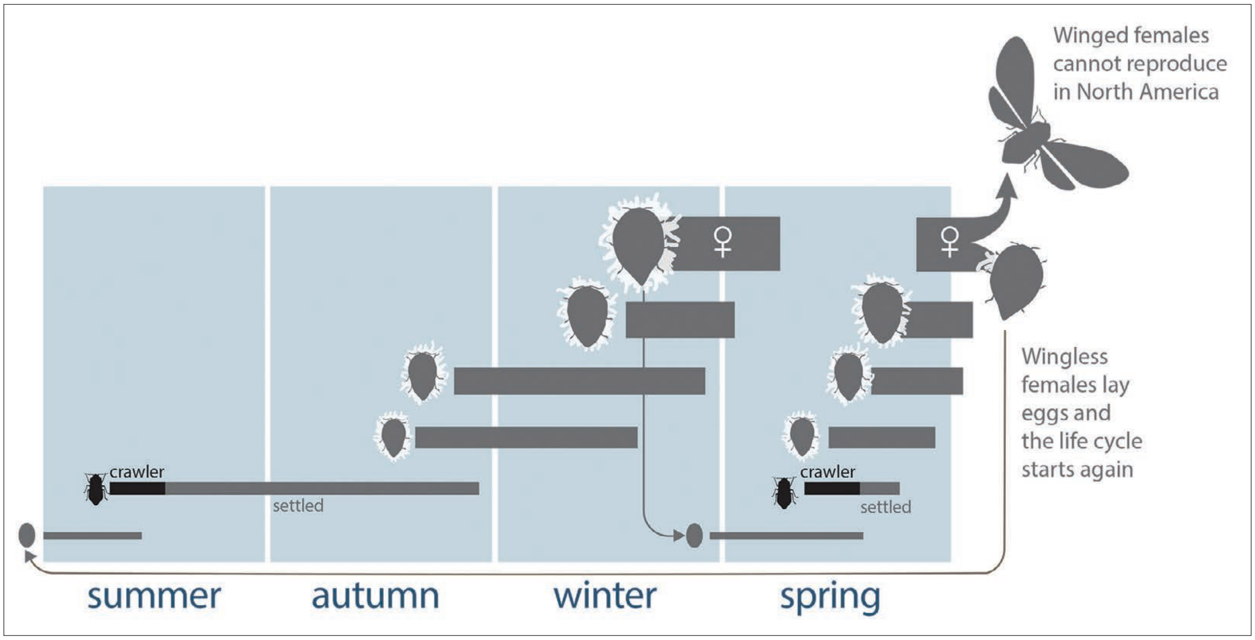

Figure 4. The life cycle of the hemlock woolly adelgid (HWA) on hemlock in North America. The sistens generation develops from summer through winter, and the progrediens generation develops in the spring. In both generations, eggs give rise to mobile crawlers, which settle on hemlock twigs and progress through three more nymph stages before becoming adult females. In North America, winged adults in the spring do not reproduce and the life cycle on hemlock is driven entirely by wingless females. (Credit: V. D'Amico and N. Havill, USDA Forest Service)

In North America, HWA has two successive, asexual generations. The progrediens generation is present in the spring, and the sistens generation is present from summer to early spring of the following year (Havill et al. 2016b) (Figures 4, 5). HWA feeds by inserting its mouthparts into twig tissues near the base of needles (Oten et al. 2014). This results in the depletion of plant sugars, drying and loss of foliage, and reduction of new growth (Miller-Pierce et al. 2010, Domec et al. 2013, Gonda-King et al. 2014). During most of the summer, HWA is in a dormant stage and does not begin feeding again until late September or October.

The health of infested hemlock stands is largely dependent on the density of HWA (McClure 1991). Following initially heavy infestations on healthy hemlocks, trees experience dieback, and the HWA population declines due to poor host quality and a lack of new shoots on which to settle. This decrease in the HWA population allows trees to partially recover and resume new shoot growth. However,

Figure 5. A springtime photograph of hemlock woolly adelgid taken through a 10x hand lens, showing the large, white, cottony ovisacs of the sistens generation, and the smaller, more numerous nymphs of the recently-hatched progrediens generation. (Credit: Bryan Mudder, USDA Forest Service)

these new shoots usually become infested by HWA, and the cycle of decline continues (McClure 1991). The rate at which this process occurs is variable. Some trees die in as few as four years, whereas others may survive for 15 years or more (Havill et al. 2016b). Certain abiotic factors, such as sudden changes or extremes in temperature, can negatively affect HWA, prolonging stand survival and slowing HWA range expansion (Parker et al. 1998, 1999; Skinner et al. 2003; Paradis et al. 2008; McAvoy et al. 2017b; Mech et al. 2018).

CHEMICAL CONTROL OF HWA: BENEFITS AND LIMITATIONS

Chemical insecticides are effective against HWA and have been used widely in urban and landscape settings, for highly valued trees in campgrounds and recreation areas, and in managed forests. This has included large-scale chemical treatment efforts in certain state and national parks and forests in which hundreds of thousands of trees have been treated. Although insecticide treatment of hemlocks has been a critical means by which hemlock mortality has been reduced, it is applied on an individual tree basis and is thereby relatively cost- and labor-intensive (Vose et al. 2013).

The most commonly used class of insecticides for control of HWA has been neonicotinoids. Neonicotinoids are neurotoxic compounds with relatively low mammalian toxicity that are widely used in agriculture and other pest applications worldwide (Durkin 2016). Recent research indicates that these compounds are persistent in ecosystems and have negative non-target effects on beneficial organisms, including pollinators (Hladik et al. 2018, Calvo-Agudo et al. 2019). Compared with typical agricultural applications, however, application of neonicotinoid insecticides for HWA management greatly limits potential exposure to non-target organisms. The insecticides are applied directly to the trunk or soil immediately around the base of the tree, and are distributed systemically through the tree's internal vascular system to fine branch tissues where the adelgids feed. Furthermore, hemlock is wind pollinated and does not produce flowers that would be visited by pollinating insects. Because of their value in reducing the impact of non-native forest pests, state forestry agencies in the U.S. have advocated for the continued use of neonicotinoid insecticides in forestry (Southern Group of State Foresters 2017).

Neonicotinoid insecticides should be used carefully and judiciously in HWA management. This guide recognizes that application of insecticides is not a stand-alone, long-term strategy for HWA, and stand-level, pre-emptive insecticide treatments are not recommended. Rather, a goal of this guide is to use insecticides conservatively and strategically in a way that ultimately reduces the amounts applied on the landscape. Human health and ecological risk assessments associated with USDA Forest Service uses of neonicotinoids have been completed and are available online (Durkin 2009, 2016).

One of the early insecticides in the neonicotinoid class, imidacloprid, was evaluated and found to be highly effective against HWA (Steward and Horner 1994, Cowles et al. 2006). Not only is the imidacloprid compound directly lethal to HWA, secondary metabolites, such as olefin, persist in the plant tissue longer and are more toxic to the adelgids than imidacloprid (Coots et al. 2013, Benton et al. 2015). The most common method of application for imidacloprid involves soil treatments, including soil drench, soil injection (Steward et al. 1998), and placement of subsurface tablets (Figure 6). Soil treatments result in better distribution of imidacloprid within the tree as compared to stem injection (Dilling et al. 2010; Figure 6), but stem injection can be useful when proximity to water or other site limitations preclude the use of soil application.

Soil-applied imidacloprid moves slowly from the roots to the top of the tree, may take 3–12 months to reach all of the canopy (Coots et al. 2013, Joseph et al. 2011a), and typically protects hemlocks from HWA for

Figure 6. Common delivery methods of treating hemlock trees with imidacloprid. (a) soil drench; (b) soil injection; (c) tablet formulation, and (d) stem injection. (Credits: a,b. Great Smoky Mountains National Park Resource Management, USDI National Park Service, Bugwood.org; c. Elizabeth McCarty, University of Georgia, Bugwood.org; d. N. Schneeberger, USDA Forest Service)

a period of 4–6 years (Silcox 2002, Benton et al. 2016b). Traces of imidacloprid and its metabolites have been detected in hemlock tissue up to 7 years post-treatment (Benton et al. 2015, Mayfield et al. 2015). Description of an optimized dosage application based on size of the trees is presented in Benton and Cowles (2017).

An aquatic assessment was conducted with 10 southern Appalachian streams associated with chemical treatments for HWA in riparian areas. Although imidacloprid was detected in adjacent waterways, sensitive aquatic invertebrate communities were just as diverse and healthy as communities in areas were no insecticide was used (Benton et al. 2016a, Benton et al. 2017). In addition, no secondary insecticidal metabolites were recovered from these streams (Benton et al. 2016a).

A different neonicotinoid product that is more water-soluble and faster-acting than imidacloprid is dinotefuran (Durkin 2009). For treatment of HWA, it can be applied as a basal bark spray, soil injection, or soil drench (Valent 2014) and can suppress HWA populations in as little as one month after treatment (Joseph et al. 2011a). However, the efficacy of dinotefuran persists for only 1–2 years. Recent recommendations have included tank mixing both imidacloprid and dinotefuran to obtain the best of both products: quick uptake with longer-lasting efficacy (Whitmore 2014, McCullough 2017).

BIOLOGICAL CONTROL OF HWA: BENEFITS AND CURRENT STATUS

Natural enemies of HWA are comprised principally of host-specific and generalist predatory insects. Several host-specific predators from the native range of HWA have been studied and released as biological control agents since the 1990s (Onken and Reardon 2011, Mausel and Salom 2013). *Sasajiscymnus tsugae*, a ladybird beetle from Japan, was the initial focus of this effort (Cheah and McClure 1998). Millions of beetles were subsequently reared by several labs and released throughout the eastern U.S. However, difficulty in recovering the beetle consistently (Hakeem et al. 2010, 2013) led to increased emphasis on other specialist predators.

Laricobius beetles from the family Derodontidae are adelgid specialists (Leschen 2011), and several geographically separated species are predators of HWA. Two species currently being reared, collected, and released are *L. nigrinus* from western North America and *L. osakensis* from Japan. *Laricobius nigrinus* was first released in 2003 and was reported to be established following an extensive assessment of 22 release sites (Mausel et al. 2010). The number of lab-reared and field-collected *L. nigrinus* beetles released is approaching 400,000. These beetles have been released at hundreds of locations, and are now being collected from selected field sites in the eastern and western U.S. for redistribution to new sites in the eastern U.S. (Virginia Tech 2020).

Laricobius osakensis was first released in 2012 (Mooneyham et al. 2016), has been released at more than 60 locations, and is established at several sites (Toland et al. 2018). This species was discovered in 2005 in southern Japan (Montgomery et al. 2011). Since HWA in the eastern U.S. is descended from HWA in southern Japan (Havill et al. 2006, 2016a), it is likely that this predator is well adapted to this strain of adelgid. How it compares in establishment and impact with *L. nigrinus* will take time to determine.

Both *Laricobius* species are active as adults (Figure 7a) in the fall and winter, where they feed on developing sistens. Female *Laricobius* beetles lay eggs in sistens ovisacs around the time progrediens eggs are being laid in early spring. Upon hatching, *Laricobius* larvae (Figure 7b) feed on HWA eggs in the ovisac and early stage progrediens nymphs. After mature *Laricobius* larvae finish feeding on their prey, they drop to the soil to pupate. Thus, later stage progrediens nymphs and adults, and sistens eggs, are free from significant predation in the late spring when *Laricobius* beetles are pupating.

Figure 7. *Laricobius nigrinus*. (a) adult on a hemlock twig; (b) larva within an HWA ovisac. (Credits: a. Bryan Mudder, USDA Forest Service; b. David Mausel, Virginia Polytechnic Institute and State University, Bugwood.org)

An additional biological control agent that would feed on HWA during this late spring season could greatly enhance current efforts to control HWA populations. *Leucopis* silver flies are adelgid-specialist predators active during this critical time. Two *Leucopis* species are closely associated with HWA in the western U.S. (Kohler et al. 2008, 2016). Since 2015, these predatory flies have been collected and shipped to the eastern U.S. for caged release studies (Motley et al. 2017). The goal is that over time, with continued releases, these western silver flies will establish and become an important biocontrol agent for the late spring life stages of HWA.

WHY INTEGRATE CHEMICAL AND BIOLOGICAL CONTROL?

The USDA Forest Service and its management partners are trying to achieve an overall integrated pest management (IPM) strategy for addressing the HWA problem in eastern North America. An end goal is to retain, in a sustainable way, the unique characteristics that hemlocks provide in an ecosystem. Despite substantial developments in both chemical and biological control, neither of these options is likely to solve the HWA problem alone. This is because 1) it is neither practical nor ecologically responsible to chemically treat all the hemlocks in a stand into the indefinite future, and 2) patterns of hemlock decline and mortality suggest that biological control agents alone cannot act quickly enough to save all the hemlocks in many locations. It takes years for biological control populations to build up, and often trees cannot survive the wait.

With this in mind, we are proposing a strategy that combines both chemical and biological control tactics in the same stand. The goal is to prolong and improve hemlock health on certain hemlock trees through temporary insecticide protection, while simultaneously establishing predators on nearby untreated trees, or unprotected portions of trees treated with low rates of insecticide (Joseph et al. 2011b, Eisenback et al. 2014, Mayfield et al. 2015, Sumpter et al. 2018). In concept, this approach will allow predator populations to increase on the untreated trees, and eventually disperse onto the temporarily-treated trees after the insecticide protection wears off. Those previously-protected hemlocks should then have better health and potentially greater longevity than hemlocks that have never been chemically treated. The previously-protected trees should also be a better source of prey because they have more new shoots for HWA to infest (Mayfield et al. 2015).

Exposure of predatory insects to systemic insecticides should be limited because 1) the insecticides are delivered primarily within the plant tissue, and 2) chemically-protected branches will not support HWA and thus will not be attractive to predators. Exceptions may occur with soil-applied insecticides, because *Laricobius* beetles spend part of their spring and summer in the soil. Thus, a proportion of the *Laricobius* population could become exposed to the product when they drop to the ground near the base of treated trees. Another exception may occur if trees are chemically treated after predatory beetles are already present in the stand, and insecticide is actively being consumed by adelgids when predators are feeding on them. In the IPM strategy outlined below, guidelines are offered to help minimize these kinds of exposures and ensure that most of the predator population does not encounter the insecticide.

The IPM strategy presented herein does not propose the complete prevention of hemlock decline and mortality. Realistically, land managers should be prepared to accept some impact from HWA without losing all their hemlock trees. The intent is a strategic use of insecticide application that facilitates predator establishment and growth, hopefully reducing and maintaining HWA populations below unacceptable levels. Current research is attempting to determine what impact predators have on HWA populations and tree health in stands where they are established. A recent multi-year, multi-site field study demonstrated that *L. nigrinus* has a significant impact on ovisacs of the winter sistens generation (Jubb et al. 2020). However, there is also evidence that densities of the progrediens generation rebound following *Laricobius* predation (Crandall et al. in review). As work continues on assessing the contribution of biological control, the proposed strategy is offered as a starting point for managing hemlock stands and HWA in a more integrated, sustainable way.

IMPLEMENTING AN INTEGRATED STRATEGY

WHERE TO APPLY

Hemlock trees are found in diverse settings, ranging from large expansive natural stands to small yards and parks. Due to the limited availability of predators for release, distribution of biological control agents has been concentrated on public lands that typically support natural forests of either pure hemlock or hemlocks mixed with other tree species. Additionally, high-value trees growing in recreational areas or preserves have been targeted as well.

The following guidelines should be considered when choosing a site to integrate biological and chemical control of HWA. Most of the thresholds mentioned below are not derived from specific research trials, but are recommendations based on manager experiences and current knowledge about HWA, their predators, and their interaction with hemlock ecosystems. Additional site selection criteria can be found on the HWA Predator Database (Virginia Tech 2020).

OWNERSHIP

The owners or managers of the property should have a long-term commitment to managing the forest in a way that is consistent with the IPM strategy. Often this requires public ownership or lands with conservation status. Incompatible management practices may include excessive hemlock removal or prescribed fire treatments that might kill aestivating *Laricobius beetles* and/or hemlocks.

STAND SIZE AND HEMLOCK SPACING

Sites should be large enough, and with a sufficient hemlock component, to support predator population increase and dispersal. Ideally, stands should be at least 4 ha (10 ac) in size with hemlock comprising at least 20% of the basal area. Try to avoid stands in which the average hemlock spacing is excessively wide (>30 m or >100 ft) such that predators cannot readily find each other or their prey.

HWA POPULATION

A population of HWA must be present in order to support predators and to warrant use of insecticides. If HWA has only recently arrived to the stand and adelgid densities are very low, the prey population may not yet be large enough to achieve predator establishment. As a lower threshold for implementing an IPM strategy, we recommend that at least 20% of the hemlock trees in the stand be infested with HWA. A statistically reliable estimate of the percentage of infested trees can be determined using the methods and data sheet provided in Costa and Onken (2006). Trees onto which predators will be released should have at least some branches with a high density of HWA ovisacs (Figure 8).

Figure 8. A healthy, hemlock branch with a high density of HWA. Such branches are desired locations for releasing adult predator beetles. (Credit: S. Salom, Virginia Tech)

HEMLOCK HEALTH

Choose stands in which the majority of hemlocks are in good health. The trees should have abundant new shoot growth necessary to sustain HWA as food for predators (Figure 8), and should possess sufficient vigor to survive infestations for several years. Such trees may include hemlocks that 1) are in the early stages of infestation (first 2–3 years) with little to no dieback or decline apparent; 2) have rebounded well from a first wave of HWA infestation; or 3) are just coming out of chemical protection. Most of the hemlocks should have a crown density rating 60% or above and a foliage transparency rating of 45% or lower (see “Hemlock Health” in Chapter 4: Assessing the Strategy).

CROWN STRUCTURE

At least some of the hemlocks within or on the edges of the stand should have lower branches that extend near the ground and can be reached by hand. These trees will typically have a live crown ratio greater than 80%. Having branches that can be reached by hand from the ground greatly facilitates the assessment of HWA populations, the release of predator beetles onto branches, and future monitoring of both HWA and predators. However, not all hemlock trees in the stand need to have this characteristic.

OTHER FACTORS

Choose sites that have a consistent, organic duff layer over the mineral soil and beneath the drip lines of the hemlock trees that is at least an average depth of 2.5 cm (1.0 in). This organic layer is habitat for *Laricobius* larvae in the spring and adults in the summer.

CHEMICAL TREATMENTS

A proposed strategy for integrating chemical and biological control in the same stand is to create different "classes" of hemlock trees on the landscape. The classes are created by varying the level and duration of insecticide protection among hemlocks. The level of chemical protection can be manipulated by varying the amount of insecticide applied (e.g., full rate, reduced rate, none), whereas the duration of protection can be manipulated by the frequency of insecticide re-application or the type of insecticide used. In this strategy, some trees remain untreated to harbor HWA and support early predator establishment and population growth. Other trees are chemically treated to temporarily preserve crown health, but eventually support prey after predator populations have the opportunity to establish and increase in the stand. If resources permit, a limited number of high-value trees are treated perpetually.

CLASS 4

CLASS 4: PERPETUAL, FULL PROTECTION

Class 4 trees are hemlocks that receive the full rate of the insecticide and are retreated on an interval that maintains protection from HWA for as long as possible. If using imidacloprid, trees are retreated approximately every 5–7 years or when chemical protection wears off (based on observance of HWA on the branches). No predators are released on these trees. Class 4 is expensive to maintain and thus might comprise only 1–10% of the hemlocks in the stand. It should be reserved for hemlocks with the highest ecological, economic, or aesthetic value (e.g., very large trees, trees valued for seed production, trees adjacent to recreational sites, etc.) (Figure 9).

CLASS 3

CLASS 3: TEMPORARY, FULL PROTECTION

Class 3 trees receive a one-time treatment of imidacloprid at the full rate and are not retreated. These are trees for which good crown health is being maintained for 5–7 years while predator populations are increasing on the Class 1 and 2 trees (described below). When Class 3 trees lose chemical protection, both HWA and their predators are permitted to colonize these trees. Managers may consider designating 10–20% of the hemlocks in the stand as Class 3 trees.

CLASS 2

CLASS 2: TEMPORARY, PARTIAL PROTECTION

Class 2 trees receive a one-time imidacloprid treatment, but at a reduced rate (e.g., 25–50% of the full rate). Based on previous experience (Joseph et al. 2011b, Eisenback et al. 2014, Mayfield et al. 2015), HWA will colonize these trees, or portions thereof, within 1–4 years. To achieve partial tree protection through a reduced rate treatment, reduce the number of fluid ounces, injection pumps, or tablets applied (depending on the product and delivery method used) to approximately 25–50% of that recommended for a given tree diameter in Benton and Cowles (2017). Like Class 3 trees, Class 2 trees represent hemlocks for which future crown health is being maintained while predator populations increase on other trees, but to a lesser degree and for a shorter time. Managers may consider designating 10–20% of hemlocks in the stand as Class 2 trees.

CLASS 1

CLASS 1: NO PROTECTION

Class 1 hemlocks receive no insecticide treatment. They are infested with HWA or are expected to be infested in the very near future. As such, Class 1 trees represent hemlocks on which predators will be released or to which they will initially disperse. Early predator populations will establish and begin to increase in number on Class 1 trees before prey becomes available on Class 2 and 3 trees. Managers may consider designating a moderate to high percentage (≥50%) of hemlocks in the stand as Class 1 trees.

Figure 9. Large hemlocks with high aesthetic, recreational, and ecological value are good candidates for perpetual chemical protection (Class 4). (Credits: A. Mayfield, USDA Forest Service)

Figures 10 and 11 provide a schematic of how the classes might be arranged on a hypothetical landscape to support both predator proliferation and hemlock health. The number of classes and their arrangement could vary depending on the objectives of the resource manager and the local conditions. For determining the "full rate" dosage for imidacloprid (see Classes 3 and 4 above), we recommend using the diameter-optimized tables and instructions presented in "Optimized Insecticide Dosage for Hemlock Woolly Adelgid Control in Hemlock Trees" (Benton and Cowles 2017).

SPATIAL CONSIDERATIONS

The treatment classes described above should be arranged on the landscape to facilitate the dispersal of predators onto newly infested trees over time. Thus, the Class 1 trees onto which predators are released should be in close proximity (within 30 m) to other Class 1 trees, where prey is expected to be available during the first few years (Figures 10, 11). These Class 1 trees should also be in close proximity to Class 2 trees, which will begin to support HWA within 1–4 years. In turn, Class 2 trees should be located near Class 3 trees, which should begin to support prey after 5–7 years.

Two different hypothetical scenarios for arranging Class 1–4 hemlock treatments on the landscape are shown in Figures 10 and 11. In Figure 10, the chemical treatment classes are applied in a mosaic pattern among hemlocks on both sides of a stream. The highest value trees (Class 4) are scattered throughout the stand. The Class 1 trees, chosen for predator release, are immediately adjacent to other Class 1 trees onto which predators can disperse. Class 2 and 3 trees are intermixed to allow predator dispersal from Class 1 to 2, and 2 to 3, over time. Class 4 trees do not support predators because they are not infested with HWA. The design illustrated in Figure 10 also favors conservation of hemlock genetic diversity because the Class 4 trees are widely spaced and thus are less likely to be closely related (Jetton et al. 2013).

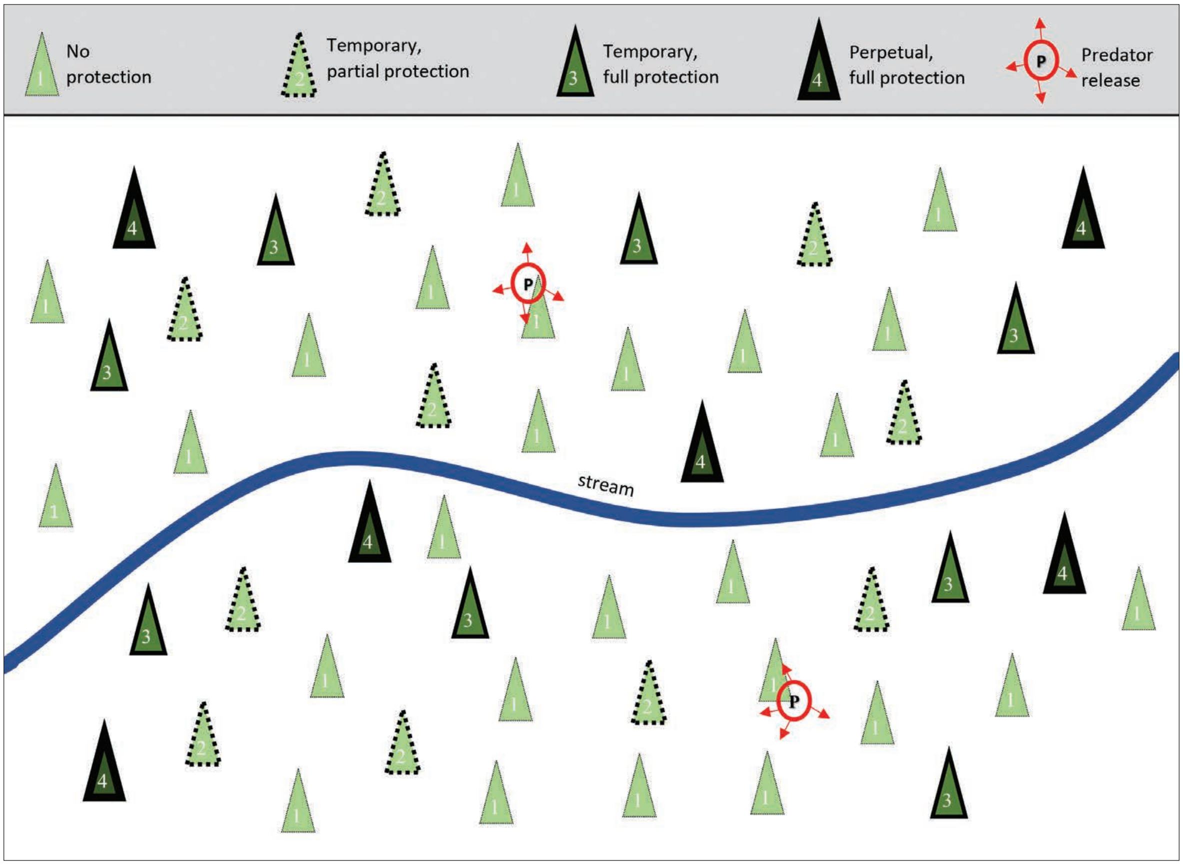

Figure 10. A hypothetical, integrated chemical-biological control scenario. In this spatial arrangement, treated trees (classes 2–4) are scattered among untreated trees (Class 1). Predators are released on Class 1 trees, spread initially to other Class 1 trees, and eventually colonize Class 2 and 3 trees when the chemical protection wears off (in 1–4 years for Class 2; 5–7 years for Class 3). High-value class 4 trees remain perpetually protected.

In contrast, the chemical treatment classes in Figure 11 are arranged as a spatial gradient in which predators are expected to disperse in the direction of a recreational area over time. The highest value trees are those next to the recreational area and are treated as Class 4 for perpetual protection. Beetles are released on Class 1 trees at the margins of the stand and initially disperse to other Class 1 trees. Established predators are expected to move towards the recreational area as prey becomes available first on Class 2 and then on Class 3 trees. Again, predators are not expected on Class 4 trees because their prey is absent. A slight variation on this design would be to create a "core" area of Class 4 trees that are surrounded by concentric circular groupings of Class 3, 2, and 1 trees radiating outward.

VARIATIONS

These are hypothetical scenarios that could be modified to fit different stand conditions, available resources, and manager objectives. For example, the percentage of untreated (Class 1) trees in the stand could be increased or decreased. In the examples above, we presented the number of untreated trees as a moderately high percentage (about 50% in Figures 9 and 10). One reason for this is that chemical treatment is expensive to maintain, and is usually viewed as a stopgap measure against HWA until other more sustainable controls (such as biological control) are developed and optimized. Thus, a strategy that minimizes the amount of insecticide needed to sustain a hemlock stand is a desirable goal when integrating chemical and biological control.

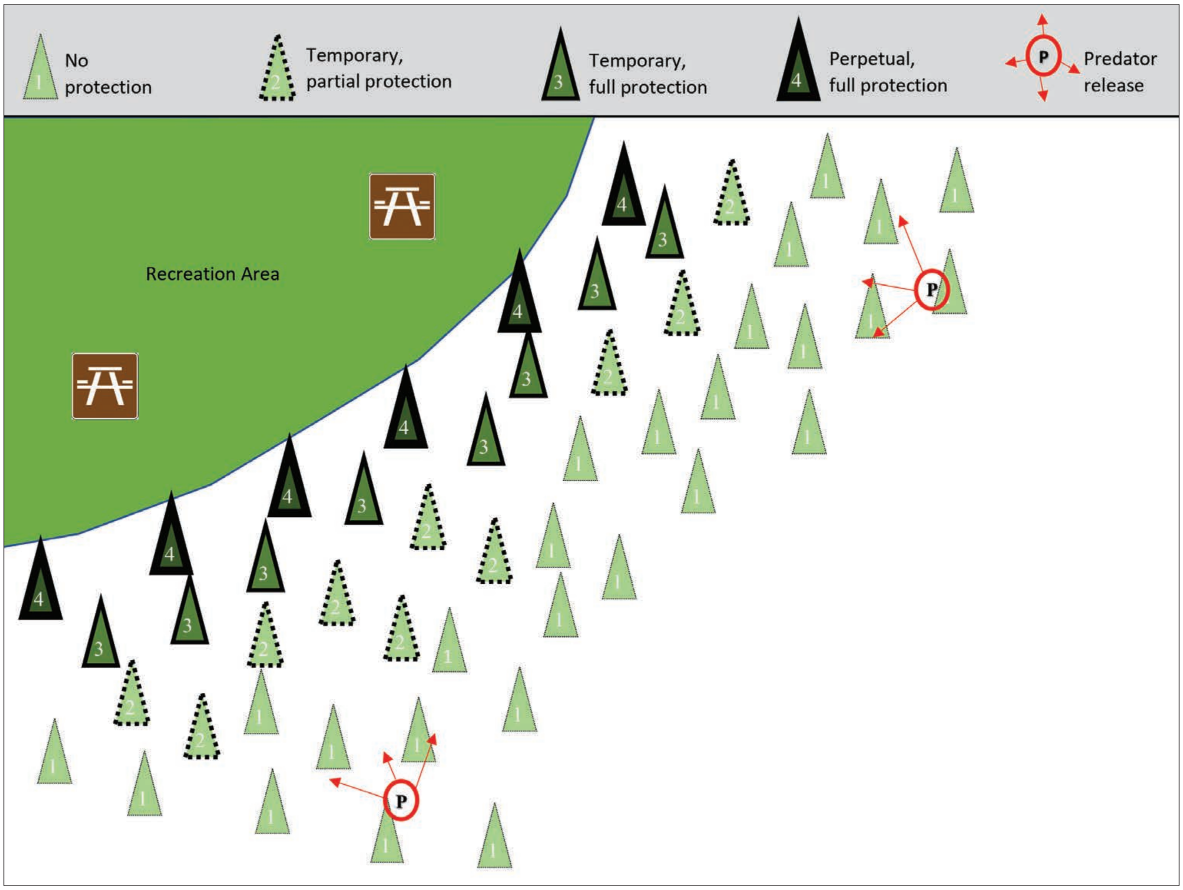

Figure 11. Another hypothetical, integrated chemical-biological control scenario. In this spatial arrangement, the highest-value trees are located adjacent to a recreation area. Treatment classes are therefore arranged in a spatial gradient that will allow predators to first become established on Class 1 (untreated) trees, and then move directionally toward the recreation area over time as the Class 2 and 3 trees lose protection. Class 4 trees remain perpetually protected.

At the same time, it is realistic to assume that some, or even many, of the Class 1 trees are going to decline in health or die from HWA infestation. In order to provide an initial abundance of prey, the health of Class 1 trees is sacrificed so that the predator population may build and ultimately colonize Class 2 and 3 trees (and even Class 4 trees, if chemical treatments are eventually discontinued) in the longer term. If resources allow, managers may decide that they wish to chemically protect more than 50% of the trees in a stand to help minimize early hemlock losses.

Managers should consider a diversity of canopy positions when choosing trees to receive chemical treatment. As noted above, large hemlock trees may be good candidates for perpetual chemical protection (Class 4) given their high ecological or aesthetic value. However, depending on stand composition, it may be beneficial to include some mid-story or understory trees in the chemically-treated classes. This could serve to promote stand structural diversity and the presence of canopy-dominant hemlocks in the future.

Variations on the classes presented above are also possible. For example, some Class 3 trees could be re-treated more than once to extend foliage health further into the future. A very simple variation would be to use just two classes of trees, such as Class 1 (untreated) and Class 4 (perpetually treated). Which variation managers choose may depend on factors such as available operating budget, stand size and composition, existing health of the trees, and the degree to which climatic or other environmental conditions affect HWA populations.

As an alternative to using a reduced rate of imidacloprid to create Class 2 trees, managers could use the label rate of a shorter-duration insecticide such as dinotefuran. Applying dinotefuran at the prescribed label rate (Valent 2014) is expected to suppress adelgid populations within 1–2 months of application, with efficacy lasting for 1–2 years (Joseph et al. 2011a). Due to this shorter period of efficacy, Class 2 trees created using dinotefuran may support predators and prey sooner than Class 2 trees created using a reduced rate of imidacloprid.

Regardless of the number of classes used or trees treated, the amount of imidacloprid applied should not exceed 0.45 kg of active ingredient per ha (0.4 lbs per ac) per year (Durkin 2016, Bayer 2019). Thresholds for this per-acre limit, in terms of fluid ounces applied, number of soil injection pumps applied, or tablets applied, is provided in Benton and Cowles (2017). Similarly, dinotefuran application should not exceed 0.6 kg of active ingredient per ha (0.54 lbs per ac) per year. Some pesticide products are restricted use and can only be applied by a certified and licensed applicator, and then only under specific conditions. Managers should ensure that applications are being performed within the limits and requirements of the product label(s), and should consult with their state cooperative extension service with specific questions regarding insecticide use and applicator certification requirements. Caution should be applied when treating hemlocks in riparian areas, and soil applications should not be made within 3 m (10 ft) of a stream channel, lake, pond, or wetland. For additional guidelines on imidacloprid application see Benton and Cowles (2017).

There is a growing body of evidence to suggest that elevated levels of sunlight, and associated elevated temperatures, have negative effects on adelgids and beneficial effects on infested hemlock trees (Sussky and Elkinton 2015, Hickin and Preisser 2015, Brantley et al. 2017, McAvoy et al. 2017a). Recent and current research is exploring the potential use of silvicultural treatments, such as thinning and gap creation, to enhance hemlock resilience in the presence of HWA (Mayfield et al. 2019, Miniat et al. 2020). However, management recommendations based on this research are still in development. As specific silvicultural prescriptions become available, these could be integrated strategically with the chemical treatment classes described above to improve the health and longevity of hemlocks that are not chemically protected. In the meantime, it is worth noting that hemlocks located in small canopy gaps, along forest edges, or in other environments with elevated light levels may be good Class 1 candidate trees for predator releases, provided they are infested with HWA at the time of release (Figure 12).

TIMING CONSIDERATIONS

Consideration should be given to the timing of chemical treatments relative to the timing of predator releases. In experimental settings, *L. nigrinus* adults can experience lethal or negative sublethal effects from eating adelgids on branches recently treated with imidacloprid (Eisenback et al. 2010). Although predators should be released onto untreated (Class 1) hemlock trees, it is expected that predators will disperse to other hemlocks nearby. If nearby hemlocks have been recently treated, they may harbor poisonous HWA prey, because the insecticide may still be moving into infested branches.

Figure 12. Hemlocks located in canopy gaps, along forest edges, or other environments with elevated sunlight may be good trees on which to release predators in years when they are infested with HWA. (Credit: A. Mayfield, USDA Forest Service)

The amount of time required for insecticides to be distributed though hemlock trees and eliminate adelgids on the branches can vary depending on the type of insecticide used, its formulation and delivery method, the time of year, and site-specific conditions (e.g., soil organic matter, moisture conditions, temperature) (Dilling et al. 2010, Joseph et al. 2011a, Faulkenberry et al. 2012, Coots et al. 2013). Table 1 presents a conservative guide for minimizing the possibility that *Laricobius* beetles will encounter poisoned adelgids when they are released in stands where imidacloprid or dinotefuran has been recently applied. When hemlock trees have been treated with a liquid or tablet formulation of imidacloprid, consider delaying release of *Laricobius* beetles in the same stand for one year, to allow time for the insecticide to eliminate adelgids on the treated trees. When applying dinotefuran, which is more water soluble and faster-acting than imidacloprid (Joseph et al. 2011a, Faulkenberry et al. 2012), consider delaying the release of adult *Laricobius* in the stand for at least 3 months (Table 1).

BIOLOGICAL CONTROL TREATMENTS

Laricobius beetles for release in eastern North America are typically obtained either from rearing laboratories or from field insectaries where they are collected and redistributed to other areas (Salom et al. 2011). In either case, adult beetles are typically transported to the field in small, ventilated jars or vials containing clippings of hemlock foliage, shredded paper, or some other substrate to which the beetles can cling. Successful establishment of both *L. nigrinus* and *L. osakensis* from releases of adults is well documented (Mausel et al. 2010, Mayfield et al. 2015, Toland et al. 2018). It is also possible to release *Laricobius* in the egg or larval stage, but the degree of establishment success using this method is not well understood or documented.

Table 1. Timing guidelines for release of adult *Laricobius* beetles following applications of imidacloprid or dinotefuran insecticides to hemlock trees, by season of insecticide treatment.

SEASON	IMIDACLOPRID Applied to the soil (as liquid or tablet)				DINOTEFURAN Applied to the soil or bark (as liquid)			
Fall	Fall Treatment				Fall Treatment			
Winter	Delay release	Winter Treatment			Delay release	Winter Treatment		
Spring[a]	Delay release	Delay release	Spring Treatment		OK to release	Delay release	Spring Treatment	
Summer[b]	N/A	N/A	N/A	Summer Treatment	N/A	N/A	N/A	Summer Treatment
Fall	OK to release	Delay release	Delay release	Delay release	OK to release	OK to release	OK to release	Delay release
Winter	OK to release	OK to release	Delay release	Delay release	OK to release	OK to release	OK to release	OK to release
Spring[a]	OK to release	OK to release	OK to release	Delay release	OK to release	OK to release	OK to release	OK to release
Summer[b]	N/A/	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Fall	OK to release	OK to release	OK to release	OK to release	OK to release	OK to release	OK to release	OK to release

[a]Spring releases of adult *Laricobius* shoud be conducted as early as possible. Releases in late spring are not recommended because females may have already laid their eggs and adults are nearing the end of their lives.

[b]Summer releases of adult *Laricobius* are not applicable (N/A) because the adults are inactive at this time of year.

RELEASE TIMING

Laricobius adults can be released in the fall, winter, or early spring when the HWA sistens generation is present. A study of 22 *L. nigrinus* release sites found that the timing of release (made primarily between October and March) had no significant effect on the probability of establishment success (Mausel et al. 2010). Laboratory-reared beetles should be released as soon as possible after they emerge, so that labs do not have to store and feed beetles for extended periods of time under artificial conditions. Similarly, beetles reared in field insectaries should be redistributed and released as soon as possible after they are collected. Although adult *Laricobius* may be available in the late spring (late April–May), releases at this time are not ideal, because females may have already laid their eggs, and the adults are nearing the end of their lives.

RELEASE METHOD AND TREE SELECTION

Laricobius adults should be released on healthy, untreated (Class 1) hemlock branches that have an abundance of HWA. Beetles may be released by gently lifting the foliage, wood shavings, or shredded paper (to which beetles will cling) from the transport container and placing this material on infested hemlock trees in the field (Figure 13a,b). Alternatively, open containers may be held or attached beneath hemlock branches for several minutes to allow *Laricobius* adults to disperse from the container on their own (Figure 13c,d).

Figure 13. Various methods for releasing adult *Laricobius* beetles. (a) hemlock foliage with *Laricobius* beetles clinging to it is lifted from the transport container for placement on hemlock trees in the field; (b) vials containing beetles on shredded paper are emptied onto the branches of infested trees; (c,d) open tubs containing beetles and excelsior are attached beneath hemlock branches to allow beetles to disperse naturally onto the tree. (Credits: a. USDA Forest Service; b. A. Mayfield, USDA Forest Service; c,d. Maine Forest Service)

Laricobius larvae drop to the soil in the spring and adults spend the summer in organic duff layer. Therefore, when selecting release trees, avoid hemlocks that overhang roads, water, managed turf, or other terrain that would be inhospitable for *Laricobius* larvae and aestivating adults.

Although releases during very cold weather (<25°F or −4°C) should generally be avoided, sometimes beetles are available during such conditions, and it is not possible to hold them for later release. In such cases, consider releasing beetles into the organic duff layer or a pocket of leaf litter beneath the hemlock canopy, which provides a more insulated environment.

RELEASE NUMBERS

The number of beetles released at a site is usually determined by the number of beetles available from a laboratory or from field collections at other locations. Release sizes typically range from 200 to 2000 beetles per site per date, depending on the size of the site and the number of predators available. Research has shown that establishment success improves as more beetles are released (Mausel et al. 2010).

Within a site, consider releasing beetles in groups of about 50 to 100 per tree to help increase the probability that beetles will be able to find each other for mating. This practice can be facilitated if beetles are packaged in vials containing groups of this size, and the entire contents of a vial is placed on one tree. If beetles are packaged in larger containers of several hundred beetles or more, try to divide the contents of each container relatively evenly among several release trees.

Additional predator release criteria can be found on the HWA Predator Database (Virginia Tech 2020).

MONITORING AND MAINTENANCE

After the initial predator release, the site should be monitored for predator establishment. Monitoring for establishment could begin as early as one year post-release, but in practice it is probably better to wait until the second year. This allows more time for the new predator population to increase to detectable levels.

BEAT SHEET SAMPLING

Monitoring for establishment of *Laricobius* can be accomplished by sampling for adults, larvae, or both. Sampling for adults can be accomplished by the use of a beat sheet in the fall, winter, or early spring when HWA are visible on the branches. The observer holds the beat sheet directly under an infested hemlock and firmly taps the branch up to 10 times with a telescoping walking stick, a piece of PVC pipe, or some other type of durable rod (Figure 14).

Branches without HWA are unlikely to yield *Laricobius*, so the best branches to sample are those with an abundance of HWA. If present, *Laricobius* adults will typically be dislodged from the branch and fall onto the sheet. Here, they can be examined with a hand lens to confirm that they are *Laricobius* and returned to the tree using a fine-tipped paint brush or by gently lifting them from the beat sheet with a moistened fingertip. Alternatively, beetles can be brushed or aspirated into a vial, preserved in 95–100% ethanol, and saved for microscopic or genetic identification.

Figure 14. Sampling for *Laricobius* adults using a beat sheet. (Credit: A. Mayfield, USDA Forest Service)

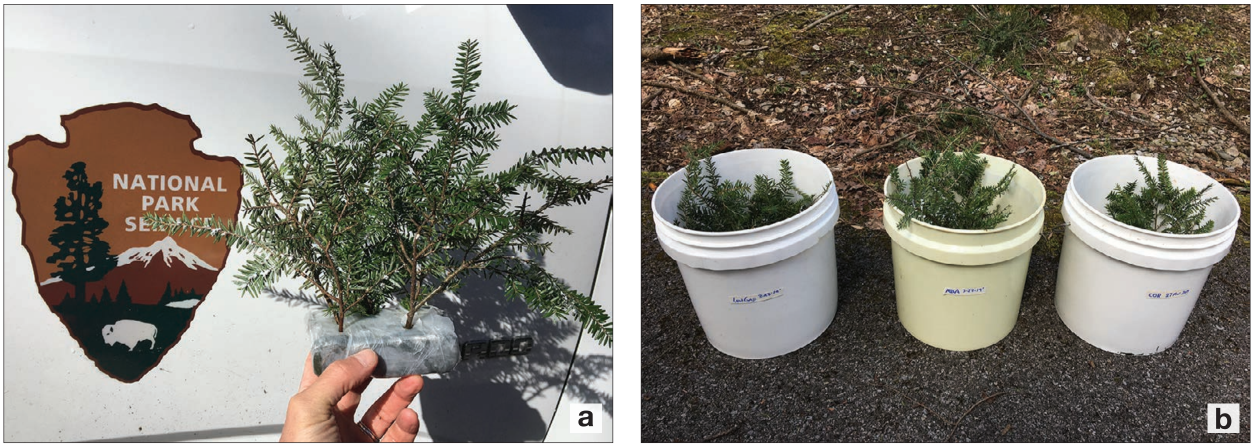

Figure 15. Hemlock branches clipped to sample for *Laricobius* larvae. At left (a), the cut ends of infested branch tips are pressed into a block of hydrated floral foam wrapped in laboratory film. At right (b), the hemlock “bouquets” are placed into plastic buckets to monitor for *Laricobius* larval drop. (Credits: A. Mayfield, USDA Forest Service)

LARVAL SAMPLING

Larval sampling is a more reliable monitoring method for detecting beetle presence and establishment. *Laricobius* larvae can be targeted specifically by clipping HWA-infested hemlock branches about 25 cm (10 in) in length during March or April. Optimal dates will vary with latitude and elevation, but sampling should occur when overwintering HWA adults are in peak egg production, and *Laricobius* larvae are feeding on the eggs. The cut ends of infested hemlock branches can be pressed into blocks of hydrated floral foam (soaked in tap water for at least 5 minutes) that are wrapped in laboratory film or other plastic wrap (Figure 15). These hemlock “bouquets” can then be placed into open-topped plastic buckets and transferred to a cool indoor room or a cool, sheltered outdoor space. Observers should check every 2–3 days for *Laricobius* larvae in the bottom of the bucket over a period of 4–6 weeks (Figure 16). Larvae can be identified as *Laricobius* species using a microscope, and transferred to vials of 95–100% alcohol for specimen preservation or genetic identification later if desired. Additional information on predator sampling and identification is posted on the HWA Predator Database (Virginia Tech 2020).

Figure 16. Several *Laricobius* larvae that have dropped from hemlock foliage into a collection container. Notice that the larvae near the pencil tip are coated with white wax from the HWA ovisac in which they were feeding. (Credit: A. Mayfield, USDA Forest Service)

AUGMENTATIVE PREDATOR RELEASES

After chemical and biological control treatments have been applied at a site, managers may wish to augment their efforts with additional treatments in subsequent years. If predators are available, managers should consider augmenting the initial release with another release in the second year to increase the chances of successful establishment and enhance *Laricobius* population growth.

Furthermore, environmental conditions that dramatically reduce HWA populations may also reduce the predator population, hindering or even preventing *Laricobius* establishment. For example, cold weather associated with the winter "polar vortex" events of 2013 and 2014 likely caused a crash in HWA populations at two hemlock Appalachian research sites. Subsequently, no *Laricobius* beetles were recovered after these events, even though predators had been previously recovered at these sites post-release (Sumpter et al. 2018). In similar cases, augmentative beetle releases may be necessary, but should be delayed until adelgid prey are present again in the stand. Regular monitoring of the predator population using the methods described above will help determine whether augmentative beetle releases are warranted.

AUGMENTATIVE CHEMICAL TREATMENTS

Managers may also wish to augment the site with additional chemical treatments if the health of some untreated (Class 1) or temporarily-protected (Class 2 and 3) hemlocks is declining at an unacceptable rate. If *Laricobius* beetles are already present in the stand, however, care should be taken to minimize the potential exposure of predators to the insecticide. In addition to the timing consideration presented earlier in Table 1, consider the following guidelines for augmentative chemical treatments when *Laricobius* is already present in the stand:

> Delay chemical treatment of trees until after *Laricobius* has finished feeding and has dropped to the soil in April and May. For this application (May–Jun), consider using dinotefuran (either alone or in combination with imidacloprid, depending on the duration of protection desired) to achieve faster delivery of insecticide to the foliage, so that adelgids are killed before *Laricobius* begins actively feeding again in the fall (Oct–Nov).
>
> For soil application, apply the chemical close to the base of the tree (within 0.5 m, or 1–2 ft from the trunk) (Cowles et al. 2006). Not only is this standard operating procedure for soil application of imidacloprid, it also minimizes the volume of soil in which *Laricobius* larvae could encounter imidacloprid when they drop from the branches to pupate and aestivate.

ASSESSING THE STRATEGY

One of the most challenging parts of implementing an IPM strategy for HWA is assessing its efficacy. In concept, efficacy could be assessed by comparing areas where the integrated strategy has been implemented with "control" areas where it has not. In practice, however, finding true control stands (i.e., those that have received neither predators nor chemical treatments) that also have biotic and abiotic conditions that are similar to the treated stands, can be difficult. Aside from chemical and biological control, hemlock health and survival are potentially affected by numerous site-specific conditions such as soil quality, aspect, sunlight exposure, temperature and moisture regimes, tree age, history of HWA infestation or other disturbances, and stand structure and composition. These factors can vary considerably across landscapes, making it difficult to confidently attribute differences between stands to IPM treatments. Furthermore, because introduced predators like *L. nigrinus* are widely established and continue to disperse in the eastern U.S., it can be difficult to conclude with confidence that certain areas do not have biological control agents present.

Despite these challenges, managers should attempt to assess the efficacy of an IPM strategy, either by comparing implementation areas with the best available control areas, and/or by monitoring changes at individual sites over time. Efficacy should be evaluated primarily on the basis of hemlock health and survival, but could also include long-term trends in HWA population levels, predator population levels, or both.

HEMLOCK HEALTH

VISUAL CROWN RATINGS

The health of hemlock trees is commonly assessed by making visual ratings of crown condition. Specific methods for making these estimates vary and have different advantages and disadvantages. Rather than advocating exclusively for a specific method here, we will highlight a few different types of health assessments, with cited references that contain more detailed information.

One method for rating hemlock crown health is to utilize the USDA Forest Service Crown Condition Classification Guide (Schomaker et al. 2007), which has been designed for use on a wide variety of tree species. Schomaker et al. (2007) describes numerous variables that can be used to assess tree crowns, but the four following measures can be particularly useful for assessing hemlock crown symptoms related to HWA:

- **FOLIAGE TRANSPARENCY**
  An estimate of the amount of skylight visible through the live, normally foliated portion of the crown. It is useful for capturing the foliage-thinning effect caused by HWA feeding. Values generally decrease as health improves.

- **CROWN DENSITY**
  An estimate of the proportion of the normal, expected crown area actually present. It is

useful for accounting for sections of crown that may be missing due to previous branch death or breakage. Values generally increase as health improves.

- **CROWN DIEBACK**
  An estimate of recent mortality of branches with fine twigs located in the upper and outer portions of the crown. Values generally decrease as health improves.

- **UNCOMPACTED LIVE CROWN RATIO**
  An estimate of the length of live crown relative to the total height of the tree. Values generally increase as health improves; an exception to this may occur when part of the lower crown is lost due to heavy shading and/or adelgid impact, but the upper part of the crown is improving due to better sunlight.

These variables are estimated on a percent basis, ideally by two observers standing at different angles from the tree. A rating card illustrating a scale of transparency, density, and live crown ratio values can be used to help improve objectivity and consistency between observers (Appendix 1). Observers mentally draw crown outlines when making density and transparency measurements (Figure 17). After making ratings independently, the two observers briefly discuss their estimates to come up with a single, final rating for the tree (Figure 18). These variables can be averaged on a stand basis and tracked from year to year.

A variation on the USDA Forest Service crown classification system is that developed by McAvoy et al. (2019). In this methodology, five percentage-based variables (live crown ratio, live branches, live branch tips, new foliage, and foliage density), all of which increase as crown health improves, are averaged to create a single Crown Health Index. Furthermore, the stand averages for each of these variables can be combined with an estimate of the percentage of live hemlocks in the stand to create a Stand Health Index. These values can also be tracked over time for individual trees and stands to determine whether hemlock health is improving, remaining stable, or declining.

BRANCH TIP SAMPLING

Another way to estimate and track hemlock health is through branch tip sampling. In this approach, hemlock branch tips of about 25–30 cm (10–12 in) in length are evaluated for new shoot production, tip dieback, and/or adelgid densities. These branch tip assessments can be made non-destructively in the field when branches can be reached by hand from the ground, a ladder, or lift truck. This is particularly advantageous when the same trees will be sampled year after year, as it does not contribute to canopy loss and can be completed relatively quickly. Alternatively, the branch tips can be clipped using hand or pole pruners and evaluated in the field, or later in the laboratory or office. This is advantageous when branches cannot be reached from the ground or when detailed measurements on branches are desired.

One rapid method of using branch tips to assess hemlock health is to create indices of new shoot growth and dead shoot tips (Mayfield et al. 2015). In this approach, the outer 10 shoot tips on a 25 cm (10 in) branch (the terminal tip and the nine most distal side-tips) are identified. Multiply by 10 the number of these shoots that represent a) new growth of the most recent growth flush, and b) dead tips, to express these variables as percent new growth (positive health measure) and percent dead shoots (negative health measure). Several branches (5–10 per tree) can be sampled and averaged to compute tree-level means (Mayfield et al. 2015).

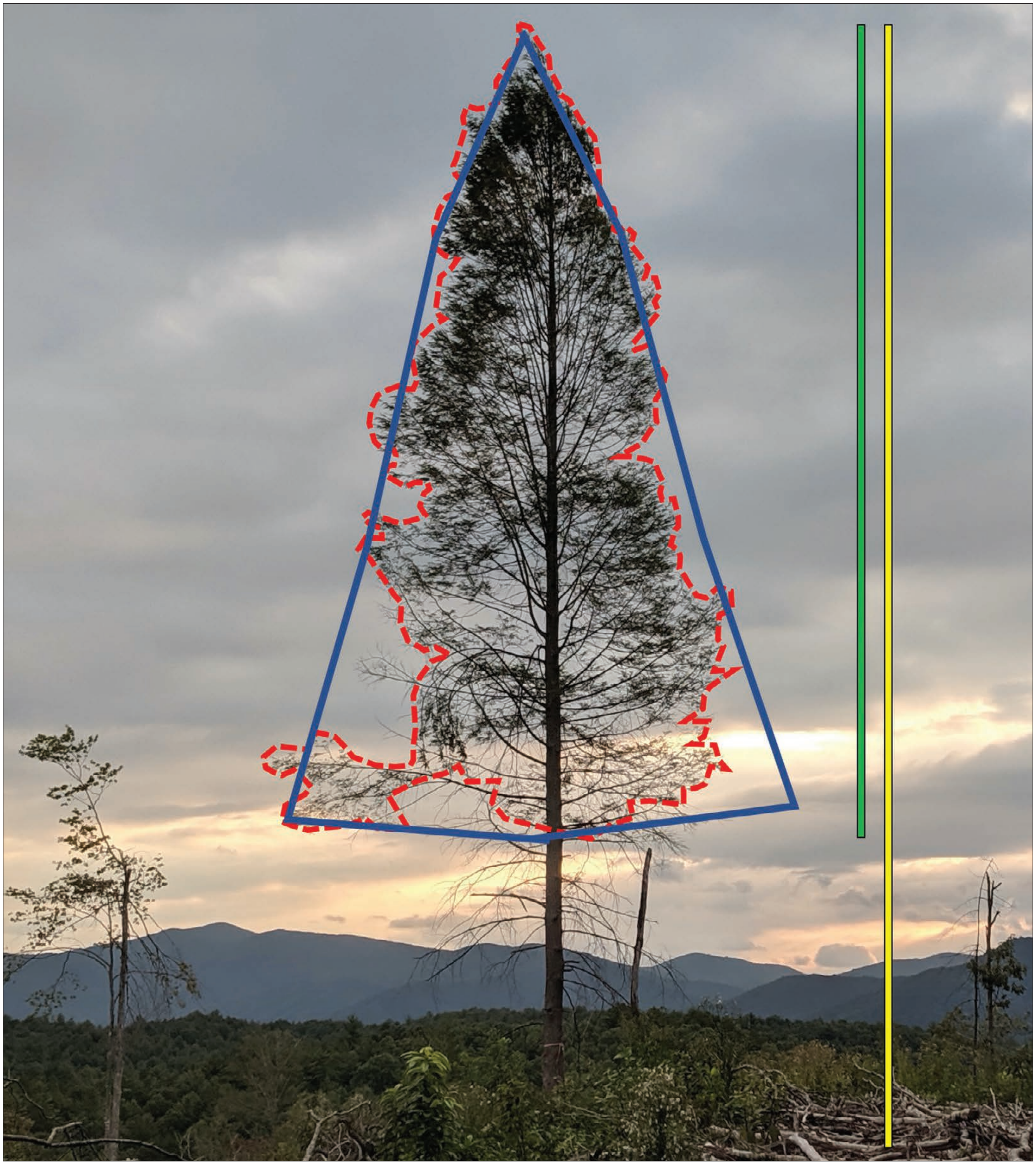

Figure 17. Crown outlines mentally drawn for rating hemlock crown health. To rate foliage transparency, the observer draws a tight outline that clings to the currently-foliated portion of the crown (red dashed line). The relative proportion of skylight visible within this outline is used to estimate foliage transparency. In contrast, when rating crown density, the observer draws a loose outline that touches the outer branch tips and projects the expected symmetrical crown shape for the tree (blue solid line). The relative proportion of skylight blocked by tree structures within this outline is used to estimate crown density. When estimating live crown ratio, the height of the live crown (green line) is divided by the total height of the tree (yellow line). A rating card (Appendix 1) can be used to aid with the estimation of these variables. See the USDA Forest Service Crown Condition Classification Guide (Schomaker et al. 2007) for more detailed instructions and guidelines for special scenarios. (Credit: A. Mayfield, USDA Forest Service)

Figure 18. Visual crown ratings. (a) a rating card is used to make estimates of hemlock health using the USDA Forest Service Crown Classification Guide; (b) two observers discuss their individual ratings to arrive at a final assessment for each tree. (Credits: A. Mayfield, USDA Forest Service)

HWA POPULATION SAMPLING

HWA PER CM AND HWA INDEX

The 25 cm (10 in) branches described above for branch health ratings can also be used to estimate HWA density at the same time. This can be done intensively by counting the number of HWA ovisacs on the branch and dividing by the cumulative total length of shoot growth to compute adelgids per cm. Several branches per tree (5–10) can be used to compute tree-level averages.

Alternatively, for increased speed, an index can be computed by counting the number of HWA ovisacs on each branch up to a pre-defined number (e.g., 100), and stopping when that number is reached. Multiple branches per tree can be averaged to create an HWA Index value that ranges between zero and the pre-defined maximum count (Cowles et al. 2006, Mayfield et al. 2015). Although these kinds of indices will not discriminate differences in adelgid density among very heavily infested trees (>100 HWA per 25 cm [10 in] branch), it is an efficient way to distinguish among lightly (index < 20), moderately (index 20–60), and heavily (index > 60) infested trees without spending an excessive amount of time counting adelgids when HWA populations are very high.

PERCENT TREES AND PERCENT BRANCHES INFESTED

Another way to assess the level of HWA in a stand is to estimate the percentage of hemlock trees that are infested. As noted above, Costa and Onken (2006) present a statistically reliable method for estimating the percentage of infested hemlock trees in a stand. Using a semi-random sampling strategy, an observer visits between 8 and 100 trees per stand, with the sample size depending on the cumulative number of infested trees encountered. A tree is considered infested if at least one HWA ovisac is detected after examining 2 branches per tree.

A modification of this approach is to estimate the percentage of hemlock branches that are infested, as presented by McAvoy et al. (2019). In this method, examine the terminal 30 cm (12 in) of the underside of a maximum of 5 branches per tree on a minimum of 10 trees per site for a total of 50 hemlock branches per stand. If one or more HWA is present on the branch, the branch is considered infested. The total number of branches infested divided by 50 and multiplied by 100 will yield the percent of branches infested.

Perhaps more important than the exact methods used is that managers choose an assessment method they have confidence in replicating, and they use it consistently year after year. Additional information for evaluating hemlock health and HWA population is available at the HWA Predator Database (Virginia Tech 2020).

CONCLUSION

As noted above, the strategy and tactics offered in this guide can be considered a starting point for managing hemlock stands in a more integrated, sustainable way. It is fully expected that as new information, tools, and manager experiences become available, this strategy can and will be modified to achieve better results. Managers integrating biological and chemical control of HWA are encouraged to share the specific methods and outcomes of their efforts with other managers and researchers. In this way, the HWA research and management community can continue to collectively improve our efforts to sustain hemlock and the unique ecosystems in which they occur.

GLOSSARY

TERM	DEFINITION
abiotic	Non-living environmental factors, such as temperature and humidity
aestivation	Period of dormancy to survive predictable, unfavorable environmental conditions, such as temperature extremes, drought, or reduced food availability
asexual reproduction	Type of reproduction by which offspring arise from a single organism and inherit the genes of that parent only
biological control	The reduction in the abundance of a pest through intentional use of its natural enemies (predators, parasitoids, and pathogens)
biotic	Living environmental factors, such as plants, animals and micro-organisms
chemical control	Using pesticides to control pest insects, weeds, or diseases
crown (tree)	Top part of a tree which features branches that grow out from the main trunk and support the various leaves/needles used for photosynthesis
emergence (insect)	Act of adult insect leaving the pupal exoskeleton, or leaving winter or summer dormancy
foundation species	Species that plays a large role in structuring an entire community
HWA	Hemlock woolly adelgid, *Adelges tsugae*
invasive	Tending to spread prolifically and undesirably or harmfully
IPM	(Integrated Pest Management) Series of pest management evaluations, decisions, and often a combination of control methods to solve pest problems while minimizing risks to people and the environment
larva (pl. larvae)	Immature stage of some animals, including insects and mites. In insects with complete metamorphosis, it is the stage between the egg and pupa (examples include grubs, caterpillars, and maggots)
neonicotinoids	Neurotoxic compounds with relatively low mammalian toxicity; the most commonly used class of insecticides for control of HWA
non-target effect	When control efforts affect a species other than the species they were enacted to control (can be positive or negative)
nymph	Immature form of invertebrates, including some insects such as the HWA, that undergoes gradual metamorphosis; resembles adults
organic duff layer	Decomposing dead organic material, such as leaves, bark, needles, and twigs, that has fallen to the ground, combined with other organic matter
ovisac	Waxy sac into which the females of some insects, including the HWA, place their eggs
progrediens generation	Generation of the HWA which is present in the spring
pupa (pl. pupae; v. pupate)	Non-feeding, inactive stage between larva and adult for an insect with complete metamorphosis
sistens generation	Overwintering generation of the HWA which is present from summer to early spring of the following year
specialist predatory insect	Insect that preys on only a limited range of species

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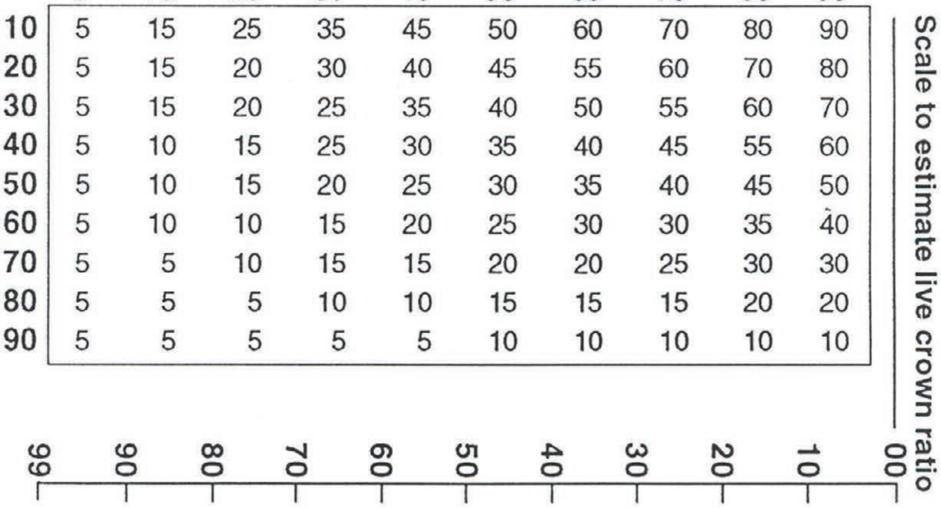
APPENDIX

CROWN DENSITY-FOLIAGE TRANSPARENCY CARD FOR RATING TREE HEALTH

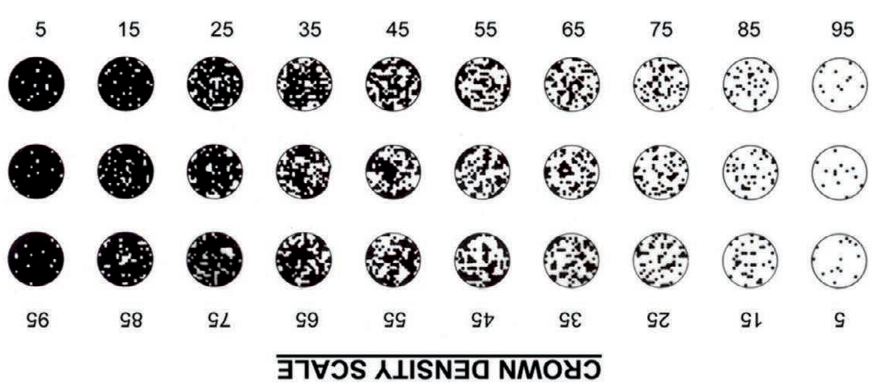
1. Print and fold paper at the line between the top and bottom of the card. Trim the other 3 sides. Laminate the card if desired. The card can be re-sized if desired.
2. The crown density-foliage transparency card is a training and field aid. White areas of the card represent skylight visible through the crown area, and black areas represent a portion of the tree that is blocking skylight. Use the card to calibrate visual estimation.
   - For CROWN DENSITY, hold the card so that "Crown Density" is right-side up ("Foliage Transparency" should be upside down). Use the numbers that are right-side up.
   - Conversely, for FOLIAGE TRANSPARENCY, make sure that "Foliage Transparency" is right-side up.
3. The back of the card has two uses: 1) adjustments for CROWN DENSITY when a portion of the crown is missing and 2) a general scale for estimating UNCOMPACTED LIVE CROWN RATIO. For more information on use, see Schomaker et al. (2007).

Density of Tree, Present

Percent of Tree Missing	5	15	25	35	45	55	65	75	85	95
10	5	15	25	35	45	50	60	70	80	90
20	5	15	20	30	40	45	55	60	70	80
30	5	15	20	25	35	40	50	55	60	70
40	5	10	15	25	30	35	40	45	55	60
50	5	10	15	20	25	30	35	40	45	50
60	5	10	10	15	20	25	30	30	35	40
70	5	5	10	15	15	20	20	25	30	30
80	5	5	5	10	10	15	15	15	20	20
90	5	5	5	5	5	10	10	10	10	10



FOLIAGE TRANSPARENCY SCALE



The Forest Health Technology Enterprise Team (FHTET) was created in 1995 by the Deputy Chief for State and Private Forestry, USDA, Forest Service, to develop and deliver technologies to protect and improve the health of American forests. FHTET became Forest Health Assessment and Applied Sciences Team (FHAAST) in 2016. This booklet was published by FHAAST as part of the technology transfer series.

http://www.fs.fed.us/foresthealth/technology/