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Review

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Hemlock Woolly Adelgid (Hemiptera: Adelgidae) Management in Forest, Landscape, and Nursery Production

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Abstract

Hemlock woolly adelgid, *Adelges tsugae* (Annand) (Hemiptera: Adelgidae), has caused significant damage to both eastern [*Tsuga canadensis* (L.) Carrière] and Carolina hemlock (*Tsuga caroliniana* Englemann) (Pinales: Pinaceae) since it was first reported in the eastern United States. This adelgid is particularly damaging to these hemlock species due to a lack of co-evolved plant defenses and natural enemies able to suppress hemlock woolly adelgid populations. Management of hemlock woolly adelgid relies heavily on insecticides to prevent death of vulnerable trees. Biological control programs have released natural enemies of hemlock woolly adelgid to aid in control at the landscape level. Quarantine restrictions on hemlock are in place in some regions of the United States and Canada. These quarantines impact sales and shipment of hemlock trees from nurseries as well as other hemlock products. A review of insect biology, description of life stages, damage, management options, and quarantine restrictions for hemlock woolly adelgid is presented.

Key words: hemlock, adelgid, landscape, nursery, quarantine

Hemlock woolly adelgid, *Adelges tsugae* (Annand) (Hemiptera: Adelgidae) is an insect native to Japan, China, and the United States Pacific Northwest. In 1922, hemlock woolly adelgid was first described and documented in British Columbia living on western hemlock (*Tsuga heterophylla* [Rafinesque] Sargent) (Pinales: Pinaceae) (Annand 1924, 1928). The first hemlock woolly adelgid population in the eastern United States was documented in Richmond, Virginia in 1951 (Stoetzel 2002). According to phylogenetic analysis of hemlock woolly adelgid populations across their known range, the eastern United States introductions are unrelated to lineages from China or the Pacific Northwest. The eastern United States hemlock woolly adelgid population originated from populations in Honshu, Japan (Havill et al. 2006). The introduced hemlock woolly adelgid genotype came from a lineage feeding on southern Japanese hemlock *Tsuga sieboldii* Carrière (Pinales: Pinaceae) (Havill et al. 2006).

There are nine *Tsuga* species worldwide; however, hemlock woolly adelgid has only been problematic on eastern [*Tsuga canadensis* (L.) Carrière] and Carolina hemlock (*Tsuga caroliniana* Englemann) (Pinales: Pinaceae). Asian and western North American hemlock species are resistant to hemlock woolly adelgid. Thus, hemlock woolly adelgid populations are not sufficiently high for feeding to cause significant damage. Hemlock resistance is attributed to a combination of host resistance, host tolerance, and the presence of diverse arthropod predators, which manage hemlock woolly adelgid populations under natural conditions (Oten et al. 2014).

Hemlock woolly adelgid feeding can cause death of previously healthy eastern and Carolina hemlock. Neither of these eastern United States hemlock species have co-evolved with hemlock woolly adelgid, and thus, have developed no natural defenses against hemlock woolly adelgid (McClure 1991a, Havill et al. 2006). Eastern and Carolina hemlock have exhibited no widespread resistance against hemlock woolly adelgid, and native predators do not suppress hemlock woolly adelgid populations sufficiently to prevent hemlock mortality (McClure 1987, 1995). Since infested eastern or Carolina hemlocks rarely recover without pest management intervention, significant declines in hemlock populations have occurred (Ford et al. 2012).

Hemlock Woolly Adelgid Distribution in North America

In western North America, where hemlock woolly adelgid is not considered a pest, its range extends from northern California to southeastern Alaska. In the decade following its discovery in the eastern United States, hemlock woolly adelgid was recognized only as an ornamental/landscape pest of minimal importance. When hemlock woolly adelgid began colonizing nearby forest ecosystems in the early 1960s in the Blue Ridge Mountains near Rocky Mount, VA, the severity of the hemlock woolly adelgid outbreak behavior changed (Souto et al. 1996). Hemlock woolly adelgid spread more quickly after introduction into native hemlock stands. Native hemlock species exhibited severe stress and mortality in forest ecosystems as hemlock woolly adelgids spread. Historically, the range of hemlock woolly adelgid expanded from its original sites of infestation at an estimated rate of 3.6 ± 0.2 km/y along the eastern/western axis of its range and 5.8 ± 0.28 km/y in the northern/southern direction (Morin 2002). By the mid-1990s, hemlock woolly adelgid's range was expanding at a rate of 16–24 km/y (Souto et al. 1996). Hemlock woolly adelgids are passively dispersed, or relocated (McClure 1990). The spread of hemlock woolly adelgid is aided by birds, deer, logging activities, other hemlock product movement (McClure 1990), and wind, including extreme weather events such as hurricanes (Souto et al. 1996).

The hemlock woolly adelgid range has expended from the original identification point in Virginia to 19 other states, including Connecticut, Delaware, District of Columbia, Georgia, Kentucky, Maine, Maryland, Massachusetts, Michigan, New Hampshire, New Jersey, New York, North Carolina, Ohio, Pennsylvania, Rhode Island, South Carolina, Tennessee, Vermont, and West Virginia (Fig. 1).

Hemlock Woolly Adelgid Life Cycle and Biology

Hemlock woolly adelgid produce two generations each year: a shorter progrediens generation and a longer sistens generation. In early spring, the progrediens generation hatches and lives approximately 3 mo, producing 25–125 eggs each (McClure et al. 2001, Cheah et al. 2004). The sistens generation hatches in late spring, goes through a dormant phase (aestivation) until late fall, lives approximately 9 mo, and produces 50–175 eggs each (McClure et al. 2001, Cheah et al. 2004). Hemlock woolly adelgids progress through immature stages, called instars. The first-instar hemlock woolly adelgids, called crawlers (Fig. 2A), are the only mobile life phase. While crawlers do not move far on their own, they can be passively dispersed by wind, wildlife, and movement of infested nursery plants or cut plant material (McClure 1990). Crawlers seek feeding sites at the base of hemlock needles. Hemlock woolly adelgid then insert their stylet bundle into the xylem ray parenchyma cells and feed on hemlock carbohydrate reserves (Young et al. 1995). As hemlock woolly adelgids grow, they progress through four instars (Fig. 2B). The insects produce a wax-like protective secretion that appears similar in texture to wool, hence their common name (Fig. 2C) (McClure 1989).

Hemlock woolly adelgid feeding causes a decline in hemlock tree health. Visible symptoms as the infestation progresses are graying needles, dead branches, and canopy thinning (Orwig and Foster 1998, Jenkins et al. 1999, McClure and Cheah 1999, Stadler et al. 2005, Eschtruth et al. 2006). Some effects of hemlock woolly adelgid feeding include decreased growth, bud death, altered solute transport, and lower water availability (Radville et al. 2011, Domec et al. 2013, Gonda-King et al. 2014, Soltis et al. 2014). Mature hemlocks may die in as little as 2–4 y after initial infestation, however, it can take up to 10 y after infestation for hemlocks to die in some locations (Orwig 2002). The rapid mortality is especially prevalent in more southern portions of the hemlock range, as winter temperatures are not cold enough to reduce hemlock woolly adelgid populations during winter (McClure 1991a, Orwig et al. 2002, Skinner et al. 2003, Nuckolls et al. 2009).

Hemlock Woolly Adelgid Impacts on Hemlock Ecosystems

The structure and function of many forest types are dependent on the contributions of eastern hemlock, as it is a slow-growing evergreen tree that functions in a distinctive role in these forest ecosystems (Orwig and Foster 1998, Ellison et al. 2005). Forests with large hemlock components are characterized by deep shade, because hemlocks are shade-tolerant, resulting in a thick multi-layered forest canopy (Canham et al. 1994). The threat of hemlock woolly adelgid to hemlock decline is not restricted to effects on a single tree species, but to entire forest systems.

Hemlocks are an important resource for terrestrial arthropod and vertebrate wildlife. Hemlock canopies provide habitat to greater than 400 arthropod species (Wallace and Hain 2000; Buck et al. 2005; Lynch et al. 2006; Dilling et al. 2007, 2009; Mallis and Rieske 2011; Coots et al. 2012). Many vertebrate wildlife species, such as snowshoe rabbit (*Lepus americanus* Erxleben), turkey (*Meleagris gallopavo* Linnaeus), deer, and ruffed grouse (*Bonasa umbellus* Linnaeus), use hemlock resources (Jordan and Sharp 1967).

Aquatic ecosystem features such as stream discharge rates, aquatic communities, canopy cover, temperature, and foliage and woody debris inputs are all affected by the presence of hemlocks. Because hemlocks transpire year round, stream flow is regulated in the winter when deciduous trees do not transpire (Ford and Vose 2007). Streams also receive hemlock foliage and coarse woody debris inputs. Increased shading from evergreen hemlock canopies results in a cool stream microclimate (Rogers 1978, Huddleston 2011). Hemlock-dominated watersheds have on average one and a half times more aquatic insect species compared with hardwood-dominated watersheds (Snyder et al. 2002). Brown trout (*Salmo trutta* Linnaeus) and brook trout (*Salvelinus fontinalis* [Mitchill]) were two and three times, respectively, more prevalent in streams flowing through hemlock compared with hardwood-dominated riparian areas (Ross et al. 2003).

Unfortunately, the devastation hemlock woolly adelgid causes to hemlock populations results in cascading ecological effects to many facets of hemlock forest systems. Canopy biomass and changes in forest tree communities occur in response to hemlock declines (Orwig and Foster 1998). Black birch (*Betula nigra* Linnaeus), black cherry (*Prunus serotine* Ehrhart), red maple (*Acer rubrum* Linnaeus), and oaks (*Quercus* spp.) have high regeneration rates due to greater light infiltration to the forest floor (Orwig and Foster 1998). Other native tree species such as black gum (*Nyssa sylvatica* Linnaeus), white pine (*Pinus strobes* Linnaeus), and yellow poplar (*Liriodendron tulipifera* Linnaeus) are increasingly common in some post-hemlock woolly adelgid forests (Orwig and Foster 1998, Stadler et al. 2005, Ford and Vose 2007, Ford et al. 2012). Invasive species, such as tree of heaven [*Ailanthus altissima* (Miller) Swingle], Japanese barberry (*Berberis thunbergii* de Candolle), Asiatic bittersweet (*Celastrus orbiculatus* Thunberg), and Japanese stiltgrass [*Microstegium vimineum* (Trinius) A.Camus.], have exhibited increased populations in response to hemlock decline (Orwig and Foster 1998). While many of the native tree species will convey benefits to forest systems, they will not provide similar habitats or ecosystem services compared with hemlock (Ford and Vose 2007).

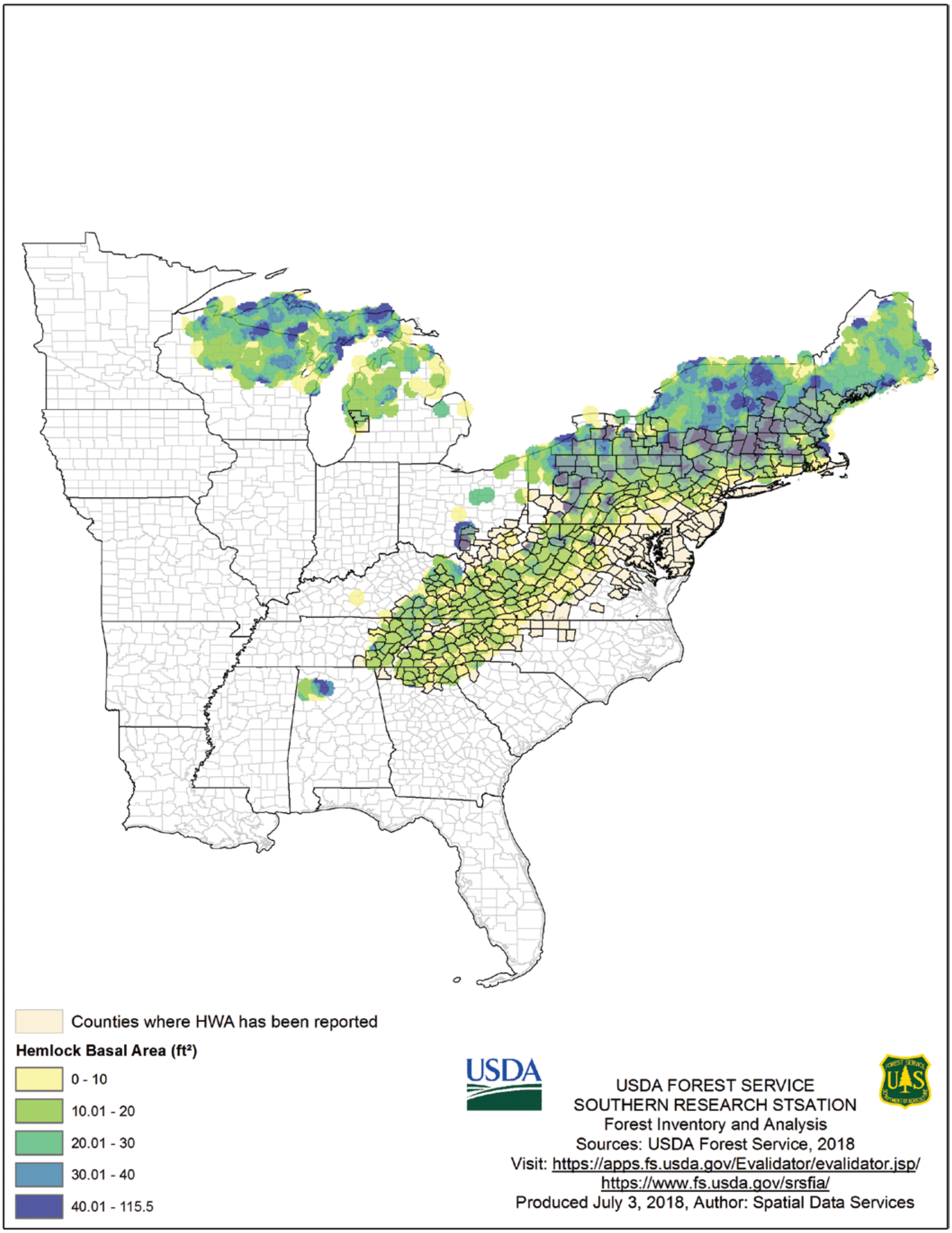

Fig. 1. Hemlock woolly adelgid distribution map. Modified from McCarty et al. (2019).

Plant community regeneration also can be dominated by rhododendron (*Rhododendron maximum* L.) when the flowering shrub was previously a component of the forest understory (Ford et al. 2012, Webster et al. 2012). The prevalence of rhododendron generally occurs in the southern portion of the hemlock range, where hemlock often occurs along streams (Ford et al. 2012, Webster et al. 2012). Rhododendron thickets reduce light levels on the forest floor and restrict the seedling success of other plant species (Clinton and Vose 1996).

Unfortunately, hemlock foliage does not regrow and seeds are only viable in the soil for up to 4 y (Olson et al. 1959, Orwig and Foster 1998). Seed recolonization numerous years after hemlock woolly adelgid-induced hemlock mortality is not likely, thus, the effects of hemlock decline may be permanent, causing irreparable ecosystem damage.

Hemlock Woolly Adelgid Management

Millions of dollars have been spent and numerous research efforts initiated to study, promote, and implement effective chemical and biological hemlock woolly adelgid management (Aukema et al. 2011). These efforts have been met with various degrees of success, and finances and logistics can limit implementation of hemlock woolly adelgid management tactics on large tracts of land. For example, Great Smoky Mountains National Park had 55,846 ha of hemlock resources before hemlock woolly adelgid was detected in the Park (Webster 2010). The Park has an extensive and successful hemlock woolly adelgid management program, with over 250,000 trees protected by chemical treatments and approximately 305 releases of biocontrol predators. Despite these efforts, it was not possible to treat a large percentage of these original resources due to overwhelming hemlock woolly adelgid populations and extremes in terrain. The result has left a forest that has experienced dramatic change in a short period of time (J. Webster, personal communication).

While generally considered a forest issue, hemlock woolly adelgid can affect hemlocks in urban and suburban landscape settings (i.e., ornamentals), becoming a homeowner issues (Sidebottom and Bradencamp 2011). Hemlock mortality in areas with a higher human interface brings the additional burdens of public safety threats due to falling dead hemlocks, tree removal costs, higher management costs, and reduced property values. The choice and implementation of hemlock woolly adelgid management tactics are determined by the management objectives of a particular site, whether the site is deep in the forest, in a front yard, or at a nursery.

Management goals may include hemlock woolly adelgid population suppression using chemical or biological tactics, singly or in combination, or population eradication, which can be difficult in most settings (Cowles et al. 2006, Benton et al. 2015, Mayfield et al. 2015). Accessibility, feasibility, and appropriate goals are important considerations when assessing management options. For example, the accessibility of urban and suburban settings compared with forest settings makes some tactics, such as those involving high pressure sprays, more feasible (Joseph et al. 2011a). In addition, a method appropriate for a forest landscape may not be a good option for a yard or nursery tree. Carefully considering the benefits and limitations of each management option is critical to choosing the appropriate management plan for a site or a specific hemlock tree.

There are numerous options for hemlock woolly adelgid management: contact or systemic insecticides, biological control, silviculture techniques, genetic resistance and doing nothing, which is

Fig. 2. Hemlock woolly adelgid: (A) Crawler, (B) second instar, (C) adult.

sometimes the only option for some sites. Chemical control is considered the last resort of integrated pest management programs; however, insecticides are the only viable method for immediate hemlock resource protection. Use of insecticides causes concern for environmental impacts, which is covered in a later section. Some larger hemlock woolly adelgid management programs are able to use a multi-faceted approach by employing numerous management tactics (Webster 2010).

Contact Insecticides

Numerous broad-spectrum contact insecticides are labeled for hemlock woolly adelgid suppression in sites ranging from forest and landscapes (i.e., ornamentals) to nurseries and interiorscapes (Table 1) (Chong et al. 2017). Contact insecticides used in hemlock woolly adelgid management come from many insecticide classes such as carbamates, organophosphates, avermectins, and pyrethroids. Active ingredients include, but are not limited to, carbaryl, bifenthrin, lambda-cyhalothrin, chlorpyrifos, and abamectin (Chong et al. 2017). These products must be sprayed on all of the foliage of the seedling or tree for effective hemlock woolly adelgid population suppression. Contact insecticides do not have long residual efficacy and should be applied twice a year. Sprays should be timed to target early instars, which would be more susceptible than woolly-coated adults.

Contact insecticides are generally not used in forest settings and should be carefully considered when used in suburban and urban settings, as these products will kill most insects that intercept the spray treatment. Also, many of these products have higher toxicity to vertebrates than systemic products (Jeschke et al. 2011). Insecticidal soap and horticultural oil, less toxic alternatives to most contact insecticides, are broad-spectrum contact products with modes of action suitable for controlling many insect pests (Sunoco 1994, Coots 2012). All of these products must be applied to the entire hemlock canopy, often by high pressure sprays (Vose et al. 2013). Despite the effectiveness of contact products, there are limitations, which include trouble with uniform coverage, a brief period of effectiveness, and tree accessibility, (Joseph et al. 2011a, Vose et al. 2013). Since most hemlock woolly adelgid insecticide control research has been conducted in forest settings, there is a paucity of research-based guidance on the hemlock woolly adelgid suppression effectiveness and environmental risks of contact insecticides, with the exception of horticultural oil (Dilling et al. 2009).

Neonicotinoid Systemic Insecticides

Neonicotinoids were developed for their lower toxicity to vertebrates compared with older insecticide classes (Jeschke et al. 2011). Once neonicotinoids are applied, they are absorbed by the plant and translocated through the xylem up to the foliage (Castle et al. 2005, Byrne and Toscano 2006). This systemic activity provides control without applying insecticide directly to all foliage surfaces. Due to high efficacy with insect pest populations, low toxicity to vertebrates, systemic activity, and ease of application, neonicotinoids have become the most commonly used insecticide class worldwide (Sánchez-Bayo and Hyne 2014). Dinotefuran and imidacloprid (U.S. Environmental Protection Agency 1994, 2004) are the most commonly used neonicotinoids for hemlock woolly adelgid suppression in forest settings, but both products are also appropriate for landscape use (Table 1). Imidacloprid can be applied to hemlocks via numerous application methods, including soil drench, soil injection, trunk injection, trunk spray, and slow release tablets (Cowles et al. 2006, Coots et al. 2013). Insecticide costs can be limiting for some management programs; however, availability of generic imidacloprid has reduced cost of treatments, enabling management programs to treat more trees.

Imidacloprid does not cause immediate mortality of hemlock woolly adelgid infesting mature trees. Once applied to the soil, imidacloprid is translocated from hemlock roots to foliage and begins providing hemlock woolly adelgid control in approximately 3 mo (Coots et al. 2013). Control is more rapid in saplings and smaller trees. The concentration of imidacloprid within hemlock foliage peaks between 9 and 15 mo after soil application (Dilling et al. 2010, Coots et al. 2013). Hemlock woolly adelgid populations are effectively suppressed for multiple years after a single imidacloprid treatment (Cowles et al. 2006, Coots et al. 2013, Eisenback et al. 2014, Mayfield et al. 2015). Olefin, an insecticidal metabolite of imidacloprid, is over 10 times more toxic to insects than imidacloprid and greatly contributes to the longevity of imidacloprid treatments in hemlock (Nauen et al. 1998, Coots 2012). Residues of imidacloprid and olefin are present in hemlock foliage and maintain low hemlock woolly adelgid populations for up to 7 y post-treatment, possibly longer (Benton et al. 2015, 2016a and 2016c). The presence of both imidacloprid and olefin increases the degree and duration of insect suppression (Nauen et al. 1998, Benton et al. 2016c).

Dinotefuran (Safari) was registered in the United States in 2004, 10 y after imidacloprid entered the United States market (U.S. Environmental Protection Agency 2004). However, most research conducted in these systems has centered on imidacloprid rather than dinotefuran. This focus has occurred because imidacloprid was registered for hemlock woolly adelgid use before dinotefuran and is now more economical. Fortunately, the products do have important longevity and mobility differences that translate specific best uses for each product. Dinotefuran is more mobile than imidacloprid, reaching the canopy more rapidly after treatment and providing population reductions in as little as 1 mo in mature trees (Joseph et al. 2011b). After 2 y, dinotefuran is no longer effective and offers no benefit when compared with untreated trees (Joseph et al. 2011b). Thus, dinotefuran is a fast-acting, but less-persistent management tool, whereas imidacloprid is slow acting but more persistent (Joseph et al. 2011b, Coots et al. 2013, Benton et al. 2015). Dinotefuran is the optimal choice for heavily infested hemlocks, as it will quickly provide relief from hemlock woolly adelgid feeding pressure, but the hemlock woolly adelgid suppression longevity will be for a shorter duration. Imidacloprid is the better choice for light to moderate hemlock woolly adelgid infestation levels, because hemlocks can withstand the feeding pressure during the time it takes imidacloprid to begin suppressing hemlock woolly adelgids.

Often when trees are heavily infested, both products are used either simultaneously, or dinotefuran is applied first, followed by imidacloprid the next year. Use of both products for light to moderately infested trees is not necessary if the management goal is to maintain canopy health, which is generally the objective in the southern United States. Some management programs aim to eradicate individual hemlock woolly adelgid ‘spot’ infestations in the forest landscape. The simultaneous use of both products fits the local population collapse management goal (M. Whitmore, personal communication). Dinotefuran is more costly than imidacloprid, so when hemlock canopies are in relatively good health, management programs opt to use the less-expensive, longer-acting product.

Individual tree-level treatments of systemic insecticides can be cost- and time-intensive, and it is often not possible to protect every hemlock in the forest or landscape (Vose et al. 2013, Abella 2014). These insecticide tactics are and will continue to be critical for hemlock woolly adelgid management (Vose et al. 2013). However, the ultimate

Table 1. Products available for management of hemlock woolly adelgid in nursery, landscape, greenhouse, interiorscapes forests, and Christmas trees[a]

IRAC #	Active ingredients	Activity	Selected trade names[b]	Use sites[c]	R.E.I. (hours)[d]
1A	Carbaryl	Contact	Sevin SL	LFC	12
			Sevin T&O	N	
1B	Chlorpyrifos	Contact	Dursban 50W	N	24
	Oxydemeton methyl	Systemic	Harpoon	LFC	0
			MSR Spray Concentrate	NC	10 d
3A	Bifenthrin	Contact	OnyxPro	LNI	12
	Tau-fluvalinate	Contact	Mavrik Aquaflow	LGNI	12
3A+4A	Bifenthrin + clothianidin	Contact/systemic	Aloft LC, G, LC, SC	L	N/A
	Bifenthrin + imidacloprid	Contact/systemic	Allectus SC	LI	N/A
	Cyfluthrin + imidacloprid	Contact/systemic	Discus N/G	NGI	12
	Lambda-cyhalothrin + thiamethoxam	Contact/systemic	Tandem	L	N/A
	Zeta-cypermethrin + bifenthrin + imidacloprid	Contact/systemic	Triple Crown T&O	LI	N/A
4A	Acetamiprid	Contact	TriStar 8.5 SL	LNG	12
	Dinotefuran	Contact/systemic	Safari 2G; 20 SG	LNGI	12
			Zylam Liquid	L	12
			Transtect 70	LF	N/A
	Imidacloprid	Contact/systemic	Xytect 75 WSP; 2F	LNGI	12
			Marathon II; 60 WP	NGI	12
			Merit	LIF	N/A
			CoreTect	LNGIF	N/A
			Discus Tablets	NG	12
	Thiamethoxam	Contact/systemic	Flagship 25 WG	NGC	12
			Meridian 0.33G; 25 WG	LI	N/A
6	Abamectin	Systemic	Aracinate TM	LNGIF	N/A
23	Spirotetramat	Contact/systemic	Kontos	NGI	24
28	Chlorantraniliprole	Contact/systemic	Acelepryn	LI	N/A
Unknown	Azadirachtin	Contact	Azatin O	LNGI	4
			Tree-Azin	LF	Until dry
Unclassified	Horticultural oil	Contact	Ultra-Pure Oil	LNGIC	4
	Insecticidal soap	Contact	M-Pede	LNGI	12

[a]Adapted from Southeastern U.S. Pest Control Guide for Nursery Crops and Landscape Plantings.
[b]Trade names are provided as examples only. Check product labels for up-to-date restrictions and use requirements.
[c]Use site codes: L = landscape, N = nursery, G = greenhouse, I = interiorscape, F = Forest, C = Christmas trees.
[d]R.E.I. = re-entry interval.

management goal is long-term, sustainable hemlock woolly adelgid control.

Biological Control

Many research and management efforts have focused on developing biocontrol management tactics. Developing biocontrol options from the native range of hemlock woolly adelgid that effectively reduces hemlock woolly adelgid populations and maintains hemlock health would be a more sustainable hemlock woolly adelgid management option compared with insecticides (Onken and Reardon 2011). Research efforts have focused on predators from Asia and the northwestern United States. Hemlock woolly adelgid is a good prey candidate for classical biocontrol because adelgids are sessile organisms, which facilitates predation (Mooneyham et al. 2016). The most appropriate goal is to employ a suite of hemlock woolly adelgid predators, rather than a single biocontrol organism (Flowers et al. 2007). The process of effective biocontrol in hemlock systems involves slow biocontrol population growth over a longer time period. Biocontrol, while having the benefit of being more sustainable, has the limitation of not providing quick hemlock woolly adelgid suppression. However, the effectiveness of biocontrol for maintaining hemlock health is under assessment.

Numerous predatory species have been assessed as potential biocontrol agents. Biocontrol predators that are to some degree being currently assessed include: *Sasajiscymnus tsugae* (Sasaji and McClure) (Coleoptera: Coccinellidae), *Laricobius nigrinus* Fender (Coleoptera: Derodontidae), *Laricobius osakensis* Montgomery (Coleoptera: Derodontidae), *Scymnus coniferarum* (Crotch) (Coleoptera: Coccinellidae), *Scymnus sinuanodulus* Yu and Yao (Coleoptera: Coccinellidae), *Leucopis argenticollis* (Zetterstedt) (Diptera: Chamaemyiidae), and *Leucopis piniperda* (Malloch) (Cheah et al. 2004, Kohler et al. 2008, Darr and Salom 2014, Mooneyham and Salom 2014, USDA Forest Service 2015).

Sasajiscymnus tsugae (Fig. 3A), a native of Asia, has been released since 1995. Greater than two million *Sas. tsugae* have been released in the eastern United States (Havill et al. 2014). Establishment of *Sas. tsugae* was more successful when temperatures in the 7 d following release were warmer; between 10 and 25°C (50–77°F) (Hakeem et al. 2013). Recovery of *Sas. tsugae* in biocontrol release areas may take up to 5–7 y (Hakeem et al. 2010, Jones et al. 2012). Southern Appalachian hemlocks upon which biocontrol was released may die before effective biocontrol is obtained, given the apparent and long time lag between release and population growth to detectable levels (Vose et al. 2013). Unfortunately, results of hemlock woolly adelgid population suppression by *Sas. tsugae* have not been consistently exhibited (Havill et al. 2014).

Laricobius nigrinus (Fig. 3B), a native of the western United States, has been released on eastern hemlock since 2003 (Havill et al. 2014, Lamb et al. 2006, Mausel et al. 2008). Greater than 200,000 *Laricobius nigrinus* adults have been released (Havill et al. 2014). *Laricobius nigrinus* is currently the most successful biocontrol predator for population establishment (Mausel et al. 2010), with populations in many states (Mausel et al. 2010, Mayfield et al. 2015). Populations have grown to the extent that collection for beetle relocation to new release sites is occurring in some areas (Mausel et al. 2010, Onken and Reardon 2011). Hemlock woolly adelgid sistens population reduction by *La. nigrinus* has been exhibited (Mayfield et al. 2015). However, effective hemlock woolly adelgid suppression has not been fully assessed, although studies are in progress.

Laricobius osakensis (Fig. 3C), a predator native to hemlock woolly adelgid's range in Japan, was evaluated as a biocontrol option (Havill et al. 2006, Lamb et al. 2011). In 2010, *La. osakensis* was approved for release (Lamb et al. 2011). Initial establishment data for *La. osakensis* is encouraging for successful hemlock woolly adelgid suppression (Mooneyham et al. 2016). While extreme cold temperatures may have delayed establishment, *La. osakensis* has been recovered from over half of the monitored release sites (Toland et al. 2018).

Two silver fly species (*Leucopis* spp.) (Fig. 3D) from populations in the northwest United States are currently promising biocontrol agents (Motely et al. 2017). Difficulty in rearing *Leucopsis* spp. has slowed the development of a release program (Ross et al. 2010). In a recent cage study, *Leucopsis* spp. persisted in eastern U.S. climate and fed on hemlock woolly adelgid adults (Motley et al. 2017). Observed densities of both *Leucopsis* spp. and *La. nigrinus* in the northwest United States suggest that they would be complementary biocontrol organisms (Kohler et al. 2016).

A suite of potentially successful biocontrol predators have been developed through years of research. The rate of hemlock survival has not yet been affected by releases of both *Sas. tsugae* and *La. nigrinus* (Motley et al. 2017). However, the success of these biocontrol species is still being assessed, and release programs for some predators are still in the early stages. The undetermined success of biocontrol should further emphasize that this control option is a slow, hopefully longer-term solution that should be applied to an entire forest system rather than for the preservation of individual trees. The sustainability of biocontrol is a benefit of this management tactic, but control expectations should be realistic and in keeping with the temporal limitations of biocontrol.

Recent research efforts have assessed integration of chemical and biological control tactics to maintain hemlock health. The objective is to offer initial hemlock protection using a low-dose neonicotinoid systemic treatment and adding biocontrol agents at a later time (Eisenback et al. 2010, 2014; Joseph et al. 2011a; Mayfield et al. 2015). Low-dose imidacloprid applications successfully provided hemlock protection while allowing biocontrol establishment at 5–7 y post-treatment (Mayfield et al. 2015). Thus, the solution for maintaining hemlock health in some locations may not be choosing one tactic, but integrating multiple control options.

Fertilization

Fertilizing trees with hemlock woolly adelgid infestations is not recommended because fertilizer results in detrimental effects to hemlocks and conveys no benefits (McClure 1991b, Raupp et al. 2004). Nitrogen fertilizer application can cause greater hemlock woolly adelgid populations (McClure 1991b, McAvoy et al. 2017). Higher nymphal survival, greater egg production, and less new growth have been observed after fertilization (McClure 1991b). In addition, spider mite populations and injury rates increase when hemlocks are fertilized (Raupp et al. 2004). While fertilizer applications are often desirable to maintain tree health and appearance, this is not the case with hemlock woolly adelgid-infested hemlocks.

Silviculture

Silvicultural techniques, specifically canopy gap creation, to preserve hemlock health may be a viable management tactic in the future. Anecdotally, there was evidence that lower adelgid density occurred on hemlock trees that were exposed to more sunlight (Jetton and Mayfield 2018). An initial nursery experiment on 4-y-old hemlock seedlings exposed to different light regimes was the first step to assessing this concept. Seedlings were artificially infested with adelgids and then exposed to 0, 30, 50, 70, and 90% shade. Adelgid density increased and hemlock growth rates decreased at the higher shade levels (Brantley et al. 2017). Now Camcore and the U.S. Forest Service are conducting studies to determine how increased light levels affect adelgid densities on hemlocks growing in forests (Jetton et al. 2017). Two different canopy gap sizes are being assessed to determine if this silvicultural technique can be used to manage hemlock stands (Jetton and Mayfield 2018).

Genetic Resistance

Natural resistance to adelgids is another possibility for long-term hemlock conservation. Hemlocks from Asia and western North America that co-evolved with hemlock woolly adelgid exhibit resistance or tolerance (McClure et al. 2001, Montgomery et al. 2009). There are numerous possible causes of resistance, and the observed resistance is likely a combination of many factors. Resistant hemlock species have thicker leaf cuticles, which would affect the ability of adelgids to penetrate the cuticle with their stylet bundle (Oten et al. 2012). Terpenoids, which are plant chemicals that can be toxic or repellant to insects, vary between resistant hemlocks and susceptible eastern North American hemlocks (Lagalante et al. 2007). Resistance of different hemlock species is a well-researched area and research is ongoing to develop resistance management into part of the integrated pest management plan for adelgids (Preisser et al. 2014).

Creating hybrid crosses of resistant hemlock species and eastern and Carolina hemlocks is an area of ongoing research and assessment between the U.S. Forest Service, the U.S. National Arboretum, and other collaborators. The most promising hybrid is a cross between Carolina and Chinese hemlocks, which exhibits intermediate adelgid resistant compared to the parent species (Montgomery et al. 2009). Unfortunately, hybrids between eastern hemlock and resistant species have not been successful (Bentz et al. 2002, U.S. Forest Service 2015). Assessments of the hybrid crosses continue in numerous common gardens to evaluate tree growth and adelgid tolerance (U.S. Forest Service 2015).

In addition, resistance is observed in some Carolina and eastern hemlocks that are reported to remain healthy while being surrounded by infested, dying, and dead hemlocks (Caswell et al. 2008, Ingwell and Preisser 2011). The continued health of these rare hemlocks suggests some level of adelgid resistance (Caswell et al. 2008). The observed resistant hemlocks has led to efforts to search for

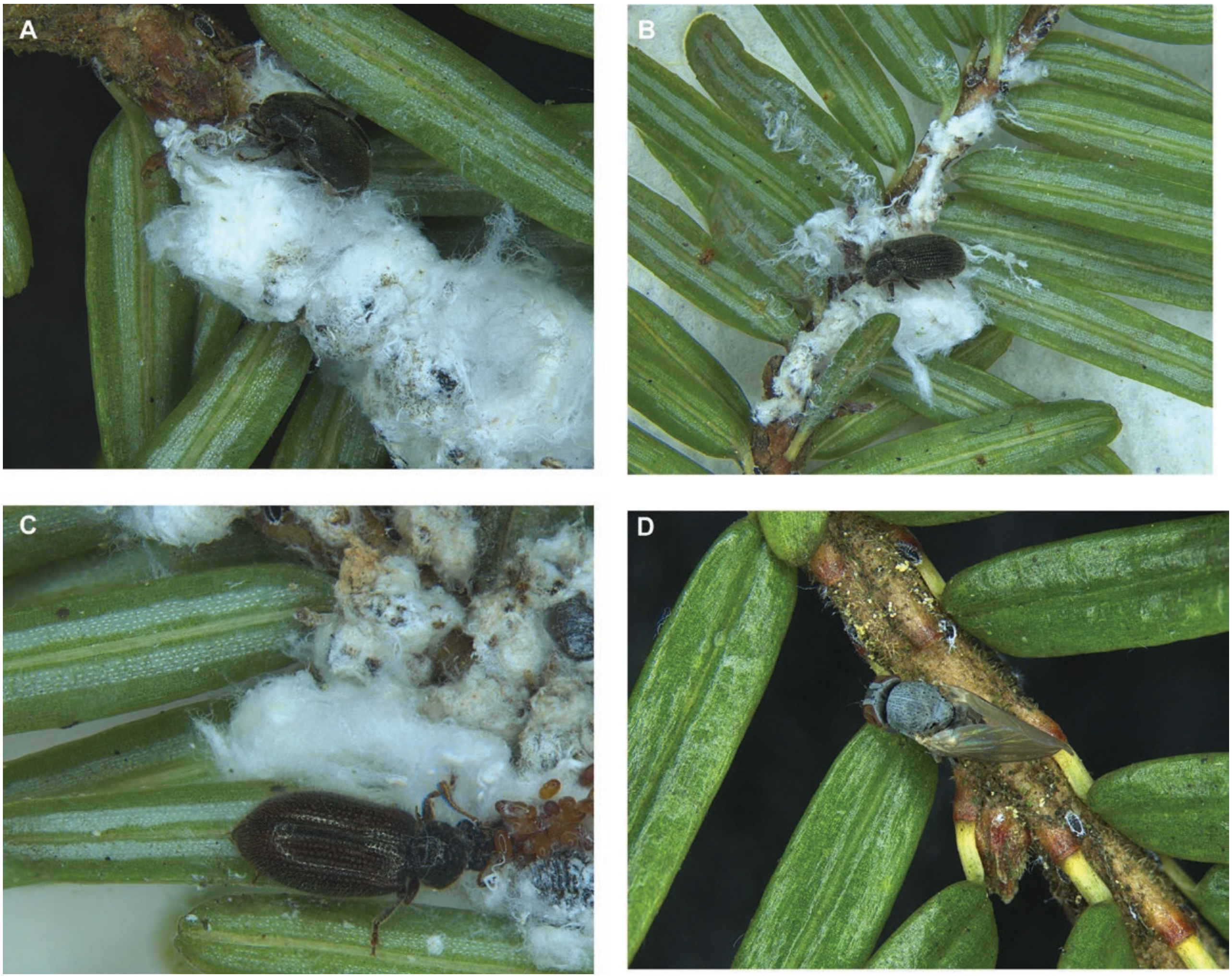

Fig. 3. Biological control agents (A) *Sasajiscymnus tsugae,* (B) *Laricobius nigrinus,* (C) *Laricobius osakensis,* and (D) *Leucopis* spp.

naturally resistant trees for research and conservation (Ingwell and Preisser 2011, Oten et al. 2014).

Seeds from numerous hemlock populations have been collected from Carolina and eastern hemlocks growing throughout their native range in the United States to preserve the genetic diversity of hemlocks for restoration use when conditions are appropriately protective of hemlocks (Jetton et al. 2013). Seeds are collected and either moved to cold storage for long-term holding or are planted in seed orchards. Much of this work was initiated by Camcore (a non-profit international tree breeding organization at North Carolina State University), state forestry agencies, and the U.S. Forest Service (Oten et al. 2014).

Management in Nursery Production Systems

In addition to the key role it plays in forest ecosystems, hemlock is also a cultivated landscape tree, with over 270 eastern hemlock cultivars available for purchase (Swartley 1984, Quimby 1996). Hemlock can add economic value to homes and undeveloped properties when well maintained (Holmes et al. 2005). While most hemlock woolly adelgid management research has been conducted in forest and landscape settings, hemlock woolly adelgid is also a major pest of hemlocks in ornamental landscapes and urban forests, where these trees are planted as hedges, shrubs, shade trees, and specimen trees (Hough 1960, McClure 1987).

Hemlock is a minor crop in nursery production, where it is grown mainly in areas of the United States and Canada where hemlock woolly adelgid is already present in nearby natural areas. Forest populations of hemlock woolly adelgid provide bi-annual inoculum to neighboring nursery fields, where the crawler stage may be blown or otherwise dispersed by insects or birds to new plant hosts (McClure 1990).

In nursery production, treatment recommendations for adelgids include contact and systemic insecticide applications (Neal et al. 2017). Due to the additional time and labor requirements of soil drench applications, growers may prefer foliar sprays of contact insecticides which can be applied by one worker to multiple rows simultaneously with an air blast system. Best practices for foliar treatment of adelgids is during the crawler stage, when hemlock woolly adelgid is most vulnerable. Hence, scouting for crawler activity patterns in production regions when this stage first appears can improve treatment success. In most of its range, the first-generation crawlers appear in early-late spring around 203 growing degree-days (Gill and Shrewsbury 2013), which is also the busiest time of year for shipping nursery plant material, particularly in field grown production where plants are dug while dormant and shipped in spring (Beeson 1991, Knox et al. 2003). Timing of systemic insecticide drenches are less critical, and may be a better option for nursery production due to the longer residual of such products.

Currently, little research has been conducted on hemlock woolly adelgid control under nursery production conditions. Nursery growers must use data from forest systems to make management decisions in production. However, due to differences in tree size and substrate media, forestry data may not translate directly to nursery conditions (Frank and Lebude 2011). Nursery trials were conducted by Frank and Lebude (2011) to provide data relevant to containerized hemlock stock. Foliar, drench, and granular applications were made of both active ingredients commonly used in managing hemlock woolly adelgid in forest ecosystems and additional products labeled for nursery and landscape settings. The results of these container trials provided several products suitable for treatment of hemlock under nursery conditions, including the active ingredients acetamiprid, imidacloprid, dinotefuran, bifenthrin, spirotetramat, and horticultural oil (Table 2). All products tested provided 96% or better control of first-generation hemlock woolly adelgids at 46 d post-application. Additionally, all tested active ingredients and application methods prevented second-generation hemlock woolly adelgid establishment, with the exception of bifenthrin and horticultural oil. The longevity of many of these products permits growers to manage hemlock woolly adelgid with a single application in the spring, when first-generation hemlock woolly adelgids are most vulnerable. If a fast-acting treatment is required, foliar applications of spirotetramat or dinotefuran are options for growers wanting to treat and ship plants quickly (Frank and Lebude 2011).

In addition to the previously mentioned products, other insecticides that do not currently have efficacy data are labeled for adelgid control in nursery settings (Table 1). These products include neonicotinoids (thiamethoxam), pyrethroids (*tau*-fluvalinate), neonicotinoid–pyrethroid combinations, an anthranilic diamide (chlorantraniliprole), avermectin (abamectin), azadirachtin, as well as various carbamates, organophosphates and insecticidal soaps. Further research on chlorantraniliprole would be particularly useful. The product class has been touted as an alternative to neonicotinoids, as it is gentler on some beneficial insects (Brugger et al. 2010, Larson et al. 2014) and less likely than imidacloprid to cause secondary mite outbreaks (Raupp et al. 2004). Because hemlock woolly adelgid infestations can cause water stress in hemlocks (Coots et al. 2015), proper irrigation of hemlock trees will aid in uptake of systemic treatments and mitigate water stress, allowing for faster recovery. Growers must weigh the value of treating hemlock trees once per season with a product that has a long residual time or multiple treatments timed to control first- and second-generation hemlock woolly adelgid. The choice of product by nursery growers requires balancing a need for short or long control duration, product efficacy, cost, and safety concerns.

Environmental Concerns

Ecosystem benefits and risks of hemlock conservation tactics must be approached from the perspective of the entire forest system, as hemlock preservation is often protection of an ecosystem. Any management tactic, even the choice to do nothing, carries risks and benefits, and every decision requires trade-offs. Research on environmental risks of management tactics has centered on non-target risks assessments of imidacloprid applications (Dilling et al. 2009, Churchel et al. 2012, Knoepp et al. 2012, Benton et al. 2017).

Table 2. Efficacy data from hemlock 30-L container nursery trials following a single treatment application[a]

Product	Active ingredient	Application method	Application rate	Percent control first generation (42 DAT)	Percent control second generation (154 DAT)
TriStar 30SG, Cleary Chemical Corp., Dayton, NJ	Acetamiprid	Foliar	0.6 g/L	100[b]	100
Talstar F, FMC Corp., Philadelphia, PA	Bifenthrin	Foliar	1.6 g/L	97[b]	50
Safari 2G, Valent USA Corp., Walnut Creek, CA	Dinotefuran	Granular	0.7 g/L	100	100
Safari 20 SG, Valent USA Corp., Walnut Creek, CA	Dinotefuran	Foliar	0.6 g/L	100[b]	100
Marathon 1%G, OHP, Inc., Mainland, PA	Imidacloprid	Granular	1.32 g/L	100	100
CoreTect 100, Bayer Environmental Science, Research Triangle Park, NC	Imidacloprid	Tablet	5 tablets/pot	98	100
Marathon II, OHP, Inc., Mainland, PA	Imidacloprid	Foliar	0.12 g/L	96[b]	100
Horticultural Oil	Paraffinic oil	Foliar	12 ml/L	100	0
Kontos (Low), OHP, Inc., Mainland, PA	Spirotetramat	Foliar	0.12 g/L	99[b]	100
Kontos (High), OHP, Inc., Mainland, PA	Spirotetramat	Foliar	0.25 g/L	100[b]	100
Kontos (Low), OHP, Inc., Mainland, PA	Spirotetramat	Drench	0.05 ml/L	98[b]	100
Kontos (High), OHP, Inc., Mainland, PA	Spirotetramat	Drench	0.1 ml/L	100[b]	100

[a]Data summarized from Frank and Lebude (2011).
[b]Significant reduction in live insects within 24 h post-treatment.

Risks to invertebrates rather than vertebrates are more commonly assessed, because neonicotinoids have high invertebrate risk and low vertebrate risk (Jeschke et al. 2011). Environmental assessments include studying effects on soil arthropods, aquatic insect communities, and canopy arthropod communities. Since imidacloprid is a broad-spectrum insecticide, it is toxic to non-target soil, aquatic, and terrestrial arthropods in hemlock forest systems.

Aside from the potential hazard of imidacloprid in these systems, there are three critical questions that must be considered in assessing environmental risk and making trade-offs. Will imidacloprid occur in hemlock systems in sufficient concentrations to negatively affect soil, aquatic, and terrestrial insects? To what degree are these communities negatively affected? Is the trade-off between possible community effects reasonable given the benefits that hemlock preservation conveys to the forest system?

Hemlocks are often located in forests with a thick organic surface layer in which many hemlock absorptive roots are located (Cowles et al. 2006). Imidacloprid binds tightly to organic matter in the soil and can persist for long time periods (Cox et al. 1998, Baskaran et al. 1999, Fernandez-Bayo et al. 2009). However, imidacloprid does not migrate far from the area of soil applications (Knoepp et al. 2012) and is absorbed by the hemlock roots over time (Cowles et al. 2006). Assessments of imidacloprid impacts to soil arthropods have yielded varying results. No overall difference between soil arthropod communities between treated and untreated trees has been documented (Knoepp et al. 2012). However, lower collembolan abundance (the number of specimens collected) and richness (the number of species collected) in the immediate area of imidacloprid soil application has occurred (Reynolds 2008). Some community effects in the immediate area where a broad-spectrum insecticide is being poured on the soil should be expected. Since imidacloprid in soil does not migrate far laterally (Knoepp et al. 2012), these effects are not expected to occur far beyond the application point. Possible non-target effects, such as soil arthropod impacts at the point of application, are the types of information to consider in making risk versus benefit trade-offs.

Imidacloprid has a short-term negative effect on canopy arthropods. Canopy arthropod species richness and abundance was reduced as a result of imidacloprid treatments in the first 2 y after treatment (Dilling et al. 2009). Order-level taxa richness and abundance did not vary between treated and untreated trees 2 y after treatment, but hemipteran and lepidopteran larvae were less abundant (Falcone and DeWald 2010). Three years after treatment, no difference was observed in canopy arthropod communities, and 9 y after treatment, species richness was higher in treated trees (Kung et al. 2014). The trade-off between short-term negative effects compared with the longer-term loss of hemlock canopies in forest systems must be considered when making hemlock conservation decisions.

After soil applications, imidacloprid can leach through soils and potentially impact surface water quality (U.S. Environmental Protection Agency 2008). Imidacloprid has previously been documented in surface waters in agricultural and forest settings (Churchel et al. 2012, Starner and Goh 2012, Hladik and Kolpin 2015, Benton et al. 2016b). The presence of imidacloprid in surface waters associated with treatments for hemlock woolly adelgid suppression has been documented in three studies (Churchel et al. 2012, Benton et al. 2016b, Wiggins et al. 2018). Ephemeroptera (mayfly), Plecoptera (stonefly), and Trichoptera (caddisfly) aquatic insects, which are environmentally sensitive organisms (Mohr et al. 2012), have been assessed in two studies to determine if imidacloprid treatments have a negative effect on aquatic insects (Churchel et al. 2012, Benton et al. 2016b). Mayfly, stonefly, and caddisfly richness did not differ among a control stream and three streams associated with imidacloprid treatments (Churchel et al. 2012). Mean mayfly, stonefly, and caddisfly richness, abundance, feeding groups, and life habits were statistically similar in streams sites upstream and downstream from imidacloprid treatment areas in nine stream systems (Benton et al. 2017). When imidacloprid is used according to the label, hemlock forests can be protected without risking negative effects to water quality and aquatic insect fauna.

The possible role neonicotinoids play in pollinator declines has been under much scientific and public scrutiny. Many other factors are greater contributors to pollinator decline and colony collapse disorder, such as parasites, pathogens, and decreased resource diversity (Kaplan 2012). The U.S. Department of Agriculture and Environmental Protection Agency released a join report stating that Varroa mites are the leading cause of pollinator declines (U.S. Department of Agriculture 2012, 2013). Since hemlocks are wind pollinated, potential imidacloprid risks to pollinators are lower in comparison to agricultural systems. The most likely route pollinator exposure would be from imidacloprid uptake and translocation to flowering structures by non-target flowering plants. The risk should be restricted to plants whose roots are very near the area of imidacloprid soil application.

Preliminary data on imidacloprid concentrations in nectar and pollen from flowering shrubs growing adjacent to hemlock indicate imidacloprid concentrations are less than 30 parts per billion (E. Benton and G. Wiggins, personal communication), which is below the concentration that causes minor honey bee (*Apis mellifera* Linnaeus) colony-level effects (Housenger et al. 2016). However, small herbaceous flowering plants growing adjacent to hemlock trees, which were treated by soil drench, soil injection, or bark spray 3 wk before assessment, contain imidacloprid residues that could be problematic for pollinators (Benton et al. 2018). This study to determine the extent and longevity of pollinator risk for herbaceous flowering plants and the application methods that are most protective of pollinators is ongoing (Benton et al. 2018).

Given the non-target plant uptake route of exposure and restricted area where this occurrence is possible, widespread landscape-level negative effects are unlikely but as yet undetermined. Despite differences in initial data between shrubs and flowering plants, more comprehensive studies are needed to fully understand risks for pollinators of different kinds of plants, and how this risk translates to improved management recommendations that are more protective of pollinators. It is important to note that honey bees are often used as a representative study organism for pollinators, but the possible effects of imidacloprid on native solitary bees are of a greater concern in hemlock systems.

While environmental risks of insecticide use are very low in hemlock systems, it is more beneficial for forest health if hemlock woolly adelgid is not present at all. Thus, while effective management practices are being implemented, quarantines are a very important management tactic to reduce the spread of hemlock woolly adelgid.

Hemlock Woolly Adelgid Quarantine Regulations

Hemlock producers in hemlock woolly adelgid-infested and non-infested regions are required to follow quarantine restrictions for each state to limit hemlock woolly adelgid movement into uninfested areas. Currently, six states in the United States (Maine, Michigan, New Hampshire, Ohio, Vermont, and Wisconsin) and all Canadian provinces have external quarantines to regulate the movement of

Table 3. Hemlock quarantines and regulations

Location	Regulated items	Rules summary[a]	Regulatory documents
Maine	*Tsuga* spp. (hemlock); seedlings, nursery stock, and any hemlock wood products with bark such as, but not limited to logs lumber, chips, and uncomposted shipments of bark	No hemlock imports from infested counties to uninfested counties; shipments from non-infested counties require phytosanitary certificate	01-001 Department of Agriculture, Conservation & Forestry Division of Animal & Plant Health. Chapter 266: Hemlock Woolly Adelgid Quarantine. http://www.maine.gov/dacf/php/horticulture/importinghemlocks.shtml
Michigan	HWA in any living form; *Tsuga* spp. (hemlock) and *Picea polita* (tiger-tail spruce); nursery stock, uncomposted chipped/shredded/ground or otherwise mechanically processed products bearing twigs or needles, including branches, boughs, logs, lumber, and firewood	No hemlock imports from infested counties or adjacent counties; hemlocks moved from infested counties within the state require compliance agreement; hemlocks from non-infested areas into state require general nursery inspection	Michigan Department of Agriculture and Rural Develop, Pesticide and Plant Pest Management Division. Hemlock Woolly Adelgid Interior State Quarantine. 5 July 2017. http://www.michigan.gov/documents/mdard/Hemlock_Woolly_Adelgid_Interior_Quarantine_June_5_2017_573038_7.pdf Hemlock Woolly Adelgid Exterior Quarantine. 24 June 2014. http://www.michigan.gov/documents/MDA_Hemlock_Woolly_Adelgid_Quarantine_97324_7.pdf
New Hampshire	*Tsuga* spp. (hemlock); seedlings, nursery stock, and any hemlock wood products with bark such as, but not limited to logs lumber, chips, and uncomposted shipments of bark	No hemlock imports from infested counties; shipments from non-infested areas require phytosanitary certificate	State of New Hampshire, Department of Agriculture, Markets and Food, Department of Resources and Economic Development, Hemlock Woolly Adelgid Quarantine, Joint Quarantine No. 1. February 2014 Revision. https://www.agriculture.nh.gov/divisions/plant-industry/hemlock-woolly-adelgid.htm
Ohio	HWA all life stages; *Tsuga* spp. (hemlock) seedlings, nursery stock, logs, lumber or chips with bark, uncomposted bark, branches	No hemlock from infested counties; shipments from non-infested counties require a phytosanitary certificate	Hemlock Pest. Ohio Administrative Code. Chapter 901:5–48. http://codes.ohio.gov/oac/901%3A5-48
Vermont	Hemlock seedlings, nursery stock, logs, lumber with bark and chips	No hemlock from infested counties; shipments from non-infested counties require a phytosanitary certificate	State of Vermont, Agency of Agriculture and Department of Forests, Parks and Recreation. Joint Quarantine #2 - Hemlock Woolly Adelgid. http://fpr.vermont.gov/node/1114
Wisconsin	Hemlock seedlings, hemlock nursery stock, hemlock logs or lumber with bark; uncomposted hemlock chips with bark, uncomposted hemlock bark	Hemlock shipments from infested counties require a phytosanitary certificate, inspection and, if needed, require treatment; compliance agreements	Hemlock Woolly Adelgid Quarantine Requirements. https://datcp.wi.gov/Pages/Programs_Services/HWAQuarantine.aspx
Canada	*Tsuga* spp. (hemlock), *Picea jezoensis* (Yeddo spruce), and *Picea polita* (tiger-tail spruce); seedlings, nursery stock; Christmas trees; fresh decorative wreaths, foliage and branches; forest products with bark attached such as logs and lumber with bark; bark chips; wood mulch with bark; firewood; and dried branches	Hemlock from non-regulated areas of the United States to all areas of Canada require phytosanitary certificate Hemlock from regulated areas of the United States to regulated areas of Canada requires a phytosanitary certificate with declaration of insecticide treatment Hemlock from regulated areas of Canada to non-regulated areas of Canada requires movement certificate with declaration of insecticide treatment Hemlock from non-regulated areas of Canada to all areas of Canada are exempt	D-07-05: Phytosanitary requirements to prevent the introduction and spread of the hemlock woolly adelgid (*Adelges tsugae* Annand) from the United States and within Canada. Effective Date: May 15, 2015. 3rd Revision. http://www.inspection.gc.ca/plants/plant-pests-invasive-species/directives/forestry/d-07-05/eng/1323754212918/1323754664992#c2

HWA = hemlock woolly adelgid.
[a]A detailed explanation of rules and restrictions can be found in the quarantine guidelines for each region. Check documents for full details and latest updates.

Table 4. Regulated areas in United States and Canada[a]

Country	State	Counties
United States	AK	All counties
	CA	All counties
	CT	All counties
	DE	All counties
	GA	Dade, Dawson, Fannin, Gilmer, Habersham, Lumpkin, Murray, Pickens, Rabun, Stephens, Towns, Union, Walker, White
	ID	All counties
	KY	Bell, Breathitt, Carter, Clay, Elliott, Fayette, Floyd, Harlan, Jackson, Johnson, Knott, Knox, Laurel, Lawrence, Lee, Leslie, Letcher, Madison, Martin, McCreary, Menifee, Morgan, Owsley, Perry, Pike, Powell, Pulaski, Rockcastle, Rowan, Whitley, Wolfe
	MA	All counties
	MD	All counties
	ME	Androscoggin, Cumberland, Kennebec, Knox, Lincoln, Sagadahoc, York
	MT[b]	All counties
	NC	Alamance, Alexander, Alleghany, Ashe, Avery, Buncombe, Burke, Caldwell, Caswell, Catawba, Cherokee, Clay, Durham, Forsyth, Graham, Haywood, Henderson, Iredell, Jackson, Macon, Madison, McDowell, Mitchell, Orange, Polk, Rockingham, Rutherford, Stokes Surry, Swain, Transylvania, Wake, Watauga, Wilkes, Yancey
	NH	Belknap, Carroll, Cheshire, Hillsborough, Merrimack, Rockingham, Strafford, Sullivan
	NJ	All counties
	NY	Albany, Bronx, Broome, Cayuga, Chemung, Columbia, Delaware, Dutchess, Erie, Greene, Kings, Livingston, Monroe, Nassau, New York, Orange, Otsego, Putnam, Queens, Rensselaer, Richmond Rockland, Schenectady, Schoharie, Schuyler, Seneca, Steuben, Suffolk, Sullivan, Tioga, Tompkins, Ulster, Westchester, Wyoming, Yates
	OH	Hocking, Lawrence, Meigs, Monroe, Vinton, Washington
	OR	All counties
	PA	Adams, Allegheny, Beaver, Bedford, Berks, Blair, Bradford, Bucks, Cambria, Cameron, Carbon, Centre, Chester, Clarion, Clearfield, Clinton, Columbia, Cumberland, Dauphin, Delaware, Elk, Fayette, Forest, Franklin, Fulton, Huntingdon, Indiana, Jefferson, Juniata, Lackawanna, Lancaster, Lebanon, Lehigh, Luzerne, Lycoming, McKean, Mifflin, Monroe, Montgomery, Montour, Northampton, Northumberland, Perry, Philadelphia, Pike, Potter, Schuylkill, Snyder, Somerset, Sullivan, Susquehanna, Tioga, Union, Warren, Wayne, Westmoreland, Wyoming, York
	RI	All counties
	SC	Greenville, Oconee, Pickens, Spartanburg
	TN	Anderson, Bledsoe, Blount, Campbell, Carter, Claiborne, Cocke, Cumberland, Fentress, Franklin, Grainger, Greene, Grundy, Hamblen, Hamilton Hancock, Hawkins, Jefferson, Johnson, Knox, Loudon, Marion, McMinn, Monroe, Morgan, Pickett, Polk, Putnam, Rhea, Roane, Scott, Sequatchie, Sevier, Sullivan, Unicoi, Union, Washington
	VA	Albemarle, Alleghany, Amherst, Appomattox, Arlington, Augusta, Bath, Bedford, Bland, Botetourt, Buchanan, Buckingham, Campbell, Caroline, Carroll, Chesterfield, Clarke, Craig, Culpeper, Dickenson, Essex, Fairfax, Fauquier, Floyd, Fluvanna, Franklin, Frederick, Giles, Grayson, Greene, Hanover, Henrico, Henry, Highland, King William, Lee, Loudoun, Lunenburg, Madison, Montgomery, Nelson, Northumberland, Orange, Page, Patrick, Pittsylvania, Prince William, Pulaski, Rappahannock, Roanoke, Rockbridge, Rockingham, Russell, Scott, Shenandoah, Smyth, Spotsylvania, Tazewell, Warren, Washington, Wise, Wythe
	VT	Bennington, Windham, Windsor
	WA	All counties
	WV	Barbour, Berkeley, Boone, Braxton, Cabell, Clay, Fayette, Grant, Greenbrier, Hampshire, Hardy, Harrison, Jackson, Jefferson, Kanawha, Lewis, Lincoln, Logan, Marion, Marshall, Mason, McDowell, Mercer, Mineral, Mingo, Monongalia, Monroe, Morgan, Nicholas, Pendleton, Pleasants, Pocahontas, Preston, Putnam, Raleigh, Randolph, Ritchie, Roane, Summers, Taylor, Tucker, Tyler, Upshur, Wayne, Webster, Wirt, Wood, Wyoming
Canada	BC	All counties

[a]Check with your state plant inspector for up-to-date quarantine information.
[b]Canada lists Montana as subject to its import quarantine.

hemlock plants from infested areas into their states (Table 3). The most up-to-date list of states and counties from which imports may be regulated include 25 states and 1 Canadian province where hemlock woolly adelgid has been reported (Table 4). Regulated areas include all or parts of Alaska, California, Connecticut, Delaware, Georgia, Idaho, Kentucky, Massachusetts, Maryland, Maine, Montana, North Carolina, New Hampshire, New Jersey, New York, Ohio, Oregon, Pennsylvania, Rhode Island, South Carolina, Tennessee, Virginia, Vermont, Washington, West Virginia, and British Columbia in Canada. Not all hemlock products are regulated. Items are regulated if they have a reasonable chance of carrying live hemlock woolly adelgid adults, immature stages, or eggs into regulated areas. Regulated items may include: live hemlock woolly adelgid insects; propagated materials of the *Tsuga* spp. (hemlock), *Picea jezoensis* ([Siebold & Zuccarini] Carrière) (Yeddo spruce), and *Picea polita* (Siebold & Zuccarini) (Tiger-tail spruce); Christmas trees; fresh wreaths, foliage, and branches; forest products with bark attached (logs and lumber); bark chips; wood mulch with bark; and firewood and dried branches (Table 3). Non-regulated items may include seeds, cones, debarked wood or lumber, processed wood material (banisters, flooring, furniture, etc.), railway ties, wood mulch without bark, composted wood mulch with bark, shingles and shakes, wood shavings or wood chips without bark, and wood packaging material (Table 3).

Specific guidelines for each state imposing a quarantine must be followed if shipping material to those locations (Table 3). Restrictions on hemlock products differ between states and whether shipping from infested to infested areas, infested to non-infested areas, and non-infested to non-infested or infested areas. All hemlock materials may be restricted by one state, while another state may only restrict materials from infested counties or infested and adjacent counties. Some states will require phytosanitary certificates whether or not the products were produced in an infested county. Guidelines for treatment of live material may be included in state quarantine guidelines. Additional restrictions may apply to shipping conditions of hemlock transported through infested areas. For example, states may require trees to be shipped in a closed box trailer. Additionally, shipments of hemlock may require a second inspection upon arrival to ensure no hemlock woolly adelgids arrived on the shipment. If hemlock woolly adelgid is observed on received materials, single plants or entire shipments may be destroyed. Additional regulations may be placed on the sale of hemlocks by nurseries and landscapers, including Record of Sale requirements. Nursery growers shipping or receiving hemlocks must adhere to regulations of the state where hemlocks originate and where they are headed.

Closing Remarks

Hemlock woolly adelgid and the associated landscape-level devastation is an unfortunate reality. Fortunately, the management community does have tools that can suppress adelgid populations. Land managers, homeowners, and nurseries currently have management options (contact insecticides, systemic insecticides, and biocontrol) of varying efficacies and costs in hemlock woolly adelgid suppression. In addition, state and federal agencies work with the nursery industry to implement quarantines that can delay hemlock woolly adelgid damage in the uninfested hemlock range. Each management option has risks and benefits, and thus appropriate management tactics for every situation must be carefully considered. However, with continuing research, our ability to effectively manage hemlock woolly adelgid populations should be enhanced with more tools, lower costs, and more environmentally protective methods.

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