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Recommendations

Urban ash management and emerald ash borer (Coleoptera: Buprestidae): facts, myths, and an operational synthesis

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Survival of North American species of ash (Oleaceae: *Fraxinus* spp. L.) is threatened by emerald ash borer (EAB), *Agrilus planipennis* (Fairmaire), a phloem-feeding beetle that destroys the vascular system of its host. In forested sites where ash is a dominant overstory species, mortality caused by EAB can substantially alter conditions, with potentially cascading effects on ecosystems. In urban forests, ash trees were often abundant and provided an array of ecosystem services because of their rapid growth, capacity to withstand stressful urban conditions and prior to EAB, low pest load. Annualized costs of managing EAB on urban ash trees over the next 30 yr in the United States has been estimated to approach $1.8 billion. Numerous cost-benefit analyses have demonstrated that it is more cost effective to retain mature ash trees with systemic insecticides than to replace these trees in urban areas. Effective protection of urban ash trees depends on deployment of systemic insecticides before EAB injury disrupts the vascular system that transports insecticide to the canopy. Given the ongoing spread of EAB, timely management is critical for protecting urban ash canopies. Over the last 2 decades, we have encountered persistent myths that have hindered the adoption of protective measures to preserve urban ash in communities recently infested by EAB. Here we review these myths and counter them with research-based evidence that supports and justifies an ash management program. Finally, we use the 5 basic tenets of IPM to outline an approach for managing EAB in urban forests.

Key words: invasive forest pest, urban forestry, decision making, policy development

Emerald ash borer (EAB), *Agrilus planipennis* (Fairmaire), is a metallic phloem-feeding beetle native to Asia that threatens many North American species of ash (*Fraxinus* spp.) with functional extinction (Ward et al. 2021). Currently, EAB is established in at least 36 US states and 5 Canadian provinces. Federal regulatory activities and detection surveys were discontinued in 2021 (USDA APHIS 2020), although some state and local agencies in uninfested areas still deploy traps or monitor ash trees. Populations of EAB continue to spread via natural dispersal by adult beetles and perhaps by people accidentally transporting infested firewood or similar material into new areas (Haack et al. 2010). For example, the discovery of EAB in Oregon in 2022 seems likely to have resulted from human-assisted movement, given the distance of the infestation from any other known EAB population (USDA APHIS 2022, EAB.info 2023). Populations of EAB that invaded Moscow, Russia in the mid-2000s are continuing to spread, posing a threat to ash trees in Europe (Baranchicov et al. 2008, Orlova-Bienkowskaja 2014, Schrader et al. 2021, US Forest Service and Michigan State University 2023). Although much has been learned about the biology and management of EAB since it was first detected in southeast Michigan in 2002 (Cappaert et al. 2005), this insect continues to imperil ash trees in urban and natural forests across North America.

Ash trees, particularly cultivars of green ash (*F. pennsylvanica* Marsh.) and white ash (*F. americana* L.), have long been popular in landscapes, parks, and along roads in urban and residential areas. They were widely planted due to several traits including their ability to tolerate a range of soils and environmental stresses, relatively rapid growth, straight form and, until EAB became established, a lack of significant pests. In the early and mid-2000s, ash comprised 20–30% of the street trees in many North American municipalities and accounted for more than 50% of the trees in some cities (Raupp et al. 2006, Ball et al. 2007, Sydnor et al. 2011). To date, approximately 30% of the urban ash trees occur in areas where EAB is known to be established (Kovacs et al. 2010, US Forest Service and Michigan State University 2023). Recent estimates indicate that between 2020 and 2050, approximately 135 million urban ash trees in the US will likely be killed by EAB, corresponding to annualized costs of $1.8 billion (Hudgins et al. 2022). Urban foresters in recently infested areas or locations where EAB is not yet present can benefit from what has been learned about managing this pest over the past 20 yr.

Here we summarize aspects of EAB biology that are relevant to arborists and pest management specialists. We review scientific advances that have improved our ability to protect ash trees in urban and residential areas in the United States. Many municipalities are successfully managing EAB populations and protecting ash in urban forests, but this effort depends on knowledgeable arborists, long-term support from local leaders and commitment from communities. Over the last 2 decades, we have encountered persistent myths that can hinder decision-makers in developing and implementing an EAB management strategy. Here, we identify these myths and address them with relevant research. We conclude with recommendations based on IPM principles for developing programs to help urban foresters and policy makers protect ash trees in the path of EAB.

Biology of EAB and Its Relevance to Management

While many arborists are familiar with the basic life cycle of EAB (Cappaert et al. 2005, Poland and McCullough 2006, Herms and McCullough 2014), particular aspects of EAB biology are relevant to managing this pest in urban forests. For example, adult EAB beetles typically emerge over several weeks in mid-May and June and nibble on the margins of ash leaves throughout their 4- to 6-wk life span during the summer (Fig. 1). This includes a 5- to 7-day period before adults begin mating and the additional 5–7 days of feeding needed by females before they can begin to lay eggs. This maturation period provides a 2–3 wk opportunity to control leaf-feeding beetles with effective systemic insecticides before any eggs are laid. Female beetles not killed by feeding on toxic leaves will lay individual eggs in bark cracks or crevices or under flaps of bark. While most EAB females likely lay a total of 30–50 eggs during their life span (Poland and McCullough 2006), a few long-lived females reared in a laboratory laid more than 250 eggs each (DGM unpubl. data). Treating trees with systemic insecticides in spring to ensure beetles encounter toxic leaves during their maturation period or minimally during the period of egg-laying results in fewer eggs and EAB larvae.

Eggs hatch within 10–14 days and the tiny first stage larvae immediately chew through the outer bark to reach the phloem (inner bark) and cambium tissue, which provides nutrients needed for them to grow and develop. Larval feeding carves serpentine galleries in the phloem, which disrupts the ability of the tree to transport carbohydrates produced by leaves down to the roots. Larval galleries, however, also typically score or "etch" the outer sapwood. This interferes with the ability of ash and other ring porous trees to transport water from roots to the leaves through xylem vessels in the outer ring of sapwood (Dickison 2000).

Research with ^{14}C-labelled imidacloprid showed that systemic insecticides are carried from the base of trees to the canopy in xylem tissue but are not transported in phloem (Mota-Sanchez et al. 2009, Tanis et al. 2012). Presumably, larvae feeding in trees treated with effective systemic insecticides encounter a toxic dose when their galleries score the outer sapwood, although some insecticide may eventually move into phloem via transverse rays that run horizontally from xylem to phloem tissue. If larvae are not killed, they will continue to feed, grow and develop during the summer and early fall.

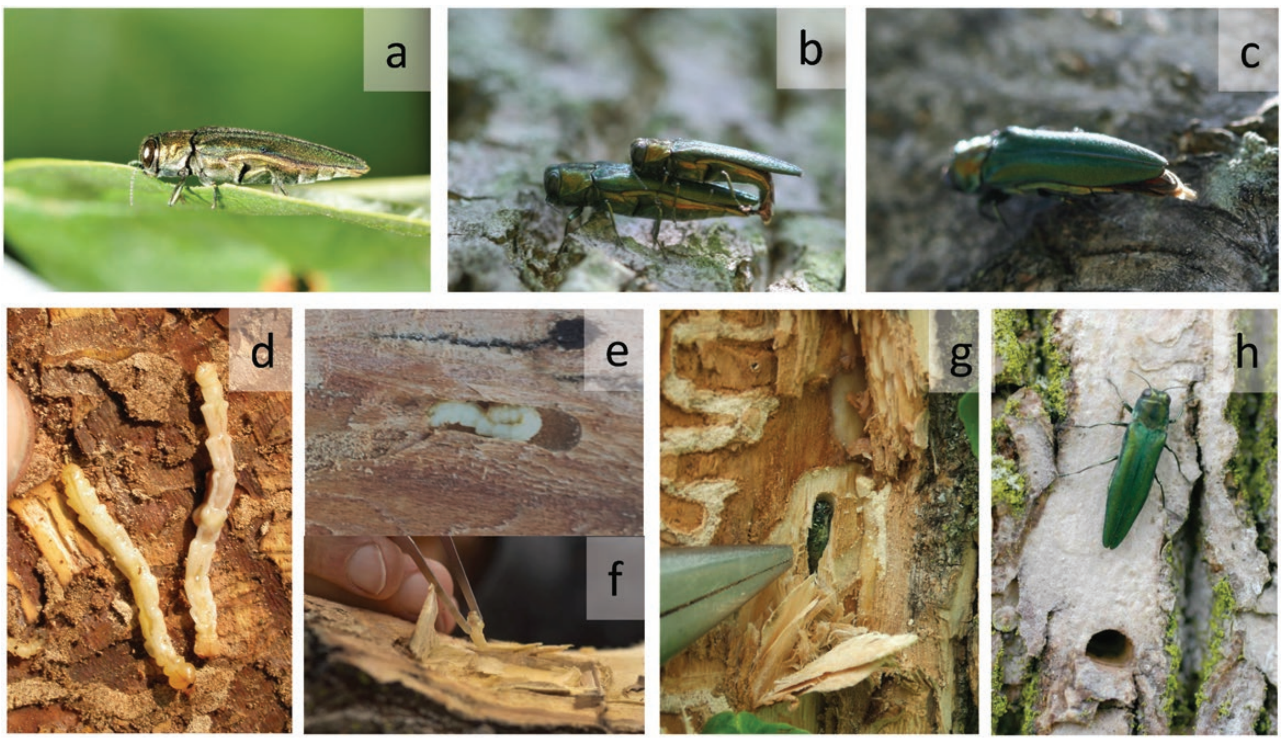

Fig. 1. Key moments of emerald ash borer life history: a) adult emerald ash borer feeding on leaves, b) mating pair on trunk, c) adult female ovipositing in bark crevice, d) late stage larvae feeding on phloem and cambium, e) J-shaped larva in overwintering chamber, f) exposed pupa in spring, g) adult beneath bark and h) emerging from "D" shaped exit hole.

As temperatures fall, most larvae chew small elliptical cells approximately 1 cm (0.5 in) below the surface, either in thick bark on large trees or in the outer sapwood beneath thin bark. These prepupal larvae fold over into a J-shape in the cell and remain there through the winter until the following spring, when they pupate and eventually emerge as adult beetles from characteristic D-shaped exit holes (Cappaert et al. 2005, Poland and McCullough 2006). Individuals that do not reach at least the 4th instar or prepupal stage by winter typically feed the following year, overwinter and then emerge the second summer. This 2-yr life cycle is most often observed when low densities of larvae feed on healthy, newly infested trees, typically before external signs or symptoms of EAB are present (e.g., Siegert et al. 2010, Tluczek et al. 2011, Jones et al. 2020). Extended development serves to slow EAB population growth initially but the delayed appearance of external signs of EAB infestation can also slow detection of new infestations. Recent surveys of EAB life stages in southeastern states that reported that all or nearly all larvae overwintered as prepupae (Gould et al. 2020, Nalepa et al. 2021, Bohanan 2022), did not involve debarking any newly infested trees (e.g., trees without external EAB signs and symptoms). Extended larval development in healthy ash trees is likely indicative of some level of host resistance, rather than simply temperatures and degree day accumulation.

Large-scale field studies have shown most EAB adult females lay their eggs on ash trees within 100 m of their own emergence point (Mercader et al. 2009, Siegert et al. 2010, 2015). Like native *Agrilus* beetles, such as bronze birch borer (*Agrilus anxius* Gory) and two-lined chestnut borer (*A. bilineatus* Weber), EAB adults initially colonize branches in the upper canopy of trees (Cappaert et al. 2005, Herms and McCullough 2014, McCullough 2019). At the low larval densities typical of newly or recently infested trees, galleries generally have little effect on healthy ash trees. Over time, however, as larval densities increase, more branches and the trunk are colonized, foliage thins, branches die and eventually the tree succumbs. Research in forested sites has shown that most ash trees are dying or severely declining 4–10 yr after symptoms of EAB infestation become apparent (Klooster et al. 2014, Siegert et al. 2021).

We note that branches and trunks of ash trees killed by EAB tend to desiccate and become brittle fairly quickly relative to other trees and can pose a hazard. For example, tensile strength of limbs is significantly reduced in trees with 30% canopy dieback (Persad et al. 2013, 2019). Timely removal of EAB-killed ash trees is important to mitigate potential damage to utility lines and public safety or property risks caused by falling trees.

Which Ash Trees Are Most Likely to Be Colonized in a Newly Invaded Area?

While all species of North American ash trees that EAB has encountered to date appear to be suitable hosts, there is consistent variation in susceptibility between stressed and healthy trees as well as among ash species (Anulewicz et al. 2008, Rebek et al. 2008, Tanis and McCullough 2015, Robinett and McCullough 2019). In its native range in Asia, EAB is a secondary pest, meaning that it only attacks severely stressed, dying, or recently dead ash trees. In North America, EAB can colonize healthy trees of most ash species, but given a choice, female beetles strongly prefer to feed and lay eggs on stressed ash trees (McCullough et al. 2009a, 2009b, Mercader et al. 2013). Stress can be caused by girdling, poor site conditions, or injuries to the vascular system, such as the damage caused by EAB larval feeding.

This preference for stressed ash trees has been used to attract EAB adults to “trap trees”, e.g., small (10–15 cm DBH) trees that are girdled by removing a 15- to 20-cm-wide band of outer bark and phloem. Trap trees that attract and kill EAB can include trees that were previously treated with systemic insecticides (McCullough et al. 2016) or trees that will be debarked, chipped, or removed before larvae developing under the bark can complete development (Mercader et al. 2013, 2015). Using girdled trap trees can slow EAB population growth and reduce the rate of ash mortality in the local area (Mercader et al. 2015, Siegert et al. 2017). However, girdling is only effective in relatively new infestations where most ash trees remain healthy (Mercader et al. 2011, Siegert et al. 2017). Once EAB densities build and many trees are stressed by larval feeding, volatile (airborne) compounds released by girdled trees (Rodriguez-Saona et al. 2006, Crook et al. 2008, de Groot et al. 2008) are no longer unique and the girdled trees will not be particularly attractive to adult beetles (Siegert et al. 2017).

Understanding which ash species are most preferred by EAB can also be useful for municipal and urban foresters. Numerous studies and observations have shown that black ash (*F. nigra*), typically found in northern hydric forests, swamps, and bogs, is the most highly preferred and vulnerable native ash species EAB has encountered to date (Tanis and McCullough 2015, Siegert et al. 2021). Black ash is uncommon in US urban forests but green ash, a notably common landscape and boulevard tree, is nearly as preferred and vulnerable as black ash. White ash, which is also common in urban and residential areas, is an intermediate host for EAB. In some forested sites, a high proportion of white ash trees have survived EAB invasion for more than 15 yr (Robinett and McCullough 2019), while in other forested areas, all or nearly all white ash were killed (Klooster et al. 2014). In urban sites where green ash and white ash co-occurred, green ash was consistently colonized first, but as those trees succumbed, EAB densities increased on white ash (Anulewicz et al. 2007, Sadof et al. 2021). In contrast, healthy blue ash (*F. quadrangulata*) is relatively resistant to EAB, although suppressed or otherwise severely stressed trees can still be killed (Tanis and McCullough 2016, 2015, DGM, unpubl. data).

In recently infested areas or in municipal areas not yet known to be infested, monitoring stressed, highly preferred ash trees, particularly green ash, for signs of EAB infestation should be a priority (Fig. 2). Adult EAB beetles are strongly attracted to sun and open-grown trees such as those in parks, along roadsides or surrounded by impervious surfaces. Ash trees in these sites are typically colonized before ash trees grow in full or nearly full shade (Cappaert et al. 2005, Wang et al. 2010, Tluczek et al. 2011, Tobin et al. 2021). Note that relatively large holes in branches of the upper canopy left by woodpeckers preying on large EAB larvae and prepupae in winter are often the first evidence of EAB invasion in an area.

Dynamics of an EAB Invasion

Progress of an EAB invasion has been likened to 3 stages of a wave; the cusp, crest, and the post-invasion core (Burr and McCullough 2014, Flower et al. 2015, Burr et al. 2018). In the cusp phase, EAB is established but densities remain low, trees are generally healthy and there is little external evidence of infestation. This stage is followed by exponential growth of the EAB population (Anulewicz et al. 2007, McCullough et al. 2019). During this mid-invasion crest, EAB densities are relatively high and a mix of dead, dying, declining, and healthy ash trees are present. In the post-invasion core, most ash trees that were not protected with systemic insecticides are dead, which means that the availability of live ash phloem, the resource required by EAB larvae, has dropped sharply (Burr and McCullough 2014, Siegert et al. 2021). Despite this often dramatic decline in the EAB carrying capacity, field studies have shown that

Fig. 2. Symptoms and signs of emerald ash borer: a) late-stage larva removed from gallery, b) current-year serpentine (zigzag) galleries in spring, c) bark split over an old larval gallery, d) holes left by woodpeckers preying on late stage EAB larvae, e) bark scraped by woodpeckers preying on EAB larvae, f) stump sprouts and epicormic shoots on heavily infested tree.

EAB populations persist (Robinett et al. 2021) and continue to colonize available ash trees, including young trees (>2.5 cm in diam).

Myth: There Is No Point in Trying to Protect Ash Trees—EAB Will Eventually Kill Them Anyway

When EAB was first detected in 2002, few systemic insecticide products were available and application methods were, by today's standards, fairly primitive. Early trials included trunk injections of imidacloprid products with Mauget® capsules (Arcadia, CA) or with the Wedgle, Direct-Inject System (ArborSystems, Omaha, Nebraska), a modified injection device originally used to inject swine. Although imidacloprid injected with Mauget capsules slowed tree decline to some extent, most trees treated with these early systems continued to decline with high EAB densities (Cappaert et al. 2006). Moreover, the pressure generated by the Wedgle sometimes damaged phloem, cambium, and even xylem tissue (Smith and Lewis 2005). An organophosphate insecticide sold as Injecticide-B [(Bidrin, dichrotophos) and applied with Mauget capsules, similarly did not provide effective levels of EAB control. Unfortunately, their experience with these unreliable management tools led some arborists and landscapers simply to stop paying attention to advances in EAB control options.

However, over the next few years, much was learned about EAB biology and ash physiology, while at the same time, insecticide chemistry and application methods were advancing. New and more effective approaches were developed, providing higher levels of EAB control. When systemic insecticides were applied in spring, female beetles that fed on toxic leaves were killed, resulting in fewer eggs and larvae. Spring applications were especially effective if female beetles died during the preoviposition period of maturation feeding. New formulations of imidacloprid also became available. Dinotefuran, another neonicotinoid, was found to move more rapidly to the canopy than imidacloprid because of its high water solubility. Basal trunk sprays with dinotefuran provided an efficient option to treat trees, including small trees that are difficult to inject. Azadirachtin, a compound derived from the neem tree (*Azadirachta indica*) native to India, provided another alternative insecticide option. While azadirachtin does not kill EAB adults, it can interfere with larval molting or pupation, and in some cases, reduce the number of viable eggs laid by EAB females (DGM, unpubl. data, McKenzie et al. 2010, Kilani-Morakchi et al. 2021).

Numerous field trials were launched to compare treatments, often by monitoring the condition of treated and untreated trees over time (Smitley et al. 2010, 2015, Bick et al. 2018). More intensive studies that involved felling then debarking trees yielded quantitative comparisons between larval densities on nontreated trees and trees treated with various insecticides or application methods (McCullough et al. 2011, 2019, Lewis and Turcotte 2015). Annual applications of imidacloprid, dinotefuran, and azadirachtin, when properly applied at effective doses, could protect ash trees in many areas.

Development of a systemic insecticide containing emamectin benzoate, however, was a game changer (McCullough et al. 2011, Poland et al. 2016). This compound, which has a relatively safe environmental profile (US EPA 2009), is unusually toxic to EAB adults and larvae (McCullough et al. 2011, Poland et al. 2016). Long-term field studies have consistently shown that a single trunk injection of emamectin benzoate provides 3 yr of nearly complete EAB control, at moderate or even the lowest rate on the label (Lewis and Turcotte 2015, Bick et al. 2018, McCullough et al. 2019, Sadof et al. 2022). As research progressed, our understanding of the importance of application timing, treatment methods, and the advantages and disadvantages of various systemic insecticides expanded, facilitating development of increasingly efficient and effective EAB management strategies (Herms et al. 2019).

Translating these advances into effective recommendations hinged on the dependable delivery of these products to tree canopies and particularly leaves, where EAB adults feed. Studies with ^{14}C-labeled imidacloprid showed how the sectored structure of the vascular system of ash trees affected distribution of insecticide into branches and foliage (Mota-Sanchez et al. 2009, Tanis et al. 2012). The number of injection ports used to successfully protect a tree is determined by dividing the diameter at breast height (DBH) in inches by 2 then evenly spacing ports around the circumference of the basal portion of the trunk. This spacing assures that the insecticide is well distributed throughout the canopy and will consistently kill adults feeding on leaves. Although reducing the number of injection ports may shorten the time it takes to treat a tree, it can decrease the proportion of leaves receiving insecticide, potentially diminishing the effectiveness of the product (Sadof et al. 2022). The dose (i.e., the amount of insecticide product applied) is also based on tree DBH, and should ensure that enough product is applied to protect a specific tree. Dosage rates for larger trees (DBH > 38 cm) are often higher for large, open-grown trees (Herms et al. 2019) to account for an exponential increase in phloem surface area relative to DBH in such trees (McCullough and Siegert 2007).

Effectiveness of the most recent recommendations for EAB control (Herms et al. 2019) has been supported by long-term studies. In a 6-yr study (McCullough et al. 2019), 224 green ash trees across a 4-ha forested area were assigned to 8 blocks, each consisting of 28 trees. Within each block, trees were treated annually, at 2-yr intervals or at 3-yr intervals with trunk injections of emamectin benzoate applied at either moderate or low rates, basal trunk sprays of dinotefuran, trunk injections of imidacloprid applied via Mauget capsules or left as nontreated controls. A portion of treated and nontreated trees from each block were felled and debarked annually to quantify larval densities, along with woodpecker attacks on larvae, and related variables. After 6 yr, results showed that annual trunk sprays of dinotefuran reduced EAB larval densities by > 95% compared to nearby control trees. However, few and often zero EAB larvae were present on any trees injected with emamectin benzoate, regardless of whether trees were injected annually, at 2-yr intervals or at 3-yr intervals during the 6-yr study, even when the insecticide was applied at the lowest label rate. Effectiveness of annual treatments with imidacloprid injections varied but on average, this treatment reduced larval densities by ~75%. This level of control could effectively protect trees when EAB populations are low but not when infestations are near peak levels. These results are consistent with observations reported in numerous other studies (Smitley et al. 2010, 2015, McCullough et al. 2011, Bick et al. 2018).

Despite clear and consistent evidence that a single injection of emamectin benzoate can provide 3 yr of highly effective EAB control, most arborists continue to suggest injecting trees at 2–3 yr intervals, depending on EAB pressure (Herms. et al. 2019). A study was initiated in the spring of 2013 to determine the persistence of protection provided by spring and fall injections of emamectin benzoate (moderate rate 5 ml/in DBH) applied to large (average DBH 101.4 ± 4.79 cm), white ash trees growing in a city park (Sadof et al. 2022) (Fig. 3). Treatment efficacy over time was based on visual estimates of canopy thinning (to the nearest 10%) during

Fig. 3. Large white ash tree (DBH ~40 in; 102 cm) on left protected by injections of emamectin benzoate in Eagle Creek Park in Indianapolis, IN, USA in 2016.

August of each year (Smitley et al. 2008). Spring injections consistently provided better protection (e.g., less canopy thinning) than fall treatments, and canopies of trees treated in spring 2013 sustained minimal thinning through August 2015 (Fig. 4). In 2016, as EAB neared peak densities, thinning exceeded 50% in the untreated control trees and protection provided by the insecticide began to wane (~20% thinning in spring-treated trees). Following a second trunk injection of emamectin benzoate in spring 2016, however, canopy thinning of treated trees was minimal through 2019 (Fig. 4). By this point, all the untreated trees had died. Extended protection provided by a second injection presumably reflects both the efficacy of the treatment along with an overall reduction in local EAB density caused by a decline in the amount of living ash phloem remaining in the study area. By 2020, canopy thinning began to increase in trees treated in 2016 (Fig. 4). The slow but steady increase in canopy thinning observed through 2022 is consistent with other studies that have shown EAB continues to injure ash trees in post-invasion sites even after most overstory ash trees have been killed (Engelken and McCullough 2020, Siegert et al. 2021, Robinett et al. 2021).

Myth: Wounds From Drilling Trees to Inject Systemic Insecticides Injure Trees

In the early years after EAB was identified, substantial injury to trees was sometimes observed during or after trunk injections of systemic insecticides, particularly with some of the relatively primitive systems available at the time. Devices that could generate high pressure (e.g., 300–600 psi or 2,068–4,136 kPa) to force the insecticide into the tree could cause phloem to separate from the outer bark and cambium, and at times also injured the xylem (sapwood) (Smith and Lewis 2005). Injecting insecticide at lower pressure (e.g., 45–60 psi or 310–414 kPa) avoided such injury (Doccola et al. 2011). Although arborists often reported wood discoloration following injections, even with low pressure systems, research showed the vast majority of injection wounds readily healed and infection by plant pathogens was rare (Mota-Sanchez et al. 2009, Tanis and McCullough 2015). In one large study, the base (ground to 0.5 m) of 46 trees injected annually with 1 of 2 different systems was cut, returned to the laboratory, and evaluated using confocal laser scanning microscopy to assess phloem, cambium, and xylem. There was no evidence of injury or decay near the 233 injection ports on the logs of these injected trees, with the exception of a few instances where plastic plugs were set at an improper angle (Tanis and McCullough 2016).

In addition to avoiding high pressure injections, operation manuals for modern trunk injection systems emphasize the need for a sharp, double-helical bit to ensure cuts have smooth edges and plant tissue is not injured by heat generated by friction (Bernick and Smiley 2022). Some devices involve embedding a plastic plug in the drilled hole, then injecting the insecticide through a membrane in the plug, which prevents leakage (e.g., Arborjet Systems, Woburn, MA). Other "plugless" systems deliver insecticide into drilled holes via spiles, similar to those used for tapping maple syrup or with metal needles that fit snugly into the drill holes (e.g., J.J. Mauget, Arcadia, CA; Rainbow Tree Care, Minneapolis, MN; Lallemand Plant Care, Sault Ste Marie, ON, CA). A recent survey in 4 midwestern cities examined 190 ash trees treated with plugless systems and 175 larger ash trees that had been treated with a plugged system (Hauer et al. 2022). While wounds were not common, plugs that were set incorrectly resulted in more wounds than the plugless systems. Proper training in plug insertion is essential to avoid this injury. Injection technology continues to advance, reducing the time, labor, and effort needed to treat trees effectively.

Myth: Using Systemic Insecticides to Protect Ash Trees Harms Nontarget Species and the Environment

The catastrophic loss of unprotected ash in urban and residential areas is likely to adversely affect arthropods that are specialists and, to a lesser extent, facultative feeders of ash. Gandhi

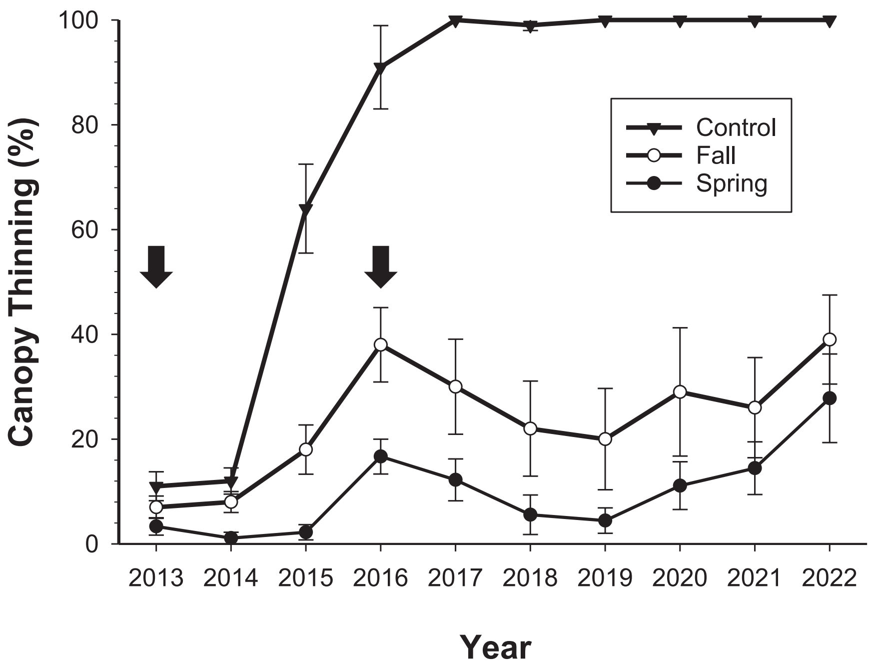

Fig. 4. Estimated canopy thinning caused by emerald ash borer on large white ash trees in Eagle Creek Park, Indianapolis, IN, USA. Trees were treated with emamectin benzoate (4%) in spring or fall of 2013 and again in 2016 (indicated by black arrows) with the Tree I.V. injection system (Arborjet Systems, Woburn, MA). Study details in Sadof et al. (2022).

and Herms (2010a) suggested over 200 species of native and exotic arthropods that feed exclusively or preferentially on ash trees could be adversely affected by EAB-caused mortality. Some ash-feeding insects are known to the nursery and landscape industry because of their status as pests, including the blackheaded ash sawfly [*Tethida barda* (Say)], banded ash clearwing moth (*Podosesia aureocincta* Purrington and Nielsen), eastern ash bark beetle [*Hylesinus aculeatus* (Say)], and the ash flower gall mite [*Aceria fraxiniflora* (Felt)]. Other insects, however, are known for their association with unique ash habitats, such as the *Sphinx canadensis* (Boisduval) found in black ash forests (Wagner 2007). Research to understand cascading effects of widespread mortality of overstory ash trees on populations of terrestrial and aquatic organisms, as well as ecological processes, is continuing. Losing ash trees may have profound impacts in habitats, such as riparian forests where green ash or black ash are dominant overstory species or in the case of black ash, ecologically critical foundation species (Gandhi and Herms 2010b, Klooster et al. 2018, Engelken and McCullough 2020, Engelken et al. 2020, Larson et al. 2023, Siegert et al. 2021).

Although insecticides used to control EAB can kill most nontarget insects if they feed on treated trees, systemic products are unlikely to harm beneficial natural enemies of EAB, including parasitoid wasps, predatory insects, or woodpeckers. Systemic insecticides are contained within the tree tissue and parasitoids contacting the surface of the bark or foliage will not encounter toxins (McCullough et al. 2015b). Thus, survival of egg parasitoids released for EAB biocontrol (*Oobius agrili* (Zhang and Huang)) is not affected by systemic insecticide applications. Moreover, native and introduced parasitoids of EAB larvae only attack live larvae and will not deposit eggs in larvae killed by a pesticide. Similarly, woodpeckers will not attempt to prey on dead larvae and thus will not encounter insecticide in xylem tissue beneath the bark (McCullough et al. 2015b).

If a treated tree is heavily infested with sucking insects, it is possible that systemic insecticides could be excreted in honeydew at levels that might harm beneficial insects (Quesada et al. 2020). Of the systemic insecticides labeled for use against EAB, only the neonicotinoids (clothianidin, dinotefuran, imidacloprid) have been identified as potential contaminant in honeydew (Calvo-Agudo et al. 2022). Such a scenario would be limited to ash trees infested with sucking pests, like *Prociphilus fraxinifolii* (Riley) (Hemiptera: Aphididae) and their ash-feeding congeners and generalist soft scales such as European fruit lecanium, *Parthenolecanium corni* (Bouché, 1844) (Camacho et al. 2017). During the optimal time for neonicotinoid applications in early to mid-spring (Herms et al. 2019) these insects are in immature stages and rapidly killed by these insecticides. This timing of application greatly reduces the potential for tainted honeydew to accumulate on infested trees. Furthermore, outbreaks of these pests in cities tend to be limited to areas where populations of sucking insects are already uncoupled from natural enemy populations (Frank and Just 2020, Dawadi and Sadof 2023). Taken together, these limits on both the spatial scale and time for tainted honeydew to accumulate make it very unlikely that honeydew feeders could be harmed by systemic insecticides applied to protect ash trees from EAB.

Some systemic insecticides, primarily neonicotinoids, applied to trees or other plants can potentially harm pollinators if the toxic compounds move into pollen or nectar at levels high enough to kill them (e.g., Mach et al. 2018). Potential impacts of systemic insecticides on pollinators depend on which products are used, application timing, insecticide concentration in ash pollen or nectar, and pollinator foraging behavior. Ash trees produce flowers early in spring, before leaves expand. When honeybee hives were placed near ash trees in 3 Ohio agricultural settings, ash pollen accounted for <20% of the early season pollen collected (Johnson 2015). However, because systemic insecticides are applied in spring after bud break, when leaves are expanding, translocation of insecticides to the canopy will typically occur after pollen has been shed. Thus, spring applications of insecticides have almost a full year to dissipate before new flowers and pollen are produced. Several studies have demonstrated that the time between insecticide application and the flowering of woody plants affects the presence and concentration of toxic compounds in pollen (e.g., Coslor et al. 2018, Mach et al. 2018). To date, we are aware of no published literature on insecticide concentration in ash pollen, although there is some evidence that the emamectin benzoate molecule is too large to move into pollen in ash and some other tree species (DGM, MDG, unpubl. data).

Myth: It Costs Too Much to Protect Ash Trees

Ash trees in urban forests are valuable to the residents in the communities where they grow. Monetary value can be assigned to landscape trees using well-established methods rooted in functional, cultural, and aesthetic attributes. For example, property owners can assess the replacement value of damaged landscape trees via a process developed by the Council of Tree and Landscape Appraisers (CTLA 2019) and, in some cases, choose to seek compensation through the court system. Estimates of value are based on tree characteristics including species, location, health, and structural condition prior to the damage or loss. Municipal arborists and city planners regularly justify budgets based on the economic value of services provided to the community by trees. These estimates are based on research that quantifies how trees contribute to property value, improve public health, reduce heating and cooling costs, capture storm water, air pollutants and sequester CO_2 (Sander et al. 2010, Donovan 2017, McPherson et al. 2017). Software such as i-Tree can be used to determine the contribution of individual trees or aggregated by species (Lin et al. 2021). Although there has been some debate about metrics used to assign value, the capacity of trees to help cities adapt to climate change and pollution is well accepted (Pataki et al. 2021).

A wide range of economic evaluations have consistently shown that it costs less to protect ash trees from EAB with insecticide treatments than to either remove ash trees proactively or remove ash trees as they decline and die. This savings through treatment can be demonstrated with a simple comparison of out-of-pocket costs for a homeowner with an ash tree that has a DBH of 30 in (76 cm). Assuming an arborist charges US $10 per DBH inch (2.54 cm) to inject a tree with emamectin benzoate, a single treatment for a 30 in (76 cm) DBH tree would cost $300. Assuming the injection provides 3 yr of protection, the annualized cost is $100. If the tree is healthy, relatively free of obstruction, including wires, and not near the house or other structures, the cost of removing the tree and grinding the stump could easily be 6 times the treatment costs ($1,800). If the tree is near the house and brittle because it has already sustained some EAB damage, the removal costs could easily double ($3,600). Thus, for the cost of removing the tree, a homeowner could reap the visual and ecological benefits of the tree for 18–36 yr. A similar analysis conducted by the city of Milwaukee using their in-house labor showed removal costs for a tree with a DBH of 16 in (41 cm) were similar to the costs of protecting the tree for nearly 29 yr (Krouse 2010). This result was achieved despite assuming that emamectin benzoate injections would need to be repeated at 2-yr intervals. Extending the treatment interval to 3 yr would reduce costs even further.

More rigorous analyses by economists have yielded the same conclusion over a wide range of time horizons. Vannatta et al. (2012) developed a tool that integrates local tree inventories, removal and treatment costs, and tree growth. They determined that protecting established trees (DBH >8 in [20 cm]) with insecticide provided the most benefit per dollar invested over a 20-yr interval for a city. Kovacs et al. (2010), using a dynamic linear programming model, determined that optimal benefits for treating ash trees in eastern North America (at 2-yr intervals) are achieved when community control efforts are directed towards mature ash trees with a DBH of 12 in (30 cm) or greater. A web-based cost calculator used to simulate costs and tree growth when programs are initiated at different stages of the EAB invasion also supported the benefits of protecting trees versus removing and replacing them (Sadof et al. 2017). A recent study of 21 communities in New Jersey compared the costs of EAB control with ecosystem services provided by the protected ash trees also supported these findings (Arbab et al. 2022). Programs that provided the most benefits to communities initiated a treatment program soon after EAB was detected but before trees began to die. Delaying management reduced the number of trees that could be saved and increased annual costs of tree removal by compressing activities into a shorter time period. In addition to economic justification, biological factors also support treating ash trees before EAB-related decline is evident. The capacity of emamectin benzoate or other systemic insecticides to effectively protect ash trees declines as EAB densities increase over time, because cumulative injury to the vascular system caused by larval feeding can disrupt the ability of trees to transport insecticide (McCullough et al. 2011, 2015a,b, Flower et al. 2015, Bick et al. 2018). In contrast to wholesale tree removal, delaying ash mortality affords municipal foresters and property owaners an opportunity to gradually replace landscape or roadside ash trees with other species, without severely altering neighborhood aesthetics or diminishing ecological services.

Area-wide approaches to managing EAB in the urban forest, as well as forested settings, have the potential to improve efficiencies and reduce overall costs of protecting ash, as well as slowing rates of ash mortality locally. McCullough and Mercader (2012) proposed a strategy called SLow Ash Mortality (SLAM) and compared the effects of different EAB management tactics using simulation models developed with data from many field studies at various sites. This effort integrated a spatially explicit model of ash phloem area in a model city that became infested when EAB beetles emerged from a load of firewood. They assumed emamectin benzoate treatments would protect trees for 2 yr and simulated EAB dispersal, changes in EAB densities, and tree mortality over a 10-yr period. Management strategies evaluated in the study ranged from removing all ash trees to treating anywhere from 10 to 50% of the ash trees annually in spring. Costs of tree removals were acquired from municipal foresters in large cities and small towns. Results showed that costs of every treatment option were consistently lower, and often substantially lower, than the costs of simply removing trees. Additionally, when trees were treated, more than 90% of the ash trees in a model city remained alive and healthy after 10 yr. Success of this approach was facilitated by killing preoviposition female beetles as well as mature females as they fed on ash foliage. Further exploration of an area-wide approach in the greater Minneapolis metro area (Minnesota) indicated that economic benefits were more likely to be achieved if deployed across political boundaries, which optimized protection of ash trees (Kovacs et al. 2014).

Subsequent field studies conducted to test the SLAM approach documented that treating some trees slowed overall EAB population growth in a local area and associational protection was conferred to some nontreated trees when nearby trees were treated with emamectin benzoate (McCullough et al. 2015a, O'Brien 2017). In a large, operational-scale project, a combination of tactics including emamectin benzoate treatment (to less than 1% of the ash trees), small (10–15 cm DBH) girdled trap trees, and some ash removal (e.g., via timber sales) reduced EAB population growth and the rate of ash mortality across an area of >390 km^2 (150 sq mi) in Upper Michigan (McCullough et al. 2015a). In another study, treating approximately 11% of the ash trees with emamectin benzoate in Maryland State Parks resulted in consistently less canopy thinning in untreated trees nearby compared with trees that were further from treated trees (de Andrade et al. 2021). In Indiana, a 7-yr study conducted on 3 university campuses showed that treating 40% of the ash trees once every 2 yr (average 20% of trees per year) with emamectin benzoate slowed the rate of ash decline compared to levels experienced in Indiana cities where trees were not protected (Sadof et al. 2021). When the Indiana data were used to model tree survivorship, the associational protection of ash trees was greatest for white ash trees that were within 10 m of a treated tree and the insecticide treatment began before significant canopy thinning occurred. Recent results of a 5-yr study in 12 Minnesota sites suggest that the distance of associational protection may increase as greater proportions of ash trees are treated (Mwangola et al. 2023).

It is difficult to overstate the potential negative economic impacts of EAB on the overall health of an urban forest. A recent survey of more than 100 communities in 25 infested US states shows that the impacts of EAB on municipal forestry budgets represent 3 distinct phases (Hauer and Peterson 2017). In the first 4 yr after EAB is detected in a state, there is a minimal impact on forestry budgets. The greatest impacts are sustained 5–8 yr after detection. Large-scale mortality of ash trees results in a 300% increase in annual costs in Year 8. Given the structural weakness of dead or dying ash trees (Persad et al. 2013, 2019), timely removal is needed to prevent the trees from falling and injuring people and property. Costs then decrease in Years 9–12. Overall, survey respondents reported a 20% per capita increase in annual expenditures (~$280 million) attributed to EAB infestations to the detriment of routine maintenance and health of non-ash trees in the urban forest. Although ash trees can be replaced, given the typically high mortality rates (up to 68%) of newly planted trees in deforested cities (Hilbert et al. 2009), it will take decades to replace the canopy and benefits provided by ash in urban forests. Clearly, protecting ash trees from EAB will positively affect the urban forest canopy and municipal forestry budgets.

Recent advances in computational methods have allowed economists to explore how resources can be best allocated in urban forests to optimize forest benefits and minimize risks of failure (Kibiş et al. 2020, Bushaj et al. 2021a). These investigations employ a continuum of treatment and removal options that incorporates real-time scouting to assess the EAB population and levels of tree injury over time. Results from these assessments are consistent with previous investigations that show optimal results are achieved when insecticides are applied early before trees are injured by EAB. Interestingly, these studies noted that pre-emptive removal of trees was advisable only when managerial decisions were dominated by risk aversion (Bushaj et al. 2021b). In this situation, long-term viability of trees was so compromised by other mortality factors, such as urban development and construction, that it made no economic sense to allocate more resources to protect trees from EAB.

Conclusions and Recommendations

Based on our experience, along with this review of evidence generated by many researchers, incorporating systemic insecticides to

Fig. 5. Tree condition affects the likelihood of successful management with systemic insecticide applications. Urban trees with >30% canopy thinning are usually not worth protecting with insecticides.

protect ash trees from EAB is a viable strategy that fits squarely within a classical 5-step IPM framework.

1. **Define the problem and identify management objectives**

Ideally, ash trees should be inventoried before EAB is detected in a region. Tree inventories that identify species, size (DBH), and tree condition will help quantify the scope and extent of the resource at risk. This inventory can also be used to identify trees that are worth an investment because of their condition, size, site, species, and historical value to the community. In contrast, trees that are structurally unsound, have outgrown their site or have other problems are unlikely to be worth treating and can be removed as resources permit. Mature, healthy trees will likely be prioritized for treatment because they are more costly to remove and will take years longer to replace than small trees. Green ash trees worth saving should be monitored and will likely require treatment before white ash trees because they are typically colonized and killed sooner by EAB. Open-grown trees in parks, parking lots, and along roads are also more likely to be colonized by EAB, especially in stressful sites, than trees growing in shaded areas. City foresters will need to work with their staff and communities to develop a treatment priority list, then communicate with city planners. Investing in trees slated for removal because of road construction or urban development planned for the near future should obviously be avoided.

2. **Monitor and assess the local EAB population to determine when a treatment program should be initiated**

Successful treatment depends on the ability of insecticide to be transported within the tree from the trunk to the canopy. Therefore, treatment should ideally begin while the vascular system is still healthy enough to carry the insecticide to branches and leaves (Fig. 5). Given the cost of EAB treatment, however, insecticide applications are not necessary until there is evidence that EAB is present in the community. Indeed, the presence of a few damaged trees in a community early in the invasion wave may serve to garner community support for a management program with little increase in the cost-benefit ratio (Sadof et al. 2017). Regular inspections of ash trees for visible signs of EAB infestation will need to be conducted (Fig. 2). Woodpecker holes on upper portions of the trunk have often been the first evidence of EAB presence. As EAB densities increase over time, external signs including bark splits over larval galleries, epicormic sprouting, canopy thinning, or dieback become apparent. As above, keep an eye on high-risk trees, particularly open-grown green ash on stressful sites. In newly infested cities, symptomatic trees can be debarked to look for the characteristic serpentine (zigzag) larval galleries to be sure that the injury is due to EAB and not another pest or problem. This is especially true for trees growing on stressful sites, in areas experiencing a drought, or in relatively dry regions where ash trees are routinely watered and canopy decline can result simply from irrigation failures.

3. **Identify and gather resources needed to implement an insecticide treatment program**

Treating ash trees will require resources. Web-based calculators that use tree inventories to project short- and long-term costs of a treatment program can be useful for developing budgets and determining how many high-priority trees can be treated in a given year (e.g., Vannatta et al. 2012, Sadof et al. 2017). Several cost-cutting measures can help stretch treatment dollars. Spring application of insecticides are consistently more effective than fall applications. Establishing a rotation where one-third of trees are treated annually with emamectin benzoate facilitates planning, both in terms of financial costs and personnel. As EAB densities reach their peak, some trees in a 3-yr program may sustain some noticeable EAB injury as insecticide concentrations wane in Year 3. These trees can be a high priority for treatment the following year. On a city-wide level, additional costs of removing the few dying branches that escaped control are likely to be offset by the ability to protect 50% more trees in a 3-yr program compared with a two-year program. Whenever feasible, consider training city forestry staff to do trunk injections. This reduces the expense of hiring contractors and as personnel gain experience, treatment quality and efficiency will improve.

4. **Incorporate multiple tactics to protect tree health and control EAB.**

Trees must be actively transpiring to move systemic insecticides from the injection ports or soil to the canopy. If conditions are especially dry, irrigation will certainly help trees carry insecticide up to the canopy and will also help treated trees lay new tissue over areas that were injured by EAB larval feeding. In some situations, paclobutrazol, a plant growth regulator, can be applied to slow aboveground growth of trees, including green ash (Tanis and McCullough 2015). Slowing tree growth will reduce the volume of insecticide needed over time to protect trees and also encourages fine root production by trees.

Effective systemic insecticides control EAB in treated trees, encouraging parasitoids and woodpeckers to forage in nontreated trees with live EAB larvae (McCullough et al. 2015a, McCullough 2019), thereby facilitating biological control of EAB. In areas where ash trees are closely spaced, an area-wide urban SLAM approach using emamectin benzoate might be considered (McCullough and Mercader 2012, Sadof et al. 2021). In this strategy, not all trees must be treated with insecticide at two-year intervals. Some portion of adult beetles will be killed when they feed on treated trees, reducing egg production and overall EAB population growth within the area. Nontreated trees with EAB larvae may function as "banker plants" by supporting parasitoid populations whose offspring can attack EAB larvae on previously treated ash trees as the emamectin benzoate concentration wanes (Frank 2010, McCullough et al. 2015a).

1 **Establish a monitoring program to facilitate sustained community support for ash management within a community urban forestry program.**

Successful IPM relies on continued monitoring to assure timely intervention to avoid loss. Enlist members of the community to help with an ash monitoring program to foster community support for sustained ash management. Urban forestry programs have a successful history of benefiting from local community volunteers (Elton et al. 2022). Community participation has been associated with improved tree health and participation in ash management programs (American Forests 2012, Vogt et al. 2015). This approach is most effective when community volunteers can share observations with professionals who then take appropriate and timely action. Such an approach has been successful in cities across the country (Boyce 2010, American Forests 2012). Partnerships between city forestry personnel and the community can be incentivized by sharing treatment costs in communities that monitor tree status and "adopt" ash trees in rights of way.

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