Emerald Ash Borer: Invasion of the Urban Forest and the Threat to North America's Ash Resource

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ABSTRACT

The emerald ash borer (EAB), a phloem-feeding beetle native to Asia, was discovered killing ash trees in southeastern Michigan and Windsor, Ontario, in 2002. Like several other invasive forest pests, the EAB likely was introduced and became established in a highly urbanized setting, facilitated by international trade and abundant hosts. Up to 15 million ash trees in urban and forested settings have been killed by the EAB. Quarantines in the United States and Canada restrict the movement of ash trees, logs, and firewood to prevent new introductions. Research studies are underway to assist managers leading eradication and containment efforts. Long-term efforts will be needed to protect ash in urban and forested settings across North America.

Keywords: *Agrilus* sp., *Fraxinus*, invasive pest, quarantine

The emerald ash borer (EAB), *Agrilus planipennis* Fairmaire, a phloem-feeding beetle (Coleoptera: Buprestidae) native to Asia, was determined to be the cause of widespread decline and mortality of ash (*Fraxinus* sp.) in Detroit, Michigan, and nearby Windsor, Ontario, in July 2002. Results from initial delimitation surveys in Michigan in 2002 showed that the EAB population densities and tree mortality were highest in the greater Detroit area. This evidence, along with recent dendrochronological data used to determine the year of EAB attack or tree mortality across the infested area, indicates that the EAB initially was introduced, became established, and developed into an invasive pest in the highly urbanized area of Detroit.

At first glance, Detroit may seem an unlikely locale for an exotic forest pest problem. Several features of urban forests, however, are particularly conducive for invasive forest pest introductions and establishment. Nonindigenous organisms likely arrive more often in cities than in rural or natural settings because of the ever-increasing volume of international commerce and trade at ports of entry. Historically, imported nursery stock was an important source of nonindigenous forest insects and plant pathogens (Niemelä and Mattson 1996, National Research Council [NRC] 2002). More recently, solid wood packing material, including crating and pallets that often accompany commodities shipped to the United States, has emerged as a major source of potentially invasive forest pests (USDA Animal and Plant Health Inspection Service and Forest Service 2000). In addition to the EAB, at least 10 nonindigenous forest insects associated with solid wood packing material have been discovered in the United States or Canada since 1990 (Haack 2005).

Nonindigenous organisms that arrive in a new habitat must find suitable hosts to become established (NRC 2002). Forest insects and pathogens that originate in regions of Europe and Asia often have a remarkably good chance of encountering North American tree species of the same genus or family as their native hosts (Niemelä and Mattson 1996, NRC 2002). For instance, in nine US cities, 12–61% of the urban trees were preferred hosts of the Asian longhorned beetle (*Anoplophora glabripennis;* Nowak et al. 2001). Ash trees that can serve as hosts to the EAB are among the most common fast-growing woodland trees in the northeastern states and have been widely planted as a popular shade tree in urban areas. Nonindigenous ornamental plants that have been naturalized are common in urban landscapes and also may serve as hosts to nonindigenous organisms. In addition, urban trees frequently are planted in unfavorable sites such as parking lots or other areas where they experience stress from pollution, soil compaction, or damage from human activities. Such stressful conditions may predispose trees to insect or pathogen attack, increasing the likelihood that nonindigenous forest pests will successfully establish and increase in density.

Large residential or business developments or roadside plantings in urban areas often are composed of a single shade tree species. When an invasive pest becomes established in a monoculture planting, the impacts can be devastating, as evidenced by the rapid spread and impact Dutch Elm disease (*Ophiostoma ulmi* and *O. novo-ulmi*) on American elm (*Ulmus americana;* Karnosk 1979). Ironically, in several northeastern and midwestern cities, many dead elms were replaced with maple (*Acer* spp.) or ash trees, which now are threatened by *A. glabripennis* and EAB, respectively.

Identification of the EAB infestation in Michigan began when iridescent green beetles collected from dying ash near Detroit were submitted to Michigan State University Department of Entomology in June 2002. On July 9, 2002, the beetles were conclusively identified as *A. planipennis* by Dr. Eduard Jendek of Slovakia, the world authority on Asian species of *Agrilus*. Published reports indicated *A. planipennis*, which has several synonyms including *A. marcopoli*, *A. marcopoli ulmi,* and *A. feretrius*, was native to northeastern China, Korea, Japan, Mongolia, Taiwan, and eastern Russia (Jendek 1994, Haack et al. 2002). Until 2002, however, the EAB had not been collected previously outside of its native range in Asia and little was known about it beyond taxonomic descriptions (Jendek 1994) and a few paragraphs published in Chinese reference books (Chinese Academy of Science 1986, Yu 1992). In Asia, the EAB is not considered a major pest, in part because Asian ash species (*Fraxinus mandshurica* and *F. chinensis*) appear more resistant than North American species (Herms et al. 2005). High-density EAB populations in China have been largely associated with plantations of North American ash species used for reforestation (Liu et al. 2003, Bauer et al. 2005, Gould et al. 2005).

Biology

The life cycle of the EAB in Michigan generally appears similar to that described by Chinese scientists (Chinese Academy of Science 1986, Yu 1992). In spring, adult beetles chew their way out of the tree, leaving D-shaped emergence holes approximately 3–4 mm in width. In southeast Michigan in 2003 and 2004, adults first emerged in mid-May at roughly 230–260 degree days, using a base 10° C threshold (Brown-Rytlewski and Wilson 2005), and adult activity peaked from late June to early July (Cappaert et al. 2005). Beetles feed on ash foliage (Figure 1), causing superficial aesthetic damage that is not very evident until it is quite extensive. Adults feed for 5–7 days before mating begins and female beetles feed for an additional 5–7 days before beginning to lay eggs. Each female beetle can lay 50–90 eggs during her lifetime. Beetles continue to feed and mate during the remainder of their lifespan, which can last from 3 to 6 weeks (Bauer et al. 2004, Lyons et al. 2004). Eggs, laid in bark crevices, hatch within 2 weeks. Larvae feed

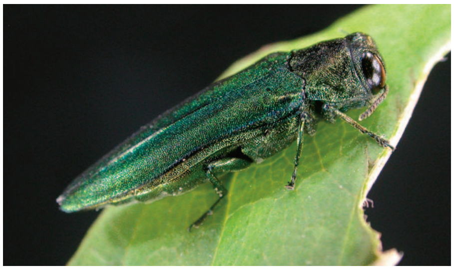

Figure 1. Emerald ash adult feeding on ash leaf. (Photographer: David Cappaert, Michigan State University.)

in the phloem and cambium from July through autumn, excavating serpentine-shaped galleries packed with frass. Extensive larval feeding disrupts translocation, girdling the tree and ultimately results in tree death within 1–3 years. Larvae pass through four instars (Cappaert et al. 2005) and most larvae complete feeding in October or November. Prepupae overwinter in cells about 0.5 in. deep in the sapwood or outer bark. Pupation begins in mid-April and continues into May, followed by adult emergence roughly 3 weeks later.

Some EABs, however, overwinter as young larvae rather than as prepupae, and then require a second year of development before emerging as adults (Cappaert et al. 2005, Siegert et al. 2005). Although the cause of multiyear development still is not known, it appears to be most common in low-density populations and may reflect a combination of factors such as host resistance, host quality, or weather. Multiyear development clearly has major implications for EAB population dynamics and for trapping, survey protocols, and other aspects of the operational program. For instance, multiyear larval development slows EAB population growth but delays the onset of external symptoms on infested trees, reducing the efficacy of visual surveys. Applications of cover sprays to protect apparently healthy trees will not be effective if small larvae are already present.

Detection and Distribution

Recent dendrochronological data, using cross-dating techniques to determine year of initial infestation for cores collected from trees throughout the infested area, show that the EAB had been established for at least 10 years before detection (N. Siegert, personal communication, March, 2005). This lag phase is not uncommon; other invasive insect pests have remained at densities below detection thresholds for several years until suitable weather, an abundance of susceptible hosts, or other factors led to an exponential increase in density (Shigesada and Kawasaki 1997, Crooks and Soulé 1999, NRC 2002). Detection of the EAB was complicated by the widespread occurrence of ash decline across the Upper Midwest and northeastern states during the past 20 years (Castello et al. 1985, Woodcock et al. 1997). Occasional reports of insects colonizing declining or dying ash were consistent with secondary infestations of native borers, such as the redheaded ash borer (*Neoclytus acuminatus acuminatus*), the banded ash borer (*Neoclytus caprea*), and several clearwing borers.

Once the EAB had been identified, damage and delimitation surveys were conducted by personnel from natural resource and regulatory agencies from throughout the Upper Midwest. Initial results suggested that roughly 5–7 million ash trees in forests, woodlots, and urban settings were dead or dying as a result of EAB infestation in a six-county area of southeastern Michigan. These estimates were based on visual surveys of ash trees using external symptoms of infestation such as D-shaped exit holes left by emerging adults, longitudinal cracks over larval galleries, canopy dieback, and epicormic shoots on large branches or the trunk. Visual surveys and trace backs of ash nursery stock shipped from Detroit continued in 2003 and the regulated area in southeastern Michigan expanded to 13 counties.

It became apparent in 2003, however, that detecting trees with low to moderate densities of EAB was exceedingly difficult using visual surveys. Typically, EABs initially colonize the upper canopy of all but the smallest trees, and at low EAB densities, D-shaped exit holes are much more likely to be high in the canopy than on the trunk (Cappaert et al. 2005). Other external symptoms including bark cracks, dieback, and epicormic shoots generally are not evident until trees become heavily attacked.

Research is underway to evaluate various trapping techniques and attractants for detection of EABs. The number of EAB adults captured by sticky bands and density of larvae was compared on healthy, girdled, and herbicide-treated ash trees and large (6 ft long) ash trap logs at multiple sites. Girdled (stressed) trap trees were more attractive than the healthy trees or cut logs (Poland et al. 2004, 2005). As a result, the Michigan Department of Agriculture (MDA) implemented a statewide grid of girdled trap trees in their EAB survey in 2004. The trap trees were inspected visually during the summer to collect any captured EAB adults from sticky bands. Trees were felled during fall/winter 2004 and bark was peeled from sections of the upper trunk and canopy to locate any EAB larvae and galleries. Despite the relatively low density of trap trees (only two to nine trap trees per 36 mi^2), several new outlier infestations were detected and it became clear that the generally infested area was much further advanced in southeastern Michigan than previously thought. Infested trees in the outlier populations typically had few or no external symptoms and probably would not have been found using visual surveys alone. Trace backs of ash nursery stock and surveys of high-risk sites such as campgrounds and sawmills by regulatory personnel also led to the discovery of additional outlier populations in Michigan, Ohio, and Indiana in 2004. As of April 2005, the regulated area in southeastern Michigan had expanded to include 20 counties and at least 25 outlier populations in Michigan (MDA 2005), as well as outliers in two counties in Indiana (Indiana Department of Natural Resources 2005) and seven counties in Ohio (Ohio State University [OSU] 2005).

Although trap trees have proven useful in detecting previously unknown EAB infestations, they are not ideal for large-scale survey efforts. Locating suitable trees can be difficult in some areas, girdling and peeling trees is labor intensive, and the attractive radius of a trap tree is unknown. Program managers would much prefer an effective lure and trap for the EAB. Adult EABs do not appear to use pheromones but they respond to olfactory cues such as blends of ash volatiles (Poland et al. 2004, 2005) and to color or other visual stimulants (Francese et al. 2005a, 2005b, 2005c). Researchers are continuing to work on the development of traps and attractive lures (Crook et al. 2005, Francese et al. 2005a, Otis et al. 2005, Poland et al. 2005); however, EAB surveys in 2005 in Michigan, Ohio, and Indiana will continue to rely on girdled trap trees.

The area known to be infested with EABs will undoubtedly expand as survey efforts continue and as EAB disperse naturally. The outlier infestations identified to date resulted from movement of infested nursery stock, firewood, or logs before the EAB quarantine was established. Movement of ash material from the infested areas now is prohibited by federal quarantine regulations and subject to penalty. However, unintentional movement still may occur because of lack of awareness of the quarantine regulations. Outreach and education programs, which are critical for preventing artificial movement of the EAB in ash firewood and other material have been launched by Michigan State University, OSU, and Purdue University, in cooperation with state and federal agencies.

Studies to evaluate dispersal of EAB adults and the natural rate of spread of EAB populations are continuing. Laboratory tests using adult beetles tethered to flight mills suggest that some EABs have the ability to fly more than 3 mi (Taylor et al. 2005). Extensive sampling of trees at several outlier sites, however, indicates that expansion of low-density EAB populations may be less than 0.6 mi/year (McCullough et al. 2005b, Siegert et al. 2005).

Ecological and Economic Impacts

Surveys in southeastern Michigan in autumn 2004 suggested that roughly 15 million ash trees in forested and urban areas are dead or dying as a result of the EAB, including green ash (*F. pennsylvanica*), white ash (*F. americana*), and black ash (*F. nigra*). Blue ash (*F. quadrangulata*) appears to be less preferred by the EAB but will be attacked as nearby ash species succumb (Agius et al. 2005). Although stressed trees initially may be preferred or less resistant to EAB attack, once beetle densities build, even the healthiest ash trees will be attacked and killed. Large ash trees may die within 3–4 years of initial infestation and saplings or small trees may die after a single year. Laboratory and field tests are underway to evaluate the EAB host range to assess whether trees other than ash are at risk. Results to date indicate that EAB female beetles occasionally may lay eggs on species other than ash, but larvae have not been able to complete development on other genera of trees (Agius et al. 2005). Estimates derived from USDA Forest Service Forest Inventory and Analysis data indicate that nearly 850 million ash trees in forests and riparian areas are threatened by the EAB in Michigan alone. Projected loss of the ash resource in Michigan, based on stumpage value, would likely exceed $1.7 billion (Federal Register 2003).

Continued spread of the EAB through North America threatens at least 16 endemic ash species (Harlow et al. 1991, USDA Natural Resources Conservation Service 2004, Wei et al. 2004). At least six ash species are commercially important (Stewart and Krajicek 1973) and the wood is used for numerous products including tool handles, baseball bats, furniture, cabinets, crating, cardboard, and paper. In the eastern United States, ash comprises roughly 7.5% of the volume of hardwood sawtimber, with an undiscounted stumpage value estimated to be at least $25.1 billion (Federal Register 2003). More than 8 billion ash trees occur across the United States; 40% of those trees fall into large-diameter classes. The undiscounted compensatory value of forest ash in the United States was estimated at $282.3 billion (Federal Register 2003).

Economic impacts associated with the EAB also include the loss of ash from city and suburban landscapes. Ash has been a popular choice for urban plantings since the "Marshall Seedless" green ash cultivar was introduced in the 1940s (MacFarlane and Meyer 2002). Popularity of ash continued to increase across much of the United States and cultivars such as the "Autumn Purple" white ash were among the most commonly recommended trees for street plantings in the 1980s and 1990s (Giedriaitis and Kielbaso 1982, Boris and Kielbaso 1999). Naturalized ash species and cultivars such as the European ash (*F. excelsior* L.) also became common in landscapes in some areas of the country (MacFarlane and Meyer 2002). In a sample of nine cities in southeastern Michigan (conducted before the discovery of the EAB), ash cultivars comprised an average of 12% of all street trees (MacFarlane and Meyer 2002). Data collected from eight US cities (Atlanta, Baltimore, Boston, Chicago, New York, Oakland, Syracuse, and Philadelphia) showed that ash trees comprised up to 14% of the total leaf area in the cities, with an estimated value of $565 million (Federal Register 2003). Impacts of the EAB on urban trees could be even greater in north central states and areas of the western United States, where ash has been widely planted. The undiscounted potential loss of all urban ash trees in the United States was estimated at $20–60 billion, a figure that represents costs of removal but not replacement (Federal Register 2003).

The potential for widespread mortality of ash is a major concern for several Native American tribes who particularly value black ash for basket making and as a cultural resource (Reo 2005). Several Native American communities in Michigan have begun to work with scientists, resource managers, and

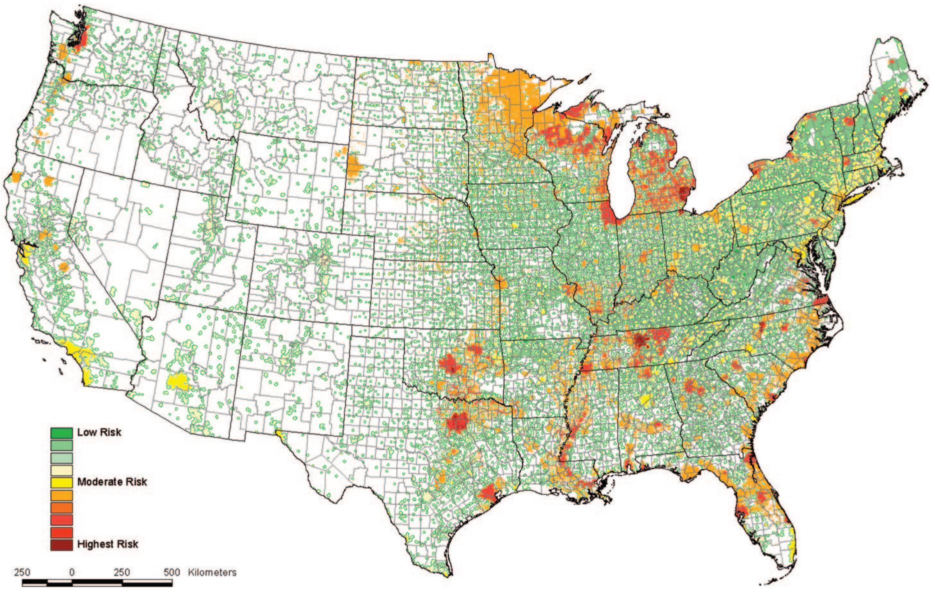

Figure 2. Risk map of EAB introduction and establishment in the United States. Risk was defined as a geographic function of preferred host range, urban ash forests, proximity of urban ash forests to natural forests, and phloem insect interceptions at US ports of entry (USDA Forest Service Forest Health Technology Enterprise Team 2005).

regulatory officials to assess black ash resources and develop plans to mitigate damage caused by the EAB.

Long-term ecological impacts of the EAB are difficult to quantify but could be profound. Ash species grow on a variety of soil and sites across much of the eastern United States (Eyre 1980) and are at risk of infestation by the EAB (Figure 2). Ash trees provide browse, thermal cover, and protection for a variety of wildlife species and beavers, rabbits, and porcupines feed on the bark of young trees (Heyd 2005). Seeds, which often are produced in prodigious amounts, are consumed by ducks, song and game birds, small mammals, and insects. White ash, the most valuable ash lumber species, often grows in mixed species stands with other upland hardwoods. It is listed as a component of at least 26 different forest cover types (Wright 1959, Burns and Honkala 1990) but it rarely dominates the forest canopy. In contrast, green ash, the most widely distributed ash species in the United Sates, is frequently a dominant overstory species on heavy, wet soils and is especially common along riparian corridors. Black ash can be found in mixed stands but most often grows in poorly drained sites such as bogs and swamps. Pure stands of black ash are especially common in cold, wet areas in the northern Great Lakes region and Canada (Erdmann et al. 1987, Tardif and Bergerson 1999). Widespread mortality of green and black ash could have especially significant ecological impacts.

Containment Strategies

Potential impacts associated with continued spread of the EAB through North America led the national EAB Science Advisory Panel (SAP) to recommend implementation of a long-term program to contain the EAB, reduce population densities, and eventually eradicate this nonindigenous pest (EAB SAP 2002, 2004, 2005). Federal, state, and provincial regulatory and natural resource agencies have begun to implement programs that focus on preventing artificial movement of the EAB, detecting and eradicating outlier populations and containing the major infestations in Michigan and Ontario. Federal quarantines in the United States and Canada regulate transport of all potentially infested material, including ash trees, limbs, or cut firewood; ash logs and untreated lumber with bark attached; uncomposted ash wood chips and bark chips larger than 1 in. in diameter; and any other articles determined to present a risk. In Michigan, sale or transport of ash nursery trees is prohibited statewide. In addition, because most people can not distinguish ash firewood from other species, transport of any nonconiferous firewood out of the 20 quarantined counties is prohibited. In southwestern Ontario, the Canadian Food Inspection Agency established an “ash-free” zone by removing all ash in a 6-mi-wide band between Lake Erie and Lake St. Clair in a predominantly agricultural area east of Windsor and west of Chatham-Kent to impede natural spread of the EAB. Additional trees believed to have been infested before the establishment of the ash-free zone have since been detected, however, and eradication efforts are underway.

When localized outlier populations are discovered in the United States, surveyors attempt to delimit the extent of the infestation. Research at outlier sites found that ash trees within 0.5 mi of a known infested tree may contain EAB larvae, despite having no external symptoms of infestation (McCullough et al. 2005a). When a site is designated for eradication, all ash (>1 in. diameter) within 0.5 mi of an infested tree are felled and chipped, and then chips are burned at an electricity cogeneration plant. Stumps are treated with herbicide to prevent sprouting. To date, eradication cuts have been conducted at eight sites in Michigan, three sites in Indiana, and six sites in Ohio at an average cost of roughly $500,000 per site. Over 290,000 ash trees have been removed in the three states as part of eradication and containment activities. In addition, many dead and dying ash trees have been cut and destroyed in the core-infested area (Figure 3). Limited 2005 funding for the EAB program has necessitated prioritization of outlier sites for treatment. Outlier populations near three designated “gateways” are considered the highest priority, to prevent the EAB from expanding beyond lower Michigan. The gateways include the Straits of Mackinac between lower and upper Michigan, the southern border between Michigan and Ohio or Indiana, and an eastern gateway that lies between St. Clair County in southeastern Michigan and the area of Ontario to the east of the St. Clair River. Activities at other outlier sites may range from no action, to regulatory or commercial removal of heavily infested trees to suppress EAB populations.

There is an increasing emphasis on use of ash in the quarantined areas and beyond. Collection sites in quarantined areas have allowed landscapers, private residents, and municipalities to dispose of ash trees, most of which are chipped and transported to a cogeneration facility. As of April 2005, more than 270,000 tn of wood had been processed at the MDA collection sites. Interest is growing in other value-added products that can be produced from ash including

Figure 3. Neighborhood before and after removal of infested ash trees. (Photographer: Michigan Department of Agriculture)

lumber, railroad ties, tool handles, and pulp (Simons et al. 2005). Debarking and related processing removes the bark, phloem, and outer sapwood where the EAB resides, minimizing risks of new introductions. A new sawmill established in southeastern Michigan processed over 6,000 ash logs in 2004. Other markets are being explored including the use of chips for composite lumber (Kim et al. 2005), paper and cardboard packaging, landscape chips, and in composting, metallurgical, and industrial markets.

Research is underway on other critically needed management tools to help suppress populations as part of the containment effort. Insecticides appear to be a viable option to reduce EAB populations and protect high-value urban and shade trees within the quarantined area of Michigan. Recent studies show that widely available insecticides including cover sprays and trunk and soil injected products can substantially reduce EAB larval density compared with untreated trees. Effectiveness varies depending on insecticide product, injection method, timing, tree size and the extent of previous EAB injury (McCullough et al. 2003, 2005a; Smitley et al. 2005). Although none of the products tested provided 100% control of the EAB, ash trees are relatively resilient and can tolerate minor damage from the EAB. Annual treatment appears to be necessary, however, in areas where EAB population pressure is sustained and high. Insecticide products are not currently used for regulatory activity beyond the quarantined area.

In woodlots and forested areas, insecticidal control is neither economically viable nor environmentally desirable. Maintaining or enhancing tree vigor through silvicultural practices typically is recommended for controlling native *Agrilus* species such as bronze birch borer (*A. anxius*) and twolined chestnut borer (*A. bilineatus*). Unlike its native congeners, however, the EAB is not functioning as a secondary pest that attacks only weakened trees; it also is attacking and killing healthy trees. Biological control with Chinese or indigenous natural enemies and control with pathogens or microbial insecticides may have potential for suppressing populations of the EAB in woodlots and natural areas (Liu et al. 2003, Bauer et al. 2005, Gould et al. 2005).

Restoration and Future Outlook

In Michigan, restoration programs have been initiated to assist communities and property owners affected by the EAB to restore, maintain, and protect the health and diversity of the forest resource. In 2004, 54 grants totaling more than $850,000 were awarded to municipalities within the quarantined counties, allowing the planting of over 10,000 nonhost trees. An additional 11 grants totaling more than $200,000 were awarded to communities in outlier areas where eradication cuts occurred. Although these efforts help, only a fraction of the dead urban ash trees in southeastern Michigan has been replaced.

The scope of EAB damage in Michigan indicates that successful containment of the EAB will be necessary to protect ash in urban and forested settings across North America. This task is especially difficult given the scale of the infestation and our lack of knowledge about EAB biology and ecology. Scientists are under pressure to develop improved detection and control methods and to provide more information to regulatory officials about EAB dispersal and population dynamics. Public education and outreach activities help to prevent artificial spread of the EAB and build support for containment and control efforts. Restoration programs that emphasize diverse plantings could help mitigate future impacts of invasive pests in urban forests. Sustained operational programs, research, and outreach will be required if the North American ash resource is to be protected from this new exotic pest.

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