MANAGEMENT IMPLICATIONS OF INVASIVE INSECTS (SPECIAL ATTENTION TO EMERALD ASH BORER) IN SMALL COMMUNITIES

Written by

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MANAGEMENT IMPLICATIONS OF INVASIVE INSECTS (SPECIAL ATTENTION TO EMERALD ASH BORER) IN SMALL COMMUNITIES

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ABSTRACT

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Agrilus planipennis Fairmaire, or more commonly known as the emerald ash borer (EAB), is a Buprestid beetle native to eastern Asia and Russia. It has been introduced to North America by way of anthropogenic factors. During its time in North America, it has killed millions of ash trees (*Fraxinus* spp.) and it has the potential to completely eradicate ash trees from the ecosystem. This research details the options available for managing EAB in the urban forest, in addition to the discrepancies in management between small and large communities. The most effective techniques for slowing the spread of EAB varies greatly between small and large communities. Furthermore, research shows that techniques vary slightly between communities of similar sizes, signifying that there are many factors that determine which plan will benefit each individual community.

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INTRODUCTION

The world as a whole is no stranger to dealing with the impacts of invasive species; due to the presence of historical land bridges and the spread of man, the invasion of species has become more feasible. Species from North America are transported by people across the ocean to other continents and vice versa. An invasive species is any plant, fungus, or animal species that is not native to a location and has the tendency to cause extensive damage to the existing ecosystem. This is different from alien species, which are also non-native species, but ones that do not negatively affect the new location significantly. In most situations, these new habitats are not equipped to deal with the invasive presence and as such, the impacts are often severe. Over the course of history, humanity has seen how the introduction of foreign bodies can negatively impact the ecosystem and the species that depend on it. Some examples of severe cases where invasive species have completely changed an ecosystem or caused the extinction of local species are Asian carp, Norway rat, and phragmites. As a result of the harsh impacts invasive species have on ecosystems, many management strategies have been created and implemented to deal and minimize with the consequences.

In the last few decades an invasive wood-boring insect known as the emerald ash borer, or EAB, (*Agrilus planipennis* Fairmaire) has been causing immense destruction to forest, riparian, and urban ecosystems in North America. In its native habitat of northeastern China, the Korean peninsula, and eastern Russia; EAB prefers host species including ash (*Fraxinus* spp.), walnut (*Juglans* spp.), and elm trees (*Ulmus* spp.) (Herms and McCullough 2014; Siegert et al. 2014). It is not considered a serious threat in its native habitat as the tree species have evolved and adapted with the insect. Natural predators, tree defenses, and other abiotic factors have limited this beetle to only targeting weakened or stressed trees in their native ecosystems. In North America, this beetle has been found to target all species of ash trees, with the exception of mountain ash (*Sorbus americana* Marshall) which is not a true ash (Lyons et al. 2007). In this foreign land, EAB does not have any natural predators and the native species of ash trees have no defenses that are effective against this pest. As such, EAB is able to attack and kill completely healthy trees by girdling the tree and cutting off the vascular system. It will be necessary to assess the importance of ash trees in North America as this insect has the capability to completely eradicate this species of tree.

EAB first arrived in North America in 2002 in the northeastern United States and it quickly spread north into Canada. It has been assumed that it arrived via ash packing material on planes or boats (Herms and McCullough 2014). In the United States, it is present in 29 states, ranging east to west from Maine to Oregon, and north to south from Minnesota to Texas (USDA 2017). In the short time period that it has been present in Canada, its range has expanded throughout most of southern Ontario and Quebec, as well as across Manitoulin Island and up to Sault Ste. Marie. Even more recently, the range of EAB has extended up to the city of Thunder Bay. This has brought about many concerns regarding what the city should do in terms of the best management strategy. Unlike larger communities such as Toronto or Michigan, smaller communities do not have the same management options due to a number of reasons which include a lack of funds, staff, and resources. This thesis will look into possible management options for EAB in smaller North American communities.

This will be accomplished by assessing possible management options that are currently available, as well as looking at what management strategies were used or are currently being used to deal with emerald ash borer. Comparisons between large and small community management options will be taken into account, in addition management effectiveness and cost will be assessed. It is necessary to assess this, as a cheap but ineffective method may be just as detrimental to a small community as an expensive method. To assess the possible management options, a number of representative communities will be selected. Possible cities to research include Sault Ste. Marie, Peterborough, Windsor, and Toronto in Ontario, Canada as well as a few cities in the United States including Toledo, Ohio and Duluth, Minnesota.

Objective

Determine if there is a difference between large and small communities in terms of the most effective emerald ash borer management strategy. Determine the best possible management strategy for smaller communities when dealing with EAB.

Null Hypothesis

There will be no difference in the most effective management strategy between large and small cities in North America.

LITERATURE REVIEW

Impacts of Invasive Insects

There are thousands of insects that depend on trees as a food source or as a means to complete their life cycles. Some insects can be beneficial for plant species such as pollinating species like the tiger swallowtail butterfly (*Papilio glaucus* L.), or the western honey bee (*Apis mellifera* L.). Other species can be detrimental to plants, wherein their presence may cause harm, either to the tree or to the forest ecosystem. Most of the time, the most destructive forest insects are invasive species that have free range of the new habitat. However, not all detrimental insects are invasive. North America has a number of destructive native insects like the eastern spruce budworm (*Choristoneura fumiferana* Clemens) which causes mass defoliation in forests in Ontario, Quebec, and the northeastern United States. Forest insects vary greatly it terms of the type of destruction they cause, which is a result of the method of feeding. There are insects that feed on the foliage, reproductive structures, or on the wood.

Defoliating Insects

Defoliating insects are the insects that feed on the leaves of coniferous and deciduous trees. This type of feeding can cause significant damage to the trees. The leaves are important organs as they are sites for photosynthesis and transpiration. Photosynthesis is the process of combining atmospheric CO_2 and H_2O to make glucose. The tree uses glucose as an energy source but it is also used as a component in cellulose and starch (Lovett et al. 2002). Transpiration is the loss of water to the atmosphere through spiracles on leaves. Insects that feed on these leaves/needles are referred to as defoliators. Most defoliators of trees fall into three orders of insects: Lepidoptera (moths and butterflies), Hymenoptera (sawflies, ants, and termites), and Coleoptera (beetles). Within each of these orders, there are three main methods of eating leaves/needles. They include skeletonizing, meaning the insects feed on all parts except for the vascular tissue (veins); mining, where the insect tunnels between the upper and lower leaf cuticle; and whole leaf chewers, where the entire leaf is eaten. Leaf defoliators can stunt tree growth when populations are high and defoliation is severe. Successional years of defoliation may even lead to tree death. Defoliation can also have cascading effects on the ecosystem by altering nutrient cycles and changing the amount of light reaching the forest floor. One highly destructive invasive defoliator in North America is the gypsy moth (*Lymantria dispar* L.) (Malinoski 2001). The gypsy moth is a lepidopteran insect native to Europe and Asia, and during its larval stage it defoliates a variety of native deciduous trees.

Conophagous Insects

An alternative food source for insects are the reproductive structures of trees, which include the cones and seeds. This is a good food source, as these structures have some of the highest levels of nitrogen of any tree structure. Orders of insects that utilize the reproductive structures include Lepidoptera, Hemiptera and Homoptera, Hymenoptera, Diptera (flies), Coleoptera, and Thysanoptera (thrips) (Eaton and Kaufmann 2006). Insects that eat the reproductive structures are commonly called conophytous. Insects can be either facultative or obligate conophytes. Facultative conophytes feed on cone or seed material during a portion of their life cycle, but can survive without this food source. An example of a facultative conophyte in North America is the eastern spruce budworm. Obligate conophytes are specialists that require the seed or cone to complete their life cycle. An example of this is the western conifer seed bug (*Leptoglossus occidentalis* Heidemann). Seed and cone insects can be grouped into three categories: 1) defoliators that damage cones as a secondary pest, 2) insects that bore into the cone to eat like the spruce cone worm (*Dioryctria reniculelloides* Mutuura & Monroe), and 3) insects that complete development inside of the cone. When the reproductive structures are compromised, growth is stunted and the weakening of the tree can increase the susceptibility of the tree to additional attacks.

Wood Boring Insects

Wood boring insects are a largely various group of pests that damage the structural features of the tree. Some borers feed upon the wood and others will simply bore into the tree to complete their life cycle. These pests can be highly destructive, often impacting the aesthetic, structural, and economic aspects of the forest (Buss and Foltz 2009). They can be generally separated into phloem and xylem borers. Phloem borers feed on and destroy the tissues of the tree, which are responsible for transporting food and nutrients as well as producing new wood and bark. Feeding on the phloem in a way that circles or girdles the tree generally results in entire tree death. Xylem borers feed on the sapwood, disrupting the flow of nutrients and water, as well as structurally weakening the plant. Wood borers can then be split up beyond phloem and xylem phloem borers. They can be separated into distinct families, the most destructive of which include the bark beetles (Curculionidae), the long-horned or round-headed beetles (Cerambycidae), and the metallic wood-boring or flat-headed beetles (Buprestidae).

Bark beetles (Curculionidae) feed and reproduce in the phloem of trees. Most bark beetles live in dead, weakened or stressed trees, but there are a few species in North

America that are extremely aggressive and will attack and kill completely healthy trees (Franceschi 2005). Some of the most destructive members of this family include the native mountain pine beetle (*Dendroctonus ponderosae* Hopkins) and the invasive European elm bark beetle (*Scolytus multistriatus* Marsham). The mountain pine beetle (MPB) inhabits most western North American pine (*Pinus* spp.) species and is currently in outbreak levels causing the death of 18 million hectares of forest in British Columbia alone. MPB is also a vector for introducing blue stain fungus into the sapwood which prevents the tree from producing sap to pitch out the insects. The European elm bark beetle is an invasive bark beetle from Europe that is causing the severe decline of elm trees in Ontario and the Northeastern United States. This beetle is a vector for Dutch elm disease which causes the tree to plug its own xylem system to stop the spread of the disease resulting in tree death.

Round headed borers (Cerambycidae) are another group of wood borers. This group of insects are generally much larger in size than the bark beetles. They are named round headed borers due to the shape of the exit holes, which are always a distinct circle (Buss and Foltz 2009). They are also commonly called long-horned beetles which is characterized by their extremely long antennae. In North America, some of the most destructive members of the Cerambycidae family include the brown spruce longhorn beetle (BSLB) (*Tetropium fuscum* Fabricius) and the Asian long-horned beetle (ALHB) (*Anoploplura glabripennis* Motschulsky). The BSLB is an invasive pest native to Europe that feeds on the phloem of spruce trees in Nova Scotia (Smith 2000). The damage caused by the BSLB feeding can kill a tree within one to five years. The ALHB is another invasive beetle in North America, which is native to China and Korea. It has no native predators in North America and it will attack almost all deciduous tree species (OFAH/OMNR Invading Species Awareness Program 2012).

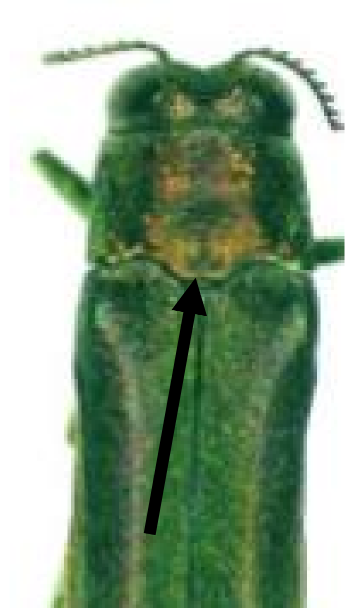
The final group of wood boring insects are the flat headed or metallic wood borers (Buprestidae). Named after the shape of the exit hole or the distinctive metallic colouring (Buss and Foltz 2009). These species tend to target weakened or stressed trees, but some invasive species are able to target healthy trees. Currently, in North America, the most destructive Buprestid insect is the emerald ash borer.

Emerald Ash Borer (EAB)

Biology/Taxonomy

The emerald ash borer is a beetle residing in the Buprestidae family, commonly referred to as jewel beetles or metallic wood-boring beetles due to their shiny/iridescent exterior (Herms and McCullough 2014). Most beetles in this family are cylindrical or elongate, ranging from 3 mm up to 80 mm in the largest species. This family consists of wood boring type beetles that typically target stem tissue. Most buprestid beetles typically colonize stressed trees while only a few attack healthy wood. The EAB in particular is one of the most destructive Buprestid forest pests in the world (Orlova-Bienkowskaja and Bieńkowski 2016). EAB is a flat headed borer in the genus *Agrilus*, which is the largest genus in the buprestid family. Species in this genus have a very distinctive shape, allowing them to be easily separated from other genera in Buprestidae (Parsons 2008). They are more linear and cylindrical than most other genera and the base of the prothorax is a backwards lobe as seen in Figure 1. There are currently 171 species of *Agrilus* in North America. EAB in particular are a bright, metallic green colour, and about 7.5 to 15 mm in length and 3.1 to 3.4 mm in width (Lyons *et al.* 2007).

It is generally larger and a brighter green than most *Agrilus* species. Under the elytra (wing cover) and wings, the abdomen of this species is a bright copper-red colour, which is unique to this species of *Agrilus* in North America (Parsons 2008). The antennal segments of the EAB are both cylindrical and serrated. The first three segments are cylindrical in shape, while segments 4-11 are triangular and serrate in shape. It is native to parts of Asia but it has spread to both North America, in 2002, and Europe in 2003 (Orlova-Bienkowskaja and Bieńkowski 2016). A full guide to identifying EAB compared to other *Agrilus* species can be accessed in the appendix.



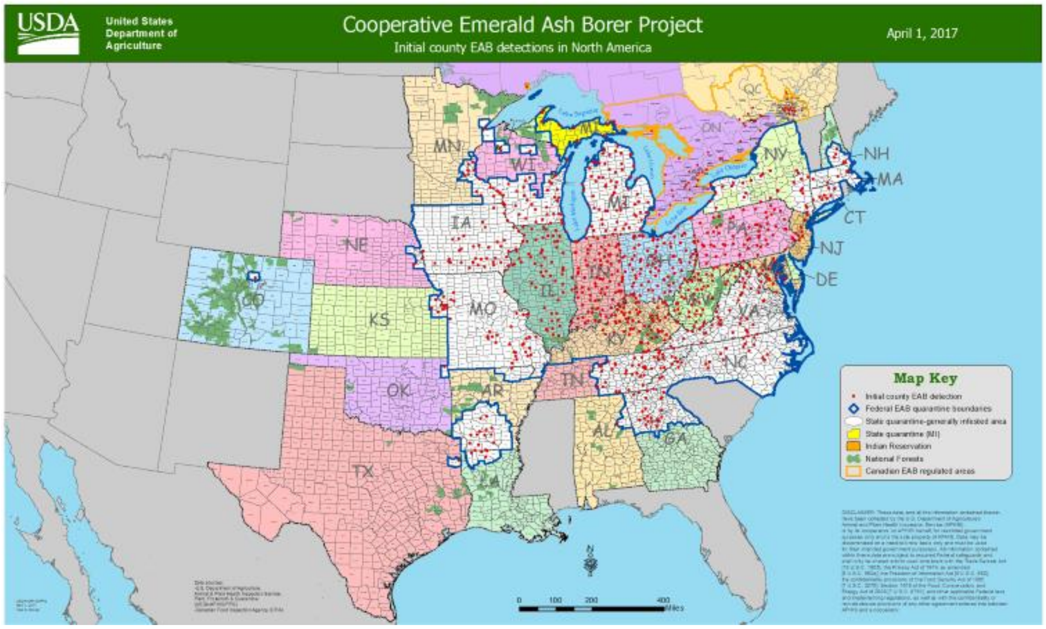
Source: Parsons 2008

Figure 1. Backwards pronotum found in *Agrilus* spp.

Spread in North America

The spread of non-indigenous forest insects in North America can lead to severe impacts on the constitution of forests (Siegert et al. 2014). In its' native habitat, the emerald ash borer is a secondary pest that feeds on the phloem of weakened or stressed ash, walnut, and elm trees (Herms and McCullough 2014; Siegert et al. 2014). In 2002, a previously unknown pest was causing ash decline and mortality in the cities of Michigan in the United States of America and Windsor in Canada. During initial research in 2001, ash trees could be seen declining in Detroit, Michigan but when it was looked into further, the cause was misidentified and the symptoms seen on the ash trees were thought to be a disease caused by phytoplasma called ash yellows. In the summer of 2002, beetles reared in ash logs were identified to be in the genus *Agrilus* by the Michigan State University Department of Entomology. After this, the beetles were shipped to taxonomic specialists in North America and Europe in an attempt to identify them.

This was the first case of emerald ash borer in North America although the insect likely arrived many years earlier (Parsons 2008). Using dendrochronological reconstruction, it is known that EAB has been in North America since about 1992, and the first tree confirmed to have been killed by the borer was in 1997 (Herms and McCullough 2014). By the time the beetle was identified in 2002, there were already five to seven million ash trees in Michigan that were dead or dying. Following this, the quick spread of this invasive pest has led to the mortality of millions of ash trees in North American forest, riparian, and urban habitats. As of April 2017, EAB is confirmed in 29 States in America and 2 Canadian provinces as seen in Figure 2 (USDA 2017). EAB is extremely harmful to North American ash trees because they have not built up the same resistance that Asian ash trees have to the beetle (Herms and McCullough 2014). So while in Asia, EAB only targets weakened host trees; in North America it has the ability to target and kill completely healthy ash trees since they have no effective native biological controls such as parasitoids or predators to keep the borer's population in check.



Source: USDA 2017

Figure 2. Spread of EAB in North America as of April 2017

Life Cycle

The life cycle of emerald ash borer in North America has been thoroughly researched and is therefore very well-known. Adult EAB beetles feed on the leaves of ash trees until they reach sexual maturity (Orlova-Bienkowskaja and Bieńkowski 2016). The adult flight period in North America is between May and early September. The female beetle lays eggs singly, or in small clusters, in crevasses on the surface of the bark during the months of June to August. The larvae hatch after about two weeks and then they tunnel into the trees' cambium region (Bauer 2016). The insect grows through four larval instars/developmental stages which are distinguished by body size. The first larval stage is less than a millimeter in length and the fourth and final larval instar can be between 26 and 32 mm long. The larvae feed until they are mature, creating characteristic s-shaped galleries in the sapwood of the tree as they feed on the phloem

(BenDor *et al.* 2006). The fully grown larvae overwinter in the cambial layer in a pupation cell (Bauer 2016). From this point, the larvae can either feed for another summer or they can pupate depending on how much they grew during the past year. If the larvae fails to reach the fourth instar before the overwintering period, pupation is put off until the following autumn causing a two year life cycle (Orlova-Bienkowskaja and Bieńkowski 2016). This type of life cycle is common in more northerly populations of EAB as larval development is heavily influenced by climate, especially temperature. It is also possible to witness a two year life cycle in healthy ash trees. The EAB has an exarate pupa, meaning the appendages are not fused to the body during the pupal stage (Lyons et al. 2007). Pupation generally occurs in the months of April and May and takes one to two weeks before the adult beetle emerges from the tree. The adult beetle chews distinctive D-shaped exit holes, seen in Figure 3, which can be used to determine infested individual trees.

Source: de Groot et al. 2006

Figure 3. D-Shaped exit holes made by EAB adults emerging

Signs and Symptoms

Currently, the most deterministic signs that an area has an emerald ash borer infestation are done by completing visual ground surveys (Persad and Tobin 2015). Even then, infestations can remain undetected for a number of years due to the method of larval feeding, which results in a decline in tree health that is almost impossible to recognize before it becomes too late. Larval feeding on the phloem, or nutrient system, causes the tree to be girdled in such a way that when symptoms begin to show, the tree is already severely infested and beyond saving (Lyons et al. 2007). The first step in completing EAB surveys would be the identification of host species. Knowing how to tell ash trees apart from other North American tree species and being able to distinguish between different ash species is key in identifying areas where infestation is probable.

Trees can be broadly separated based on leaf arrangement. They can have either opposite or alternate arrangement, and simple or compound leaves. Ash trees have opposite branching and compound leaves, which is two or more leaflets on a single stalk. Species of ash usually have between five and nine finely toothed leaflets. Each individual leaflet is elongate and spade shaped. In the winter, surveyors need a different method of identifying ash trees as there are no leaves. The most deterministic winter identifying technique is to look at the twig and bud arrangement. Ash trees have blunt buds and stout twigs.

Next, surveyors need to know what signs and symptoms are associated with EAB. They can do this by performing a number of surveying techniques including visual inspections, panel traps, and branch sampling (Campbell et al. 2015). The main symptoms to look for include crown dieback and chlorosis, epicormic shoots, D-shaped exit holes, bark deformities, and woodpecker feeding (Lyons et al. 2007). These symptoms may or may not be present but should indicate to surveyors the need to take a closer look for secondary, more deterministic symptoms. Signs and symptoms can be broadly separated into two different groups: insect signs and tree symptoms. Insect signs include larval galleries, exit holes, and leaf notches. Larva feed in serpentine patterns leaving distinctive S-shaped galleries that can be seen on the outer sapwood after the bark has been pulled away (de Groot et al. 2006). Larval galleries are a secondary symptom to look for after a tree is suspect for infestation. Looking for larval galleries as a main symptom is difficult as it is not visible without removing the bark. Exit holes created by the EAB are always D-shaped and about 1/8th of an inch in size, as seen in Figure 3, as a result of the flat headed shape of the borer. During the adult stage, this beetle feeds on the leaves of ash trees leaving notches.

Tree symptoms include epicormics shoots, bark deformities, crown yellowing or dieback, and an excess production of seeds (Lyons et al. 2007). Epicormic shoots are produced when a tree is under stress. They can be found in the crown, on the stem, or emerging from the roots. It is important to remember that not all trees attacked by the EAB develop epicormic shoots and not all epicormic shoots are because of EAB induced stress (de Groot et al. 2006). The presence of larvae feeding on the sapwood may cause a wound response on the tree. Vertical splits or cracks in the bark over larval galleries can be seen on the trunk and branches of infested trees. Feeding by the larvae also results in damage to the vascular system which results in discolouration of foliage and dieback.

Impacts of EAB

When looking at the impacts of emerald ash borer infestations, it is easy to see how this insect can directly impact the physical environment. Less noticeable than the biophysical impacts, but just as important to remember is that invasive insects can also indirectly impact societies by disrupting ecosystem services (Jones 2016). To determine the whole extent of the impacts caused by EAB, it is necessary to look at all areas of forestry they could affect; this includes physical impacts to rural, riparian, and urban forests as well as any socioeconomic effects.

Rural Forests

The most obvious effects of the emerald ash borer are the physical ones that can be seen throughout rural forests in southwestern Ontario and the northern United States. Driving down any road in the summer, all one needs to do is look out the window and evidence of EAB is present. Dead, standing ash trees make up a large part of the canopy of the once luscious Carolinian forest. Healthy mature ash trees are no longer a part of the forest structure in most of southwestern Ontario (Jones 2016). EAB can host on all 18 species of native ash trees in North America but it shows preference to green (*Fraxinus pennsylvanica* Marsh), black (*F. nigra* Marsh), and white ash (*F. americana* Linnaeus). It can also host on blue ash (*F. quadrangulata* Michx.) but this particular species appears to be the most resistant of North America's ash species (Herms and McCullough 2014). A decrease in ash volume can be observed six to seven years after EAB is detected (Morin et al. 2016). This decrease continues until ash population levels are so low that ash is functionally extirpated from the area.

As the larva feed and girdle the tree, it results in the tree experiencing chronic water stress and canopy dieback which eventually leads to tree mortality (Flower et al. 2013). It has been estimated that over time 99% of all white, green, and black ash over 2.5 cm diameter at breast height will be killed throughout their ranges in North America (DeSantis et al. 2013; Herms and McCullough 2014). The ecological effects of EAB in the forest habitat include altered forest composition and structure, and negative impacts on the associated wildlife and ecological functions of the forest. As trees in the forest begin to die, it results in widespread gap formation. This can cause cascading effects to occur in the ecosystem as it will alter nutrient cycles and the composition of the understory environment. Changes in the forest composition may even facilitate the spread of invasive plant species (Perry and Herms 2016). After the death of the tree, the understory is now open to more influence by light and there is an increase in the amount of coarse downed woody debris. In the forests of Ontario, there are over 280 arthropod species that feed on ash, 43 of which are monophagous; meaning they are completely dependent upon ash (Herms and McCullough 2014). As the ash species face extirpation in North America, so do these arthropods.

Riparian Forests

Another area to pay attention to are treed riparian areas. Riparian forests are sections of transitionary species between aquatic and terrestrial ecosystems. They are similar to regular riparian areas except they consist of mostly treed species. They act as a natural buffer between the aquatic and terrestrial areas and often directly influence the productivity of aquatic ecosystems (Nisbet et al. 2015). These areas have influence over the productivity of aquatic systems by filtering nutrients and sediment runoff; providing canopy to maintain water temperatures; and by providing structural elements of stream beds. In the case of the spread of EAB, managers have begun to wonder about the effects of the loss of riparian ash trees on the surrounding water bodies.

The loss of ash trees bordering the water bodies could lead to a change in nutrient input as well as a change in sedimentation and temperature (Nisbet et al. 2015). In riparian forests, the leaf litter is often a major source of nitrogen input into the soils. In riparian forests dominated by ash, the loss of this source of nitrogen input could disrupt the delicate environment. This is important because nitrogen is often a limiting resource in terrestrial environments, and a deficit of it could lead to serious detrimental effects on the function of the ecosystem if it is compromised. Therefore, any change in structure of the riparian zone has the potential to cause adverse effects on both terrestrial and aquatic systems. The loss of ash trees in the treed riparian zone also has the potential to negatively affect the adjacent water body through loss of nutrient subsidies. Tests show that 99% of total energy input into these water bodies was from the surrounding forest through leaf litter and forest derived dissolved organic matter. A study by Wallace et al. (1997) shows the results of removing leaf litter input from streams proving bottom up effects including a 90% drop in benthic invertebrate abundance.

Urban Forests

The final system to look at, where emerald ash borer is concerned, are the urban forests. The urban forest can include the surrounding municipal forests, as well as the number of tree species directly in the urban sprawl. The surrounding municipal forests are included to encompass the entire community and not just the direct urban city. The loss of ash trees in the urban environment can have economic, ecological and social impacts (Hauer and Peterson 2016). In the past, most cities planted thousands of ash trees along streets, as they are a popular boardwalk tree, because of their straight trunks and large canopies (Raupp et al. 2006; Yemshanov et al. 2014). Most North American cities consist of streets full of white ash, green ash, oak (*Quercus* spp.), and maple (*Acer* spp.). This low level of street tree diversity has led to a crisis where the beetle has invaded (Kovacs et al. 2010). For example, in the city of Chicago in the United States of America, there are 140 ash trees per hectare on residential land and 550 ash trees per hectare on non-residential land. Non-residential areas would include downtown areas, industrial lands, open spaces, and commercial lands. Across the whole of the United States, ash is the second most abundant genera of tree, second only to *Acer* (maples). In Canada, surveys indicate that there are approximately 1.2 million ash street trees (Hauer and Peterson 2016).

A healthy tree can provide many benefits to the urban community, including influencing the physical/biological environment, providing energy and carbon dioxide conservation, increasing air quality, assisting urban hydrological processes, providing noise reduction, and raising the social aspects of the environment (Dwyer et al. 1992; Kovacs et al. 2014). Urban trees contribute to reducing energy costs in communities by lowering the costs of heating in the winter and cooling in the summer. For example, if the annual cost for heating and cooling a house is $900 when surrounded by mature trees, it will be $950 without trees (Dwyer et al. 1992). Urban trees also increase the quality of air by exchanging atmospheric gases and capturing harmful particulates. The removal of these particulates will enhance human physical and mental health reducing health care costs. Urban trees function as retention structures for urban runoff and ground water, reducing flooding occurrence and damage, while also increasing the quality of ground water.

The presence of trees increases the quality of the environment in terms of people as well. People find urban areas with trees or forests present a more pleasurable place to work or live (Dwyer et al. 1992). Urban forests provide urban areas with a certain aesthetic and recreational value. There is also a confirmed relation between the presence of trees and real estate value. Urban trees have the added benefit of increasing mental health by creating a more desirable environment and reducing stress. With the death of thousands of ash trees in urban areas, we can see a number of social and physical impacts. The proximity of dying ash trees to humans can cause additional problems related to human safety and interests. As time since EAB invasion increases so does the occurrence of human death or respiratory ailments (Hauer and Peterson 2016). Overall, the loss of ash in communities can lead to increased air pollution, less storage of rain water, less carbon sequestration, and a decrease in social well-being.

Urban Economy

No matter the strategy, managing for EAB in the urban environment will cost the community money. In the United States, *Fraxinus* spp. are expected to have a total value of around $282 billion American ($378 billion Canadian) in urban environments (Hauer and Peterson 2016). McKenney et al. (2012) estimates the value of street ash trees in Canada at approximately $890 million. In the city of Toronto, Canada, there are approximately 800,000 street, backyard, and non-residential ash trees worth just over 800 million dollars (Winmill 2015). Computer simulations show that in the United States, 100 million urban trees can reduce energy costs by about $2 billion (Dwyer et al. 1992). Simulations also show that 500,000 trees can reduce storm water management costs by about $650,000.

The estimated value of the trees in the urban environment is not the only cost to think about. Managers and the public must also consider the costs of managing for the dead ash after EAB has passed. The estimated cost of removing a tree is around $700 which does not include the cost to replace the tree or the cost of upkeep for the newly planted tree. Maintenance throughout a tree's life is an important factor, as not maintaining a tree early on in its life may lead to more costs later on (Vogt et al. 2015). This cost can be variable depending on the diameter of the tree. A study conducted in the United States looked at the difference in management cost for three methods of treatment: removal, removal and replacement, and injection treatment (Kovacs et al. 2010). They separated these minimum costs depending on diameter at breast height (DBH) into small (2.5-30 centimeters), medium (30-61 centimeters), and large (>61 centimeters) diameter classes. For the small class, removal costs $268, remove and replace $800, and treatments are $72 per tree. For the medium class, removal costs $530, remove and replace $1100, and treatments are $160 per tree. For the large class, removal costs $1500, remove and replace $2000, and injection treatments are $268 per tree. This data can be seen in Canadian currency in Table 1 below. It is crucial to remember that the treatment costs are not a 'one-time deal' as most injections must be completed on a biennial basis for the rest of the trees life cycle.

Table 1. Management costs and benefits (in Canadian currency).

Annual Costs and Benefits of Urban Ash ($/tree)				
Tree Size (cm DBH)	Remove	Remove & Replace	Treat	Benefit
2.5 - 30	200 - 300	600 - 800	60 - 80	380 - 400
31 - 60	400 - 600	800 - 1100	130 - 160	900 - 1000
> 61	1200 - 1500	1600 - 2000	200 - 300	1500 - 2000

Source: Kovacs et al. 2010

Possible Management for EAB

The severity of the emerald ash borer invasion has led to a need for management options. At this point, there are not any viable options to completely eradicate EAB but it is possible to slow the spread or reduce the amount of losses. Most EAB management plans have the same basic components. The goal is almost always aimed at minimizing costs to the community, reducing liability and public risk, and maintaining the economic benefits of shade trees (City of Cornwall 2014). All plans should begin with an inventory of trees in the community. This step is crucial as it lays the groundwork for what management techniques will be feasible in each particular area. If managers do not know how many ash trees are present or what the impact will be of losing them, how can they possibly decide on the most effective management plan? The second step is constant surveying for EAB presence. After completing an inventory, managers can decide on which specific techniques to use. These management methods vary depending on the area, the type of forest, the budget of the urban area, and the available resources (Winmill 2015). The strongest management plans will use a combination of techniques in a method known as integrated pest management (McCullough et al. 2015). Integrating two or more tactics to manage an insect pest population can result in outcomes that yield additive or synergistic effects. An additive effect could be achieved by targeting two life stages of a pest. A synergistic effect is achieved when the combination of techniques produces an outcome that is greater than the combined individual effects of the techniques. There are a number of possible management options to slow the spread of EAB in the urban forestry environment, including: 1) using lethal trap trees, 2) removing and replacing ash trees, 3) applying a systemic insecticide, and 4) introducing a parasitoid predator (Mercader et al. 2011; McCullough et al. 2015; Jennings et al. 2016).

Trap trees

The first option of using trap trees involves girdling the tree to attract female EAB adults looking for somewhere to deposit their eggs (McCullough et al. 2015). By girdling the tree, managers attract more females leading to a higher larval density inside the tree. The girdled tree is more attractive to egg-laying females due to changes in volatiles and visual cues associated with stressed trees. By gathering large densities of EAB larva in one tree, managers can use trap trees like a population sink (McCullough et al. 2011). After the larvae have hatched, the destruction of the tree before they complete their life cycle can reduce the local EAB populations. Another method of using trap trees is by first injecting an insecticide into the tree and then girdling it a few weeks later to attract the beetle (McCullough et al. 2015; Mercader et al. 2016). The time delay between injecting the tree and girdling it is to ensure that the tree has time to translocate the insecticide throughout the tree's vascular system. This technique enhances the effectiveness of the insecticide as the girdled tree attracts a higher number of beetles than normal. Combining trap trees with insecticide treatments will create a synergistic effect. In simulations in which trees were girdled within 300 metres of the initial infestation source, reductions in the radial spread by 15% and population size by 40% were observed after 15 years (Mercader et al. 2011). However, there are some issues with this technique. This method is meant to serve as a population sink but only really works in local areas that have relatively low densities of the pest or in isolated populations of EAB. This particular method is less likely to generate economic benefits as the tree will no longer be useable for silvicultural purposes and the effectiveness of it diminishes as EAB population densities increase (Mercader et al. 2015). Another major issue with this method is that by attracting the beetle to the girdled trees, it is also possible to increase colonization on nearby non-girdled trees.

Remove and Replace

The second option includes the removal and replacement of ash trees. Managers or the general public must decide whether they want to replace the removed tree or not. This removal could be done either after the invasions has been confirmed or it could be done before hand in preparation for infestation. Unlike the trap tree option, removing the trees has the potential to have economic benefits from harvesting while simultaneously reducing the potential population size (Mercader et al. 2011). Removing large, merchantable trees in the community could be a practical approach. The downside to this option is that in an urban setting a professional tree removal company is recommended. There is also the cost of removing a tree; which can range anywhere from $250 to $1500 depending on the size of the tree (Kovacs et al. 2010). If the homeowners wish to replace their tree, either with another ash sapling or another tree species, the price range rises to $800 to $2000. In one study, the cost of removal and replacement of ash trees in Ohio communities is estimated at between $1 and $4.5 billion. This method can reduce the amount of ash phloem in the community and by association reduce the population size of EAB in the immediate area (Mercader et al. 2011). Even though this method reduces the overall population size slightly, it does nothing to slow the spread of EAB in the community. Some studies even show that this method can lead to a small increase (less than 3%) in the radial spread of the beetle. Removing ash trees without replacing them is the cheapest management technique for EAB (Vannatta et al. 2012). However, this does not account for the economic value of shade trees in urban environments.

Insecticide

The third option involves the application of an insecticide. This method has the benefit of protecting live ash trees. Applying insecticides within a 300 m radius from the infestation point source led to a significant reduction in the population size by about 40% and radial spread by about 30% beyond the treated area after 15 years (Mercader et al. 2011). Due to differences in policy between insecticides allowed in Canada and the United States, the countries have two different methods. Canada's Pest Management Regulatory Agency has three products registered for use in controlling EAB: TreeAzin, ACECAP97, and Confidor200 SL (McKenney and Pedlar 2012). TreeAzin is the most commonly used systemic insecticide and it is produced by a company based out of Toronto called BioForest Technologies (McKenzie et al. 2010). Systemic insecticides are injected directly into the trunk of the tree. The active ingredient in TreeAzin is Azadirachtin, which is extracted from the seeds of the Neem tree (*Azadirachta indica* A.Juss). The best time for injection is mid to late spring after the trees have leafed out. BioForest Technologies uses an EcoJect system, which is a microinjection system. With this system, small holes are drilled into the trees and fitted with nozzles; canisters are loaded with TreeAzin and placed under pressure; and the canisters are attached to the nozzles beginning the injection process. After it is injected under the bark of the ash tree, the insecticide is transported with the water and nutrients to the rest of the tree, providing overall coverage. It affects both the larval and egg stages of EAB by regulating growth and disrupting normal moulting processes (McKenney and Pedlar 2012; Herms and McCullough 2014). Azadirachtin also has the potential to affect adult EAB. Female beetles that fed on leaves of injected trees reduced the ability to produce viable eggs. It only provides two years protection against emerald ash borer and as such, it needs to be applied every other year continuously for however long managers or homeowners wish to protect the tree. There are other studies that predict that in high EAB densities, TreeAzin may need to be applied annually. The default cost for TreeAzin is $6.50/cm DBH meaning that larger trees will be more expense to treat and as the tree grows over the years, the price of upkeep will increase as well.

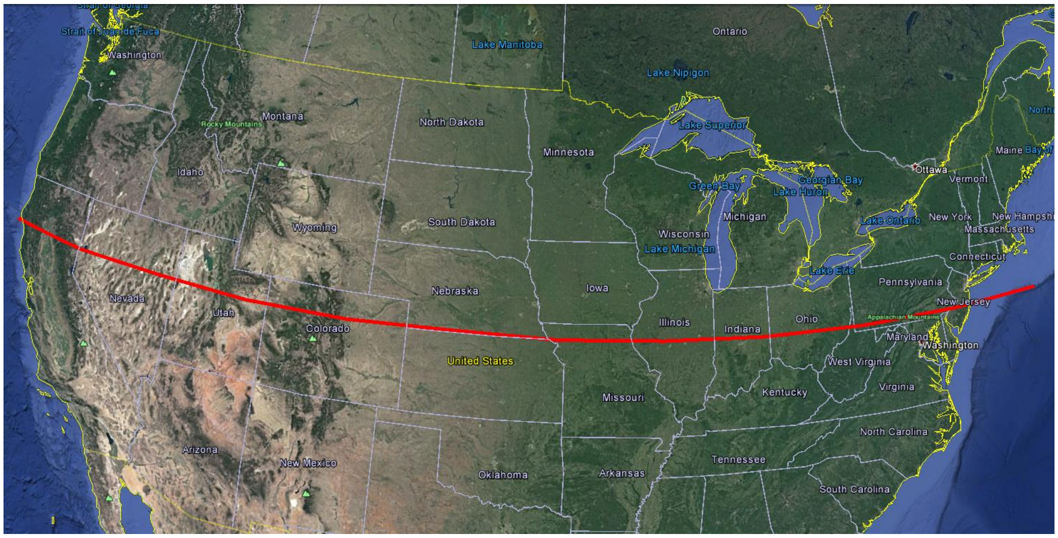
In the United States, a company based out Detroit called Arborjet has a number of insecticide treatments ranging from soil trenches to root and stem injections. The three main stem injections are Tree-äge G4, IMA-jet, and QUIK-jet. Tree-äge G4 is a trunk injection with active ingredient emamectin benzoate (Flower et al. 2015).

Emamectin benzoate is a commonly used insecticide in the US as it provides protection against a number of forest pests including bark beetles, Lepidopteran larva, and most importantly, EAB. This insecticide provides two levels of protection. The first is at the larval level and the second is at the adult stage as it travels through the xylem of the tree meaning that it targets adult beetles feeding on the foliage. This insecticide is shown to be very effective in controlling EAB populations in the first two years following injection but has decreasing efficiency in cases longer than that. The second insecticide produced by Arborjet is IMA-jet which is also a stem injection but the active ingredient is Imidacloprid (Vannatta et al. 2012; Herms et al. 2014). Imidacloprid can be used as a trunk injection, a basal trunk spray, or as a soil drench. As a truck injection, it can provide between 60% and 95% protection from EAB. This insecticide is most successful when treating small diameter trees. When used on large diameter trees, decline is still evident.

Biological Controls

The fourth and final option is the implementation of biological controls. Although systemic insecticides can provide tree level protection from EAB, biological controls represent the most economically and environmentally feasible long-term strategy for sustainable EAB management (McCullough et al. 2011; Jennings et al. 2016). This method is often involves utilizing natural enemies or predators (Winmill 2015). In 2007, USDA APHIS released three species of parasitoid wasps in Michigan. Two of which, were larval parasitoids *Spathius agrili* Yang and *Tetrastichus planipennisi* Yang, and the other was an egg parasitoid, *Oobius agrili* Zhang and Huang (Gould et al. 2016; Jennings et al. 2016). Over the years, three million parasitoids have been released in 22 states and two Canadian provinces. In 2015, a fourth parasitoid, *Spathius galinae* Belokobylskij and Strazanac, was approved for release in North America. In the United States, permits for release of parasitoids may be granted by USDA APHIS after completion of research on 1) the biology and host range of each parasitoid in quarantine laboratories; 2) risk benefit analyses including potential non-target impacts; 3) consensus by North American professionals; 4) completion of an Environmental Assessment on the Federal Register; and 5) state concurrence (Gould et al. 2016).

Spathius agrili is a gregarious idiobiont ectoparasitoid, meaning that it develops on the outside of the host (Jennings et al. 2016). It emerges in mid to late summer and attacks late instar EAB larva and prevents further development of the larva. The female parasitoid will drill their ovipositor through the bark of ash trees and lay an average of eight eggs on the larva (Gould et al. 2016). In its native habitat in China, *S. agrili* can parasitize up to 90% of all present EAB larva. The parasitoid is reared in small diameter ash bolts with EAB larvae. The entire bolt is then shipped to the location prepared for release. After it was released, tests were prepared to determine how many individuals survived through the year as well as if they dispersed from the release sites. *S. agrili* was only found in low numbers the year after release and only from release sites suggesting that populations would not persist or disperse over the years. This could be because of the relatively mild climate in China compared to the northeastern states and southern Canada. As of 2012, managers know that *S. agrili* cannot survive any further north than the 40th parallel in North America, which can be seen in Figure 4.



Source: Bennett 2017

Figure 4. Google Earth image showing the 40th parallel north

Tetrastichus planipennisi is a gregarious koinobiont endoparasitoid, meaning that it develops inside the host's body (Jennings et al. 2016). They emerge in late spring to early summer and like *S. agrili*, they attack late instar EAB larvae. Different from *S. agrili*, EAB larvae continue to develop and are only killed when the parasitoid reaches maturity and emerges. In China, these parasitoids will control about 50% of the EAB population (Gould et al. 2016). These parasitoids are smaller than *S. agrili* and have a shorter ovipositor meaning that although they appear to be having effects on population levels of EAB, they have difficulty parasitizing on larvae that are in trees with bark thicker than 3.2 cm as it is too thick for them to penetrate through (Jennings et al. 2016). Following release in North America, *T. planipennisi* was found in increasing numbers with each passing year and at both release and control sites. This indicates that this parasitoid is better equipped to deal with North American climates and will likely be successful in establishment and dispersal. *T. planipennisi* has since been released in multiple locations across southern Ontario and Quebec.

Oobius agrili is an egg parasitoid released in 2007. It lays its eggs inside the eggs of the EAB pest. It develops inside the EAB larva, eventually consuming it from the inside and emerging out of the dead larva (Jennings et al. 2016). In China, *O. agrili* parasitizes up to 60% of EAB eggs (Gould et al. 2016). Each female parasitoid will search for EAB eggs and upon finding one, will insert her own egg inside of it. Each female can parasitize upon approximately 80 EAB eggs in her lifetime. Like *T. planipennisi*, this egg parasitoid has been found in increasing numbers and dispersing quite nicely in North America.

Researchers continued to look for parasitoid that would be able to account for most of the EAB larvae. *S. agrili* had high levels of parasitism but it could not be released north of the 40th parallel North and it did not disperse well. *T. plannipennisi* survived and dispersed well but it was limited by trunk thickness. In 2015, a fourth parasitoid was approved for release in North America. *Spathius galinae* is a larval parasitoid that has the potential to be released above the 40th parallel North and it has a longer ovipositor than *T. plannipennisi* (Gould et al. 2016). Like *S. agrili*, this parasitoid is a gregarious ectoparasitoid, developing on the external surface of EAB larvae. Studies show that *S. galinae* can control approximately 63% of EAB larvae. It was collected from areas in Russia and South Korea with a colder climate than locations in China which indicates that it will have an easier time surviving in North American climates.

Case Studies in Management

Assessing the success of management plans over the years is a good way to determine best management method. Pest management for emerald ash borer has been steadily evolving. Communities that are expecting EAB often look to other cities that have experienced the pest already, attempting to determine which techniques worked best for them. Smaller communities do not necessarily have the same resources as larger cities and as such they may not be able to employ the same management techniques. It is important to remember that lowest cost does not always equal best management practice as reactive management may not preserve any of the cities' native ash species unlike the active or aggressive methods. Some known communities that have dealt with EAB infestations in the last few years include Windsor, Toronto, Sault Ste. Marie and Peterborough in Ontario and Toledo (Ohio) and Duluth (Minnesota) in the United States. Looking at these communities, managers can assess both the trend of evolving EAB management plans over time and any differences in options for small and large communities. For the sake of this thesis, small communities will be those with a city population less than 200,000 people. This would pertain to Sault Ste. Marie, Peterborough, and Duluth (MN).

Windsor, Ontario 2002

Windsor is the southernmost city in Canada found in the southwestern portion of Ontario. It is a border city, with a bridge crossing from Windsor directly into Detroit, Michigan. It has a city population of 220,000 and a metropolitan population of over 330,000 people (consisting of Windsor, Tecumseh, Amherstberg, LaSalle, and Lakeshore) making it the 23rd largest city in Ontario (Census Canada 2016). Emerald ash borer was first found in Windsor, Ontario in the summer of 2002 shortly after it was first identified in Detroit, Michigan. Windsor was the first Canadian city and the second city in North America to identify EAB and as such, their management plan needed to be put together very quickly. By the time they realized what was killing their ash trees, it was too late to truly decide on the best management plan. The first thing the city of Windsor did was conduct ground surveys to attempt to determine the spread of EAB in the area (City of Windsor 2004). The Canadian Food Inspection Agency put a quarantine on moving firewood in Windsor and the surrounding counties/municipalities. The city implemented a rigorous public information/media system, doing their best to inform Windsor's inhabitants through different forms of media including the television, radio, newspapers, and brochures. This, of course, did nothing to save the ash trees within the metropolitan area (Herms and McCullough 2014). Ash composed 9% of the canopy in Windsor and within a few years most of the city's ash species were lost to EAB. The city spent $4 million for removal and stumping. This does not include the cost of disposing of or replacing the lost ash.

Toledo, Ohio 2003

Toledo is a community in Ohio with an average population of 280,000 people (United States Census Bureau 2015). Its metropolitan area has around 650,000 people. Prior to EAB, Toledo's urban forest had 8,000 ash trees composing 8% of the canopy and within seven years, Toledo no longer had any ash (Lessons Shared 2008). By 2003, many of the States surrounding Michigan started to build their own management plan for EAB with the exception of Ohio. Communities in Ohio were reluctant to develop a management plan due to a lack of staff, time, and money. They did not fully grasp the scale of the emerald ash borer invasion and took up the opinion 'we'll deal with it when it gets here, if it gets here'. The community of Toledo was not willing to cut down what seemed like completely healthy ash trees. When EAB arrived Toledo looked at costs between two options consisting of removal or treatment. Removal would cost the city

$5-6 million and injections would have cost $1.5 million/year, as such, they decided to go with removals.

Due to their reactive approach to the problem, Toledo had issues with funding and safety later on, as did much of Ohio. Removing healthy looking trees caused some discord within the city and as such, most of the trees died before removal was an option and by that time they were a hazard as can be seen in Figure 5 below (Herms 2009). Toledo had the second highest storm damage calls about green ash in relation to population size. Within a few years of having EAB problems, the city of Toledo offered advice for cities in danger of invasion. Their advice included (Lessons Shared 2008):

- Perform inventories of ash trees in the city to get an estimate of time, costs, and impacts expected
- Toledo had to pull staff from other departments and train them very quickly leaving tasks delayed for months or years
- Ash trees died very quickly, cut pre-emptively to avoid being overwhelmed by the sheer amount of hazard trees
- Waiting to cut down trees until they are completely dead will cost more in the end
- There will be a lot of wood waste. The city of Toledo bought a grinder costing $400,000 to deal with the excess of wood waste.

Ash trees in a Toledo, Ohio neighborhood in June 2006. Credit: D. Herms

Toledo, Ohio trees after emerald ash borer in August 2009. Credit: D. Herms.

Source: Herms 2009

Figure 5. Street in Toledo, OH showing ash in 2006 and 2009

Toronto, Ontario 2008

Toronto is the largest city in Ontario with 2.7 million people in the city and about 6 million in the metropolitan area (Census Canada 2016). The city of Toronto had a total of 860,000 ash trees before EAB on both public and private land (Hart 2012). There were approximately 82,000 city trees consisting of 32,000 street trees and 50,000 parks/natural areas ash. The Canadian Food Inspection Agency (CFIA) first confirmed the presence of EAB in 2007 (City of Toronto 2017). Toronto's EAB management plan initially consisted of four key components: 1) monitoring, including branch sampling and ash mortality surveys; 2) an education plan with public meeting, media information outlets, and correspondences; 3) removal of infested trees, which would incorporate the costs of tree removals and wood waste disposal; and 4) tree canopy replacement (Hart 2012). In a 2012 update to the plan, the city added insecticide treatments to the plan.

They incorporated insecticide treatments to slow the rate at which ash trees died. They began to use the insecticides to stage removals. The plan was to treat 2,000 trees in 2012; 4,000 each year from 2013 to 2015; and 2,000 in 2016. They would only treat the trees once, allowing them to pick and choose which trees would die within which year. This sort of technique would not be feasible in smaller communities as they just do not have the funds for it. As of the 2016 EAB staff report, there are just under 10,000 ash trees left in Toronto (Romoff 2016). Funding for the emerald ash borer management plan over a 10 year period was $75 million, of which $65 million came from the Sustainable Energy Reserve.

Sault Ste. Marie, Ontario 2008

Sault Ste. Marie is a small Ontario community located near the southern tip of Lake Superior; it is a border town with a crossing into northern Michigan. It has a city population of 73,000 and a metropolitan population of 78,000 (Census Canada 2016). Sault Ste. Marie is a good example of a city that was expected to do very well when dealing with EAB but did not quite meet the bar. The CFIA confirmed the presence of EAB in Sault Ste. Marie in late 2008. This was odd as the major populations of EAB were still hundreds of kilometers to the south indicating a transport of firewood likely introduced it to Sault Ste. Marie (Wingrove 2008). This particular community had a lot of ash trees in the urban centre, especially down the main street which was a monoculture of ash. At the time, Sault Ste. Marie decided to implement a strategy using insecticide treatments on its main street. Application of TreeAzin was quickly implemented for these high value trees. Unfortunately, communication issues led to the wrong dose being applied to the trees and when surveys were taken a year later, EAB was still alive and healthy within the tree (Kerr 2010).

Peterborough, Ontario 2014

Peterborough is a fairly small southern Ontario community located north east of Toronto. It has a city population of 80,000 people and a metropolitan population of 120,000 people (Census Canada 2016). Opposite to Sault Ste. Marie, managers can see a success story when looking at how Peterborough, Ontario is managing for EAB. Peterborough had 7,000 city ash making up 10% of the urban forest in terms of tree numbers and 14% in terms of canopy cover (Hambidge 2016). The city was confirmed to have the beetle in 2014. Peterborough came up with an EAB management plan in 2013, one year before the insect was actually found showing that Peterborough was not 'reacting' to EAB but rather was 'actively preparing' for it. Peterborough considered three management plan options ranging from doing nothing to treating every tree to a hybrid plan of treatments and removals (City of Peterborough 2013). Based on cost/benefit analyses, this community decide to implement a proactive hybrid plan, where they would treat 65% of the cities street trees. Peterborough's 2013 management plan consisted of six components: 1) inventory, monitoring, and assessment; 2) treatments; 3) tree and stump removal; 4) tree replacement with a different species of tree; 5) wood waste disposal plans; and 6) public education. Over a ten year period, the city is expecting costs of approximately $5 million. As of 2017, there have been no confirmed cases of EAB killing ash trees in Peterborough; if a tree is infested it is immediately removed.

Duluth, Minnesota 2015

Duluth is a major port city located on the western shore of Lake Superior in Minnesota. It has a city population of 90,000 people and a metropolitan population of 280,000 people (United States Census Bureau 2015). Minnesota in general is an important area to pay attention to where EAB is concerned because it is the State with the highest percentage of ash trees. Duluth alone has 2,500 city ash trees making up 21% of the canopy not including park trees (City of Duluth 2015). Duluth prepared for EAB by creating a highly detailed plan consisting of seven different parts: 1) monitoring and inspection using prism traps, branch sampling, and visual inspections; 2) insecticide use; 3) community outreach programs; 4) ash tree removal and sanitation; 5) ash wood disposal; 6) reforestation and canopy replacement; and 7) biological controls. Duluth started to prepare for the possibility of an invasion by implementing an integrated pest management strategy allowing for the city to spread out the management costs over a longer period. Part of the strategy is injection, where the city has selected 911 candidate ash trees, 176 of which will get injections of TREE-äge on a yearly basis instead of a biennial one (City of Duluth 2015). These candidate trees must be over 30 cm in diameter at breast height to be considered for this treatment.

Another element of the plan is to remove ash tree with a diameter at breast height below 30 cm and replace them with resistant species. Duluth has implemented a ‘proactive, systematic removal and replacement’ plan (City of Duluth 2015). Pre-emptive removal and replacement will spread out available time, costs and resources. The goal is to treat about 37% of the ash trees leaving about 1,500 ash trees to be removed. The last part of the management plan is the release of biological controls. It is likely the only parasitoids that would survive in Minnesota are *S. galinae*, *O. agrili*, and

T. planipennisi. The city must wait until there is approximately 15-40 acres of infestation before these parasitoids can be released as they need a sufficient amount of EAB to establish a population. The combination of these management strategies is the most cost effective method of slowing the spread and reducing the damage of EAB in Duluth.

DISCUSSION

Emerald ash borer management techniques all function to slow the spread of the beetle while maintaining the benefits of shade trees in urban environments. Each individual technique varies in which situations it will be most successful. Lethal trap trees are only really useful at lowering EAB populations and spread in recently infested, isolated areas (Mercader et al. 2015). This technique could be useful as a method during the initial stages of infestation in a community. Tree removal and replacement is a technique that occurs in all EAB management plans as the community always needs to remove dead or dying trees as they are hazardous to city structures and human health. The only choice in this matter is whether the community removes the trees pre-emptively or after they have become infected. Toledo suggests removing them pre-emptively as it is more costly to remove them once they are dead (Lessons Shared 2008). It costs more after because the trees are more unpredictable and tree companies must spend more time and effort felling them safely. Insecticide treatments are a technique that vary between large and small communities. Large communities have the funds to use these treatments to control when a tree will die while small communities only use insecticides in limited amounts. The funds in small communities restrict insecticides to being used mostly on high value trees that the community wishes to save. The final technique, biological controls, is only feasible in areas where the density of EAB is high (City of Duluth 2015). The parasitoids need a decently high population of the beetle so they can become established in the area. Other requirements are high densities of ash. Some companies will only send parasitoids if the area has 20% or more ash. So while biological controls would work for cities like Duluth, MN and Thunder Bay, Ontario; it likely would not work for Sault Ste. Marie.

Emerald ash borer management strategies have been steadily evolving. For the first few years after the initial discovery, communities took either a ‘do nothing’ stance as seen with Toledo, OH or a reactive approach as with Windsor. Communities that experienced EAB were quick to share advice to help better prepare those cities in danger of infestation. After Windsor dealt with EAB, it shared the need to inventory the urban forest prior to infestation as well as the need for a sound wood disposal plan (City of Windsor 2004). Making an inventory of the urban forest helps managers to better understand the composition of the environment. This allows managers to better determine the impacts that may occur should the pest pass through. After Toledo dealt with EAB they stressed the importance of planning ahead and educating the public (Lessons Shared 2008). When the time came to begin dealing with the ash trees, the public balked at the idea of removing what looked like completely healthy trees. As such, all of the trees were dead or dying before Toledo took action. This resulted in thousands of dead trees lining the streets of the city causing dangers to the public. This reactive method also resulted in a lack of time, staff, and funds for Toledo. They had to pull people from other departments and train them quickly resulting in a lack of skilled staff and resulting in the other departments being understaffed (Lessons Shared 2008). Advice from Toledo included performing inventories, train staff ahead of time, determining a wood waste removal program, and to cut down trees pre-emptively.

Toronto and Sault Ste. Marie were both communities that experienced emerald ash borer infestations in 2008. The two communities differ greatly in size and as such, their management plans differed as well. Toronto had the available funds to create an elaborate plan. They were able to use their funds to control how and when the ash in the city died (Hart 2012). They were able to create a treatment plan to control how many trees would die in a given year. They needed to do this to deal with the sheer amount of ash trees in the city. If they had not, they would have had over 80,000 city trees dying within a few years and it would have caused issues with time and staff. This method is not feasible for smaller communities. Most small communities do not have enough trees to warrant a technique like this nor do they have the funds to treat trees just for the purpose of controlling when they die. Sault Ste. Marie's management plan for EAB consisted of removals once trees were infected and treating high value ash along the main street (Kerr 2010). Sadly, the wrong insecticide dose was applied to the trees and beetle continued to survive in the trees. Sault Ste. Marie only had the funds to protect trees of high value with insecticides and after that plan fell through, they had to decide whether to spend more money attempting another insecticide treatment or to spend the money to just remove the trees.

Peterborough and Duluth are two small communities that both came up with highly detailed, in-depth plans for recent infestations of EAB. They both pre-emptively created management plans before the beetle was confirmed in the area. These communities are of similar size but the most effective plan varied between them never-the-less. Peterborough's plan consisted of treating 65% of the city's ash trees and using a strategic removal plan for the rest of the trees, followed by wood waste disposal (City of Peterborough 2013). This plan was extremely useful in Peterborough and as of 2017, there have been no ash trees killed outright by the borer. Once a tree has been confirmed as infected, the city removes it. This indicates a better public support system as opposed to larger cities like Toledo that had issues with public outcry. Duluth, MN has a similar population size to Peterborough but other factors required changes be made to achieve the most effective plan. One main difference was the density of ash; Duluth had an ash density of 21% while Peterborough had a density of 14% (City of Duluth 2015; Hambidge 2016). This slight difference in density allowed for an additional management technique to be added to Duluth's management plan. Duluth could now add biological controls as a possible technique. They still maintained the tree removal and treatment technique but they planned to treat only 37% of their ash trees. This shows that despite both cities being classed as small communities, the EAB management plan varied based on a combination of factors.

CONCLUSION

Over time, urban communities have been learning from each other's experiences dealing with emerald ash borer and improving their management plans. Through learning from past experiences, communities now know that one of the most important things to do is to survey the urban area prior to EAB arrival. If managers do not know how many ash trees are present, or what the impact will be of losing them, how can they possibly decide on the most effective management plan? In conclusion, EAB management plans have steadily been increasing in effectiveness. Management plans must change to best suit the specific community, and managers must be aware of their options and their limitations. By looking at comparisons between large and small communities, it can be determined that sometimes, smaller urban communities do not have the funds, staff, or resources to employ the same strategies as larger communities. Large communities are often forced to use tree injections to control when a tree will die lest they be overwhelmed by the sheer amount of dead, dangerous trees. Small communities only use insecticide treatments when they have high value trees they want to preserve. In addition, it is more common for small communities to pre-emptively cut down ash trees so they are not overwhelmed. They also have an easier time with obtaining public support than the larger communities. Looking back at the case studies, there are minute differences between all of the management plans. The original hypothesis that there would not be any differences in management plans between large and small communities has been proven wrong. It is evident that not only large and small communities differ but rather all communities differ as a whole in the most effective management of EAB.

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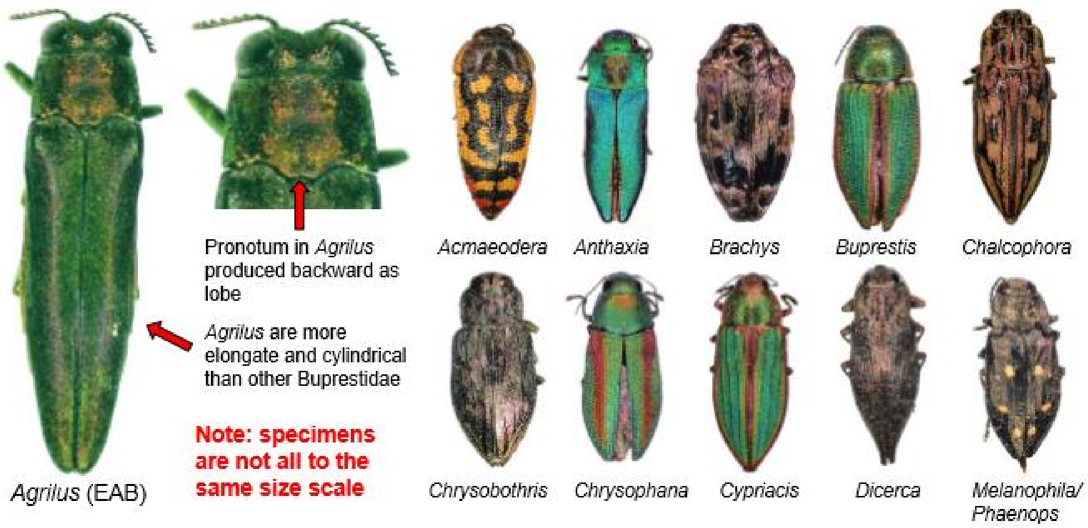
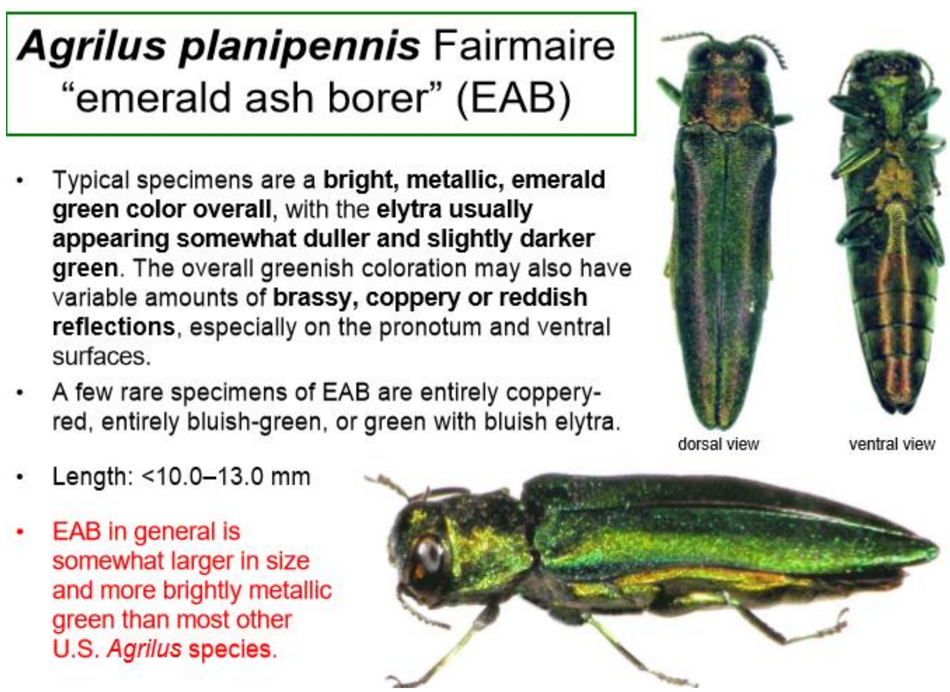
APPENDICES

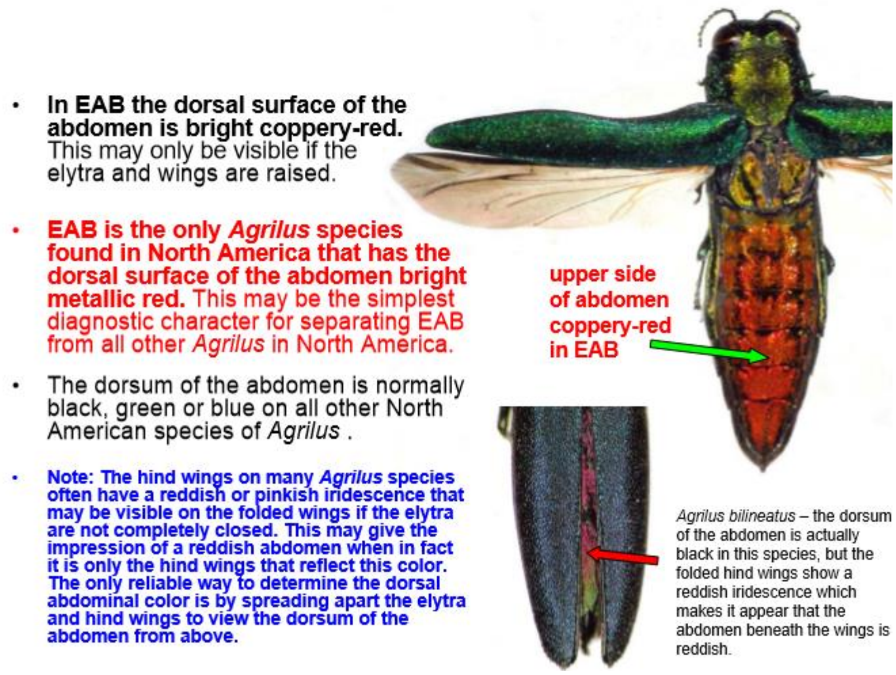
Appendix I Guide to Emerald Ash Borer Identification



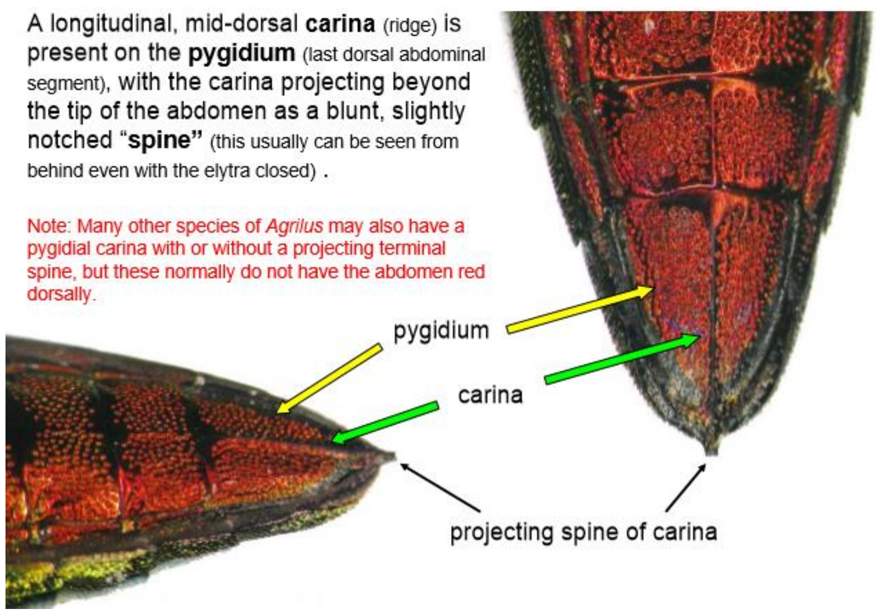
Source: Parsons 2008



Source: Parsons 2008

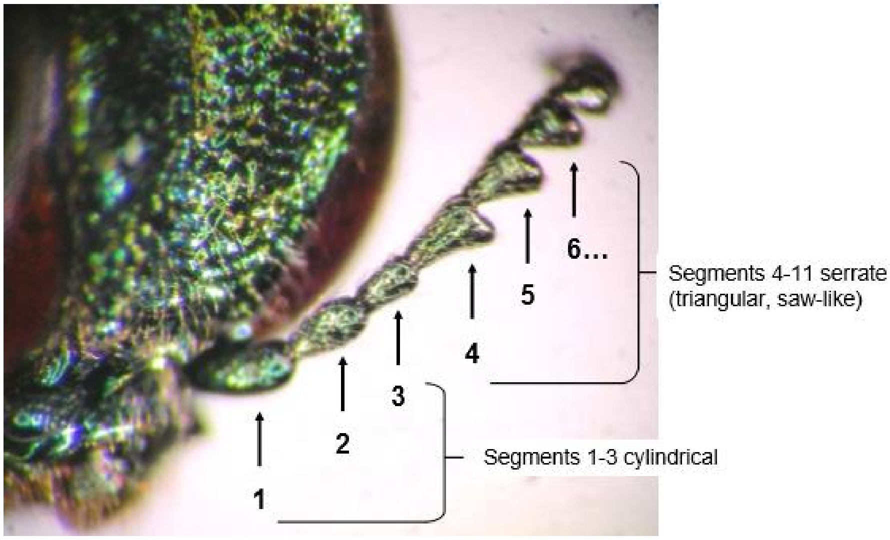


Source: Parsons 2008



Source: Parsons 2008

- In EAB the antennal segments are serrate beginning with segment 4. (segments 1-3 cylindrical, segments 4-11 are triangular or "saw-like").
- Note: Many species of *Agrilus* have the antennae serrate beginning with segment 4. However, in some species the antennae are serrate beginning with segment 5 (1-4 cylindrical).



Source: Parsons 2008

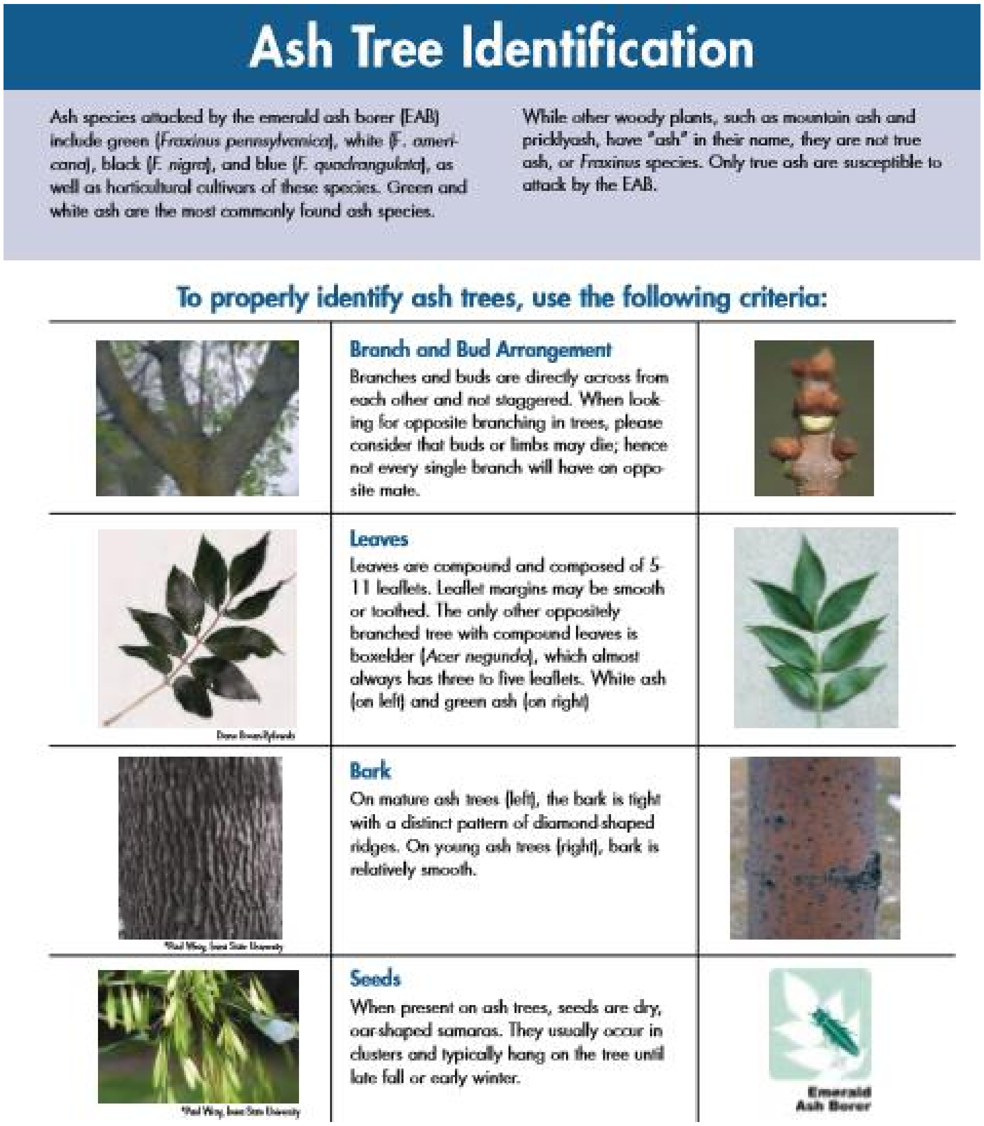
Almost all *Agrilus* species exhibit some degree of natural variation in size and coloration. This is especially so with metallic colored species.

The specimens below show some of the size range and color variation seen in the more typical specimens of EAB.

It should be noted that "metallic" coloration can be influenced by light intensity, light direction, and light quality. As you move metallic specimens around under a light, you can see them apparently change or shift color. Therefore, it is possible that individual specimens in hand may not exactly match the photos used in this guide. The individual species descriptions in this guide try to describe some of the color variations but odd variants often occur. As noted earlier, specimens in alcohol or covered in sticky trap material will seldom reflect their true colors and should be cleaned and dried before comparison to the photos in this guide.

Source: Parsons 2008

Appendix II Guide to Ash Tree Identification



Ash Tree Identification

Ash species attacked by the emerald ash borer (EAB) include green (*Fraxinus pennsylvanica*), white (*F. americana*), black (*F. nigra*), and blue (*F. quadrangulata*), as well as horticultural cultivars of these species. Green and white ash are the most commonly found ash species.

While other woody plants, such as mountain ash and pricklyash, have "ash" in their name, they are not true ash, or *Fraxinus* species. Only true ash are susceptible to attack by the EAB.

To properly identify ash trees, use the following criteria:

Branch and Bud Arrangement

Branches and buds are directly across from each other and not staggered. When looking for opposite branching in trees, please consider that buds or limbs may die; hence not every single branch will have an opposite mate.

Leaves

Leaves are compound and composed of 5-11 leaflets. Leaflet margins may be smooth or toothed. The only other oppositely branched tree with compound leaves is boxelder (*Acer negundo*), which almost always has three to five leaflets. White ash (on left) and green ash (on right)

Bark

On mature ash trees (left), the bark is tight with a distinct pattern of diamond-shaped ridges. On young ash trees (right), bark is relatively smooth.

Seeds

When present on ash trees, seeds are dry, oar-shaped samaras. They usually occur in clusters and typically hang on the tree until late fall or early winter.

Emerald Ash Borer

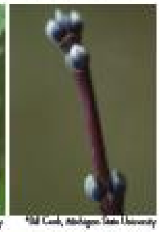
Source: Rebek and Wilson 2009

Tree Species Resembling Ash

Boxelder (*Acer negundo*)

Exhibits opposite branching and compound leaves. However, has 3 to 5 leaflets (instead of 5 to 11) and the samaras are always in pairs instead of single like the ash.

*Paul Wray, Iowa State University



*Bill Cook, Michigan State University

European Mountain Ash (*Sorbus aucuparia*)

Leaves are compound with alternate (staggered) branching. Tree bears clusters of creamy white flowers in May. Fruits are fleshy, red-orange berries.

*Boris Hrasovec, University of Zagreb

Shagbark Hickory (*Carya ovata*)

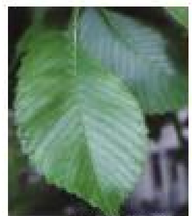
Leaves are compound with 5 to 7 leaflets, but the tree has an alternate branching habit. Fruit are hard-shelled nuts in a green husk.

*Paul Wray, Iowa State University

*Paul Wray, Iowa State University

Elm (*Ulmus species*)

Branching is alternate and the leaves are simple with an unequal leaf base.



*Paul Wray, Iowa State University

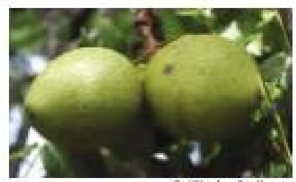
*Paul Wray, Iowa State University

Black Walnut (*Juglans nigra*)

*Paul Wray, Iowa State University

Leaves are compound with 9 to 15 leaflets, but the tree has an alternate branching habit. Fruit is a large dark brown nut inside a green husk.

*www.forestryimages.org



*Paul Wray, Iowa State University

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Source: Rebek and Wilson 2009

Appendix III Emerald Ash Borer Symptom Guide

Larval gallery: When the larva feeds between the bark and sapwood, it makes an S-shaped, "zig-zag," or serpentine gallery. When the young larva enters the wood to begin feeding, it may move up or down the tree bole or branch. You can tell which way it moved by looking at the width of the gallery: as the larva gets bigger so does the width of the gallery. In this picture, the larva moved down the tree (from the top of the picture to the bottom).

Exit hole: As a new adult exits the tree, it chews a D-shaped hole in the bark (A). The holes are slightly bigger than the adult, and are about 3.5 to 4 mm wide. These D-shaped holes are unique to the group of beetles to which the emerald ash borer belongs. Although the holes are a very good indication that the emerald ash borer has infested the tree, it is not an absolute proof because there are other beetles that can cause similar holes. Nevertheless if you see these holes and the S-shaped galleries underneath the bark, report your discovery.

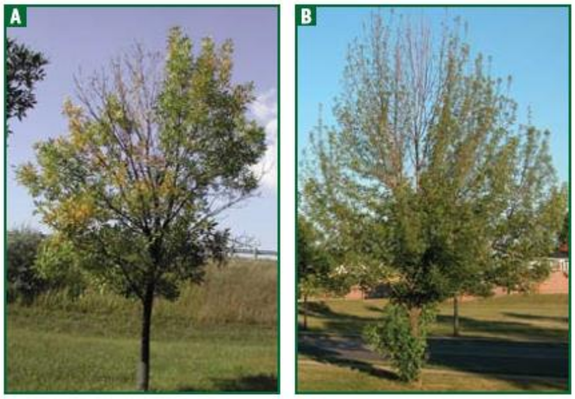
Source: de Groot et al. 2006

Leaf notch: The new adult feeds on ash leaves and cuts notches on the side of the leaf (B).

When insect populations are high, defoliation by adults (C) will be noticeable and may result in tree crowns appearing ragged.

Heavy seed production: A tree under severe stress can produce an abundant seed crop, which yields few viable seeds (C). In picture (D), note the very heavy seed crop on the small tree, the thin tree crown, and the epicormic shoots on the trunk.

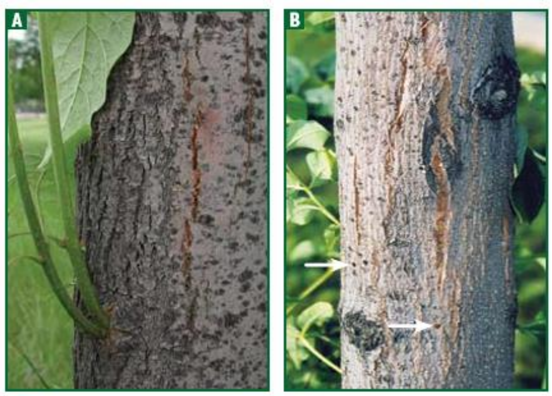
Source: de Groot et al. 2006



Yellow foliage, dead branches, and thin tree crowns: Feeding by the larvae eventually kills branches. As the branches begin to die, the foliage turns yellow, wilts and falls off leaving bare branches (A). In picture (B), you can see the thinning crowns as well as epicormic shoots on the trunk.

Epicormic shoots: These shoots are also called suckers, water sprouts or witches brooms and are produced on the tree trunk and roots when the tree is under stress. They can sometimes be found in the tree crown, on stems and on larger branches (A, B, C). Not all trees attacked by the emerald ash borer develop epicormic shoots. However, under the right conditions and intensity of attack by the beetle, they can develop and grow quickly.

Source: de Groot et al. 2006



Bark deformities: Vertical splits or cracks in the bark over larval galleries are commonly seen on the trunk and branches of infested trees (A, B). Note in picture (A), the epicormic shoots to the left of the bark split, and in picture (B), the D-shaped exit holes (see arrows). Bark splits are often 5 to 15 cm long. On young trees with thin bark (C), the bark over a gallery turns pinkish brown and dries (see arrow).

Source: de Groot et al. 2006