# The Spread of the Emerald Ash Borer in North America

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# Introduction

North America’s ash (*Fraxinus* spp.) resource is an economically important source of wood with uses in furniture, firewood, bows, and even baseball bats. Ash trees are also of aesthetic value and are a very popular tree in urban landscapes. However, these trees are facing the threat of an invasive species from Asia that has killed tens of millions of ash trees since its detection in the U.S. and Canada in 2002. This foreign invader, known as the emerald ash borer (EAB), *Agrilus planipennis* Fairemaire (Coleoptra: Buprestidae), was initially discovered for the first time outside its native range in the Detroit area as ash mortality rates were on the rise. These wood boring beetles cause fatal damage by feeding on the phloem and cambium of ash trees, cutting off the nutrient supply to the upper portions of the tree.

Since its introduction to North America, the emerald ash borer has spread across 15 U.S. states and two providences in Canada, killing millions of ash trees in the process. North America’s ash trees are far more susceptible to this foreign pest because it lacks the natural enemies and defensive traits of their Asian counterparts (Rebek et al. 2008). Efforts to control this problem have been very expensive for government and environmental agencies alike. To further complicate things, *A. planipennis* movement is very difficult to track because most of the insect’s lifecycle takes place in the inner tissue of ash trees. This makes the larvae more evasive, providing a means of unintentional human aided dispersal through ash wood product transportation (Cappaert et al. 2005).

The purpose of this paper is to introduce the emerald ash borer and discuss how it has become a problem in North America and threatens the ash resource. The structure of this paper is broken down into four sections and will cover the biology and life cycle, the ash host range in North American and China, dispersal, and economic impacts and quarantine efforts.

# Biology and Life Cycle

At the time of the emerald ash borer’s introduction to North America, very little was known about the beetle. In fact, prior to 2003, even in its native range in Asia few studies were conducted on the biology and ecology of *A. planipennis* because it there were only few areas where it was causing significant damage (Siegert et al. 2010; Wang et al. 2010). It was only because of more recent and severe ash mortality rates of *F. velutina* (velvet ash) in Tianjin, China that necessitated the need for a better understanding of this pest (Wang et al. 2010). The native range of the EAB is China, Japan, Korea, Mongolia, eastern Russia, and Taiwan, but studies have shown that they generally only attack stressed trees because the Asian ash are more resilient as a result of coevolution (Anulewicz et. al 2008).

The Asian buprestid *A. planipennis* was first discovered in southest Michigan and Windsor, Ontario in 2002 (Anulewicz et. al 2008, Poland and McCullough 2006). Several specimen were brought to the Department of Entomology of Michigan State University that were collected from dying ash trees in the greater Detroit area. It was determined that the specimens were most likely the genus *Agrilus*, and they were then sent off and later positively identified as *Agrilus planipennis* by Dr. Eduard Jendek of Slovakia. The specimens were sent to Dr. Jendek because is the world authority on the genus *Agrilus*. This marked the first time it was identified outside of its native host range in Asia (Poland and McCullough 2006).

The EAB is a member of the order Coleoptera (beetles) and is in the Buprestidae family, which are the wood boring beetles. The adult form of A. planipennis is small, usually less than ten millimeters long and approximately two millimeters wide. The USDA Animal Plant and Health Inspection Service (APHIS) describes their bodies as elongated in the shape of a bullet with bronze to gold coloring on their abdomen and metallic emerald green wing covers. However, the adult beetles are not what threaten the future perseverance of the North American ash resource. Instead, it is the EAB in its larval form that cause significant damage as the feed on the phloem and cambium of trees, effectively girdling the trees until they die (Marshall et al. 2010).

The life cycle of A. planipennis spans from one to two years, depending upon the temperatures of the infested region. The two year life cycle tends to occur in the northern parts of the North American host range in Michigan, New York, and parts of Canada where the larvae will spend a second winter season to mature, feeding on the phloem and cambium in a pre-pupae state through four instar stages (Marshall et al. 2010). The adult females lay their eggs on the bark and in between crevasses on the outer surface of trees. Oviposition typically occurs in mid-May in the native range of the EAB (Wang et al. 2010) and in late June to early July in North America (Poland and McCullough 2006). When the eggs hatch, the larvae emerge as a creamy white wormlike organism and begin boring into the inner tissue right away. In the first few months, the instars in their pre-pupae state will form shallow serpentine tunnels in the phloem and cambium of the trees leaving behind a trail of frass, which is a brown woody excrement. As the larvae feed on the vascular tissue of the tree, the nutrient supply is cut off from the roots to the upper crown of the tree. Trees with a high density of EAB infestations showed strong signs of devastation as the bark would fall off and the tree would die within 2-3 years of the initial infestation (Wang et al. 2010).

The larvae mature through four instars in their pre-pupae form by feeding on phloem from summer to fall and then bore deeper into the sapwood to form overwintering chambers where they will remain until the spring (Siegert et al. 2010; Wang et al. 2010). In regions that face harsher winters, the larvae will spend an extra season feeding on the phloem before entering a state of overwintering dormancy in the deeper chambers of the tree during the second winter (Marshall et al. 2010). In the early spring, they will transform into a sexually mature adult over the course of a few weeks before emerging from trees by forming D-shaped exit holes in the bark of the tree. This pattern is due to the physiology of the body of *A. planipennis* in its adult form because they have a rounded abdomen with a flat back.

Adult beetles usually emerge from trees between May and July, with the peak activity happening between late June and early July (Poland and McCullough 2006), leaving D-shaped exit holes and have typically have a three to six week life span. Adults will usually feed on the leaves of ash trees for a week or two before mating. This peak activity seems to differ in the native range of the EAB, as the beetles are most active during the month of May in Asia (Wang et al. 2010). After emerging from the trees, adult beetles will feed on the leaves of the ash trees for about two weeks before mating. The females will lay eggs under the bark or in cracks and the larvae will usually hatch within two weeks and start boring into the phloem of the tree (Anulewicz et. al 2008). Each female will typically lay between 50-90 eggs during her lifecycle (Poland and McCullough 2006). Research has shown that some females will lay eggs on trees other than ash but the larvae will often not survive in non-ash trees (Anulewicz et. al 2008; Rebek et al. 2008).

# Ash Host Range in North America and China

Ash trees are a hardwood species that are very common in North America, Canada, and China. They are a member of the genus *Fraxinus* in the order *Lamiales* and the family *Oleacea*. The trees most commonly attacked in North America are white ash *(F. americana*), green ash (*F. pennsylvanica*), blue ash (*F. quadrangulata*), black ash (*F. nigra*), and pumpkin ash. (*F. profunda*) in North America (Anulewicz et. al 2008; BenDor et al. 2006). They are medium sized trees with average heights reaching 50-80 feet at the top of the crown and tend to colonize gaps in older hardwood forests. Ash trees are also very common ornamental shade trees in urban settings because they are fast growing woodland trees that are used to line streets (Poland and McCullough 2006). Ash trees are especially abundant in urban settings in Michigan, Chicago, and New York comprising approximately 15-20% of all urban tree species (BenDor et al. 2006).

White and green ash trees are most commonly attacked and have bark arranged in diamond shaped patterns with pinnately-odd opposite compound leaves with 5-9 untoothed or slightly toothed leaflets that are between 2-6 inches in length (Jesse et al. 2011). It is often difficult to distinguish between the green, blue, and white ash species by looking at the leaves alone.

As of 2006, it was estimated that over one hundred million ash trees have been attacked or killed by *A. planipennis*, with over 20 million trees killed in Michigan alone (Anulewicz et al. 2007). The larval instars effectively girdle trees by chewing through the vascular tissue of trees particularly in the phloem and cambium of the tree during the fall before overwintering in the deeper sapwood chambers during the winter months. The serpentine channels bored out in the phloem cut off nutrient and water supplies from the roots to the upper crown of the tree, usually killing the tree within two to four years depending on the larval density at each tree. This process is known as slow ash mortality (SLAM, McCullough and Mercader 2012).

A study was conducted by Anulewicz et al. in 2008 to determine if *A. planipennis* would lay eggs and successfully feed on non-ash trees in areas where there are significant ash populations. The non-ash tree species that were tested were Black Walnut (*Juglans niagra*), Hackberry (*Celtis occidentalis*), Shagbark Hickory (*Carya ovata*), and American Elm (*Ulmus americana*), and drain pipe for a non-tree species control. There were 24 logs of each ash species and the non-ash species harvested for sampling purposes. There were four sites chosen, each located in Michigan with moderate to severe infestation levels. Each site was divided into four to eight blocks where the logs and drain pipe were then tied to 50% of the trees chosen at random and wrapped with clear plastic film and covered with Tanglefoot. Tanglefoot is a sticky substance designed to prevent pests from climbing trees and getting into cracks, providing a means to quantify the amounts of *A. planipennis* adults that landed on the trees. There was a total of 602 adult beetles collected from 109 logs and 16 pieces of drain pipe over a two month period. The logs were then dissected to observe the larvae and egg infestations in each log. Their study concluded that 78% of the eggs were laid on ash trees. Of the remaining 22% of eggs laid on non-ash trees, 52% of those eggs were laid on Black Walnut trees and 0 were laid on the drain pipes. While some A. planipennis adults would ovipost on non-ash hosts, the larvae could not survive by feeding on the non-ash species.

North American Fraxinus spp. are generally less resistant to A. planipennis than the Asian Ash trees because of their coevolution with the beetles in their native range. In fact, the EAB is much rarer in Asia (Gould et al. 2005) and tend to be constrained to stressed or dying ash trees (Bauer et al. 2005; Schaefer 2005). In North America, the EAB will often attack healthy trees.

In a study by Rebek et al. in 2008, they observed North American Ash trees and Asian Ash trees from 2003-2006 to compare host susceptibility and resistance to the EAB. The experiment compared five cultivar species in a 0.2 ha plantation in Novi, MI that included two varieties of green ash (Patmore and Marshall’s Seedless), one native white ash (Autumn Purple), one Asian ash Manchurian ash (*F. mandshurica* Mancana), and a hybrid of North American black ash and Manchurian ash (*F. nigra* X *F. mandshurica* Northern Treasure). All of the trees were approximately four years old and *A. planipennis* was introduced by placing ash logs infested with larvae at an interval of every seven trees within each of the five rows of trees in the spring of 2003. As part of a concurrent study, a common insecticide that effects the central nervous system of insects known as imidacloprid was drenched in the soil surrounding a subset of the trees to study how insecticides would affect the EAB at different times of the year in comparison to the untreated cultivars. Statistical analysis was performed using the results from tree canopy dieback and the number of D-shaped exit wounds each year.

The study conducted by Rebek et al. (2008) confirmed their hypothesis that the Manchurian ash is much more resistant to A. planipennis than its North American Fraxinus counterparts as shown by the high survival rates of the Manchurian ash. All of the North American species experienced high mortality rates during the three year study, although the use of imidacloprid helped provide some resistance. Within the first two years (2003-2005), all of the “Patmore” green ash that were not treated with imidaclorprid were killed off by the EAB, while 75% and 92% of the untreated “Marshall’s Seedless” green ash and “Autumn Purple” white ash died, respectively, over the entire three year period. As an unexpected result, all untreated North American X Manchurian ash hybrid trees died, while 75% of the imidacloprid treated trees died. The insecticide treatment did not seem to have an effect on the Manchurian ash and the survival rate amongst Asian ash was over 80% regardless of treatment.

Future ash tree perseverance in forest stands that have been heavily infested with the EAB will depend on the potential for regeneration (Klooster et al. 2013). This can be problematic for ash tree survival because the beetles will feed on trees as small as 2.5 cm (McCullough et al. 2008; Rebek et al. 2008; Klooster et al. 2013) and some ash species take up to 60 years before they are mature enough to produce seeds (Kurmis and Kim, 1989; Klooster et al. 2013). The regeneration of ash trees in forested areas is unlikely when ash mortality is high in the aftermath of an EAB invasion and will depend on the resilience and reproduction of an “orphaned cohort” of the ash seedlings and saplings that had previously occupied the area. Michigan has experienced this seemingly irreversible ash mortality according to this theory. By 2007, ash mortality topped 90% from the rapid spread of A. planipennis in the Great Lakes State, which had adverse effects on the ash seed bank. Within the next two years, there were not any freshly germinated ash seedlings left and only the earlier established ash seedlings and saplings remained in Michigan’s forests as ash mortality rates soared to over 99% (Klooster et al. 2013).

When ash trees are attacked by other wood boring members of the *Agrilus* spp. (*A. auriventris, A. mali, A. ratundicollis, A. sorocinus, A. zanthoxylumi*), the tree’s defense mechanism is to produce sap at the site of the wound, aiding detection. However, in the event of an EAB attack, the ash trees do not discharge sap leaving only the D-shaped exit wound. These exit wounds are often hard to spot and are not apparent until there is a high density of adult beetles. By the time the tree has dense larval populations, the tree will already have visible signs of declining health (Wang et al. 2010). Other more obvious visual cues of an EAB attack are crown dieback, epicormic shoots, and bark flaking.

# Dispersal

The EAB has infested 15 U.S. states since it arrived including Illinois, Indiana, Iowa, Kentucky, Maryland, Michigan, Minnesota, Missouri, New York, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia, and Wisconsin. When adult specimens were discovered in the U.S. and brought to the entomology department at Michigan State University, it was determined that the beetles had probably been introduced several years prior to 2002. The infestation has also traveled north, occupying the two Canadian Provinces of Ontario and Quebec (Vannatta et. al 2012, Anulewicz et al. 2007; Poland and McCullough 2006). *A. plannipennis* was likely introduced to the U.S. through international trade by use of wood crates and pallets. Through this means of transporation, the EAB was able to thrive and became an established invasive species by feeding on the abundant source of ash trees in Michigan (Poland and McCullough 2006).

Because the EAB live most of their life as larvae inside the trees it can often take several years for larger trees to show signs of stress from attacks, this presents a challenge to discover and control this pest (Wang et al. 2010). This is also problematic for identifying quarantine areas and why so much infested ash is transported by humans unknowingly. Some of the likely factors contributing to the human aided transportation of infested ash wood are sawmills, ash tree densities, major highways, tree nurseries, wood harvesting centers, and human population centers (Prasad et al. 2010). There are a lot of unknowns about the human transportation of the EAB because it is such a difficult problem to dissect. There are countless factors that could influence the “insect ride” dispersal, so predictive statistical modeling of this type of spread is more common than empirical evidence. This is due to difficulties in tracking the movements of the EAB and identifying infested trees, which is nearly impossible without the presence of epicormic shoots, D-shaped exit wounds, or canopy dieback.

The EAB problem is a much bigger problem in North America than it is in its native range in southeast region of Asia. In their native range presence of natural predators and years of ash coevolution have been able to keep the EAB populations in check. In fact, there are only a few areas where the EAB causes severe damage. Until more recent years, there was little documentation on the biology of the EAB. In their native range, Asian ash trees are attacked in lower densities and stressed trees are often the target. Evidence has also shown ash trees at the edge of the forest also receive greater densities of attacks (Anulewicz et al. 2007). Scientists believe that the dispersal of *A. planipennis* may be influenced by wind and ash abundance (Siegert et al. 2010). Several studies have been conducted to determine how far adult beetles travel in their 2-3 week life span in newly colonized or outlier sites.

The first two outlier sites found outside the original infestation area of southeast Michigan were found in St. Joseph and Shields, MI. Both sites were colonized by *A. planipennis* as a result of the planting of infected nursery trees in October 2000 and November 2003, respectively. Most EAB populations at these two sites exhibited a semivoltine (2 year) life cycle, where the larvae would feed on the phloem for a second season. Attempts were made to eradicate the pest in these areas by felling, clipping, and burning any ash trees within 800 meters of each infestation epicenter. In 2003, the Michigan Department of Agriculture destroyed all trees within the infestation radius, but it was estimated that at least one generation of *A. planipennis* adults had already emerged from the trees prior to their destruction from the Shields site. At the St. Josesph site, it was estimated that three generations had colonized by 2003 (Siegert et al. 2010). The mean distance traveled by adult beetles was 220 meters from the origin of the Shields site, which can be attributed to the presence of a large, heavily infested tree that attracted high densities of adult EAB. *A. planipennis* from the Shields site laid eggs on ash trees ranging from 91-638 meters from the infestation origin. At the St. Joseph site, adult EAB oviposted at distances between 50-540 meters of the infestation epicenter and had a mean travel distance of 323.3 meters.

The evidence has shown that larval densities of the EAB decay with increased distance from the point of emergence as adult beetles feed on ash leaves and females search for mates. Mercader et al. (2009) studied two newly colonized sites in Michigan where approximately 90% of adult beetles stayed within 100 meters of the tree from which they emerged. The first site was located at a weigh station for commercial trucks in Livingston, County that had a corridor of forest that was dense with Green Ash (*Fraxinus pennsylvanica*). The second site was located at a large pile of infested ash firewood along a drainage ditch near Tipton, MI. A total of 88.9% of the adult beetles at this site stayed within 100 meters from their origin and 100% were within 300 meters. The farthest larval gallery was found 240 meters from the origin. Site two had yielded similar results where 90.3% of adult beetles stayed within 100 meters, and 97.8% were within 300 meters. The farthest larval gallery was found 387 meters from the origin. However, it should be noted that this study focused on areas with lower ash density than the Shields and St. Joseph infestation sites.

# Economic Impacts, Control, and Quarantine

With approximately 8 billion ash trees found throughout the United States alone, the implications of the EAB threat to North America’s ash resource are obvious. Ash trees are very familiar across urban landscapes and the wood is used in common household items such as furniture, tool handles, and baseball bats. America’s ash resource worth is estimated to be more than $300 billion (Poland and McCullough 2006; Sydnor et al. 2007; Prasad et al. 2010). Ohio is a state that has suffered huge loss due to the density of ash trees located throughout the state. In fact, it was estimated that up to 70% of shade trees that were planted in or near nurseries between the years of 2000 and 2003 were ash species (Sydnor et al. 2007). Effective quarantine efforts are key to preventing further spread in places like Ohio where there are very dense EAB and ash populations. After the EAB was discovered in the U.S. in 2002, quarantines were enforced to try prevent the further spread of the pest through the exporting ash trees from nurseries and identifying forests that were infested (Poland 2007).

Sydnor et al. (2007) attempted to quantify the economic impacts of the EAB threat to the state of Ohio’s ash resource. Based on a survey of 200 Ohio communities (with only 63 reporting back information), it was estimated that there was an average of 20.5 ash trees per 1000 residents, with a median of 8.3 trees per 1000 residents. They also proposed that Ohio communities could face harsh economic ramifications of ash tree destruction by the EAB with losses in landscape value, high costs of infested tree removal, and high tree replacement costs. According to the state tree guide, the estimated total value lost from the destruction of urban ash trees would be $71,045 using the median tree density value and $301,249 using the mean tree density value. This study hypothesizes that the tree removal costs would be the most realistic economic impact on communities in Ohio. Tree removal costs were estimated to be at $60,684 and $253,427 for the median and mean tree densities, respectively. Finally, they estimated that the least expensive impact would be the tree replacement costs with the median tree density cost at $25,671 and a mean tree density cost at $110,113.

As the research has shown, there can be significant economic impacts in the destruction of North America’s ash resource and therefore it is imperative to develop methods to control and eradicate this invasive species. Research geared to early detection could be crucial to setting up quarantine zones and slowing the spread of the emerald ash borer. Insect traps have been used to get population estimates and observer what attracts *A. planipennis* adults to ash trees. Purple prism traps can often be a visual cue for identifying a quarantine area and are commonly used in Michigan and New York where there are dense insect populations. These traps can also help to warn individuals that any wood removed from these quarantine areas will likely need treatment.

Marshall et al. (2010) conducted a study to observe different trap types to test efficacy of different olfaction lures in trapping EAB adults. There were 68 total study sites in Michigan, Ohio, Indiana, and Pennsylvania. Unscented and scented traps of different colors were set up at all sites. The 5 types included: (1) A green prism trap with phoebe oil lure was used, as well as a green prism trap with no lure as a control (2). (3) A purple prism trap was used with a phoebe oil, a purple trap with manuka oil (4), and a non-baited purple trap (5). These oils are what give off the scent of a stressed ash tree. Study sites were set up in suspected low density (≤ 2) infected trees per site. Of the 68 study sites, 27 of the areas did not capture any EAB specimens. A total of 33 test sites showed signs and symptoms of having EAB attacks and had a density of ≤ 2 infected trees per site with a total 64 EAB captured. Of these sites, only 14 had symptoms that were easily identifiable upon a visible inspection. Eight test sites showed high density presence of the EAB and the trees showed signs of considerable damage with a total 300 EAB specimens captured.

The results of the study showed that the purple prism traps with manuka oil were the most effective in luring and trapping adult beetles. The purple coloring of traps appeared to be an effective visual cue while the manuka oil lured the beetles to the trees. Manuka oil mimics the scent of a stressed ash tree because it contains volatile sesquiterpenes that are present in ash bark (McCullough et al. 2009). Out of all the traps set, 80% of the purple prism traps captured adult beetles, whereas only 47% of the green prism traps were able lure in adult beetles. Key factors for the success of traps were the location of the tree, canopy thickness, and dominant tree species within each forest stand.

Another method of control is to introduce natural predators. Woodpeckers have proven to be an effective biotic control in killing EAB larvae and have even eliminated up to 95% of the instars in some trees (McCullough et. al 2002). The three North American species of woodpecker that feed regularly on *A. planipennis* are the downy woodpecker (*Picoides pubescens*), the hairy woodpecker (*Picoides villosus*), and the red-bellied woodpecker (*Melanerpes carolinus*) (McCullough et al. 2002).

In 2002, McCullough et al. observed woodpecker predation on EAB larvae in an attempt to determine what factors influenced this behavior. Evidence has shown that predation rates and behavior changes can be affected by outbreaks in preferred insect food sources and by the conditions of trees. Hairy woodpeckers in particular seem to favor stressed or dying trees. Their study also showed that woodpecker predation on the *A. planipennis* larvae was higher on white ash than that of green ash with predation rates of 79.1% and 62.9%, respectively. However, it should be noted that the woodpecker predation rates at each site were inconsistent. These inconsistencies seem to jive with different local site-specific conditions such as amount of food sources available and the composition of tree species within the forest. One important finding was that the time woodpeckers spent on ash trees was five times greater than time spent on non-ash species. This behavior confirmed that the woodpeckers were attracted to trees with larval galleries.

Another important method of control is the heat treatment of infested ash logs. Any ash logs that are exported from a quarantine area should undergo heat treatment to kill any potential EAB larvae inside the wood to help prevent further spread to new sites. In 2008, Nzokou et al. conducted a study to test the efficacy of kiln and microwave heat treatment to kill EAB larvae. The kiln heat treatment proved to be most effective and killed all larvae at temperatures of 50 and 65 °C. Strangely, there were a few larvae that survived and adult EAB emerged from logs that were treated at 55 and 60 °C. It was determined that microwave treatments were not as effective as adult EAB emerged from logs treated at all temperatures and in greater frequency. This could be a due to an irregular distribution of heat inside the microwave.

# Conclusion

The emerald ash borer has proven to be a very significant invasive species in North America and Canada. As this pest spreads to new sites through both natural flight and human-mediated transport, they threaten the ash resource in hardwood forests and urban landscapes alike. New and better techniques to providing early detection of EAB infestations are essential to help prevent further spread. Early detection can help lead to more effective quarantine efforts to eliminate adult beetle populations, preventing them from laying more eggs on the bark of ash trees. Unfortunately, *A. planipennis* populations have traveled and colonized so rapidly that this problem is virtually beyond our control and North America’s ash resource is in danger.

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