Emerald Ash Borer, *Agrilus planipennis,* in Arizona: A Management Guide and Identification Key

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Abstract

Emerald ash borer (EAB, *Agrilus planipennis* Fairmaire), an invasive insect, has destroyed millions of ash trees (*Fraxinus spp.*) since its US arrival. EAB habitat in Arizona is relatively limited, as Arizona's climate slows development and establishment in a sizable portion of the state. While relatively small, we found Arizona’s ash range to overlap significantly with the suitable EAB habitat. A present ash population with a large crossover in suitable EAB habitat (78.20% overlap) necessitates land managers be knowledgeable to protect Arizona's ash trees. Plenty of past research into EAB management is available for application in Arizona. Prevention is the most cost-effective management option. Among the prevention techniques identified, purple double-decker prism traps baited with (Z)-3-hexanol successfully reduce EAB introduction at low densities. If prevention fails, damage mitigation, rather than EAB eradication, is the most practical strategy. Among the most successful damage mitigation techniques are systemic insecticides (Emamectin benzoate trunk injections) and biological controls (*Spathius galinae*).

Acknowledgments

I express my gratitude to many people who, without their unceasing support, I would not be who I am today. Dr. Richard Hofstetter, my adviser, I thank you for the support, the time, the resources, and, most of all, the guidance you have provided me. Dr. Kristen Waring for helping guide me to grad school. Kyle Rodman, for without his help, I would have never been able to produce the maps associated with the paper. For all the folks at AZ-DFFM, who deserve praise for their input and contribution to this project. Further, I am grateful to the NAU's School of Forestry community for being incredibly welcoming and friendly. So much help came from my family that it is hard to express. To Leo, my fiancé and best friend, for being all I could ever ask for in supporting me through grad-school. To my brother Jimmy and his fiancé Taylor for offering to send me care packages through my many health scares. To my Mom for her unwavering belief and support in my pursuits. To my Dad, who always offered to spell-check my work. A special thanks goes out to all my Grandparents. Thank you, Grandpa Murt, whose financial support allowed me to attend Grad School. Thank you, Grandma Judy, who never failed to send me a Christmas present. To Grandma Brenda and Grandpa John, even though you could not see me in grad school, I know you would be proud of me.

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EAB Fact Sheet. Photo Credits: Bornand (2019), Cappaert (2002), Cappaert (2005), Cappaert (2005 [*Agrilus planipennis*, elytra]), DiGirolomo (2014), Royals (1993), Lingafelter (2016), Michigan Department of Agriculture (2004), Ash seeds (2009), Bark of mature ash tree (2015), Dogbane (2017), Emerald ash borer galleries (2023), Oten (ND), Royals (2006).

Appendix B. Table 1

Table B-1. Emerald ash borer taxonomy- taxonomic classification of EAB, *Agrilus planipennis*, information adapted from Kenis (2009).

Introduction

The emerald ash borer (EAB, *Agrilus planipennis* Fairmaire), an invasive insect, has destroyed millions of ash trees (*Fraxinus spp*.) since it was discovered in the United States in 2002 (Siegert et al. 2014). Ash trees are highly valued for their drought tolerance, cultural significance, and air purification abilities, making them a common sight in both urban and wild settings across North America. The ubiquity of ash trees raises concerns about the potential widespread damage from EAB in every US state and Canadian province, underscoring the need for local land managers to assess the risks within their respective regions.

Even in arid regions like Arizona where there have been no confirmed EAB sightings, it is imperative for land managers to be well-prepared and knowledgeable about this invasive species. Ash tree populations in Arizona are relatively less common than in other US states, and ash distribution in Arizona is not thoroughly documented. Furthermore, the capacity of EAB to establish in Arizona remains poorly understood because of climate extremes. This paper seeks to address some of these knowledge gaps by providing insights into ash habitat ranges, EAB climatic suitability, and EAB generation timings in Arizona.

The structure of this paper is organized into four sections to facilitate a comprehensive understanding of EAB threats in Arizona. The first section offers an overview of EAB, covering the insect’s biology and historical content. The second section focuses on assessing the risks posed by EAB, including vulnerable species, EAB's climatic suitability, and the timing of EAB generations. The third section serves as a practical guide for identification, assisting readers in discerning differences among EAB and its counterparts, distinguishing between ash trees and similar species, and recognizing signs and symptoms of infestation. The final section provides valuable insights into EAB management, covering treatment options and reviewing past management efforts.

Overview of EAB

Biology

The Emerald ash borer (EAB), classified under the class Insecta, belongs to the order of Coleoptera, which is primarily characterized by a pair of hardened elytra that cover the abdomen and a second pair of membranous hind wings (Balke et al. 2004). Order Coleoptera encompasses many families of beetles; one of which is Buprestidae, the family to which EAB belongs. Buprestidae, also known as jewel beetles, exhibit distinctive features as adults, including a metallic appearance, bullet-shaped body, relatively small mandibles, large eyes, and small saw-tooth antennas (Dutkiewicz 2017). During the larval stage, Buprestidae possesses a flat thorax with elongated, legless, white bodies (refer to Figure 8-2) (Dutkiewicz 2017).

EAB can be distinguished from other Buprestidae by its characteristic green coloration with a copperish shine and a bright metallic red dorsal coloration on its abdomen (Parsons 2008). For more information regarding EAB identification, refer to the identification key provided in Figure 8 of the Management Section.

Like all Coleoptera, EAB undergoes complete metamorphosis, a process termed holometabolous. In the case of EAB, the life cycle encompasses the following stages: egg, larvae, pupae, and adult, the timing of each stage is influenced by temperature (see Figures 6 and 7). The egg stage is relatively brief, lasting only 1-2 weeks (Wei et al. 2007). These small white eggs, 50-90 individually laid among many ash trees, will transition to brown as they approach hatching (Kenis 2009). Upon hatching, EAB larvae will burrow into the cambial region of its host tree (Baurer et al. 2003). Over the next 300 days, the EAB larvae will feed, overwinter, and develop through 4 distinct instars (Baurer et al. 2003) before finally pupating (Kenis 2009). Larval feeding is the likely cause of ash tree mortality, and EAB pupae are often found once trees have died. Upon emerging from their pupae as fully developed adults, EAB are capable of flight (Baurer et al. 2003) and dispersal. Once an adult, EAB will initiate mating and egg-laying within 1-2 weeks, restarting the cycle (BenDor et al. 2006). EAB adults may live many weeks and feed in the canopy of ash trees.

EAB in North America and parts of Europe is known as an invasive pest, but is native in “China, Mongolia, North Korea, South Korea, Japan, Taiwan, and the Russian Far East” (Orlova-Bienkowskaja & Volkovitsh 2018). Within these countries, EAB has the following host trees: ash, elm (*Ulmus spp.*), walnut (*Juglans spp.*), and wingnut (*Pterocarya spp.*, Mastro & Reardon 2005). However, white fringe tree (*Chionanthus virginicus*) and cultivated olive (*Olea* *europaea*) can also be hosts for EAB (Cipollini et al. 2017, Mastro & Reardon 2005) as explored in the Risk of EAB section. Additionally, in their native habitat, EAB targets weakened trees and is typically rare in the environment. However, the lack of tree defenses and natural predation in North America allows for high host mortality in relatively healthy trees (Orlova-Bienkowskaja & Volkovitsh 2018).

Introduction of EAB into the United States

Dendrological evidence suggests EAB was initially introduced in southeastern Michigan during the early to mid-1990s (Siegert et al. 2014), most likely arriving through wooden shipping containers from northeastern Asia. Michigan, with its climates and resources resembling those of EAB's native range, provided favorable conditions for the insect. Additionally, the region lacked natural predators and adequate tree defenses, facilitating the establishment of EAB and its subsequent devastation of host trees. From this infestation in southeastern Michigan, satellite colonies would spread at a rate of 7.4 per year, with an average jump distance of 24.5 km (Siegert et al. 2014).

Already well established, EAB was officially detected near Detroit, MI in 2002. While not uncommon for an invasive species, a detection lag was exacerbated due to a combination of previously declining ash populations and the presence of native secondary borer insects. This allowed EAB to establish throughout Michigan while remaining undetected (Poland & McCullough 2006). Aided by human transportation of infested ash wood, an established population of EAB in Michigan quickly led to the discovery of EAB across state lines. Much like EAB detection in Michigan, there was a lag time in detection in neighboring states.

The environmental impacts of EAB's expansion were extensive and far-reaching (Herms & McCullough 2014). The following outlines some of the broader EAB impacts: increased coarse woody debris, changes in successional trajectories, widespread formation gaps, an increase in invasive species, changes in bird communities, changes in arthropod communities, altered understory environments, and changes in overall forest processes (Herms & McCullough 2014, Klooster et al. 2018). As explored in later sections, most of Arizona's wild ash grows within riparian systems, which are valuable for biodiversity and soil water retention. As noted by Nisbet et al. (2015), the loss of ash can damage this valuable ecosystem; reductions in high-quality leaf litter input and increased canopy openings are among the more significant damages. These impacts have the following direct and indirect cascading effects: changes in water temperature, nutrient availability, aquatic species composition, increased sediments in runoff, and an increase in invasive species (Nisbet et al. 2015).

For over a decade, EAB was contained to the eastern half of the US, but in 2013 was discovered in Boulder, Colorado. Originally, Colorado's front range was relatively free of ash trees, but large urban forests now occur with the expansion of population centers (Kathleen et al. 2020). These urban forests typically contain two species of ash: green ash (*Fraxinus pennsylvanica*) and white ash (*Fraxinus americana*) (Kathleen et al. 2020). With a foothold in

Colorado, EAB can potentially spread to the remaining western states. This threat would soon become a reality as EAB was discovered in Oregon in 2022 (Popkin 2022). Oregon is home to at least eight species of ash (Popkin 2022), including Oregon ash (Fraxinus latifolia), whose range extends into southern California.

As EAB spreads through the western US, there remains uncertainty regarding its establishment in Arizona due to its unique climate. The following section explores this uncertainty by identifying vulnerable species, viability, and generation timings of EAB in Arizona's climate.

Risk of EAB

Vulnerable Species of Ash in Arizona

There are several species of ash trees in Arizona, most of which are in urban or riparian areas. However, urban trees, facing heightened environmental pressures, are notably more susceptible to pests like EAB and consequently face higher risks. The following urban tree species are categorized into distinct geographical areas based on i-Tree Streets classification: the Interior West, the northern climate, and the southwestern desert (refer to Figure 1, Table 1).

Common ash species in Arizona include white ash (*Fraxinus americana*), Raywood ash (*Fraxinus angustifolia*), Arizona/Mexican ash (*Fraxinus berlandieriana*), green ash (*Fraxinus pennsylvanica*), and velvet/modesto ash (*Fraxinus velutina*) (Arizona Urban Tree Map Field Guide 2015). Within the northern and high elevation areas of Arizona, the common ash species are white ash and green ash (Arizona Urban Tree Map Field Guide 2015). Within the southwestern desert of Arizona, the common ash species are evergreen ash (*Fraxinus uhdei*), and velvet/Arizona ash (Arizona Urban Tree Map Field Guide 2015).

Among the limited ash species in Arizona, only a few are considered favorable hosts for EAB. According to Herms & McCullough (2014), while all species of ash are at risk, EAB tends to prefer black, white, and green ash over other species. Species of green ash, in particular, are at the greatest risk. As Lyons et al. (2009) found, EAB will almost exclusively choose green ash over other species. Unfortunately, both species of green and white ash are found in urban and native settings throughout Arizona. Additionally, velvet ash, the most common ash species in Arizona, is closely related to green ash, being identified by some to be a subspecies (MacFarlane & Meyer 2005) and is a suitable host for EAB (Anulewicz et al. 2014).

Outside of the ash genus, there are two other species of trees that are known to support EAB development– white fringe tree and cultivated olive (Cipollini et al. 2017). Of these species, only cultivated olive is found within Arizona, as it is grown in urban settings within the southwest desert region (Arizona Urban Tree Map Field Guide 2015).

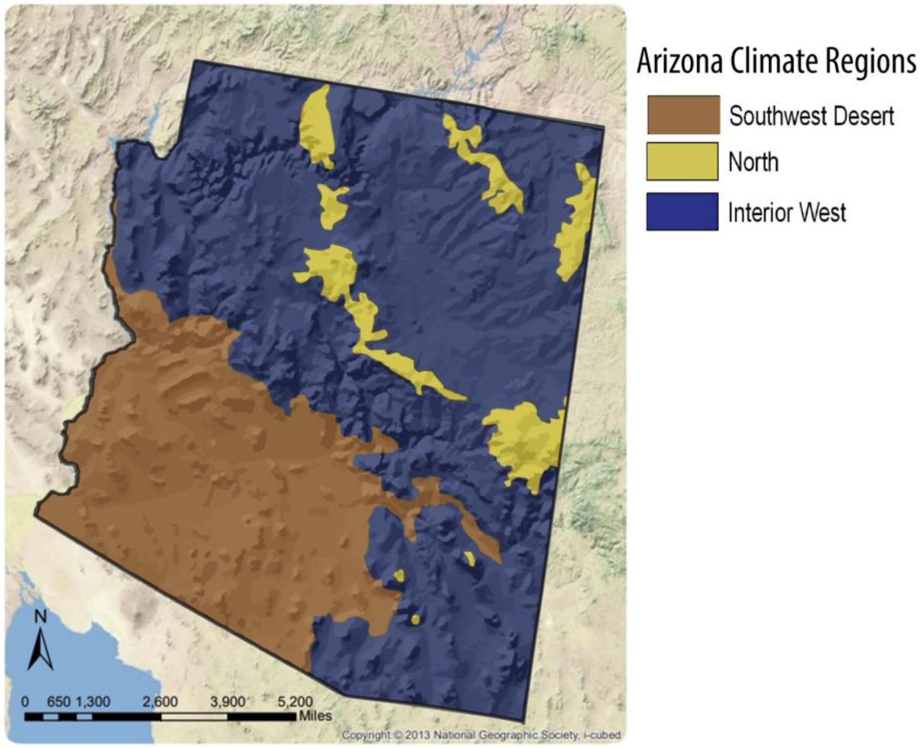


Figure 1. Arizona Climate Regions. Map of Arizona's climate regions as defined by I-Tree Street, adapted from Arizona Urban Tree Map Field Guide (2015).

Table 1. Ash Trees by Arizona Climate Regions. List of ash species by Arizona's climate regions

Region	Southwest Desert	North	Interior West
	Evergreen ash (*Fraxinus uhdei*)	White ash (*Fraxinus americana*)	White ash (*Fraxinus americana*)
	Velvet/Arizona Ash (*Fraxinus velutina*)	Green ash (*Fraxinus pennsylvanica*)	Narrow-leaved ash (*Fraxinus angustifolia*)
	-	-	Mexican ash (*Fraxinus berlandieriana*)
	-	-	Green ash (*Fraxinus pennsylvanica*)
Common Species	-	-	Velvet/Arizona Ash (*Fraxinus velutina*)

as defined by I-Tree Street (Arizona Urban Tree Map Field Guide 2015).

Viability of EAB to Live in Arizona Climate

A map of ash populations in Arizona is needed to predict EAB-associated risks. To address this information gap, we created ash range maps of Arizona utilizing SEINet data (SEINet Portal Network, 2023), LANDFIRE 30m DEM raster (LANDFIRE 30m DEM raster, 2016), PRISM climate data (30-year normals 2023), and MAF/TIGER census data (Census MAF/TIGER database, 2016).

The SEINet spatial data, identifying 15 distinct ash species occurring within Arizona, facilitated the determination of the 95% elevational bounds (658.03 – 2131.47 meters) at which native ash species have been observed. As well, we determined both the 95% temperature and precipitation bounds of the SEINet ash occurrences. The 95% temperature bounds were 40.85 °C (maximum July), 6.55 °C (minimum January), and 17.16 °C to 29.06 °C (annual average). The 95% precipitation bounds were 14.35 to 143.39 inches (minimum and maximum July), 17.59 to 81.43 inches (minimum and maximum January), and 172.40 to 727.77 inches (minimum and maximum annual). Ash trees also occur in urban areas; therefore, it was essential to include all urban areas delineated by the MAF/TIGER census data. Additionally, incorporating urban areas in the risk map encompasses cultivated olive trees. For the resulting risk map, refer to Figures 2-5.

As ash in Arizona experiences extreme temperatures, we needed to understand temperature thresholds for EAB development and survival. To do so, PRISM climate data (30-year normals 2023) from known EAB locations in other states were analyzed and restricted to 95% bounds. The temperature bounds were notable: a maximum July temperature of 34.98 °C, a minimum January temperature of -12.24 °C, and annual temperatures ranging from 2.59 ºC to 26.90 °C. These temperatures significantly overlapped with the previously estimated ash tree range (78.20%) (refer to Figures 3 & 5).

Alternatively, research by Lyons et al. (2005) and Liang & Fei (2014) suggest temperature bounds of -38 ºC and 33 ºC (refer to Figure 4). Lyons et al. (2005), through a controlled study, found that while EAB pupae and larvae can withstand temperatures up to 53 ºC, adult EAB female longevity is reduced to 5 days at 33 ºC. Liang & Fei (2014), through maxent modeling, suggest 33 ºC and -38 ºC to be the upper and lower limits to EAB's climatic suitability. Therefore, it can be expected that higher temperatures will limit climatic suitability and sustain a trend of decreased longevity.

However, it's crucial to note that our understanding of the upper-temperature of EAB tolerance is limited. Thus our risk map and models might not represent the true upper-temperature threshold for EAB survival but rather areas where the establishment of EAB might be more prevalent.

Generation and Biology in Arizona Climate

Growing Degree Days (GDDs) are widely utilized for predicting the development rates of insects. Insects require a certain number of days over a specified base temperature to develop; a GDD model sums these days per year. For example, EAB has a base temperature of 12 ºC and in its existing invasive range has enough GDDs to produce a single generation per year (termed univoltine). However, in Arizona, the accumulated GDDs were double that of its invasive range.

According to Liang & Fei (2014), without a cool period to induce diapause, EAB larvae will not develop into adults or will do so “sporadically and produce stunted adults.” Additionally, excessively high temperatures, particularly at the threshold of 33 ºC, can halt the development of EAB eggs, larvae, and adults. This suggests that despite sufficient GDDs, achieving two generations in a year might not be feasible. Using an EAB GDD model for Arizona, adapted from the USA National Phenology Network, EAB’s emergence timing was mapped (refer to Figures 6 and 7).

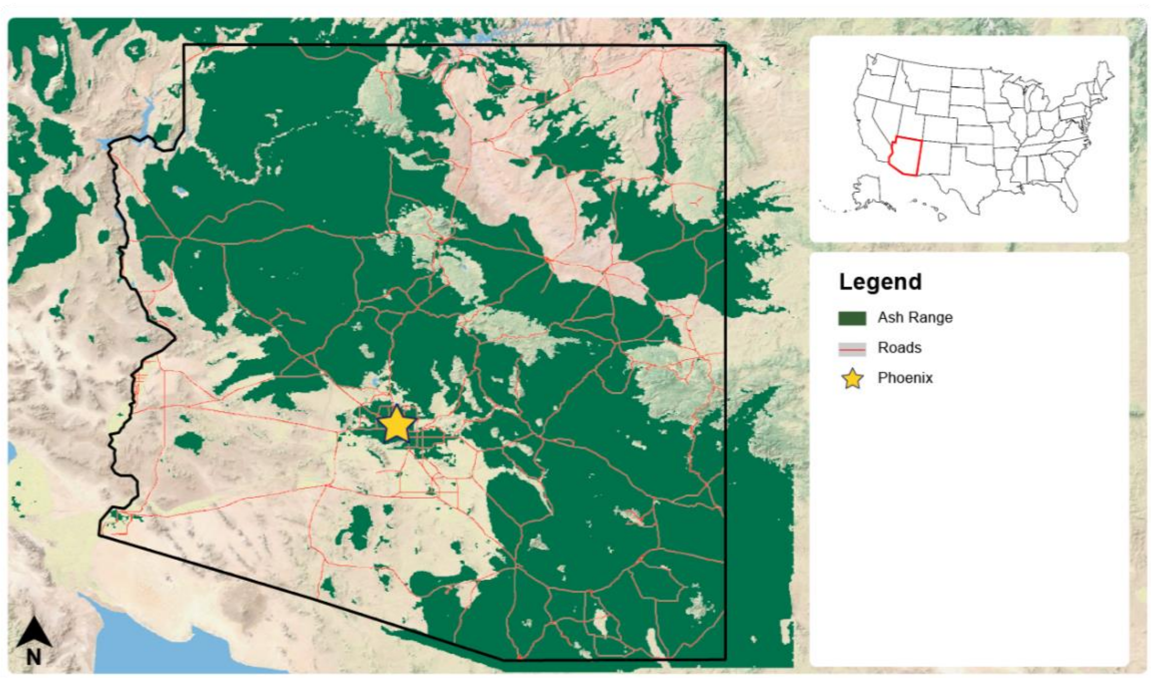
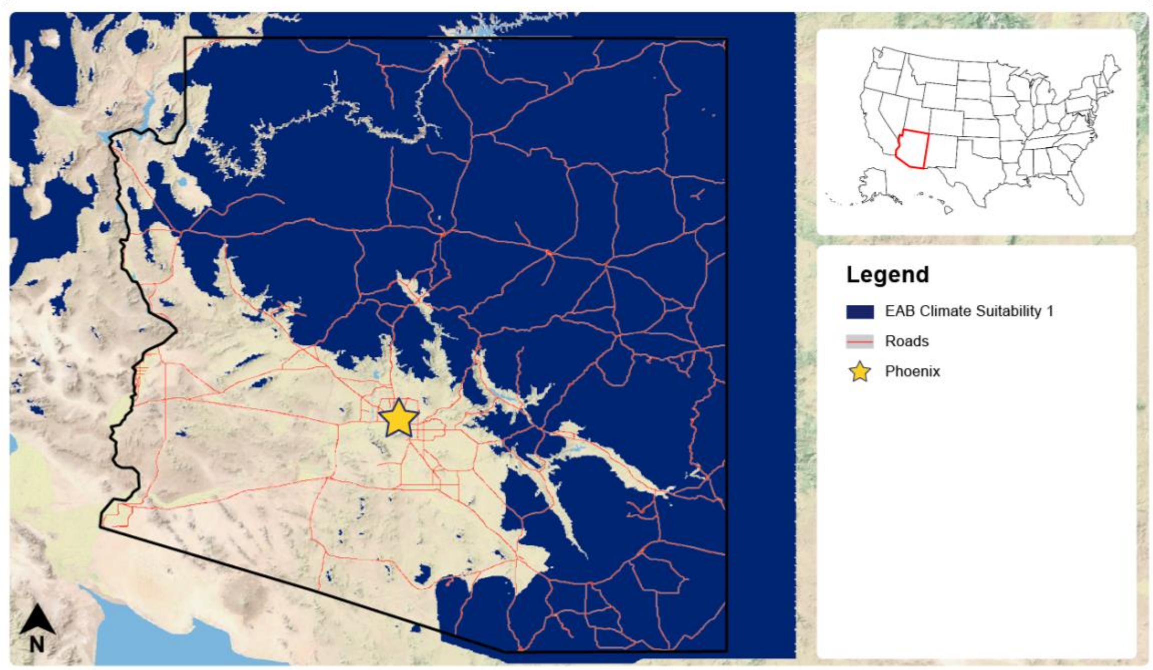


Figure 2. Estimated ash location. Ash populations (green) were estimated using 95% bounds of elevational, temperature, and precipitation determined from presence only data. Urban areas are included in this range. The size of the resulting ash range was 150283.77 km^2 or 50.90% of Arizona's total area.



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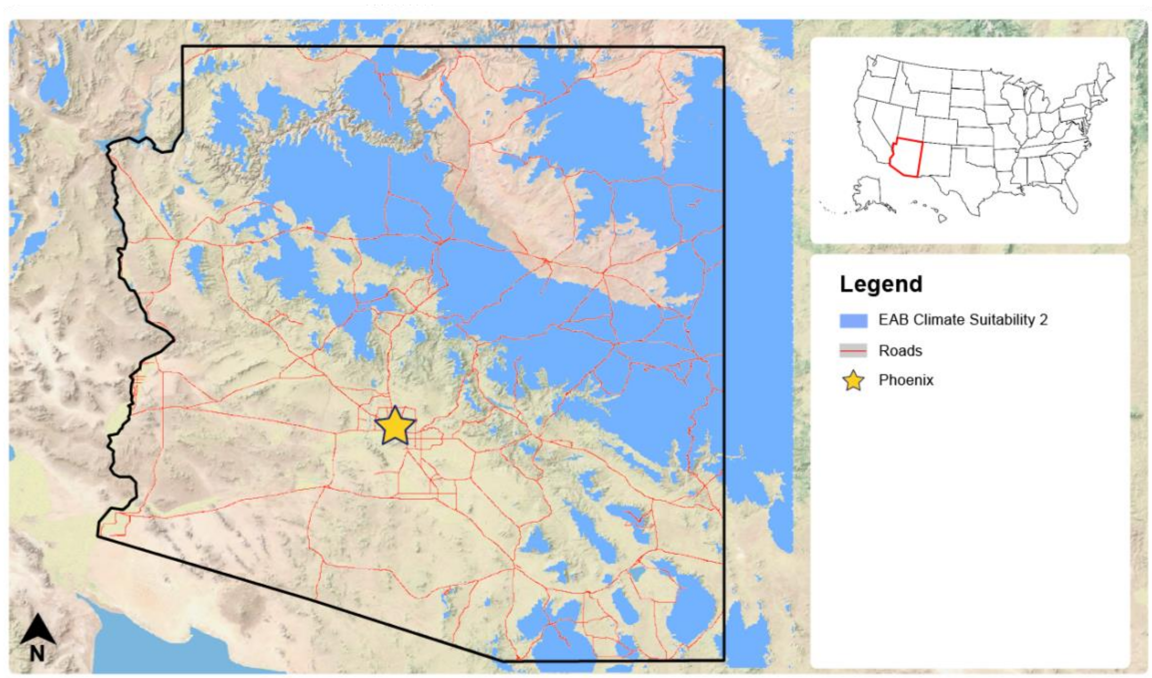

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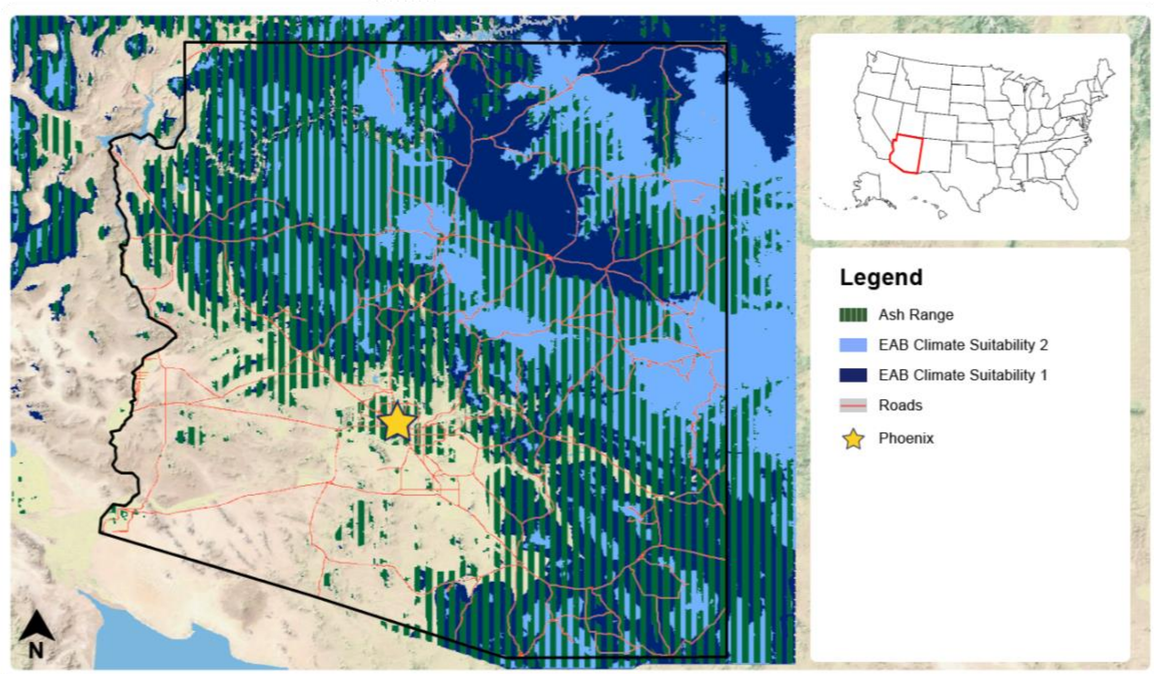

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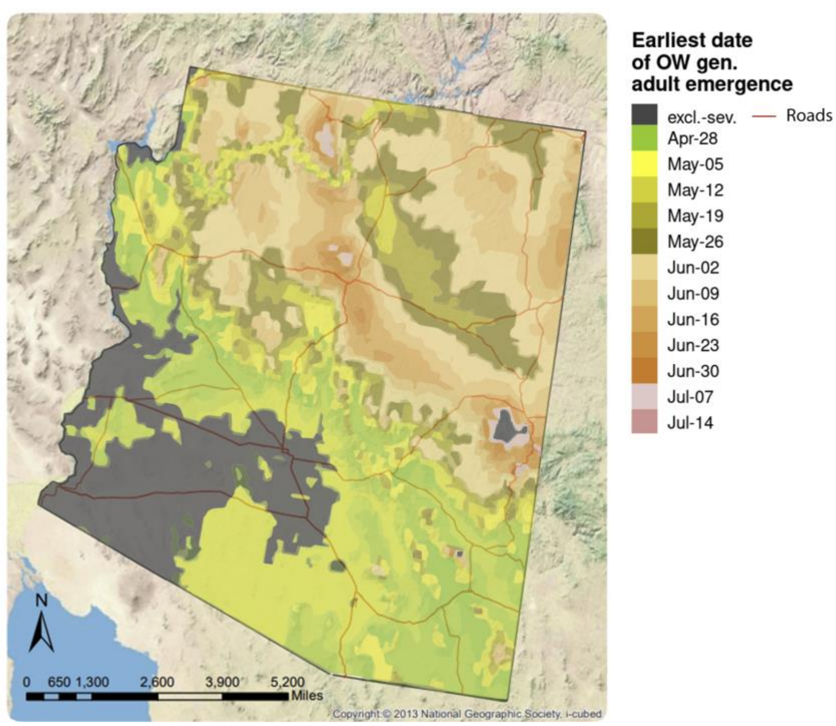

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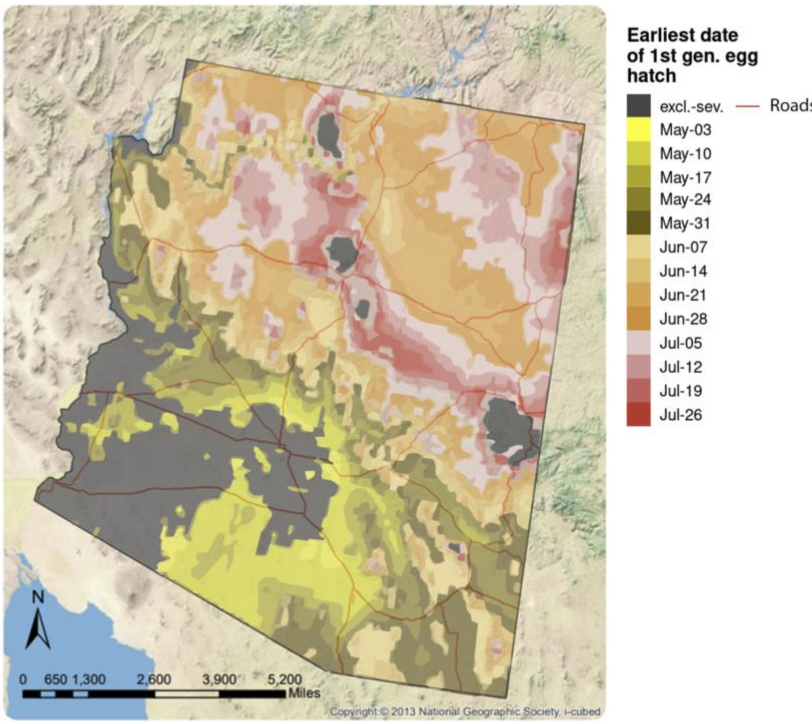

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Identification

EAB are in the order Coleoptera (beetles), distinguished by a pair of hardened outer wings referred to as elytra. Within this order there are two relevant families of wood-boring beetles: Cerambycidae and Buprestidae. EAB belongs to the latter family, characterized by their large eyes, small antennae, small mouth parts, and bullet-shaped bodies. As opposed to other Buprestidae, EABs have distinct metallic emerald coloration, sometimes displaying shades of blue or red. As well, the dorsal abdomen of the EAB appears red to purple with a metallic shine.

EAB undergoes complete metamorphosis. Therefore, identification of EAB requires discerning not only its adult stage but also its egg, larval, and pupal stages.

EAB eggs are typically 1 mm in size and may range from white to amber contingent upon their developmental timeline (Bauer et al. 2003). These eggs are individually laid on the bark surface of ash trees (Kenis 2009). Within 1-2 weeks, the eggs will reach their next life stage– larva.

EAB larvae feature ten bell-shaped abdominal segments, flat heads, and reach a size range of 26 to 32 mm long before pupating (Gould et al. 2019). These larvae inhabit the phloem and outer sapwood layers of ash trees, developing s-shaped galleries (Gould et al. 2019). Larvae may be found in stems or branches.

Measuring between 11-16 mm, EAB pupae are located in the outer sapwood. Initially, they appear j-shaped with a creamy coloration which will darken as they mature (Gould et al. 2019). Maturation also induces a transformation in the pupal shape, gradually resembling the adult form (Gould et al. 2019).

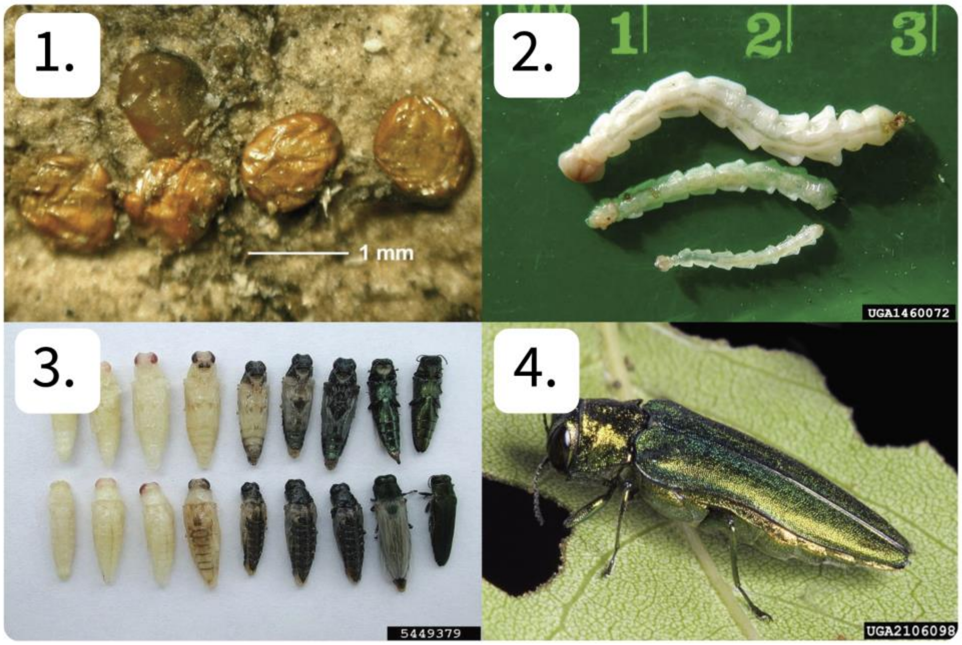

Figure 8. EAB Identification. Identification key for EAB in its four life stages. 1) EAB eggs (Cappaert 2002a). 2) EAB larvae (Cappaert 2002b). 3) EAB pupae (Miller 2011). Image 4: EAB adult (Cappaert 2005).

Look-alike Species

Arizona harbors several species that closely resemble EAB. Many of these look-alike species not only share common characteristics but are taxonomically similar to EAB; some belonging to the same order, family, or genus. This section distinguishes similar insects from EAB, such as the honey locust borer (*Agrilus difficilis*), Gambel oak borer *(Agrilus aeneocephalus)*, Arizona argilus *(Argilus Arizonicus)*, *Temnochila* beetles (*Temnochila spp.*), and dogbane beetle (*Chrysochus auratus*). Refer to Figure 9 for images of each species discussed next.

Honey locust borer (*Agrilus difficilis*)

The honey locust borer shares the same genus as EAB, *Argilus*, thus share similar physical characteristics. EAB and honey locust borer share a bullet-shaped body and coloration. EAB and honey locust borer are best differentiated by the color of their abdomens; EABs have a purple-red shine on the dorsal side of their abdomen, whereas honey locust borers exhibit a golden shine on theirs.

EABs and honey locust borers can also be distinguished through their host tree species. While EAB exclusively targets ash species, honey locust borers will only colonize locust, practically the honey locust, *Gleditsia triacanthos* (Akers et al. 1986). Despite the visual resemblance between honey locust and ash trees, they differ in their leaves, seeds, and thorn presence. In ash trees, the pinnate leaflets occur opposite each other, while honey locust leaflets alternate. In ash trees, seeds are a mass of single-winged samaras, while honey locust seeds occur in pods. While not all honey locust trees have thorns, the presence of thorns can easily differentiate between the two trees.

Arizona argilus (*Argilus Arizonicus*)

Another insect within the Argilus genus, *Agrilus arizonicus* shares many features with EAB; mainly a bullet-shaped body and coloration. Much like the honey locust borer, the EAB and *Agrilus arizonicus* are best differentiated by their abdomen; *Agrilus arizonicus* have a greenish-black shine on the dorsal side of their abdomen, whereas the EAB exhibit a purple-red shine on theirs. Unfortunately, the host plant for *Agrilus arizonicus* is not well documented, and cannot be used to distinguish between the two species.

Gambel oak borer (Agrilus aeneocephalus)

The third look-alike insect within the *Argilus* genus, the Gambel oak borer shares a bullet-shaped body and metallic coloration with EAB. Unlike the EAB's green coloration, the Gambel oak borer exhibits a golden-bronze coloration. As well, the Gambel oak borer prefers trees in the Fabaceae family (Jendek & Poláková 2014) in contrast to the *Fraxinus* genus preferred by EAB.

Dogbane Beetle (Chrysochus auratus)

Members of the leaf beetle family, dogbane beetles share the following characteristics with EAB: metallic green coloration, overlap in size, and small mouthparts. However, their oval-shaped body, small eyes, and relatively large claws distinguish this beetle from EAB. Additionally, dogbane beetles prefer the leaves of dogbane and milkweed rather than ash trees (MacEachern-Balodi et al. 2017).

Temnochila Beetles (Temnochila spp.)

Beetles within the *Temnochila* genus share many similarities with EAB: similar metallic colors, cylindrical shape, small antenna, and a significant overlap in size. However, the Temnochila beetle's small eyes, large mandibles, and pronounced thorax differ from EAB's large eyes, small mandibles and a less distinctive thorax. Adults can be found in a variety of habitats as they often are predators of other insects, such as bark beetles. Their larvae can also be found in trees killed by other insects.

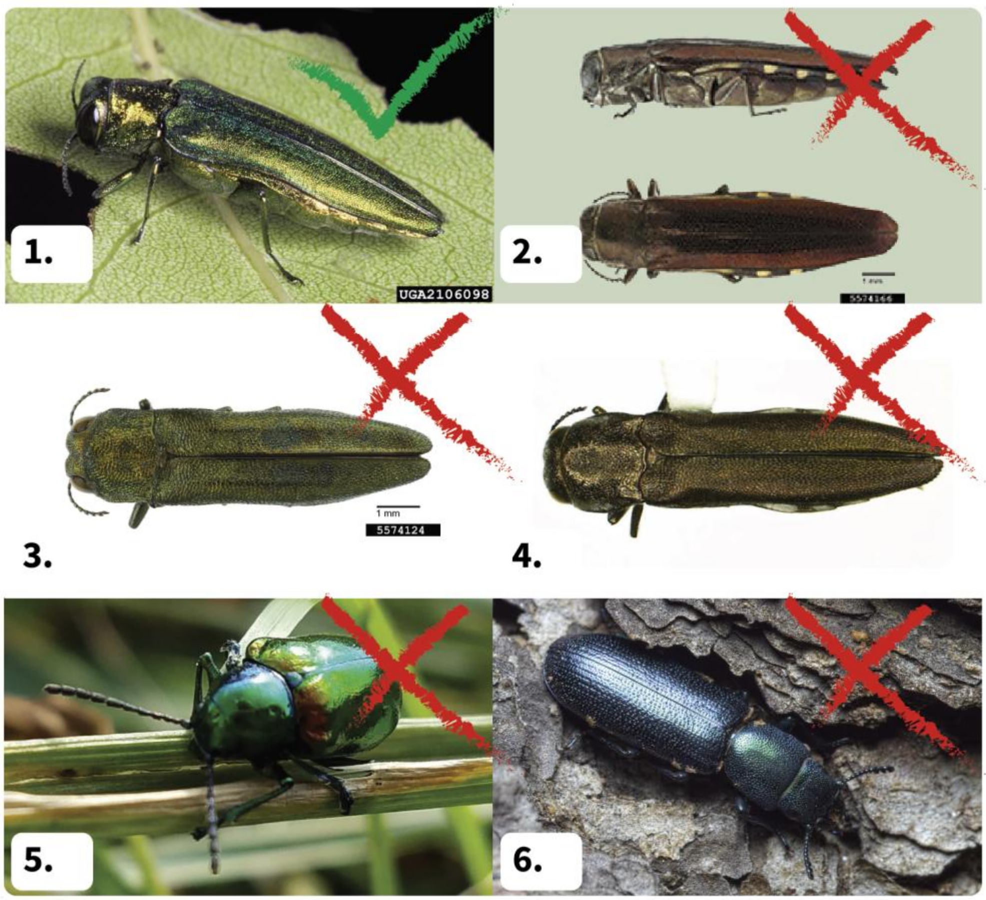

Figure 9. EAB Look-alikes. Identification key for EAB, as well as its common Arizona look-alikes. 1) Emerald ash borer (*Agrilus planipennis*) (Cappaert 2005). 2) Honey locust borer (*Agrilus difficilis*) (Royals 2006). 3) Arizona argilus *(Argilus Arizonicus)* (Royals 1993). 4) Gambel oak borer (*Argilus aeneocephalus*) (Lingafelter 2016). 5) Dogbane beetle (*Chrysochus auratus*) (Dogbane 2017). 6) Temnochila beetles (*Temnochila* spp.) (Bonand 2019).

Ash Tree Identification

Identifying the host tree is crucial for successful EAB identification, as only damages to the host tree, rather than the EAB itself, may be evident. For this reason, it is essential for land managers to be adept at recognizing the host trees and the associated signs and symptoms of EAB. Found throughout Arizona (refer to the map above), ash trees are best identified by their leaves and bark. In the genus *Fraxinus*, these hardwoods have compound leaves containing 5-9 leaflets, opposite branches and buds, and diamond-shaped furrows on mature bark (refer to Figure 10).

In Arizona, many trees resemble ash, which can complicate identification. These include boxelder *(Acer negundo)*, maple (*Acer spp*.), tree of heaven (*Ailanthus altissima*), goldenrain (*Koelreuteria paniculata*), black locust (Robinia pseudoacacia), honeylocust (*Gleditsia triacantho*s), Japanese pagoda (*Sophora japonica*), mountain ash related species (*Sorbus spp.*), hickory related species (*Carya spp.*), algarrobo europeo/carob (*Ceratonia siliqua)*, India rosewood/sissoo (*Dalbergia sissoo*), Chinese pistache (*Pistacia chinensis*), California peppertree (*Schinus molle*), silk oak (*Grevillea robusta*), ironwood *(Olneya tesota*), Texas mountain laurel (Sophora secundiflora), walnut related species (*Juglans spp.*), and sumac related species (*Rhus spp.*).

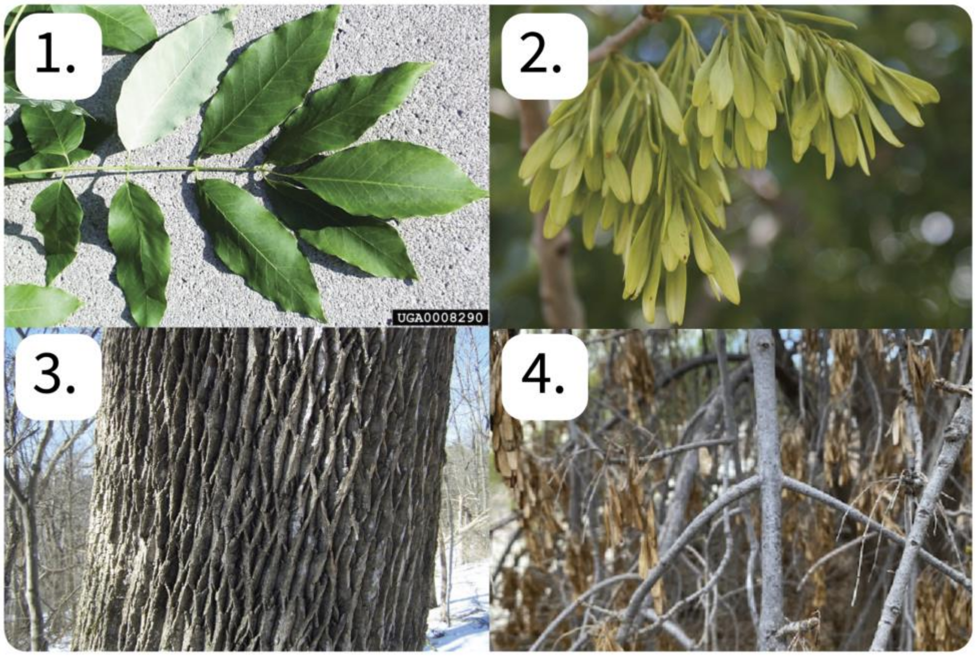

Figure 10. Ash Tree, *Fraxinus spp*. *Oleaceae*, Identification. Identification key for identifying trees in the genus *Fraxinus*. 1) Ash Leaflet (State of New Jersey c2016), compound, containing leaflets of 5-9. Oblong and occurring opposite from each other. Diverse sets of color, including yellow, red, purple, or green. 2) Ash Seeds (Ash seeds 2009), single-winged seeds called samaras. Samaras form clusters that reach maturity in the Fall months. Color can present as brown, tan, or green. Samaras can be 1-3 inches long. 3) Ash Bark (Bark of mature ash tree 2015), diamond-shaped furrows on mature trees. Ash bark can be light brown to light grey. 4) Ash Tree Branch, buds, leaflets, and branches all occur opposite each other.

These trees share urban habitats and pinnate compound leaves similar to those of ash. However, ash trees have opposite pinnate compound leaves (refer to Figure 11). In contrast, most of the above species have an alternating leaf arrangement, the exceptions being boxelder and maple.

Boxelder and maple are broadleaf trees commonly found in natural and urban settings alongside ash trees. Contributing to challenges in ash identification, both of these trees exhibit opposite pinnate compound leaves. However, leaf shape is a crucial distinguishing feature: boxelder and maple leaves feature pronounced serrations along the margins, while ash trees typically possess leaves with minimal or no serration (refer to Figure 11).

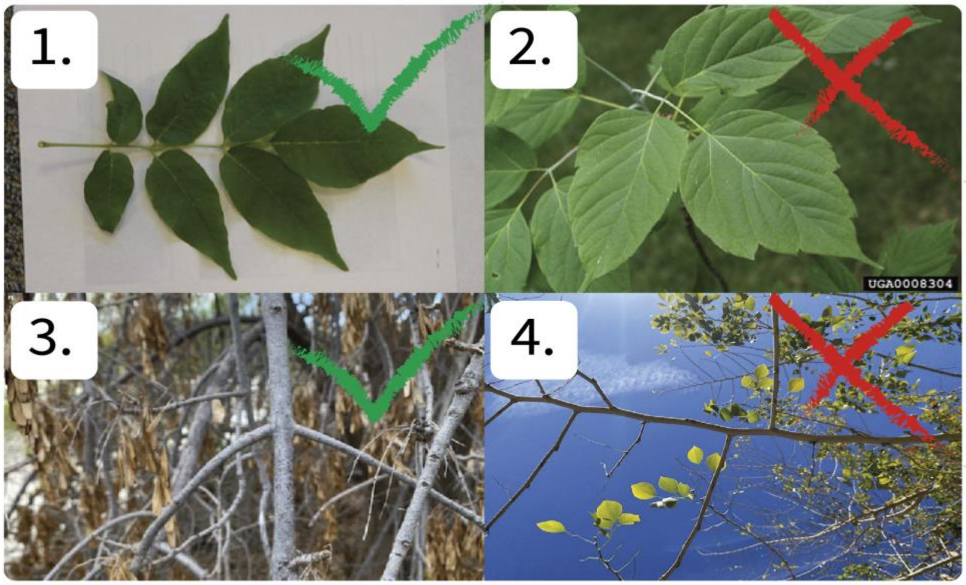

Figure 11. Ash Look-alikes. Identification key aiding in identifying ash trees and their common Arizona look-alikes. 1) *Fraxinus spp*. leaf (Michigan Department of Agriculture 2004). 2) *Acer spp*. leaf (Wray 2001). 3) *Fraxinus spp*. opposite branch. 4) Alternating branch.

Signs and symptoms of EAB

The signs and symptoms of EAB infestation are subtle until the effects become severe (refer to Figure 12). Nonetheless, detecting these signs and symptoms is crucial for managing EAB. The primary signs of EAB infestation include distinct galleries in the phloem and exit holes in the bark. Insect galleries can be distinct between species, aiding identification. For EAB, the galleries are a S shape (i.e. meandering) and packed with frass, a mixture of sawdust and excrement (Herms et al. 2004). EABs form galleries under the bark and within the phloem during their larval stage. Located on the trunks and main branches of ash trees, EAB exit holes exhibit a distinctive D shape and measure ⅛ inch in diameter. Exit holes are created when adults emerge from the phloem or bark.

Symptoms of EAB can pose additional challenges as they are broad indications of a tree in decline. These symptoms include bark splits, crown dieback, and epicormic shoots (Herms et al. 2004). Bark splits occur when trees attempt to expel larval galleries; the development of these galleries prompts the formation of wound-periderm tissue, causing vertical bark splits. Resulting from a restricted nutrient flow to the crown, crown dieback occurs when EAB larvae colonize and girdle a tree's phloem. The stress induced by girdling also triggers the growth of epicormic shoots, characterized by small leafy shoots sprouting from the trunk and major limbs of declining trees. As these symptoms are common, it is crucial to find any accompanying signs of EAB in combination with these symptoms.

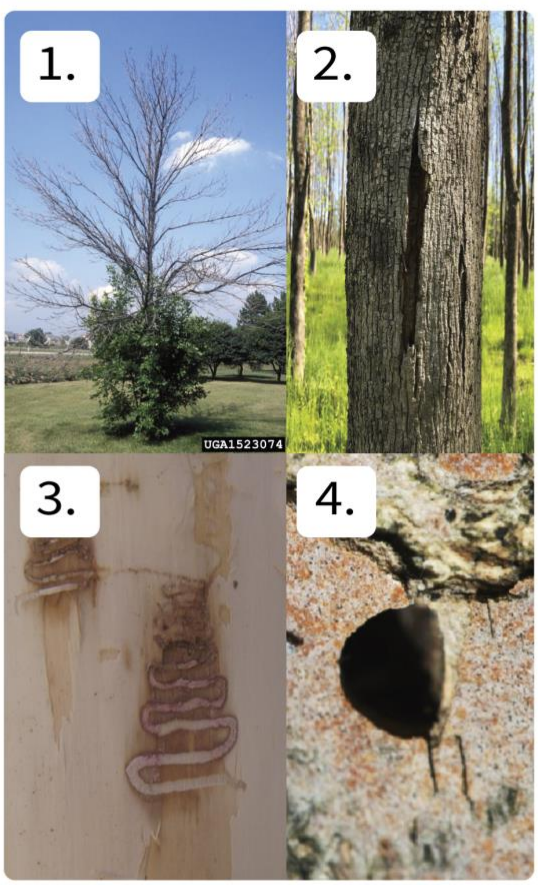

Figure 12. EAB Signs and Symptoms. Identification key for identifying EAB signs and symptoms. 1) Crown dieback & epicormic shoots (Bauer ND). 2) Bark splitting (Oten ND). 3) EAB gallery (Emerald ash borer galleries 2023). 4) EAB exit-hole (Cappaert 2002b).

Management

Treatment

As with most invasive species, the primary strategy for effective management is to prevent the introduction and establishment of a pest (Berry et al. 2017, Liebhold & Kean 2019). While prevention efforts can cost substantial sums of money, they can save significant amounts of resources in the long run. According to Berry et al. (2017), the Denver metro area would have to spend $595,000 annually to save an estimated $807 million in damages.

Given that human transportation is the primary means of EAB distribution introduction into new areas (Herms & McCullough 2014), a quarantine of possibly infested materials is the most common method for EAB prevention. These quarantined materials encompass not only ash species but other hardwood species. For example, Washington County, Oregon, has restricted movement of tree materials, including “logs, green lumber, nursery stock, scion wood, bud wood, chips, mulch, stumps, roots, branches, and firewood of hardwood species (Emerald Ash Borer 2022).”

Although prevention efforts can significantly impede the spread of EAB, it cannot ensure complete immunity against the insect’s establishment. In the event of EAB’s establishment within a state, several tools are accessible to land managers. These tools include biological controls, trap trees, silvicultural practices, chemical treatments, or a combination of these methods.

Typically involving an active human role, biological control is a method aimed at reducing pest populations through the use of natural enemies (Stenberg et al. 2021). This approach is often preferred due to its reduced environmental impact as compared to the possible effects of widespread insecticidal treatments. Several types of EAB parasitoids have been mass-reared and released for biological control. These species include *Spathius agrili*, *Spathius galinae*, *Tetrastichus planipennisi*, and *Oobius agrili*. The success of these parasitoids varies from low to moderate, with *Spathius galinae* demonstrating the most effective reduction in net population growth rates (Duan et al. 2020, Duan et al. 2023).

Woodpeckers (*Picus spp.*) have also shown the ability to reduce EAB larval densities in trees by significant percentages ranging from 33% to 88% (Murphey et al. 2018). Utilizing woodpeckers alongside parasitoids could enhance EAB biocontrol efforts. However, the extent of this benefit depends on the woodpeckers' response to EAB parasitism, of which further research is needed (Murphey et al. 2018).

Another tool available to land managers, trap trees aggregate an invasive species into individual trees meant for removal. Given EAB's tendency to target weakened or dying trees, land managers exploit this behavior by setting up girdled trap trees that emit chemical and visual signals that entice EAB colonization (McCullough 2020). Once colonization occurs, the trap trees are harvested and treated.

Similar to trap trees, artificial traps replicate stressed trees' visual and chemical cues (McCullough 2020). EAB relies largely on visual cues and volatiles emitted by ash trees to initially locate suitable hosts (McCullough 2020), artificial traps aim to replicate these cues. To replicate visual cues, traps are often colored green or purple, shaped as prisms or funnels, and positioned on full-sun trees or posts (McCullough 2020, Poland et al. 2019). Typically, the green leaf compound (Z)-3-hexanol replicates ash volatiles and is used to bait double-decker traps (McCullough 2020) (Poland et al. 2019). Studies have shown that double-decker traps, two prism traps arranged above each other, yield the best outcomes in reducing EAB introduction at low densities. In contrast, single prism and funnel traps show better use for surveying EAB populations (McCullough 2020, McCullough & Poland 2017, Poland et al. 2019).

Silvicultural methods for managing the spread of EAB are limited in application and feasibility. Still, there are several silvicultural approaches grounded in resource concentration theory, which links greater host density with increased pest abundance (Knight et al. 2013). For example, a land manager may reduce ash populations in high-value areas to diminish EAB density (Eberhart et al. 2007). As well, there is evidence of a complex and possibly beneficial relationship between girdling trees and decreasing EAB populations (Mercader et al. 2015). However, the effectiveness of this theory and associated silvicultural treatments are challenged due to variations in the contexts of ash mortality (Herms & McCullough 2014, Knight et al. 2013). As EAB behavior leads to ash mortality even in low-density environments, the resource dilution hypothesis seems more appropriate (Knight et al. 2013). Alternatively, the silvicultural focus should instead be on harm reduction. Knight et al. (2013) suggest the initial removal of stressed ash in the context of damage mitigation. Additionally, it's recommended to replace urban ash trees with non-host species. Introducing non-host species serves to enhance ecosystem and community resilience in the face of ash tree loss.

Systemic insecticide use can effectively reduce ash mortality and EAB populations (Mercader et al. 2015, Herms & McCullough 2014, Herms et al. 2014). Further, preemptive systemic use of insecticides was found to be more cost-effective than allowing the hosts to die (Herms & McCullough 2014). Effective protection of urban ash trees depends on deployment of systemic insecticides before EAB injury disrupts the vascular system that transports insecticide to the canopy (Sadof et al. 2023). Given the ongoing spread of EAB, timely management is critical for protecting urban ash trees. Efficacy of systemic application is influenced by the number of injection ports used in the injection system, time of application, and the status of the local EAB population (Sadof et al. 2022). Arborists need to be aware of these factors when planning their EAB management program.

Currently, land managers have access to four methods of insecticide application: soil-applied systemic insecticides, trunk-injected systemic insecticides, noninvasive systemic basal trunk sprays, and protective cover sprays (Herms et al. 2014). The effectiveness of insecticides and their application methods can vary significantly. Soil-applied systemic insecticides using imidacloprid and dinotefuran formulations have yielded mixed results, most likely reflecting variations in protocols and conditions of application (Herms et al. 2014). Likewise, noninvasive systemic basal trunk sprays using dinotefuran formulations yielded mixed yet promising results (Herms et al. 2014). Trunk-injected azadirachtin and imidacloprid formulations also showed various levels of success (Herms et al. 2014). As well, OnyxTM, Tempo®, and Sevin® SL effectively controlled EAB as protective cover sprays (Herms et al. 2014). Unfortunately, these protective cover sprays can cause considerable insecticide drift (Herms et al. 2014). The most promising option appears to be trunk-injected systemic insecticides utilizing Emamectin benzoate. A single injection of Emamectin benzoate provided two years of >99% reduction in EAB larvae per m^2 (Herms et al. 2014).

It's crucial to acknowledge that the above insecticides may have adverse effects, particularly on non-EAB insects interacting with ash trees. The environmental impacts of insecticides can be mitigated by complying with protocols and restrictions. Additionally, soil-injection and trunk-injection systemic insecticides, which by the nature of its application, have little to no insecticide drift (Hahn et al. 2011).

Past Management Efforts

The response to EAB has a lot of variation, as the responsibility to manage EAB will fall to different stakeholders depending on land ownership. This section will discuss the variation in management efforts undertaken by federal agencies, state agencies, private businesses, and indigenous nations.

In instances where federal agencies manage the land, the responsibility for EAB management falls under the purview of the Animal and Plant Health Inspection Service (APHIS). As part of the US Department of Agriculture (USDA), APHIS specializes in safeguarding agricultural assets– including trees within the nation's forests. Given the threat EAB poses to these assets, managing them falls under APHIS's jurisdiction. APHIS's EAB management has a broad range of strategies, such as public outreach, developing guidelines, conducting surveys, implementing trapping, and undertaking biocontrol projects like *Spathius galinae* initiatives (Emerald ash borer 2023). APHIS also enacted and later lifted a federal quarantine, as it generally failed to prevent EAB spread (Questions and answers 2023). Consequently, APHIS shifted more focus toward biocontrol projects (Questions and answers 2023). Apart from direct on-the-ground management, APHIS also serves as a centralized database to help other stakeholders and agencies in their shared goals.

State and local agencies play a significant role in the groundwork for EAB management. For instance, Oregon proactively developed an interagency readiness and response plan a year before the first detection of EAB in the state. This comprehensive plan encompasses resilience building, quarantine measures, management strategies, waste disposal, stakeholder communication, and coordination (Readiness response plan for Oregon 2021).

To preemptively address and prevent potential impacts, efforts were made to bolster ecological and community resilience through a series of measures. These included thorough risk assessments, educational initiatives, outreach programs, conducting inventories of urban trees, storing seeds for future use, implementing projects to diversify tree populations, gathering necessary resources, and establishing early detection systems for EAB (Readiness response plan for Oregon 2021). Emphasizing stakeholder identification and coordination before implementing active management actions, Oregon's plan reviews knowledge gaps, formulates plans and proposals, identifies needs, and establishes command structures and task forces (Readiness response plan for Oregon 2021). In cases of EAB discovery, investigation efforts are initiated to trace its origin and potential spread. The relevant areas then receive the necessary materials (Readiness response plan for Oregon 2021).

If Oregon's municipalities are unable to eradicate EAB using systemic insecticides and silvicultural treatments, the focus would then shift towards containing and managing the spread of EAB (Readiness response plan for Oregon 2021). Management of EAB’s spread includes tree removal, long-term biological control, and the Slow Ash Mortality (SLAM) IPM technique. SLAM uses past EAB management data to pinpoint successful practices such as insecticide application, trap trees, and selective tree removal (Readiness response plan for Oregon 2021, Herms & McCullough 2014). Fort Collins, CO, adopts a similar approach, concentrating on managing the pest population rather than eradicating it. Their plan utilizes an IPM plan consisting of insecticides, biological control, and silvicultural techniques (Fort Collins Emerald Ash Borer Management and Response Plan 2020).

. To further slow the spread of EAB, state and county-level quarantines are established and managed through state agricultural departments.

Using the Oregon Administrative Rule, Chapter 603 Division 52, Oregon's Department of Agriculture imposed a full quarantine on possibly EAB-infested materials (Readiness response plan for Oregon 2021). Initiated on December 20, 2022, the quarantine limited the movement of ash, olive, and whitefringe material out of Washington County. In this context, material encompasses “logs, green lumber, nursery stock, scion wood, bud wood, chips, mulch, stumps, roots, branches and firewood of hardwood species (Insect Pest Prevention and Management 2022)”. The California Department of Food and Agriculture (CDFA) also established an external quarantine, restricting the movement of hosts and potential carriers for emerald ash borer (California Department of Food and Agriculture Plant Quarantine Manual 2022). CDFA defines infested material as firewood, nursery stock, green lumber, logs, stumps, roots, branches, or other living or dead hardwood materials that may contain ash (California Department of Food and Agriculture Plant Quarantine Manual 2022). Products considered exempt from the quarantine must be inspected by a California State Plant Quarantine Officer, necessary for scientific research, accompanied by a waybill indicating origin and destination, passing through the quarantine zone in an enclosed vehicle, or be identifiable by species.

As of 2024, Arizona is in the initial stages of formulating its EAB readiness and response plan. Although specifics about this plan are limited, the state has already implemented restrictions on potential EAB-infested materials. Listed as an actionable arthropod threat, the Arizona Department of Agriculture (AZDA) prohibits EAB-infested materials from entering the state unless adequately treated and certified (Arizona Administrative Code 2022). As Arizona further develops its readiness and response plan, strategies from previously mentioned state and local agencies may be adopted.

Federal, state, and local agencies often extend resources to private businesses and communities. These resources include workshops and funding to better prepare for EAB. For example, the Virginia Department of Forestry offers a cost-sharing program for licensed applicators covering half the direct project costs for emamectin benzoate injection treatment (Emerald Ash Borer Cost Share program 2023). Private businesses use these resources to provide many services, including identification, silvicultural treatments, and surveys. The management plan for Fort Collins, CO, highlighted the contribution of the Davey Resource Group, which provided crucial data by surveying 200 plots to estimate the city's ash population (Fort Collins Emerald Ash Borer Management and Response Plan 2020). Additionally, private groups collaborate with state departments to help provide locations, equipment, and expertise for the collection of infested materials. For instance, in Oregon, state departments collaborate with numerous private businesses to store and treat infested materials (Readiness and response plan for Oregon2021).

Sovereign indigenous nations make up nearly a quarter of Arizona's land. While these sovereign nations are subject to federal authority, they largely exercise self-governance with distinct departments dedicated to natural resources. For example, the Saint Regis Mohawk Tribe, situated in the region between New York and Canada, has developed an EAB management plan aimed at safeguarding the culturally significant black ash (*Nigra fraxinus*) (Benedict 2017). The Saint Regis Mohawk Tribe's plan involves seed collection, improvement of forest conditions for future regeneration, and an overall goal of increasing basket making resources (Benedict 2017). As of 2024, Arizona tribal nations have released no information regarding EAB management plans.

Conclusion

To prevent significant economic and ecological issues brought by EAB, Arizona's land managers need a comprehensive plan. We offer insights into EAB biology, history, risk assessments, risk maps, identification, and management techniques to aid in this endeavor. While Arizona's limited ash population and harsh climate might slow EAB, the risk remains. An integrated strategy involving chemical injections, biocontrol, and trap trees could be adopted. However, a comprehensive statewide quarantine appears to be the most effective and cost-efficient measure, supporting and enhancing all other management strategies. As EAB progresses closer to Arizona, land managers must be ready to act if they hope to avoid the widespread devastation that results from EAB invasions.

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Appendix A

Emerald Ash Borer in Arizona

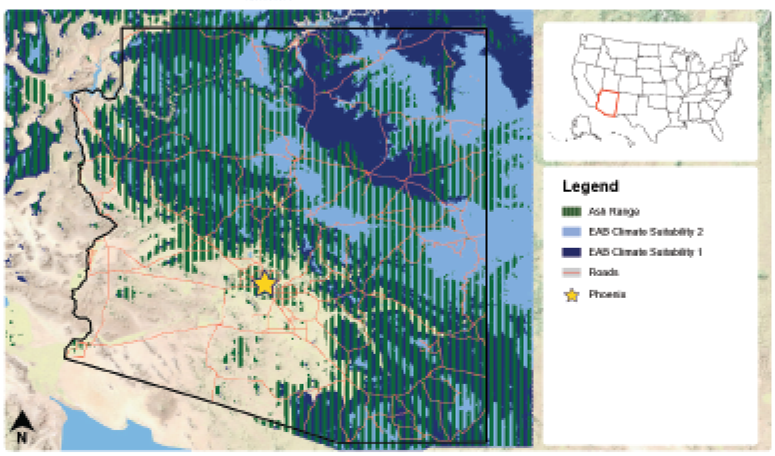
By Jack Hood

Invasive Pest Alert: Emerald Ash Borer

Avoid Transporting Quarantined Ash Material

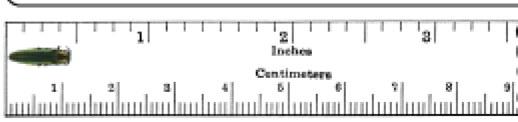
Emerald ash borer (EAB), *Agrilus planipennis Fairmaire*, is a wood-boring beetle originating from Eastern Asia. This insect first arrived in the US in the mid-1990s in Southeastern Michigan, most likely through wooden shipping containers. Since its arrival, EAB has caused billions of dollars in damages to ash trees (*Fraxinus spp.*). Without intervention, this insect could wipe ash trees from our landscapes.

Where can EAB be found? EAB can occur wherever its host, ash trees, can be found. While wild-growing ash is relatively rare in Arizona, its outstanding shading and air purification abilities make ash great for urban applications. For this reason, ash trees are quite common across Arizona's urban areas. The map to the left shows which areas are at the highest risk of EAB infestation. Climate Suitability 1 (dark blue) is defined by the temperature bounds in which EAB has been observed. Climate Suitability 2 (light blue) is defined by EAB temperature bounds as determined through controlled lab studies and modeling. The Estimated Ash Locations (green) estimate where ash trees may occur. It is important to note that, though it may be limited, EAB may still establish outside the marked areas.



Resources

To **report** an emerald ash borer sighting or to request **removal** of quarantined material, please contact a professional **arborist**. For any **questions** regarding emerald ash borer, ash trees, or management options, please visit http://www.emeraldashborer.info/. For professionals, to confirm an EAB sighting, please contact the AZ-DFFM at the resources below.



Phone number: (602) 771-1400
Email: foresthealth@dffm.az.gov
Address: 1110 W. Washington St., Ste. 500, Phoenix, AZ 85007

Scan QR code for Sources

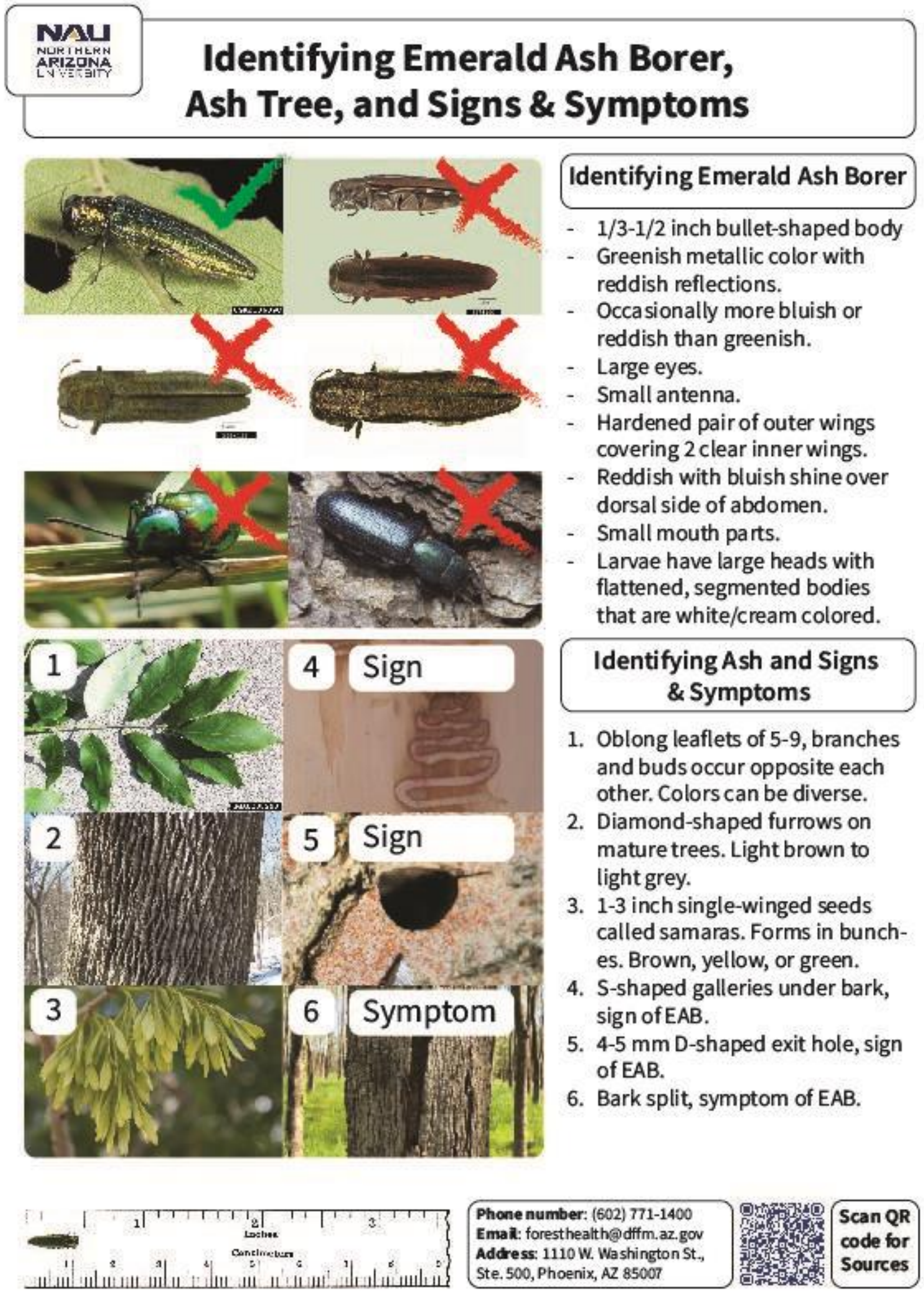


Figure A-1. EAB Fact Sheet. Photo Credits: Bornand (2019), Cappaert (2002), Cappaert (2005), Cappaert (2005 [Agrilus planipennis, elytra]), DiGirolomo (2014), Royals (1993), Lingafelter (2016), Michigan Department of Agriculture (2004), Ash seeds (2009), Bark of mature ash tree (2015), Dogbane (2017), Emerald ash borer galleries (2023), Oten (ND), Royals (2006).

Appendix B

Table B.1. Emerald Ash Borer Taxonomy- taxonomic classification of EAB, Agrilus *planipennis,* information adapted from Kenis (2009).

-	**Domain**	**Kingdom**	**Phylum**	**Subphylum**
-	Eukaryote	Metazoa	Arthropoda	Uniramia
Class	**Order**	**Family**	**Genus**	**Species**
Insecta	Coleoptera	Buprestidae	*Agrilus*	*planipennis*