Predicting Forest Succession in Response to Emerald Ash Borer Infestation

By

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Abstract

The emerald ash borer (*Agrilus planipennis)* is an invasive insect native to Asia that was first discovered in North America in 2002 near Detroit, Michigan. Since then this insect has decimated ash (*Fraxinus* spp.) tree populations across the mid-west and has been expanding ever since. This mass die-off of ash trees has potentially reshaped forest successions in infected zones by creating gaps in the ecosystem for other species to fill. This study attempts to predict which tree species will take advantage of the forest release created by widespread ash death. The emerald ash borer has also been able to expand at an alarming rate through human aided dispersal methods. This study also uses geographic information services to map the invasion of the emerald ash borer over the years post-introduction. After analyzing the collected data, it is predicted that the next dominant species within the sampled forest community will be shagbark hickory, and swamp white oak. This is due to the average size of these two species. It was also noted after observing the created map that emerald ash borer quarantines have failed to contain the spread of the insect. The spread of the insect has been greatly influenced by human aided dispersal.

Introduction

An invasive species is defined by the USDA as a "non-native species to an ecosystem who's introduction causes or is likely to cause economic or environmental harm, or harm to human health" (USDA, 2012). Invasive species fall into multiple categories of life such as insects, animals, or plants. Invasive species can be introduced to a new ecosystem by two general ways. Humans can purposely introduce invasive species into an area for their benefit, either economically or environmentally. An example of a locally introduced species is the Common Buckthorn (*Rhamnus cathartica*). This species of hedge plant was brought from Europe in the mid-1800's to be used as decorative hedging (MDNR). Early in its time in the United States it was found to be highly invasive; this was due to its ability to out compete other plants for light and nutrients (MDNR). This plant outcompeted native understory plants and began to take over as the dominant species within the ecosystem. Another way that invasive species can be introduced is through accidental means such as trade or travel. Through the building of canals and locks to connect the Great Lakes to the Atlantic Ocean, specifically the Welland Canal (Fuller et al. 2012) the Sea Lamprey (*Petromyzon marinus*) and the Zebra Mussel (*Dreissena polymorpha*) were accidently introduced to the Great Lakes. This is a problem because the Sea

Lamprey feeds on native fish (Fuller et al. 2012). In the 1940's and 50's the Sea Lamprey caused the collapse of the lake trout, whitefish, and chub populations in the Great Lakes (USDA, 2013). Zebra Mussels have an ability to out compete local mussels for food. This has caused a collapse in the mussel's population. These collapses have had major impacts on not only the fishing industry, but the local ecosystems in the great lakes as well.

The emerald ash borer (*Agrilus planipennis)* is an example of an invasive species that was introduced accidentally. The emerald ash borer is a species of beetle native to Eastern Russia, Northern China, Mongolia, Taiwan, Japan, and North and South Korea (USDA, 2010). This insect feeds on the phloem of ash trees. The phloem is the part of the tree that transports water and nutrients throughout the tree. The first record of emerald ash borer in the United States is from 2002 when the insect was found near Detroit Michigan (McCullough, 2009 Usborne 2011). It is theorized that the insect made its way to the United States through human transportation of cargo from Asia; it was likely present in the ash wood that was used to stabilize the cargo within the transport vessels (McCullough, 2009 Usborne, 2011). This insect is responsible for large scale destruction of the Mid-West's ash populations, costing billions of dollars to the states affected in attempts to stop the spread of the insect. Like most invasive species the emerald ash borer thrives due to the lack of natural predators. In its native areas the insect does not cause such wide spread destruction due to the presence of natural predators which keep in it check. In Asia the emerald ash borer is parasitized by a species of wasp known as *Spathius sp.* (Liu et al, 2003). This natural predator, as well as others have helped to control the population of emerald ash borer in its native habit. In North America the lack of predators allows the insect to thrive without interference.

This insect causes problems not only for the environment, but for the economy as well. Ash mortality ends up costing the government, both local and federal, billions of dollars. This money is spent either trying to treat infected trees with various methods of chemical treatment, or spent removing and replacing infected trees. One in every ten trees in Ohio are ash trees, with an estimate of 3.8 billion trees (ODNR). It is estimated that the state of Ohio will accrue over $3 billion in cost to fight the emerald ash borer (ODNR). The state will have to pay for infected trees living on state owned land, such as recreational parks or parkways. Many of the infected trees are used in the timber industry as well. This may not cost the state up front, but the timber industry has suffered major decline in profits with so much of its crop gone to waste. It is estimated that the ash nursery industry is valued at $20 million (ODNR). Unfortunately the state and timber industries are not the sole entities affected economically. Many property owners in Ohio have to pay out of pocket to remove emerald ash borer infected trees from their property. This costs the property owners an average of $400 per tree to remove the infected trees from their land (ODNR).

The emerald ash borer is by definition an invasive species, but it is also a disturbance that can drive forest succession. Disturbances are events or processes that disrupt the normal activity of a forest. Disturbances can be anything from invasive species, such as emerald ash borer, fires, flood events, climate change, and even human activity. Succession is defined as vegetation change, or the replacement of one community with another as a result of natural development. With the expansion of the emerald ash borer the ash populations in the infected forests have plummeted due to mass ash die off. When a species is removed from an ecosystem a space for other organisms becomes available. In the case of temperate forests, ash trees often are one of the dominant over story species. The formation of a gap in the over story allows for a type of succession that is known as understory tree release. This concept refers to the increase in resource availability that is required for growth in vegetation due to the removal of the ash canopy cover. Greatly increased amounts sunlight suddenly becomes available to the understory species. This increased sunlight allows for increased growth rates of understory trees, and herbaceous species. Unfortunately in our area there are two other prevalent invasive species that are causing trouble; these species are buckthorn (*Rhamnus cathartica*) and garlic mustard (*Alliaria petiolata)*. The increase in sunlight could allow these species to thrive in areas where they already have a distinct advantage over the native species in the area.

While the emerald ash borer can have an effect on forest succession and species diversity it can also have an effect on an infected forest's soil. When the emerald ash borer moves in and infects a forest the widespread ash mortality causes a significant increase in fallen dead trees and snags, or standing dead trees. These decaying trees can influence several factors in the soil such as soil pH, mineral concentration, and soil moisture levels (Rice, 2013). This can affect the nutrient availability in the soil for other plant species in the area.

The goal of this study is to learn more about the effect of mass die off of ash trees in local forested ecosystems. It will focus on studying the growth release and succession of understory and over story tree species such as silver maple (*Acer saccharinum*), shagbark hickory (*Carya ovata*), and basswood (*Tilia* spp). The information gathered during this study should provide forest management services with information about the transformation of forested ecosystems during and after a mass die off of ash trees due to emerald ash borer infestation. Another goal of this study is to map the spread of emerald ash borer over the years following its introduction near Detroit. This map will visualize expansion trends in expansion, and allow predictions to be made about where satellite colonies might pose a larger threat.

Literature Review

When an invasive species is introduced to a new area it is typical for that species to cause not only ecological problems, but economical problems as well. Emerald ash borer is no exception. Since its introduction near Detroit Michigan, emerald ash borer has caused billions of dollars in damages across the infected areas of the United States. In a study that was conducted in Ohio, Syndor et al. placed three separate values on an ash tree. These costs involved the landscape value of the tree, the cost to remove a dead or damaged tree, and the cost to replace the tree (Syndor et al. 2007). It was estimated by Syndor et al. (2007) that the total costs for the state of Ohio to remove and replace infected ash trees is $7.5 billion dollars. Local and state governments are spending large sums of money to help fight or in some cases prevent emerald ash borer infestations. Several Chicago suburbs have plans in action to fight against the insect. In the city of Des Plaines Illinois 20% of its trees are ash (Krishnamurthy, 2012). The city plans to remove 3,700 ash trees at an average cost of $300 per tree (Krishnamurthy, 2012). The city officials considered treating the trees, but saw it as a poor economic choice, stating that it would cost $100 every other year to treat and maintain them (Krishnamurthy, 2012). As of last year the city removed 1,000 of the targeted trees (Krishnamurthy, 2012). The village of

Frankfurt Illinois plans to spend $1.8 million replacing all of the villages parkway ash (Scheir, 2012). In the city of Bolingbrook Illinois a plan has been put in place to spend $66,000 to replace 142 affected Ash trees. (Ziezulewicz, 2013). Some areas of the United States are just beginning to feel the effects of emerald ash borer and are creating plans to try to prevent the spread. With a goal to diversify its tree population the city of Johnston Iowa has begun to remove and replace 60 ash trees in public areas (Keiler, 2011). This plan is expected to cost the city $75,000 (Keiler, 2011). In order to develop effective plans to stop the advance of the insect, or combat current infections it is important to know its lifecycle.

Between June and August oviposting emerald ash borer females lay their eggs in the cracks and crevices of the ash tree's bark, usually on the upper portion of the tree (USDA, 2010). After two weeks (USDA, 2010) the eggs hatch and the larvae emerge. After emergence the larvae burrow into the bark and begin to feed on the phloem, which is a thin layer beneath the bark that is necessary for the tree to transport water and nutrients. While feeding the larvae create serpentine canals in the cambial part of the tree, these canals are filled with frass (Wilson, 2006) which is a mixture of sawdust and excrement. These canals cut off the supply of water and nutrients to the portion of the tree above the infestation causing leaf die off. These canals will kill the tree around 3 years after infection (Haack, 2002). The larvae feed from mid-June to mid-October (Haack, 2002). Over the winters the fully grown larvae live in pupal cells in the outer sapwood, while under grown larvae overwinter in the cambial region and begin feeding again in April (Haack, 2002). The fully grown larvae pupate between April and May and emerge through D shaped emergence holes (Wilson 2006, Haack 2002). The adult insects emerge with fully functional wings and will begin feeding on the Ash leaves immediately. Within a week of emergence the insects begins to mate, and after three the females begin to lay their eggs. (Haack, 2002). Females typically lay 68-80 eggs in their lifetime (Haack, 2002) When an ash tree is infested with emerald ash borer there are several visible signs the stressed tree exhibits. While the insect is in its larval stages the serpentine canals are a very reliable sign the insect is present, as well as its emergence holes when it matures. The tree will create scar tissue around the serpentine canals, causing the bark to split open (Wilson, 2005). Woodpeckers will enlarge the emergence holes while searching for the insect. The tree will also begin to experience extreme foliage die-back, beginning in the top third of the canopy. The die-back will continue until the entire tree is bare (Wilson, 2005). Often the tree will begin to sprout from the base during infestation, the leaves of these sprouts may also be larger than normal (Wilson, 2005).

In order to understand how the emerald ash borer spreads without human aid it is important to understand the dispersal range and rate of the species. In a study by Taylor et al. (2005), the insect was studied to measure its flight distance and speeds. It was found that females are capable of twice as far as males, while oviposting females are capable of flying twice that distance (Taylor et al, 2005). The average flight speed for a mated female was 3km/day while 50% of studied females flew 4k, and 10% flew further than 7km (Taylor et al, 2005). In another study conducted by Baur et al. it was found that the average flight of mated females is 3km (Baur et al, NRS). The evidence found in these studies suggests that the emerald ash borer females are capable of long distance migrations from their emergence sites, and mated females are capable of even further flight, allowing new colony sites to form away from their emergence site. In a study conducted by Mercador et al. two sites were sampled for emerald ash borer presence. They found that respectively 88.9% and 90.3% of larvae were within 100m of their emergence point (Mercador, 2009), and 100% and 97.8% of larvae were within 300m of the emergence point (Mercador, 2009). This study suggests that *A. planipennis* prefers to stay near the original site, if there is ample space and food for the insects.

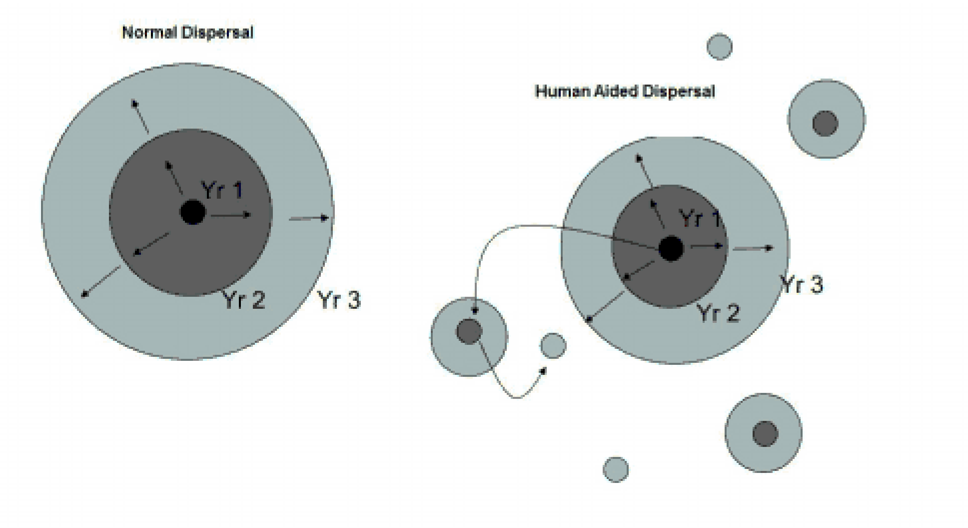

Figure 1. Dispersal Models (USDA) showing normal, unaided dispersal on the left and human aided dispersal on the right. It should be noted the randomness and unpredictability in the model on the right.

The characteristics of a forest can also lead to a difference in the resistance it will have against the emerald ash borer and can either impede or aid its spread. Hooper et al. studied the effect a forest's species diversity has on its "invasibility" or the forest's susceptibility to become invaded by an invasive species. It was found by Brockerhoff et al. that mixed forests suffer fewer infestations than pure forests. This is theorized to be due to the reduced number of host trees in the forest, which may reduce the host odor recognition for the insects (Brockerhoff et al. 2006). This is especially relevant when applied to emerald ash borer infestations due to the specialized nature of the insect. Since it only feeds on ash trees the presence of other trees could impede the spread of the insect. The distribution of ash trees within a forest community can also have an effect on the invasibility of a forest by emerald ash borer. Typically there are three types of distribution. These are regular, clustered, or random. In regular communities members of the same species have almost uniform distribution, clustered communities involve clustered individuals, and random communities have individuals randomly distributed. Clustered and uniform populations are likely to be more susceptible to infestation than random populations.

As of April 2014 the emerald ash borer has extended West into Iowa, Kansas, Missouri, Colorado, and as far south as Tennessee and Georgia (Figure 2). These states are exhibiting evidence of satellite colonies, or places of infestation not connected with the main "invasion front". While the insect exhibits the ability to travel relatively far distances these satellite colonies were established through human transportation of the insect, most likely in the form of ash firewood.

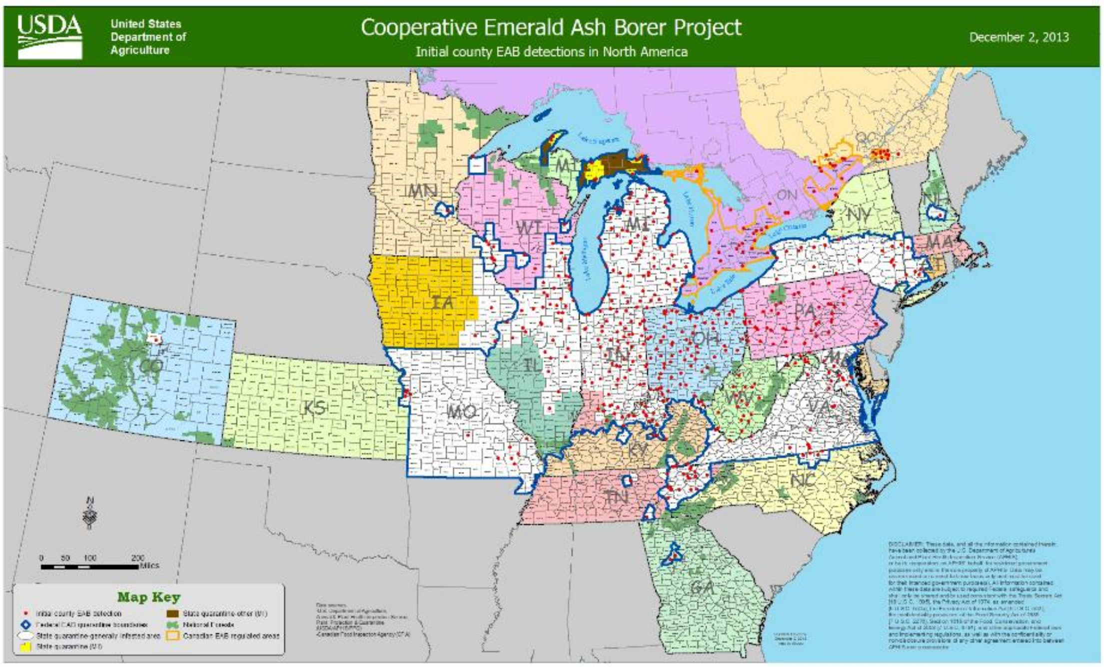

Figure 2: The map above shows the extent of the Emerald Ash Borer infestation in the United States.

In order to prevent the human transportation of the emerald ash borer local and federal governments have implemented quarantines. These quarantines are run by the USDA APHIS which stands for Animal and Plant Health Inspection Service. The first quarantine occurred soon after the discovery of the insect in Michigan. Six Southeastern Michigan counties were quarantined to prevent the spread. When the insect is first spotted within a county, that county will become quarantined (APHIS, 2011). If an infestation occurs near the border of the county, the connecting county may also be quarantined in order to prevent the insects spread (APHIS, 2011).

The state of Illinois has a wide spread quarantine in place due to its amount of infestations. The USDA APHIS has placed the entire state of Illinois under quarantine, which prevents the movement of ash products across state lines. The USDA has also quarantined 41 Illinois counties to prevent in-state spread as of November 10, 2011 (IDA). The quarantines prevent the removal of several items. These items include the emerald ash borer in any living stage of development, ash trees of any size, ash limbs and branches, any cut non-coniferous firewood, bark from ash trees and wood chips larger than one inch in two dimensions from ash trees, ash logs and lumber with either the bark or the outer one inch of sapwood still attached, any product containing or made from the wood of an ash tree, or tree that is capable of spreading the emerald ash borer, and any other article, product or means of conveyance determined by the Illinois Department of Agriculture to present a risk of spreading (IDA). Anyone who breaches this quarantine will suffer a fine of $500 unless the person was certified by the Illinois Department of Agriculture (IDA). The USDA APHIS can however issue firewood vendor licenses to people, this allows for certain types of firewood to be available to consumers.

While these quarantines have had an effect on the spread of the emerald ash borer by human transportation methods, it is still spreading across the quarantine boundaries. The insect could have been transported in commercial ash products. To combat this the International Standards for Phytosanitary Measures has determined that ash products can be heat treated at a core temperature of 56^{o} C for 30 minutes (Sobek et al. 2011). In a study conducted by Zahid et al. it was found that 9% of surveyed wood packaging materials being shipped across quarantine borders contained emerald ash borer pupae, this suggests a tolerance to high temperatures. It was found by Myers et al. that emerald ash borer pupae can survive exposure to 55^{o} C for two hours (Sobek et al. 2011). Sobek et al. (2011) conducted a study to determine if the current standards are enough to sanitize lumber products and prevent the spread of wood borne pests. It was found that the current standards are more than enough to ensure the death of emerald ash borer. However, during the study it was found that the emerald ash borer has a high resistance to increased temperatures and a high heat shock tolerance (Sobek et al. 2011). This allows the insect to colonize areas with a warm climate, and allows it to survive natural phenomena such as heat waves and abnormal temperatures.

When the emerald ash borer infests an area, there is a very high likelihood that if left untreated the ash trees in that area will become infected and die. This creates a gap in the over story and allows more light to reach the floor. The increased light availability has the capacity to influence forest succession, as well as possibly allowing invasive understory species to become established and inhibit native species from growing. Ohio State University conducted a large scale long term study to determine which species would grow in the ash tree's absence. The University also studied how an Ash population reacted in terms of reproduction. The University discovered that the forest release has allowed 14 different species of invasive species into the ecosystem. They found that the most frequent exotic understory species were *Rhamus carthartica, R. frangula, and Celestrus orbiculatus* (OSU, 2012). They also found that the most common native understory species were ash seedlings. After studying the surviving ash trees it was found that they were sexually immature, these trees did not produce any significant amount of seeds for the seed bank, and the ones that were produced had a 50% viability rate (OSU, 2012). Over time the seed bank became completely depleted, this would lead to the idea that Emerald Ash Borer would not be able to persist in areas with high ash mortality. However the University found that Emerald Ash Borer persisted in areas with up to 99% mortality. This suggests that what ash seedlings and saplings have the ability to support emerald ash borer populations.

The National Forest Service has created a model to predict what tree species will begin to fill in the gaps left by widespread ash mortality. For their model they used 100% for predicted ash mortality. Using this model they have been able to predict which tree species will become more prevalent in the different types of forests that the emerald ash borer is infecting. They have predicted that no less than 10 species of trees will be able to utilize the gaps left by ash trees in elm, ash, cottonwood forests. These species include red maple (*Acer rebrum*) and silver maple, eastern cottonwood (*Populus deltoides*), willow (*Salix* spp), Pecan (*Carya illinoensis*), sugerberry (*Celtis laevigata*), river birch (*Betula negra*), and american sycamore

(*Planatus occidentalis*) trees (DeSantis, 2013). In oak hickory forests they predicted 17 different species that could possibly fill the gaps. The oak species are scarlet (*Quercus coccinea*), bur (*Quercus macrocarpa*), white (*Quercus alba*), chestnut (*Quercus prinus*), blackjack (*Quercus marilandica*), post (*Quercus stellata*) and northern red oak (*Quercus rubra*) (DeSantis, 2013). The other predicted species include white pine (*Pinus strobus*), cherry (*Prunus* spp), yellow-poplar (*Liriodendron tulipfera*), elm (*Ulmus* spp), black locust (*Robinia pseudoacacia*), eastern redcedar (*Juniperus virginiana*), sassafras (*Sassafras albidum*), persimmon (*Diospyros virginiana*), sweetgum (*Liquidambar styracjflua*), and black walnut (*Juglans nigra*)(DeSantis, 2013) . Their results suggested that the impact of emerald ash borer mortality will have a minor forest-type group changed due to the fact that associated species that are not directly affected by the emerald ash borer can off-set the ash lost in the forest community (DeSantis, 2013) Their research also concluded that the transition to other species will not be a rapid transition due to the speed that the emerald ash borer kills infected ash trees, and the time it takes for new trees to grow with the newly available resource. (DeSantis, 2013) This is important to the timber and lumber industry because it will give the industry time to switch over to a new species.

To study the long range dispersal of the emerald ash borer GIS has been used to map its dispersal and invasion fronts. GIS (Geographic Information Services) allows data to be viewed visual and spatially in order to identify trends or patterns in the form of maps, globes, reports, and charts (ESRI). It has become an invaluable tool within research of the emerald ash borer because it allows scientists to map out where the infestations are relative to characteristics such as ash population, human populations, or even quarantine boundaries. Previously GIS has been used to map and model areas that could cause the spread of emerald ash borer due to human means. These areas were campgrounds, nurseries that had ash trees, and sawmills that produced ash products. These locations were mapped and plotted against a map of the emerald ash borer invasion (Ayersman et al. 2009). The quantity of transported ash firewood has also been mapped, as well as where it originated to its destination, and then plotted against a map of the emerald ash borer invasion. GIS has also been used to model long and short distance dispersal of the insect (Muirhead et al. 2006). GIS has been an invaluable tool to the village of Deerfield as well. The village has mapped its streets as well as the locations of ash trees that are either infected, not infected, or removed (Gianna, 2012). This allows the city to track the spread of the insect and predict which trees will be vulnerable next.

In order to predict how humans can influence the spread the emerald ash borer, GIS has been used by Ayersman et al. (2009) to map density grids for six states in the Mid-Atlantic region of the United States. These states were Ohio, Pennsylvania, West Virginia, Maryland, Delaware, and New Jersey. They mapped the densities of several different producers of ash wood and products. These included campgrounds, nurseries, and sawmills (Ayersman et al. 2009). In order to calculate the densities for each of these categories the Kernel Density calculation was used (Ayersman et al. 2009). It was found that campgrounds showed a dispersed distribution with only 24,224 acres of land recorded between a density of 16-18 campgrounds per 10 square miles, and that West Virginia had a low density of campgrounds (Ayersman et al. 2009). The only county to have emerald ash borer presence at the time of the study was Fayette County, which exhibited a density of 8-10 campsites per 10 square miles (Ayersman et al. 2009). The campgrounds were also mostly located along Lake Erie and in Western Pennsylvania (Ayersman et al. 2009). For nurseries they found that there was a positive correlation between nursery density and human population centers, the nurseries tended to cluster around large cities such as Pittsburg, Cincinnati, Baltimore, and Washington D.C. (Ayersman et al. 2009). They found that the largest density of sawmills and firewood dealers were in rural areas, which was attributed the lack of timber supplies in urban areas (Ayersman et al. 2009). When these three layers were overlayed, it was found that the highest densities were focused around rural areas, with nurseries creating most of the density in the urban areas. See figure 3 below for model. The model that was created can be used by the forest service to concentrate efforts for emerald ash borer prevention. By observing which areas have the highest density of timber dealers and suppliers, the forest service can concentrate efforts near high density locations.

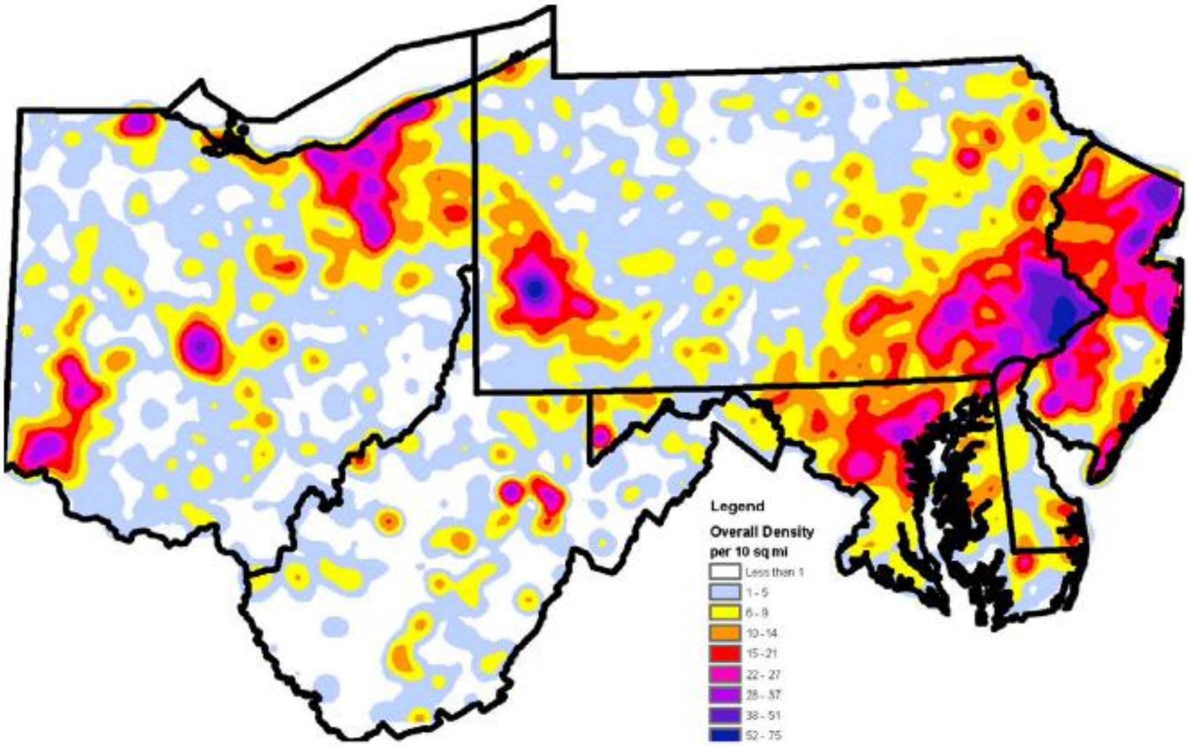

Figure 3: The map above shows the overall densities of campgrounds, nurseries, and sawmills within the sample area, these are all locations that could greatly influence the rate of spread of the emerald ash borer.

Prasad et al*.* (2010) also used GIS mapping to model the emerald ash borer expansion in the state of Ohio. They argued that previous models lacked landscape characteristics and decided to use a "spatially explicit cellular model called SHIFT" and applied its mathematical-spatial hybrid approach to the spread of emerald ash borer in Ohio (Prasad et al, 2010). Within their SHIFT model they looked at three separate modes of dispersal; insect flight, human-aided dispersal, and a hybrid of the two. This model predicted the probability of a cell being infested by its distance to and the invisibility of nearby cells (Prasad et al. 2010). They used GIS and a program called RandomForest to assign values to four different variables; traffic on roads, population density, campgrounds, and wood product industries (Prasad et al. 2010). Using this model they were able to create a final output risk map that allowed the authors and readers to visualize the high-risk areas within Ohio (Figure 4.). This map shows a prediction of invasion up until the year 2014. After applying the SHIFT model to the most recent emerald ash borer invasion data at the time they found their model could accurately predict the spread of emerald ash borer. It was found that the parts of the state that were at the greatest risk were near metropolitan areas in Northern Ohio.

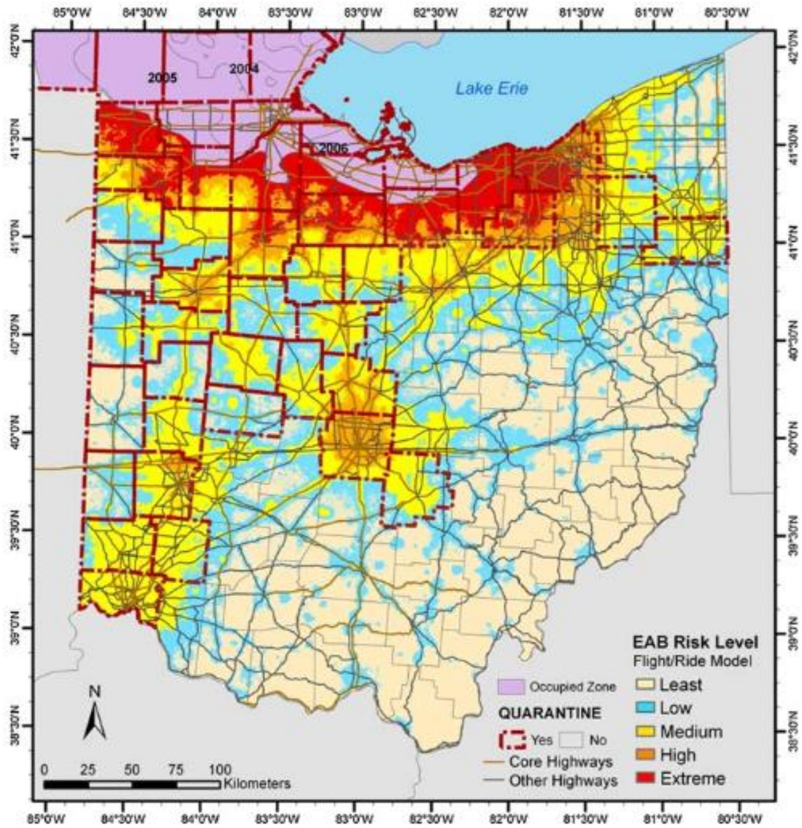

Figure 4. The map above shows Prasad and his co-author's application of their SHIFT model to the state of Ohio. It should be noted that the highest risk areas are near metropolitan areas.

While researching the topic I hypothesize that as ash species begin to die off due to emerald ash borer infestations a large scale forest release will occur, allowing other species to thrive. I predict that the dominant species within the sampled forest will become shagbark hickory, and swamp white oak. During the GIS portion of this study I hypothesize that the emerald ash borer's invasion front follows human recreation due to human-aided dispersal regardless of quarantine zones and boundaries.

Methods

Site Selection

For this study, Chain O' Lakes State Park was chosen for data collection. The state park is located in Spring Grove, Illinois in both Lake and McHenry counties. It is four miles from the Illinois-Wisconsin border. Chain O' Lakes was formed as a state park in 1945 when it was purchased by the state of Illinois. Currently the park contains 2,793 acres of land and is connected to a 3,230 acre conservation area. This lake borders three lakes, Grass Lake, Nippersink Lake, and Lake Marie, as well as the Fox River, which connects to the Chain of Lakes. There is also a 44 acre lake within the park. The park offers many camping and recreation areas, hiking and horseback trails, and a public boat launch. The park contains large amounts of restored prairie as well as hardwood forests containing ash, hickory, maple, and basswood species. The understory is sparse, with saplings and garlic mustard. In many areas buckthorn and garlic mustard are very prevalent. This site was chosen for several reasons. This park is used by the timber industry for lumber and product production. The impact the emerald ash borer has had and will continue to have on the ash trees of this state park will affect the economic worth of this park, and many others like it. By conducting this study within state managed land the data collected can be used to determine which crop trees will become more common due to the die off of ash. Data was collected across 3 weekends in late September and early October of 2013. Data collection included tree identification, diameter measurements, and tree coring. The temperature ranged from 50-60^{o}F and the weather varied between each of the sampling days. The first day was clear, second was overcast and raining, and the third was overcast.

Field Sampling: Transect Creation

Data for this study was collected using a sampling method known as Point Center Quarter, or PCQ for short. This method was developed by Grant Cottam and J.T. Curtis (Cottam, 1956). This sampling method involves laying a transect line and sampling at increments of the researchers desire. At these points the four nearest objects are sampled in four separate directions. These directions were North-East, North-West, South-East, and South-West. In the case of this study a one hundred meter transect was lain running North to South. The beginning and end of this transect were marked with stakes and flags because samples were taken over the course of several weeks. The flags and stakes allowed for accurate replacement of the transect.

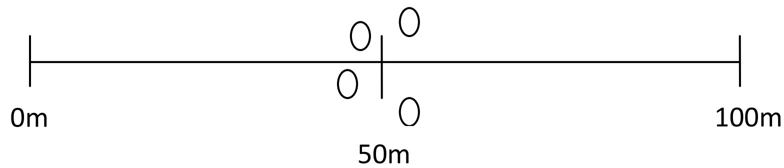

Figure 5: The figure above represents a one hundred meter PCQ transect. The ovals represent the four trees sampled at the fifty meter point.

Field Sampling: Data Collection

At each sampling point the four nearest infected ash trees were sampled in the four directions specified above. In order to determine if an ash tree was infected at least one of the tree signs of infection had to be observed. These signs as defined by the *Signs and Symptoms of the Emerald Ash Borer* are the evidence of D shaped emergence holes, epicormic shoots, and excessive woodpecker damage (Wilson). Crown damage was also observed as a sign of infestation, this was characterized as extensive foliage loss and broken or damaged branches. The D shaped emergence holes are where the adult insect emerges from the tree. The shoots are the tree's attempt to regenerate after extensive damage to the crown, and the woodpecker damage is caused when the birds feed on the larval insects. Trees were determined to be infected if they exhibited any or all of these symptoms. Once the tree was determined to be infected measurements were taken. First the ash species was identified using tree identification manuals. Once the species was determined the distance from the sampling point along the transect line was determined and recorded. The dbh or diameter at breast height was also recorded. After the dbh and the distance from the transect point were recorded each tree was cored for age samples. The core samples were taken as close to the ground as possible, this was to ensure the oldest ages could be recorded. To core a tree, a tree augur is used, which is a large metal tube with a hollow drill bit at the end. The researcher drills into the selected tree until they have reached the approximate center of the tree. After one has reached the center the tree core is removed, this core is usually the length of the radius of the tree. After the cores were removed they were placed in sample storage devices which in this case were straws donated for this study by Sam's Club and were marked for tree identification for lab work.

Figure 6: The images above show the three most visible signs of Emerald Ash Borer infestation, the D shaped emergence hole, the epicormic shoots, and the woodpecker damage.

After the ash trees along the transect were sampled and data was recorded the understory species of the sample site were sampled. This was done by sampling the number of non-ash species within 2 meters of each sampled ash tree. In order to determine the sample radius measurement tapes were laid out extending from the sampled ash tree. This was done for each sampled ash tree. The number of non-ash species was recorded per ash tree. The non-ash species were also identified, and their dbh was recorded.

Tree Aging

Once the tree cores were returned to the lab several steps were taken to retrieve data from them. The cores' carrying straws were opened and allowed to air dry for several days until they felt dry to the touch. The cores were then mounted onto core mounts. These points are long pieces of wood with grooves for the core. They were glued down using wood glue and were held in place with rubber bands to ensure they set properly. After the cores were mounted they were sanded down to allow researchers to count the rings and identify the age of the trees. Tree rings were counted using the standard USGS method. (USGS) The infestation year was determined as 2008, seeing as evidence of tree mortality becomes visible 3-5 years after infestation. This year will give a base year to judge how old the tree was when it became infested.

GIS

In order to map the emerald ash borer's expansion it was decided that the data collected would be on the county level. The data would involve what year the emerald ash borer was first detected in each individual county. This will provide an accurate visual representation of how quickly the emerald ash borer has spread. Data for the emerald ash borer was found through searching government databases. The US Forest Service had the most recent and applicable data so that database was chosen. With the creation of these maps the emerald ash borer's expansion will be easily recognizable, and patterns of "jump" dispersal, which are often caused by humans, will become visible.

Statistical Analysis

I will be using quantitative statistics to analyze my collected data to determine the following results. Average infected ash tree age will be determined, as well as age frequency for the total sampled population, and per ash species sampled. To determine if the emerald ash borer was having a profound effect on Ash tree growth in the sample site the tree cores will be analyzed to determine what percentage of trees have reduced growth after the infestation year. This will be done by observing the growth rings, where close rings signify stress and reduced growth. The percentage of trees stressed by emerald ash borer infestation will be determined. The density of the sampled ash species will be determined, as well as the average basal area of each species. The dominance and relative importance values will also be calculated. The relative importance value is a measure of how common a species is in a forest, the total number of individuals of a species, and the total amount of forest area the species occupies. A prediction will also be made about the future tree population based on the percent of non-ash species that were sampled. Their diameters will be analyzed to determine which species has the greatest presence.

Results

After aging the tree cores it was found that there was a variance in tree age, ranging from 19 to 75 years old. The average tree age was determined to be 45.5 years old, with a standard deviation of 10.86, showing an extreme variance from the mean. This is most likely caused by different cohorts of ash trees within the samples, or different generations of trees. Within the sampled green ash population the average age was 41.6 years old, and within the white ash population the average age was 47.44 years old. It was found that 70% of trees were stressed during and after emerald ash borer infestation, and not before, most likely due to the long, dry summers that have been frequenting this area over the past several years. The figure below shows the frequency of the total sampled ash ages, green ash ages, and white ash ages.

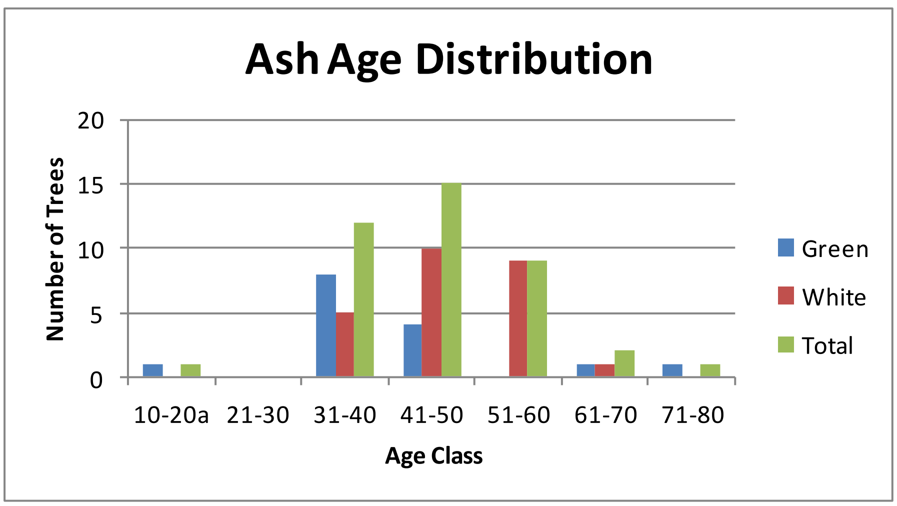

Figure 7. The age distribution of the sampled ash trees, by species and in total.

While analyzing non-ash species it was found that there were 59 individuals. Of those 59 individuals 18 (30%) were American Basswood, 16 (27%) were Swamp White Oak, 14 (23%) were Silver Maple, and 11 (18%) were Shagbark Hickory. Shagbark was found to have the highest average dbh, which was 22 cm. It was followed be Swamp White Oak with 20cm, then Silver Maple with 15.5 cm, and American Basswood with 13.75 cm. The table below displays the calculated density, and average dbh for the sampled non-ash species.

Species	Density	Average dbh
Shagbark Hickory	11%	22.05
Silver Maple	23%	15.73
Swamp White Oak	27%	20.27
American Basswood	30%	14.01

Table 1. The calculated densities and average dbh of the sampled non-ash species. It should be noted that shagbark hickory, while has the lowest density, has the highest average dbh.

After calculations were completed several values were found. It was found that the total density of the two present ash species was 876 trees/ha. The relative densities were found to be 37.5% green and 62.5% white ash. It was calculated that the absolute density of Green Ash 328.72 individuals/ha, while white ash has an absoulte density of 547.88 individuals/ha The average basal area of the sampled green ash was .00064 cm^2 and the average basal are of the sampled white ash was .11 cm^2. The relative dominance was calculated to be 25.8% for Green Ash and 74.2% for White Ash. Green Ash was found to be in 50% of the sample points, while White Ash was found to be in 70% of the sample points. For the relative importance value or RIV the calculated Green Ash RIV was found to be .35, and White Ash was found to have an RIV of .65. The table below shows the calculated results.

	Green Ash	White Ash
Relative Density	37.50%	62.50%
Absolute Density (# trees/ha)	328.73	547.88
Average Basal Area (cm2)	0.006389	0.11
Relative Dominance	25.84%	74.16%
Absolute Frequency	50%	70%
Relative Frequency	41.66%	58.33%
RIV	0.35	0.65
Average DBH (cm)	25	32

Table 2. The calculated results for the statistical analysis of the sampled Ash community.

After mapping the expansion of the emerald ash borer by year using GIS, there were several patterns that were revealed. After the initial dispersal near Detroit Michigan the insect followed a natural dispersal pattern. However as the years went on it can be observed that despite quarantine laws, the insect has accomplished jump, or long distance dispersals. As of 2013 the insect was found to be in Colorado, New Hampshire, Massachusetts, Georgia, Central

Minnesota, Western Iowa, and North-Western Wisconsin. It should also be observed that a population was detected in the year 2001 at Isle Royale National Park. The map below displays the extent of the emerald ash borer in the United States.

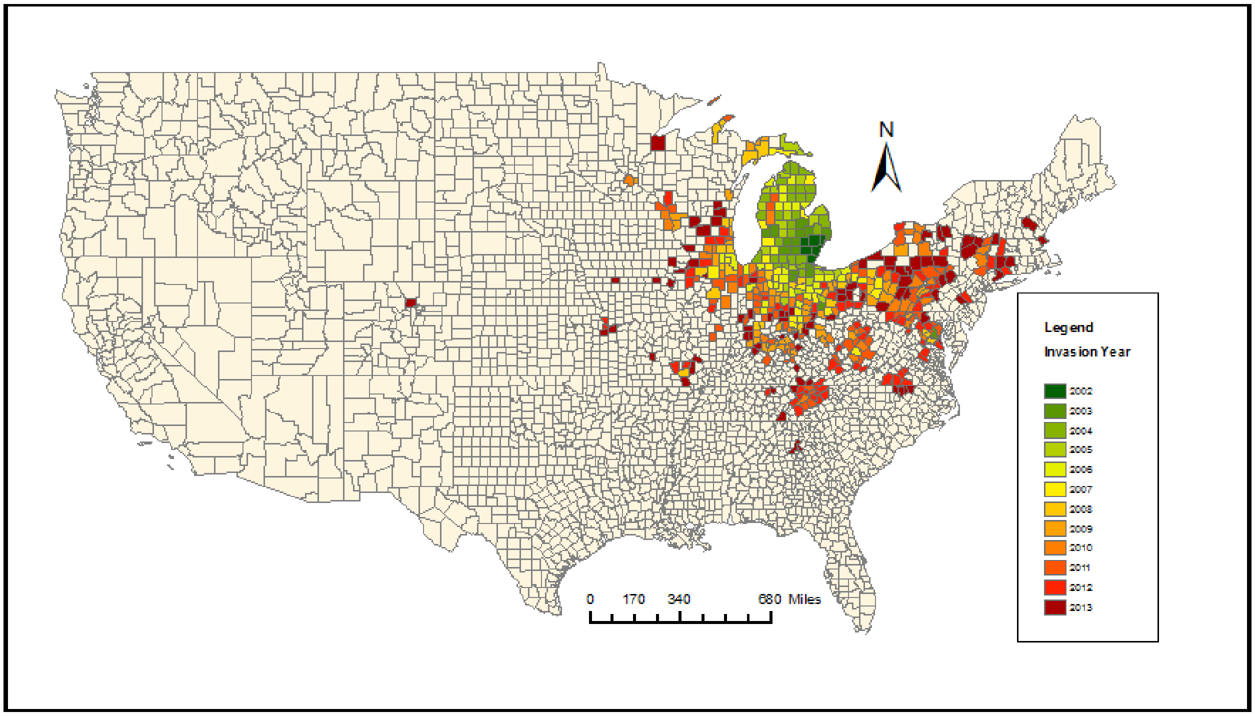

Figure 8. The map above created in Arc GIS shows the presence of the emerald ash borer in the United States by county, as well as the year the insect was first detected within that county.

<u>Discussion</u>

The relative low average age of the ash trees was expected, and can be explained by the amount of large ash tree mortality that has been observed at the sample site by the U.S. Forester. Many of the older, larger ash trees have died in recent years due to drought, emerald ash borer, and wind throw. The variance in the age distribution could possibly be caused by different ash cohorts being within the sampling transect. A cohort is a group of individuals born within the same timeframe, resulting in similar ages. The last 40m of the sampling transect contained what appeared to be a large cohort of young ash trees. After analyzing the ages of the two sampled ash species respectfully it was found that on average the sampled white ash were older, and had more old trees than the green ash. The percentage of sampled ash trees that have had observed growth retardation in the years after emerald ash borer infestation can be explained by the drought. Many of the ash trees were observed to be stressed prior to the emerald ash borer's infestation due to the very warm, dry summers this region has been experiencing over the past few years.

After analyzing the sampled ash population it was found that White Ash was the more prevalent species within the sample site. It had a higher density, dominance, frequency, and RIV value. This indicates that within this forest White Ash is the more dominant and important of the two present ash species. While both these trees were infected by emerald ash borer, it is important to understand which species has the greatest effect on the ecosystem to help make a prediction involving forest succession.

After analyzing the non-ash species data a prediction has been made pertaining to the future of the forest. While American Basswood was found to have the largest number of individuals with 18, it was found to have the lowest average dbh at 13.75cm. Shagbark however was found to have the lowest number of individuals with 11, but the largest average dbh at 22cm. Swamp white oak had the second highest number of individuals as well as the second largest average dbh. There were 16 observed swamp white oaks with an average dbh of 20cm. It is the predicted that after the emerald ash borer successfully causes mass ash mortality in the sample site the dominant species will become a mix of shagbark hickory, and swamp white oak. This prediction is made based on the average dbh, larger trees are more likely to produce more seeds, resulting in a higher successful germination rate per tree. In the following years after shagbark and oak dominance, it is predicted that basswood and silver maple will begin to flourish, due to the shade provided by the larger oaks and shagbarks. Silver maple and basswood are both shade tolerant tree species, and will be able to survive under the larger trees.

After creating the emerald ash borer presence map it became clear that quarantine zones have begun to fail in the past 5 years. These satellite colonies that can be observed on this map could only have been caused by human-aided dispersal methods. The colony on Isle Royale is especially disturbing. Isle Royale National Park is a secluded island in Western Lake Superior. This island is only accessible by ferry or plane to both park visitors and staff. While the emerald ash borer is capable of natural distribution, it is highly unlikely that the insect was able to cross Lake Superior to make it to the island. The only way the insect could have made it there would have had to have been by human-aided dispersal, most likely in the form of firewood transportation. The same is apparent for the satellite colony in Colorado. The nearest county with emerald ash borer is on the Kansas-Missouri border, a full state and a half away. It should also be noted that in 2004 a county in Virginia detected the emerald ash borer. This county experienced the insect much earlier than the surrounding counties, and was far away from the main invasion front. This satellite colony was well contained until 2008, when after 4 years the insect finally breached quarantine, after that year it can be observed that is spread from the original satellite colony.

Complications

During this study unforeseen complications occurred due to several factors. The beginning of the study began in late summer early fall, this created a significant time factor for field work. A sample site had to be chosen in haste in order to ensure that field work could be conducted. The sample site had to be within driving distance to make sampling possible, but include all the parameters needed for the determined study. Chain O' Lakes was chosen due to its ash stand and accessibility, however near the end of field sampling it was found that there were not enough Ash stands to further conduct research at that sampling site. It was then determined that another sample site was required to conduct field research. At this point in time the weather had begun to change and the leaves had fallen off of the ash trees. The state parks were also closing due to hunting seasons. This led to the premature end to field sampling. It was decided that statistical test and analyses were to be run off the data that was collected from the original site.

If this study was to be conducted in the future more research would have had to be done in searching for an appropriate sample site. This new site would need to be observed to ensure enough samples can be collected from the area. This study would also be better conducted during the summer. This would allow for optimal tree identification due to the abundance of foliage available to identify. It would have also allowed for more data to be collected. Increased numbers of participants would have made field sampling easier and would have ensured more accurate results. Sampling could also take place in one continuous sampling session instead of spacing the field sampling over several weekends. This could have lead to discrepancies. A larger sample size should be observed since this study only observed one plot, creating data that may be inconclusive. This study should also take place over a long period of time to monitor forest succession.

Conclusions

After completing this study it was found that both of my hypotheses were confirmed. When the data was analyzed and it was found that the most likely tree species that were to become dominant were shagbark hickory and swamp white oak. This corresponds in part with the study conducted by the National Forest Service. In that study it was predicted white oak, among other species, would become one of the dominant species in place of ash trees (DeSantis, 2013). They did not however predict that shagbark hickory would be one of the dominant species in oak hickory forests after ash die off. This could be due to the fact that the forest used in their model involved a wider variety of tree species than the sample area that I chose. They also concluded that the loss of the ash trees will have little effect on the forest's succession (DeSantis, 2013).

After analyzing the map created using Arc GIS, it was observed that the insect has spread well passed quarantine boundaries. It is important to be able to observe how far the insect has traveled with the aid of humans, often due to human carelessness. While the quarantines do help it is imperative that people monitor their fire wood transportation to ensure the insect does not travel any further. By comparing the map created in Arc GIS to the model created by Prasad et al (2010) it can be seen that the insect generally followed the path they predicted, beginning in Northern Ohio, then spreading to the South and West. This trend however cannot be observed when comparing the created map to the model created by Ayersman et al. (2009). The insect did not actually colonize much of New Jersey and Southeastern Pennsylvania, which according to the model, were areas with high invasion susceptibility. (Ayersman et al, 2009)

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