COST AND BENEFITS OF PROTECTING ASH (*FRAXINUS* SPP.) TREES ON THE MSU CAMPUS FROM EMERALD ASH BORER (*AGRILUS PLANIPENNIS* FAIRMAIRE) (COLEOPTERA: BUPRESTIDAE)

By

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ABSTRACT

COST AND BENEFITS OF PROTECTING ASH (*FRAXINUS* SPP) TREES ON THE MSU CAMPUS FROM EMERALD ASH BORER (*AGRILUS PLANIPENNIS* FAIRMAIRE) (COLEOPTERA: BUPRESTIDAE)

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Ash (*Fraxinus* spp) trees on the Michigan State University's campus have been injected with insecticides since 2005 to protect against the emerald ash borer *Agrilus planipennis* Fairmaire (Coleoptera: Buprestidae). Annual applications of imidacloprid and bi- to tri-annual applications of emamectin benzoate have been the primary chemicals used by the university, with emamectin benzoate becoming the primary chemical used in 2013.

Imidacloprid was the cheapest chemical to apply but must be applied annually and efficacy can vary. Emamectin benzoate was the most expensive chemical to apply, but the costs were annualized across two to three years, reducing the initial cost. The condition of the ash population improved as trees were protected from year to year with the ash population having an overall low percentage of canopy dieback and transparency. Ecosystem services were quantified via i-Tree Eco, which valued the ash population at nearly 10 times the total cost of treating the ash trees.

Alternate management strategies were simulated: 1) remove and replace all ash; 2) treat trees ≥ 20 cm, remove and replace trees < 20 cm; and 3) treat all trees with emamectin benzoate on a four-year rotation. When compared to the current management strategy, the cheapest option was to treat all ash trees on a four-year rotation of emamectin benzoate and the most expensive option was the removal and replacement of all ash trees.

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Introduction

Landscape tree values

Trees play important roles in the urban environment by moderating climate, improving air quality, capturing storm water runoff, and reducing heating and cooling costs (Asadian and Weiler 2009, Berland et al. 2017, Bolund and Hunhammarr 1999, Dwyer et al. 1992, Nowak et al. 2013, Xiao and McPherson 2002, Xiao and McPherson 2011). Trees in bioswales can transpire up to 72% of total available stormwater, reducing runoff from impervious surfaces and subsequently decreasing stress on local stormwater systems, while also removing pollutants and excess nutrients from stormwater (Denman et al. 2016, Read et al. 2008, Scharenbroch et al. 2016). Recent estimates of the value of ecological services provided by trees indicate trees in urban and community forests in the US save homeowners approximately $7.8 billion by reducing heating and cooling costs (Nowak et al. 2017). Urban trees also remove an estimated 17.4 million metric tons of air pollution annually, a service associated with improved human health in urban areas across the conterminous US and valued at $6.8 billion annually (Nowak et al. 2014). Numerous studies have cited the mental and physical benefits of urban forests, including increased physical activity, reduced stress and psychological restoration (Coombes et al. 2010, Hartig and Staats 2006, Roe and Aspinall 2011, Ulmer et al. 2016). Other studies have shown hospital patients recovered faster from surgery and had less postsurgical complications when they had a view of trees in a natural setting (Ulrich 1984).

Quantifying benefits of trees, particularly in economic terms, allows managers to assess and justify investments in urban forests and effectively use available resources to maintain healthy and productive urban forests (McPherson et al. 1997). Early efforts included the 1993 Chicago Urban Climate Project, which addressed the need to quantify and monetize ecosystem services provided by urban trees. Models of forest functions were created to quantify specific ecosystem services, including reduced energy use, air pollution removal, carbon sequestration and storage, and reduction in stormwater runoff and monetary values were estimated for each function and linked to the inventory of the tree population in Chicago (McPherson et al. 1997). The Chicago project provided the basis for the 1996 US Forest Service's Urban Forest Effects (UFORE) model, which evolved into the Street Tree Resource Assessment Tool for Urban Forest Managers (STRATUM) model in 2004. These models were subsequently updated, revised and combined into i-Tree, a software suite which was first released in 2006 (David Nowak, personal communication). This software allows users to quantify function and economic values of urban forests based on size, species and location of trees (i-Tree 2019).

Since 2006, many municipalities have utilized the i-Tree program to quantify ecological services of their tree population, allocate resources, and to justify continued investment in urban forestry programs. For example, the University of Pennsylvania estimated that approximately 4,000 trees on 65 hectares of campus provided $150,515 in annual benefits (Basset 2015). The city of Ann Arbor, Michigan reported that approximately 1.45 million trees growing on public and private lands provided $5 million in annual benefits (City of Ann Arbor 2013). Similarly, Providence, Rhode Island estimated that approximately 415,000 trees growing on private and public lands provided $4.7 million in annual benefits (City of Providence 2014). On a larger scale, California accrued an estimated $1 billion, annually from their street trees (McPherson et al. 2016), while Tennessee's urban forests, including private and public lands, provided $80 billion of services each year (Nowak et al. 2009).

Emerald ash borer

Unfortunately, urban forests in much of the eastern US continue to be affected by an array of pests, particularly invasive species (Liebhold et al. 2013). Emerald ash borer (EAB), *Agrilus planipennis* Fairmaire (Coleoptera: Buprestidae), has been especially devastating. This phloem-feeding beetle is native to Asia and was first discovered in North America in southeast Michigan and Windsor, Ontario in 2002 (Cappaert et al. 2005). Dendrochronological reconstruction, however, showed ash trees were being killed by this invader as early as 1997 in Canton, MI, a western suburb of Detroit, indicating EAB was established by the early 1990's (Siegert et al. 2014). Since 2002, research on EAB in North America has addressed a range of topics, including EAB biology, ecology, impacts, and management (Herms and McCullough 2014). Emerald ash borer is already considered the most destructive and costly forest insect to invade North America (Aukema et al. 2011, Herms and McCullough 2014). It's decimation of ash in urban, rural, and forested areas have affected property values, plant-based industries and induced large expenditures by local governments who must remove dead or declining landscape trees or protect ash with insecticides on public lands (Aukema et al. 2011, Sydnor et al. 2007, 2011). As of November 2018, EAB is known to be established in at least 35 states and five Canadian provinces (EAB Info 2019).

Emergence of EAB adults begins in late spring or early summer (Cappaert et al. 2005). Adult beetles, which leave distinct D-shaped holes upon emergence from the trunk and branches, feed on leaves for approximately one week before mating and females feed another 5-7 days before oviposition begins (Bauer et al. 2004, Cappaert et al. 2005, Poland and McCullough 2006). Beetles continue leaf feeding throughout their 3 to 6-week lifespan. Females lay individual eggs within bark crevices and cracks or beneath bark flakes (Cappaert et al. 2005). Larvae hatch within 1-2 weeks, bore through the outer bark and feed on phloem and cambium in serpentine galleries in late summer and fall (Poland and McCullough 2006). Most larvae complete feeding by fall and overwinter as prepupal fourth instars. In healthy trees with low densities of EAB larvae in areas with cold climates, some EAB may overwinter as early instars, feed for a second summer, then emerge the following year (Siegert et al. 2010, Tluczek et al. 2011). Pupation occurs the following spring from mid-April to May, followed by adult emergence approximately two to three weeks later (Cappaert et al. 2005).

Natural dispersal occurs via adult beetle flight (Mercader et al. 2012, Taylor et al. 2007, 2010) but long-distance dispersal has resulted from human transport of infested material such as nursery stock, logs or firewood (Cappaert et al. 2005, Poland and McCullough 2006, Seigert et al. 2014). Early evidence of new EAB infestations often includes holes left by woodpeckers preying on overwintering larvae. When EAB populations have increased to moderate or high densities, diagnostic signs including EAB exit holes, canopy decline, bark cracks and epicormic shoots become apparent (Anulewicz et al. 2007, Cappaert et al. 2005, McCullough and Mercader 2012). As larval density builds within trees, canopies thin, dieback and trees often succumb within a few years once canopy decline becomes apparent (Anulewiz et al. 2007, Poland and McCullough 2006).

In urban and community forests loss of ash trees associated with EAB can impact ecosystem services and human health. Economic impacts of EAB are immense. Sydnor et al. (2007) predicted that Ohio would lose an estimated 4.3 million ash trees located on private and public land from EAB, potentially generating $7.5 billion in removal and replacement costs. Subsequent estimates were expanded to include communities in Illinois, Indiana, Michigan and Wisconsin, and total costs, which included loss of landscape value and tree removal and replacement, were estimated at $13.4 billion to $26 billion (Sydnor et al. 2011). Kovacs et al. (2010) projected EAB spread from 2009-2019 and estimated economic costs of treating or removing approximately 45% of the 38 million ash trees in landscapes on public lands in urban areas would amount to $10.7 billion. They also reported that if suburbs of the cities were included, the number of affected ash trees and associated costs doubled. Estimated costs of treating 10% of ash trees on public lands in Canadian municipalities was $524 million Canadian dollars (McKenney et al. 2012).

Studies have shown the health impacts EAB has on humans. Donovan et al. (2013) showed a correlation between ash (*Fraxinus* spp.) mortality rates following emerald ash borer (EAB) (*Agrilus planipennis* Fairmaire) invasion in southeast Michigan and human death rates related to cardiovascular and lower respiratory tract illness. Women enrolled in the Women’s Health Initiative and living in a county infested with emerald ash borer were at a higher risk of cardiovascular disease (Donovan et al. 2015). Additionally, declining ash tree condition caused by EAB was associated with increases in crime in Cincinnati, OH (Kondo et al. 2017).

Management activities to maintain or remove ash trees are expensive but necessary to reduce impacts of declining and dying. Trees, when left unmanaged, can become hazardous and become legal liabilities, especially in urban areas where people, vehicles and buildings are targets of declining trees. There are many news stories that have shown the impacts of trees falling and damaging property or killing people, especially declining and dead trees. An article in The Detroit News, published October 27, 2018, discussed the impacts of declining and dying ash trees across the state of Michigan, noting at least five deaths were from falling dead ash trees. Lake Cumberland State Resort Park in southern KY has been removing dead ash trees to make the park safe for the public. Municipality budgets will increase as removals, which include stump grinding, removal of wood, and chipping, or insecticide treatments occur. Hauer and Peterson (2017) found municipality budgets increased and peaked eight years after EAB was discovered in states with confirmed EAB reports.

Simulations have consistently shown treating landscape ash with emamectin benzoate in alternate years is less expensive than removing and replacing ash trees (Kovacs et al. 2010, 2011, McCullough and Mercader 2012, Vannatta et al. 2012). Sadoff et al. (2011) found that treating ash trees with an insecticide is cheaper than removing or replacing ash trees, with cumulative costs exceeding removal costs in seven years and replacement costs in 17 years. Kovacs et al. (2014) found that centralizing budgets across jurisdictions can provide funding to adequately manage ash trees in urban areas, while also finding that treating ash trees provides the most benefits to municipalities.

Systemic Insecticides

Since 2002, substantial progress has been made in the ability of arborists to effectively protect landscape ash trees from EAB with systemic insecticides. Systemic insecticides are translocated in xylem from the base of the tree to canopy branches and foliage (Mota-Sanchez et al. 2009, Tanis et al. 2012). Cover sprays, applied to the canopy and trunk of ash trees, provide adequate protection against adult EAB beetles; however, these applications only protect against adult EAB feeding on leaves or as newly hatched larvae chew through bark while systemic insecticides kill larvae feeding on the cambium layer and adults feeding on leaves (Herms et al. 2014). Common options in the US include soil applications or trunk injections of imidacloprid, basal trunk sprays of dinotefuran, and trunk injections of emamectin benzoate and azadirachtin (Herms et al. 2014).

Many products with imidacloprid as the active ingredient are available for landscape trees but efficacy varies substantially (Herms 2009, McCullough et al. 2004, Poland et al. 2016, Rebek et al. 2008, Smitley et al. 2010, 2015). Imidacloprid products must be applied annually as concentrations vary within a tree, with leaves and trunks having the highest and lowest concentrations, respectively, and decrease after one year (Mota-Sanchez et al. 2009, Tanis et al. 2012). McCullough et al. (2011) found trunk injections of imidacloprid were more effective than basal trunk sprays of imidacloprid. Bick et al. (2018) reported annual soil applications of imidacloprid applied at a rate of 1.12 g a.i. per cm of DBH effectively reduced the rate of increase of dieback. McCullough et al. (2018) found that despite lower EAB densities in trees treated with trunk injections of imidacloprid, there was substantial variation among treated trees.

Numerous field trials have shown trunk injected emamectin benzoate is highly effective for EAB control. In field trials, the product sold as TREE-äge® with emamectin benzoate as the active ingredient, provided nearly 100% control of EAB for at least two years (Hermes 2010, Hermes et al. 2014, McCullough et al. 2011,). Smitley et al. (2010) found that low to medium rates of emamectin benzoate were able to provide 100% control of EAB for at least two years, even under intense pressure. Bick et al. (2018) found the rate of canopy dieback did not increase with biennial trunk injections of emamectin benzoate, while Flower et al. (2015) found biennial trunk injections protected trees with light to moderately infested trees. McCullough et al. (2018) found that three years after trunk injection of emamectin benzoate, very few EAB galleries were present.

Dinotefuran, when applied annually as a noninvasive basal trunk spray, provides effective control against EAB (McCullough et al. 2011, 2019). Although high water solubility allows for rapid translocation into the canopy of trees, this also is a concern as dinotefuran can easily move through soil and leach into waterways (EPA Factsheet). Drift is another other concern when applying dinotefuran as a trunk spray as the chemical can impact nearby plants, humans, and insects. Dinotefuran can be applied as a trunk injection or as a soil injection as well, but residue levels appear to be short lived and drop after one year (McCullough et al. 2007, Wang et al. 2007). Azadirachtin is a natural systemic insecticide derived from the neem tree and poses little risk of harm to decomposer invertebrates (Kreutzweiser et al. 2011). Annual trunk injections of azadirachtin have been shown to inhibit larval development and reduce adult emergence of EAB while being environmentally safe for decomposer invertebrates (Grimalt et al. 2011, Kreutzweiser et al. 2011, Mckenzie et al. 2010).

Costs and benefits of MSU's ash tree management program

Campus trees add to the aesthetics of Michigan State University and provide a living lab for numerous classes and outreach activities. Approximately 21,000 trees, representing 140 species, grow on 829 hectares of developed land on campus. Common genera include *Acer*, *Malus*, *Pinus*, *Quercus*, and *Fraxinus* (MSU Campus Tree Map). In 2003, one year after EAB was identified in southeast Michigan, EAB was detected in Ingham Co. (EAB Info 2018). Arborists first identified EAB in campus trees in June 2005. Not surprisingly, this invader was perceived as a threat to the ash population on campus. Quantifying ecological values of the ash population can provide useful information for arborists who must determine both short- and long-term costs and benefits of continuing ash treatment versus either proactive removal or removal or ash as they decline. Research shows how costly it is to treat, remove, and replace landscape ash (Kovacs et al. 2010, 2011, McKenney et al. 2012, McKenney and Pedlar 2012, Sydnor et al. 2007, 2010, Vanatta et al. 2012). Municipal budgets in counties affected by EAB have been overwhelmed with the cost of removing dead and dying ash trees (Herms and McCullough 2014). Michigan State University currently injects the ash population with an insecticide on a three year rotation.

In this study, my main objectives include determining the annual treatment costs for ash trees on Michigan State University's campus and the value of benefits provided by maintaining those trees. I acquired records to identify insecticide products used each year and costs of the products and labor. I assessed the efficacy of treatment by examining current condition of ash trees on campus. Data from these trees were used to estimate the ecological services provided by maintaining those trees and the monetary value of these ecological services provided by the treated trees.

Methods

Survey of current ash tree condition

Maps of the 161 ash trees in the 829 ha of developed land on campus were provided by personnel from MSU Campus Planning and Administration. Ash in unmanaged natural areas were excluded. Between June and August 2014, I surveyed each tree and visually inspected each tree from multiple directions. For each tree, I recorded diameter at breast height (DBH) 1.3 m aboveground. I also measured the width of the canopy, i.e., the length of the canopy from the southern to the northern edge of the drip line and from the eastern to the western edge of the drip line. I re-visited all ash trees in July 2015 to visually estimate canopy transparency and dieback (10% classes). Abundance of woodpecker (WP) holes, distinctive D-shaped EAB exit holes and epicormic sprouts were qualitatively ranked as 0 (absent), few (1-5 present), or many (>5 present). Canopy dieback and transparency were visually estimated in 10% classes where 90% indicated a nearly dead tree and 10% indicated minimal decline. If previous EAB injuries, such as larval galleries, were apparent, I recorded their location (trunk, branch, or both) and ranked their general abundance as above. I also determined whether EAB appeared to be the cause of any canopy decline and whether other insect pests or physical wounds (e.g., mower damage) were present. Trees were re-visited in June 2016 to quantify variables needed for estimates of ecological services for the i-Tree software. These variables included total tree height, height to the top of the live canopy, height to the base of the canopy and percent of the canopy that was dead or missing (e.g., pruned or broken).

Total height included any dead limbs in the canopy, while canopy live height was the height to the top of the tallest live branches or leader. Height to the canopy base represented the height of the lowest leaf. Missing canopy represented the percentage of the canopy not occupied by live branches and leaves. Total height, live height, and canopy base were measured using a Nikon Forestry PRO Laser Rangerfinder/Hypsometer (Nikon®, Melville, NY). Building interactions, which have implications for heating and cooling effects of trees, were determined by measuring the distance between the building and the trunk of the tree and the direction of the tree relative to the building was recorded.

Insecticide treatments

I acquired records of insecticide treatments applied to the ash trees annually between 2005 and 2014 from Campus Planning and Administration and arborists at MSU Landscape Services. Records included the active ingredient and name of the product applied to specific trees, application rates, timing, methods, tree DBH and general condition (excellent, good, fair, poor) at the time of treatment. Insecticide chemistries and products changed, depending on availability, price and evolving recommendations coming from researchers. Number of trees treated annually also was influenced by the available budget for treatments and the work load of the applicator. Treatments included annual soil injections of imidacloprid from 2005 to 2012, annual trunk injections of imidacloprid in 2005 and 2006, and trunk injections of emamectin benzoate applied at either two- and three-year intervals from 2008 to 2014 (Table 1). From 2008 to 2010, emamectin benzoate was applied in alternate years (two-year intervals). In 2010, the treatment interval was extended to three years for some trees. A three-year rotation of emamectin benzoate injections became the standard application approach after 2010.

Economic costs of insecticide treatments were calculated using the price of the specific product the year it was purchased and applied, along with the tree DBH and application rate. Insecticide prices and the time needed to apply products to specific trees were determined using purchase records and notes recorded by the MSU arborist who applied all the products between 2005 and 2014. Labor costs were derived using the 2014 salary and fringe benefit rate of the applicator, which totaled $46 per hour. Time required to mix the product in a tank (if applicable), travel to the tree(s) and complete the application were included in cost estimates. Labor costs for soil injections of Merit® and QualiPro® were estimated at 30 minutes per tree by the applicator. Beginning in 2009, the applicator recorded the time needed to complete emamectin benzoate trunk injections for each treated tree. Similar records were not available for trees injected with imidacloprid applied via Mauget® capsules from 2005-2008. I therefore estimated the time needed to apply imidacloprid (Imicide®) with Mauget® capsules or IMA-jet with the TREE IV in 2005-2006 by averaging the time required to apply emamectin benzoate to trees of similar DBH. State regulations stipulate that applicators injecting systemic insecticides must maintain visual contact with the treated trees until the capsules or the TREE IV are removed. Therefore, when multiple trees growing in the same location or near each other were treated, the recorded application time was divided by the number of trees treated. Vehicle costs were acquired from MSU Landscape Services and reflect fuel and maintenance costs for the pickup truck used by the arborist, along with the travel time to access the trees. Travel time was assumed to be 15 minutes from Landscape Services to locations on campus (or one location to the next location), which I confirmed by recording the time to drive to various ash trees from the Landscape Services facility. When multiple trees were present in a given location, travel time and vehicle costs were divided among the trees in that location.

Total treatment costs reflect the sum of the insecticide product, labor and vehicle costs associated with the applications. Costs of applying emamectin benzoate, now known to provide up to three years of protection (Bick et al. 2017, Herms et al. 2014, McCullough et al. 2019), were annualized, based on the treatment frequency for individual trees. For example, costs of emamectin benzoate applications in 2010 represent the costs of injecting trees in that year plus the standardized costs of treatments applied in 2008. Biennial treatments of emamectin benzoate occurred from 2008-2010 while triennial treatments began in 2011. Total costs of protecting each tree from 2005-2014 were calculated, along with the annual cost per tree and per cm DBH for each insecticide product.

Ecological services estimated by iTree

Ash tree data were imported into Eco v6, an application of i-Tree that estimates and monetizes the benefits of urban trees. Tree and canopy data were merged with location specific information to produce summary reports. Location specific information, such as weather and pollution, was established by indicating location of project, choosing a nearby weather station, and choosing the weather year of 2013, which provides information on weather for the selected year.

Air pollution removal

Urban trees can improve air quality and reduce adverse health effects by removing air pollution. Particulate matter less than 2.5 microns (PM2.5), a subset of PM10, is used by i-Tree because it is more relevant than PM10 to human health (Nowak et al. 2013). To determine hourly pollutant dry deposition per tree, the product of deposition velocity $V_d = \frac{1}{R_a+R_b+R_c}$, pollutant concentration, canopy coverage, and a time step, or base year, was determined by Baldocchi et al. (1987). These variables reflect aerodynamic, boundary layer, and stomatal resistances, respectively, which are influenced or associated to atmospheric turbulence, diffusivity to materials being transferred, and biological surface factors such as water surfaces. Hourly estimates for these resistances throughout a time step, or base year, are used to calculate removal rates for PM2.5, ozone, sulfur dioxide, and nitrogen dioxide per tree (Scott et al. 1998, Nowak et al. 2002, Baldocchi et al. 1987). The U.S. Environmental Protection Agency's Environmental Benefits Mapping and Analysis Program (BenMAP) is a software tool that estimates the number and economic value of health impacts resulting from changes in air quality to estimate the economic value of the following pollutants: ozone, sulfur dioxide, nitrogen dioxide and PM2.5 (U.S. EPA BenMAP). Carbon monoxide removal rates in iTree are based on average measured values determined by Bidwell and Fraser (1972) and Lovett (1994). The value of carbon monoxide removal in iTree is calculated using national median externality costs, which are costs based on willingness to pay for changes in welfare (Murray et al. 1994).

Carbon storage and sequestration

Carbon storage is calculated in i-Tree using biomass equations developed from forest-grown trees and DBH measurements. Biomass equations varied among *Fraxinus* species and biomass estimates calculated from equations were dependent on diameter (Schlaegel 1984, Tritton & Hornbeck 1982). Nowak (1994) found statistical differences between predicted and actual biomass for open grown, landscape trees versus forest grown trees. Equations calculated for stand occurring trees overpredict biomass for urban trees (Nowak 1994). To adjust for this difference, biomass results were multiplied by 0.8 and dry weight biomass was multiplied 0.5 to convert estimates to total stored carbon (Nowak 1994, 2002). To standardize the annual value of carbon storage for individual trees, the carbon storage value for 2016 was divided by the DBH measured in 2016. This value was multiplied by the DBH recorded at the time of treatment for a given tree.

Carbon sequestration is estimated by iTree using the average annual diameter growth for a selected genus and diameter class. To estimate tree diameter and carbon storage for future years, the average diameter growth used to estimate carbon sequestration is added to the existing diameter of a tree (Nowak, 1994). This is a linear value, which accounts for carbon released upon a tree's death. Value of carbon storage and sequestration used in i-Tree was $146.70/tonne, derived from carbon values for the United States (U.S. EPA Social Cost of Carbon, 2015).

Avoided runoff

Annual avoided surface runoff is calculated as the difference between annual runoff with and ke and evaptwithout vegetation and specifically accounts for precipitation intercepted by leaves. This value is based on the US Forest Service's Community Tree Guide Series (McPherson et al. 1999, Peper et al. 2009, 2010). During light rain events, leaf and branch surfaces that extend over impervious surfaces intercept precipitation, while any precipitation that infiltrates the soil beneath a tree is assumed to be taken up by roots. During heavy rain events, however, water cannot infiltrate into the soil fast enough for roots to affect runoff rates (Hirabayashi 2013).

Building energy use

Distance and direction of trees from buildings, tree height and tree condition were used to calculate seasonal energy usage. Trees more than 18.3 m away from a building and less than 6.1

m tall are excluded from building interactions within i-Tree. Properly located trees at least 6.1 m tall and growing within 18.3 m of buildings provide shade and heat to buildings during summer and winter months, respectively, thus reducing energy costs (McPherson and Simpson 1999). The i-Tree software used average Michigan energy costs for megawatt hours (MWH) and million British Thermal Units (MBTU) to calculate the monetary value of energy savings in US dollars, which were $140.89 per MWH and $13.95 per MBTU (U.S. EIA, 2012).

Structural value

Structural value represents the physical resource of the tree and the cost of replacing a given tree with a similar tree of the same size. Valuation procedures are based on the Council of Tree and Landscape Appraisers and values derived from these procedures vary with tree species, diameter, condition and location (Nowak et al. 2002a, 2002b). This value can be considered an asset when trees are considered as a capital investment similar to other infrastructure (i.e. buildings, streets, etc) (McPherson et al. 2016). To standardize structural value for each tree annually, the structural value for 2016 was divided by the DBH measured in 2016. This value was multiplied by the DBH recorded at the time of treatment for each individual tree.

Cost and benefits of alternate options for managing MSU's ash trees

Alternative options for managing ash populations, such as preemptively removing ash trees, have been modeled or simulated to help municipalities and other major landowners compare the benefits and costs of these options (Kovacs et al. 2010, McKenney and Pedlar, 2012, Sydnor et al. 2011, VanAtta et al. 2012). To evaluate costs and benefits of alternate strategies for the campus ash trees, I considered three options: 1) preemptively remove and replace all ash trees; 2) treat only trees ≥ 20 cm DBH with an insecticide and remove and replace all trees < 20 cm DBH; and 3) beginning in 2008, treat all trees with TREE-äge® on a 4-year cycle (rather than a 2-year cycle). Costs of removing trees and estimates of the number of trees that could be removed annually were provided by MSU arborists. Equipment, labor and time needed to remove trees were based on tree DBH (< 20 cm, 20-40 cm, 40-60 cm, and > 60 cm) (Table 2). Costs for stump grinding and brush removal were included, as they are a standard component of MSU's removal process. Estimated costs of planting trees included the purchase of balled and burlaped trees at wholesale prices and were based on information provided by MSU Landscape Services. Size of trees purchased for planting included 5.1 cm, 6.4 cm, 7.6 cm, 8.9 cm, and 10.2 cm (Table 3). I assumed no insecticide treatment or tree removal would occur until 2008 when EAB densities would presumably be high enough to result in noticeable tree decline (Anulewicz 2007).

Under Option 1, forty trees would be removed and replaced annually. This is the maximum number of trees that can feasibly be removed and replaced by MSU Landscape Services. Trees for removal and the size of the replacement tree were selected randomly. Ecological services based on i-Tree data provided in 2016 were then used to estimate values of lost services as annual tree removals progressed. I assumed insecticide products used each year along with labor and chemical costs for these trees would remain the same. Under this simulation, the removal of the ash population would eliminate any long-term insecticide treatment costs.

For Option 2, removal of the smaller trees would begin in 2008. Removal, replacement plantings and ecological services were determined as described for the first alternative option. Treatments would remain the same from 2005 to 2007. I assumed seven to nine trees could be treated per day based on recorded uptake times. Under this simulation, the possible costs of treating larger trees and the possible loss of ecosystem services with the removal of smaller ash trees would be determined. For Option 3, I considered a four-year interval of emamectin benzoate treatments to compare the differences in costs on a per tree and annual level and determine feasibility in areas where EAB populations are low. All alternate options were simulated to further inform MSU of the benefits, losses and potential costs of each option when compared to the current management option.

Results

Tree Condition

Seven species of ash grow on the developed portion of the MSU Campus, including five species that are native to North America (Table 4). White ash and green ash comprised 65% and 21%, respectively, of the total ash population. Both species are widely distributed around much of eastern and central North America. Only one Oregon ash (*Fraxinus latifolia*), which is native to the coastal areas of the Pacific northwest, is present on campus. Black ash (*Fraxinus nigra*) and blue ash (*Fraxinus quadrangulata*) are also present on campus, making up approximately 7% and 5%, respectively, of the total ash population (Table 4). There are two flowering ash (*Fraxinus ornus*) and two Korean ash (*Fraxinus chinensis* ssp *rhynchophylla*), which are native to southern Europe, Russia and Asia, respectively, present on campus.

Overall, the ash population had a wide range of diameters and nearly all trees exhibited healthy canopies. Trees in the 20-40 cm size class represented 51% of the total ash population, while only 11% of the ash were < 20 cm DBH (Figure 1). Of the 161 ash trees on campus, only 43 trees had no signs of EAB colonization. Canopy transparency averaged 10% ± 0.79 and mean canopy dieback was 9% ± 0.60 with ranges of 0 to 75% and 0 to 45%, respectively. Epicormic sprouts were present on 81% of the trees. Only six trees exhibited canopy transparencies > 30% and one tree exhibited canopy dieback > 30%.

Ash trees on the MSU campus occur in lawns, parking lots, along streets, and next to buildings (Table 4). Street trees were relatively common, comprising 35% of the ash population and averaging 27.5 ± 1.81 cm DBH. All ash street trees had epicormic sprouts, but evidence of previous EAB attacks, including woodpecker holes, EAB adult exit holes, and old larval galleries, were observed on only 21% of the street trees. All the street trees exhibited healthy canopies with ≤ 15% canopy transparency or dieback. Trees in lawn areas comprised 33% of the ash, averaging 53.8 ± 3.8 cm DBH, and nearly all (90%) had at least one epicormic sprout. Woodpecker holes, old larval galleries, and EAB adult exit holes, however, were observed on only four of the 56 trees in lawn areas. Trees in parking lots represented 22% of the ash population and had a mean DBH of 33.3 ± 1.95 cm. Woodpecker damage, adult exit holes, and old larval galleries were apparent on six of the 35 trees in parking lots. Most (94%) trees in parking lots were healthy with ≤ 25% canopy transparency or dieback, although one white ash had 45% dieback and 15% canopy transparency. This tree had no signs of EAB, but a large basal wound was present. Another white ash with 25% canopy dieback and 10% canopy transparency had epicormic sprouts, but no external evidence of EAB infestation. Only 17 ash trees were growing within 18 m of buildings. These trees averaged 15.1 ± 1.12 m in height, 48.4 ± 3.73 cm DBH, and ranged from 11.9 to 32 m tall and 34.3 to 103.1 cm in diameter, respectively. Two trees near buildings had obvious evidence of past EAB infestation, including woodpecker damage, adult exit holes, and old larval galleries. These trees had healthy canopies, in 2014, however, averaging 11% ± 1.66 in canopy transparency and 13% ± 1.67 in canopy dieback.

Other pests occasionally observed on ash trees included ash flower gall and oystershell scale (*Lepidosaphes ulmi* Linnaeus). Ash flower galls, caused by tiny mites *Eriophyes fraxiniflora* Felt feeding on male ash flowers, typically affect only the appearance of these but cause little physiological injury (Johnson & Lyon 1991, UMN Extension 2005). These galls were present on ten trees. One tree had 40% canopy transparency, possibly due to nearby building construction, but the other nine trees with galls had ≤ 25% transparency and ≤ 15% canopy dieback. Oystershell scale, which feed on phloem sap, was present on seven trees (Johnson & Lyon 1991), but all of the trees had healthy canopies (≤ 10% canopy transparency and dieback).

White Ash

White ash dominated the campus ash population, accounting for 65% of all trees (Table 1). Trees in the 20-40 cm diameter class comprised 57% of the white ash trees, while 12% of the trees were small (< 20 cm DBH). Fifteen percent of the white ash were in the 40-60 cm and 16% were in the > 60 cm DBH class (Figure 1).

White ash in lawns and along streets each represented 37.5% of all white ash while 23% were in parking lot planters (Table 4). Two white ash were within 5 m of a building. Both had old EAB larval galleries and both were large trees (DBH of 103.1 cm and 55.6 cm). Canopies were relatively healthy with ≤ 15% canopy transparency and 25% canopy dieback.

Only one white ash had an unhealthy canopy (≥ 30% canopy dieback), while four trees had somewhat thin canopies (33-38% canopy transparency). A white ash located in a parking lot planter had 45% canopy dieback and a large wound at the base of the trunk. Several ash flower galls were present on three white ash trees, including two street trees and one located in a parking lot planter, while oystershell scale was present on five street trees. There were 17 trees with multiple signs of EAB, including woodpecker damage, adult exit holes, epicormic sprouts, and old larval galleries, but these trees had healthy canopies when examined in 2014 (≤ 25% canopy transparency and ≤ 15% canopy dieback).

Green Ash

Green ash was the second most common species on campus (Table 4). Relatively large trees in the 40-60 cm DBH class comprised 48% of the green ash, while the 20-40 cm DBH class included 36% of the green ash population. Only five green ash trees were > 60 cm in diameter; the largest was 129.5 cm. No small (< 20 cm DBH) green ash trees were recorded (Figure 1). Green ash growing near buildings represented 39% of these trees, while lawn areas, streets, and parking lots each included 15 to 24% of the green ash population (Table 4).

All green ash trees had healthy canopies (≤ 25% canopy transparency and < 30% canopy dieback). Ash flower galls were present on six trees, all located along streets, while oystershell scale was not present on any green ash. Old larval galleries and epicormic sprouting were the most common signs of EAB and were observed on 79% and 88% of the trees, respectively. Only 21% and 12% of the green ash, had no signs of old EAB galleries or epicormic sprouts, respectively. Woodpecker damage and adult exit holes were observed on four trees (Table 4). Two green ash, one near a building (DBH 42.7 cm) and one next to a street (DBH 43.9 cm) exhibited all signs of EAB but had healthy canopy transparencies (< 15% and canopy dieback < 30%).

Black Ash

Seven of the 11 black ash trees were in the 20-40 cm diameter class (Figure 1). All trees had epicormic sprouts and ≤ 15% canopy transparency and dieback, while ten of the trees had old larval galleries. Two black ash exhibited some signs of EAB (woodpecker damage, adult exit holes, old larval galleries), but had healthy canopies with ≤ 15% canopy transparency and dieback. Three small trees (< 20 cm DBH) had old larval galleries but healthy canopies with ≤ 10% canopy transparency and dieback. One tree that was > 60 cm in DBH had no signs of EAB, a healthy canopy, and was the only black ash in a lawn area. All other black ash trees were planted along roads. Three trees had either ash flower galls or some oystershell scale, while one tree had both pests.

Blue Ash

Eight blue ash trees were growing in lawn areas (25%) or in parking lots (75%) and all had healthy canopies with no canopy transparency or dieback (Table 4). Four trees had a DBH of 20-40 cm diameter, two trees had a DBH of 40-60 cm, and the < 20 cm and > 60 cm diameter classes each had one tree (Figure 1). One blue ash (DBH 65.3 cm) was in a parking lot island and had a healthy canopy (≤ 10% canopy transparency and dieback) but had EAB exit holes and old larval galleries. Only one tree showed all signs of EAB, including woodpecker damage, adult exit holes, epicormic sprouts, and old larval galleries, but had a healthy canopy (no transparency or dieback). Although all blue ash had epicormic growth, only three had EAB exit holes and five had old larval damage.

Other Fraxinus species

Two small Korean ash (< 20 cm DBH) growing in lawn areas appeared healthy with < 10% canopy transparency and dieback. The Oregon ash and the two flowering ash were in the 40-60 cm DBH class. The Oregon ash was in a lawn area, had a healthy canopy with < 10% canopy dieback and transparency, but old larval damage and epicormic sprouts were present. Both flowering ash were planted next to a building and old larval galleries were visible on the trunks and branches. One of the flowering ash had woodpecker damage and adult EAB exit holes. Both trees had < 25% canopy transparency and 10% canopy dieback.

Insecticide Treatments

There were 1,025 records of insecticide applications to ash trees between 2005 and 2014. Commonly used products included two imidacloprid products, Merit® 75 WSP and QualiPro® and TREE-äge®, an emamectin benzoate product, which accounted for 41%, 24%, and 31%, respectively, of the total treatments (Table 1). Number of ash trees treated annually ranged from six trees in 2014 to 159 trees in 2008 and averaged 103 ± 13.81 trees. A total of 26,645 DBH cm were treated from 2005 to 2014. Annually, an average of 25.93 ± 0.62 cm DBH were treated, but this varied from 192 cm in 2014 to 4,833 cm in 2008 (Table 5).

Annual treatment costs varied, depending on the number and size of trees treated and the product used. Annual treatment costs ranged from $2,654 to $6,507 per year and averaged $4,832 ± 270.45 per year (Tables 5, 6). Annualized cost per 2.5 cm DBH for each product, which includes chemical and labor, ranged from $2.06 for emamectin benzoate to $1.20 for IMA-jet® (Table 1). Average cost per tree was $33.70 ± 0.47 and average cm DBH was 25.9 ± 0.65.

Imicide®

Costs to treat 21 trees in 2005 and one tree in 2006 with imidacloprid applied as Imicide® using Mauget® 3mL capsules totaled $1,916.24 (Table 5) and averaged $87.10 ± $7.39 per tree. Application rate was 0.15 g a.i. per 2.5 cm DBH, equivalent to $1.49 per cm DBH. Chemical costs per tree ranged from $21.24 to $84.96 and labor costs ranged from $15.78 to $101.73. The cheapest tree to treat was a 35.6 cm DBH white ash that required $24.78 of product and $15.78 in labor. Labor costs depended on the time per tree required for uptake (i.e. capsules to empty) and whether trees could be treated in groups or individually. For example, a single tree with a 35.3 cm DBH, treated in 2006, had a labor cost of $101.73, a chemical cost of $24.78 and a reported uptake time of 128 minutes. In contrast, a group of three nearby trees with DBH ranging from 35.6 to 50.8 cm cost $15.78 per tree in labor, $24.78 to $38.94 for product and uptake times ranged from 63 to 98 minutes.

IMA-Jet®

A new imidacloprid product sold as IMA-Jet® and applied with the Arborjet TREE IV trunk injection system became available in 2006 and was used to treat 30 trees in 2006 (Table 5). Total cost of IMA-Jet® treatments averaged $72.60 ± 4.56 per tree, equal to $1.20 per cm DBH. Labor costs ranged from $17.98 to $112.87 and chemical costs ranged from $8.97 to $58.60 per tree. The cheapest tree to treat was a 33 cm DBH white ash, which required $25.47 in labor and $15.55 of product, while a 31.8 cm DBH green ash required $14.95 of product and $112.87 in labor. Labor costs were typically higher than chemical costs; only four of the 30 trees had higher chemical costs than labor costs. Two trees (121.9 cm and 124.5 cm DBH) located near each other required $57.41 and $58.60 of chemicals, cost $36.52 each for labor and had reported uptake times of 19 minutes each. In contrast, a single tree with a DBH of 48.3 cm cost $22.72 for chemical, but $98.82 in labor because the uptake time was 124 minutes.

Merit® 75 WSP

Merit® 75 WSP, an imidacloprid product applied annually via soil injection, was used to treat a total of 427 ash trees between 2005 and 2008 (Table 5). Each tree required approximately 30 minutes to treat. Treatments averaged $26.34 ± 0.07 per tree. Chemical costs ranged from $0.92 to $7.27 and labor costs ranged from $23.13 to $26.75 per tree. The cheapest tree to treat was a 6.4 cm DBH white ash, which required $1.15 of product and $23.14 in labor. The most expensive tree to treat was a 38.1 cm DBH tree which required $6.90 of product and $24.88 in labor.

QualiPro®

In 2009, generic imidacloprid products became available and MSU began using QualiPro® instead of Merit® 75 WSP, reducing chemical costs from $0.18 to $0.13 per cm DBH. Labor costs did not vary between Merit® 75 WSP and QualiPro®. Total cost for annual QualiPro® applications averaged $25.78 ± 0.06 per tree. Chemical and labor costs ranged from $1.12 to $3.17 and $23.13 to $26.75, respectively, per tree. The cheapest tree to treat was an 8.6 cm DBH white ash, which required $1.12 of product and $23.34 in labor. The most expensive tree to treat was a 22.6 cm DBH white ash, which required $2.94 of product and $26.75 in labor.

TREE-äge®

In 2008, trunk injections of emamectin benzoate, a new insecticide sold as TREE-äge® and applied with the Arborjet TREE IV system, were used to treat a total of 313 trees at an average cost of $93.49 ± 2.42 per tree (Table 6). Chemical and labor costs per tree ranged from $18.48 to $168.00 and $8.49 to $249.08, respectively. Labor costs were as low as $8.49 per tree for a group of 12 trees, in 2008, where uptake times ranged from 70 min to 128 min per tree, while a 51.1 cm diameter white ash cost $316.62 in 2012 to treat because it took 320 min for uptake.

Total costs for each year ranged from $557 in 2014 when six trees were injected to $6,507 for 43 trees injected in 2012 (Table 6). Because emamectin benzoate provides 2-3 years of EAB control, annualized costs, were also calculated (Table 6). When annualized, the mean cost per tree dropped from $93.49 to $37.40 ± 0.70 per tree, with the biggest difference occurring in 2012 where mean cost per tree dropped from $151.33 ± 7.46 to $35.77 ± 1.69.

Monetary value of MSU's ash tree population estimated with iTree

Air pollution removal by urban trees

Trees improve air quality via removal of air pollutants including ozone, sulfur dioxide, nitrogen dioxide, carbon monoxide and particulate matter less than 2.5 microns (PM2.5). The ash population on campus removes a total of 57.4 kg of pollution annually, a service valued at $612 per year (Table 7). Pollution removal values are based on prices per kg for each air pollutant, local incidence of adverse health effects, and national median externality costs (Nowak et al. 2014) (Table 7). Ozone removal dominated this category, accounting for 82% of the pollutants and valued at $540 per year (Table 7).

Carbon storage and sequestration

Sequestration and storage of carbon is an increasingly important service provided by trees. The current campus ash population sequesters a total of 2.37 metric tonnes of carbon each year, equating to 8.69 tonnes of carbon dioxide that would otherwise enter the atmosphere, a service valued at $347.69 annually. A total of 85.1 metric tonnes of carbon is stored by the ash trees, which equates to 311.9 tonnes of carbon dioxide not present in the atmosphere, a service valued at $12,475 (Table 8). When annualized for 2005 to 2014, mean carbon storage was $66.81 ± 1.31 per year (Table 9).

Avoided runoff

Trees canopies help reduce runoff on hard surfaces by intercepting a portion of the precipitation and are especially important where they extend over impervious surface and in heavy rainfall events where the soil cannot absorb runoff quickly enough (Hirabayashi 2012). Based on canopy diameter and height ash trees on campus had a total leaf area of 4.88 ha (estimated by iTree). White ash and green ash represented 67.6% and 22.1% of the total ash leaf area, respectively. Weather information from 2013 data collected at the Lansing airport was used to estimate uptake of stormwater. Precipitation data for MSU in 2013 was collected from MSU Enviro Weather. In 2013, precipitation totaled 93.4 cm and the ash trees reduced runoff by an estimated 99.5 m^3, which was valued at $235 (Table 8).

Building energy use

Trees that are at least six m tall and within 18.3 m of a building will interact with buildings and affect heating and cooling costs. The 17 ash trees that met the iTree criteria ranged from 11.9 to

32.0 m in height. Five trees, with heights of either 11.9 or 13.1 m, are located on the west side of buildings. One tree on the north side of a building was 32 m tall, while 11 trees on the south side of buildings ranged from 13.4 to 18.4 m tall.

Location of trees influences energy costs (McPherson and Simpson, 1999). One building had 12 trees on the south and west sides of the building. Trees located on the south side provided a mean energy savings of $14.93 ± 1.76 per tree while trees on the west side of the building provided a mean energy savings of $3.80 ± 1.16 per tree. While shade provided by trees can reduce cooling costs, trees can also increase costs if more heating is required. For example, shade from trees with low hanging branches growing within three meters of a wall with southern exposure reduces sunlight reaching the building (McPherson and Simpson 1999). Four ash trees likely increased heating costs by 1.359 MBTUs and 11.691 kwh, valued at $18.95 and $1.65, respectively. Despite the increased heating costs, these four trees also yielded the greatest reductions in cooling costs, saving a total of 168.4 kwh valued at $23.73 per year. Overall, the ash trees on campus provide a net 9.6 MBTUs and 0.4 MWH of energy savings, valued at $187 annually (Table 8). Additionally, these energy savings help avoid 0.075 metric tonnes of carbon production, which is valued at $11 annually.

Structural Value

Structural value for the ash population ranged from $219 to $17,326 with a mean value of $2,929.84 ± 250.75 per tree. Structural value typically increased with diameter, but there were outliers. For example, a 103.1 cm white ash that was 32.0 m tall had a structural value of $9,688 while another white ash with a 79.5 cm diameter that was 20.1 m tall had a structural value of

$10,112. Similarly, a 62.7 cm diameter black ash that was 15.9 m tall and an 81.5 cm diameter white ash that was 17.8 m tall had structural values of $6,499 and $6,577, respectively. When annualized for 2005 to 2014, mean structural value was $2,444 ± 62.05 per tree per year (Table 9).

The current management plan of treating MSU's ash population has a total treatment cost of $48,320 for the time period of 2005 to 2014. Structural value and carbon storage, which were snapshots in time, totaled $472,000 and $12,500, respectively. Annual function services, which were pollution removal, carbon sequestration, avoided runoff and building energy savings, totaled $1,393 per year. Total annual treatment costs ranged from $2,654 to $6,162 per year. When annualized, structural values and carbon storage were $333,327 and $9,431, respectively, in 2005 and increased to $434,065 and $11,533 in 2014 (Table 9).

Alternate management options

We evaluated alternative options for managing MSU's ash population and the costs and benefits associated with three options (Table 10). If MSU were to preemptively remove and replace all ash trees (Option 1), removal and replacement costs would total $179,465 with an annual mean cost of $35,893 ± 8,632. Total removal costs were $84,056 and replacement costs were $95,409. Labor would account for 75% of the total cost. At a maximum removal rate of 40 trees per year, it would take five years to remove all the ash trees. Mean annual benefits lost each year would be $279 ± 64.7. Carbon storage would also be lost with an annual value of $2,495 ± 565.7 (Table 11).

If ash trees ≥ 20 cm DBH were treated with an insecticide but smaller trees were removed, 76 trees would require treatment. Total treatment costs decreased from $49,171 to $28,530 (Figure 2). Mean treatment cost per tree increased from $34.09 ± 0.52 to $44.03 ± 0.99, reflecting the loss of small trees that require less insecticide product and time. Value of ecological services were reduced by $113,624, from $485,561 to $371,937 (Table 12). Energy savings did not change because all 17 trees that affected energy usage had a DBH > 20 cm and would continue to be treated. Removal and replacement of 85 small trees would occur over three years and costing a total of $65,023. Removal costs for the 85 small trees accounted for only 23% of the total cost for removal and replacement cost because trees < 20 cm DBH are the cheapest tree to remove (Table 13). Removal of 85 trees reduced the value of annual benefits by $374 and carbon storage by $2,148. The remaining 76 trees provided $11,344 in annual services and carbon storage.

Option 3 involved treating ash with emamectin benzoate but involved extending the treatment interval to four years. If all trees were treated with emamectin benzoate beginning in 2008, total costs would decrease from $48,320 to $33,839, with a total mean cost per tree of $22.73 ± 0.46 (Figure 3). The annual difference between actual treatment costs and alternative option 3 ranged from $739 to $2,904, beginning in 2008. There were no differences from 2005 to 2007 because treatments with imidacloprid would remain the same in those years. Costs per cm DBH for TREE-äge® dropped from $2.06 (two to three year intervals) to $1.93 (four year interval). Value of ecological services would remain the same as no trees would be removed.

Discussion

Treating MSU's ash population with emamectin benzoate on a three-year rotation is the most economical option for maintaining benefits received from the ash trees while providing adequate protection against EAB. Functional services, such as carbon sequestration and pollution removal, represent only a small portion of the benefits provided by MSU's ash population. Carbon storage and structural value provide the highest value of the ash population. MSU's ash population stores enough carbon to offset annual carbon emissions produced by 66 automobiles or 27 single family houses (MSU iTree Report). Total value of MSU's ash population for a single year was $485,374, almost tenfold higher than the total treatment cost of $48,320 from 2005 to 2014.

Treatment costs will obviously increase as the ash trees grow, but the value of ecological services will also increase. The ash trees also provide social benefits, such as improved public health (i.e. reduced stress, increased exercise) and crime reduction, which were not quantified (Coombes et al. 2010, Donovan et al. 2013, Hartig and Staats, 2006, Kondo et al. 2017, Lazaroff 2002, Roe and Aspinall 2011, Stigsdotter et al. 2010, van den Berg et al. 2010). If these social benefits are considered, the monetary value of MSU's ash population would increase even further. The value of MSU's ash population goes beyond simple estimations of the value of functional traits. The ash population is used for several classes at MSU such as dendrology, landscape design, and insect and disease identification, and research, including ash genetics studies. The ash trees also provide a seed source, which may become increasingly important in the future. Protecting MSU's ash population is vital for educational purposes and predicting what research or opportunities they may provide in the future is impossible.

Insecticide treatments applied to the MSU ash trees effectively protected the trees from mortality or serious injury resulting from EAB. Studies have shown inconsistent effectiveness of imidacloprid; however, some of MSU's ash trees received applications of imidacloprid until 2012 and had < 30% canopy transparency and dieback, suggesting if trees were healthy when treated, imidacloprid provided effective control. In a four-year study, Smitley et al. (2010) applied basal soil applications of imidacloprid at a rate of 1.42 g a.i./2.5 cm DBH to healthy ash trees. The authors found that these street trees, which ranged in sizes from 25 to 45 cm DBH, remained healthy (< 25% canopy thinning) for a single year. A six-year study by Smitley et al. (2010), applied basal soil applications of imidacloprid at rates between 0.55-0.57 g a.i./cm DBH to ash trees of varying size (5 cm to > 65cm DBH) and conditions of health (low to moderate <60% or high > 60% canopy thinning). The authors found imidacloprid to be highly variable and was dependent on the health of ash trees at the beginning of the study. Imidacloprid products were applied to MSU ash trees at a rate of 0.56 g a.i./cm DBH to trees in various conditions of health. At this rate, Smitley et al. (2015) found ash trees treated in spring exhibited 30% canopy loss over four years. In contrast, Bick et al. (2018) applied soil injected imidacloprid at twice the rate, i.e. 1.12 g a.i./cm DBH to ash trees and recorded < 5% canopy decline over five years. The EPA approved the use of this higher rate for certified pesticide applicators in 2009, which could provide more effective control. McCullough et al. (2018) conducted a six-year study on EAB densities in trees treated with insecticide and untreated trees. The authors found EAB densities were higher in trees treated annually or triennially with imidacloprid, which was applied using Imicide® at 0.07 g a.i./2.5 cm DBH, compared to annual treatments of Dinotefuran or annual or triennial treatments of emamectin benzoate. Many studies have proven emamectin benzoate's effectiveness in controlling EAB for two years from a single application (Hermes 2010, McCullough et al. 2011, Hermes et al. 2014, Bick et al. 2018, Flower et al. 2018); however, in 2018 McCullough et al. injected ash trees at a low rate of 0.10 g a.i./2.5 cm DBH and a high rate of 0.20 g a.i./2.5 cm DBH and found few to no larval galleries on ash trees three years after treatment.

Overall, MSU’s ash population was healthy when surveyed in 2014, despite 73% of the population exhibiting at least some evidence of past EAB attacks. There were some exceptions; ten trees had relatively high canopy transparency or dieback ratings, but these problems appeared to reflect factors other than EAB. For example, two white ash had 40% canopy transparency, but both were adjacent to a construction site. Nearby ash had healthy canopies, suggesting that the two declining white ash were injured by the construction. Another white ash in a parking lot island had 45% canopy dieback but no signs of EAB infestation, suggesting poor site conditions may have impacted the tree. Epicormic sprouting was common in the ash population but sprouts were predominantly associated with pruning cuts. Although oystershell scale was present in a few trees at the beginning of the study, no scale was present when trees were revisited two to three years later. This suggests a secondary benefit of treating the ash population with insecticide. Efficacy of insecticide treatments may have varied but trees appear to have recovered. In 2013, emamectin benzoate became the primary insecticide used to protect MSU's ash population and are on a three year treatment. During the study, no trees died but four trees were removed for various reasons. One tree was removed due to storm damage, but no known reason was determined for the other removals.

Studies have found EAB host preference varies among North American ash species, with green ash and black ash being highly preferred, white ash being intermediately preferred, and blue ash being the least preferred (Anulewicz et al. 2007, Anulewicz et al. 2008, Rebek et al. 2008, Tanis and McCullough 2015). MSU's ash population is predominantly white ash followed by green ash. Green ash and white ash trees exhibited the most signs of EAB while blue ash trees exhibited little to no signs of EAB and healthy canopies. Although few black ash had woodpecker damage or exit holes, almost all black ash had evidence of old larval damage, consistent with Tanis and McCullough (2015) who reported black ash located in a plantation had the highest density of EAB larvae. Anulewicz et al. (2007, 2008) found that green ash street trees had more canopy dieback, more exit holes and higher EAB densities than white ash street trees growing in the same neighborhood. On MSU's campus, canopy dieback for green ash was similar to white ash likely because trees were treated at MSU.

Labor costs largely reflect time required to apply products. Soil injections consistently required 30 min, regardless of condition or size of tree, while trunk injection times varied greatly. Because applicators are legally required to monitor injections, labor was the biggest cost for trunk injectons, accounting for 62% of the total costs. Trunk injections had highly variable uptake times, ranging from 10 to 370 minutes, resulting in variable labor costs. For example, trunk injections with emamectin benzoate using the Tree IV system made on a 25.9 cm DBH white ash and a 26.9 cm DBH white ash required 1.5 hours and 5.6 hours, respectively, for product uptake. Weather conditions and tree physiology also play roles in the variance of uptake times. For example, trees conserve moisture by closing their stomata to reduce transpiration and when transpiration has slowed, any product will have a longer uptake time. Lewis and Turcotte

(2015) used the VIPER Hydraulic Device to inject ash trees with emamectin benzoate in April and May 2008. The authors found higher injection pressure was needed due to extremely slow uptake times and suggested the extended drought and cold spring temperatures affected the trees. At MSU, labor costs were spread across groups of trees being treated simultaneously as the applicator was in one location until the longest tree in the group finished taking up the chemical.

MSU arborists used the Tree IV system to apply emamectin benzoate. This system requires multiple holes to be drilled around the root flare, the appropriate amount of product to be mixed and added to one-liter bottles per tree, which are then pressurized and attached to the tree via plugs placed in the recently drilled holes. Labor costs could be substantially reduced by using the Quik Jet Air device, a compressed air micro injection system that became available in 2015. This system was designed to inject small volumes of chemical into the vascular system of trees at a reasonable, non-damaging pressure level. MSU did not purchase this system until 2017 (personal comm. Joe Aiken, Arborjet). This system allows the applicator to apply the product to the tree via a pressurized gun, which is attached to a bottle with the appropriate amount of product. The Tree IV system requires a passive application in that the applicator must hook up bottles with low pressure to the tree and wait for the product be taken up by the tree. For example, a 51 cm white ash took five hours to uptake 100 mL of via the Tree IV. If the Quik Jet Air were used, application time could be reduced to 15 to 30 minutes, resulting in a substantial cost savings.

Insecticide products used at MSU changed over time due to advancing research and available funds for treatment. Imicide® and IMA-Jet®, applied with TREE- IV, were not used more than one to two years. Partly due to research showing variable efficacy for Imicide® and effectiveness for IMA-Jet®, both were overshadowed by emamectin benzoate (Herms 2009, McCullough et al. 2004, Poland et al. 2016, Rebek et al. 2008, Smitley et al. 2010, 2015). Although initial application costs are more expensive than Merit® or QualiPro®, emamectin benzoate's proven efficacy of ≥ 90% control and multiyear protection from a single application outweigh the cost of the product (Hermes 2010, 2014, McCullough et al. 2011, 2018, Smitley et al. 2010). Studies to determine efficacy of emamectin benzoate began in East Lansing, Troy and Adrian, MI in 2005 and Smitley et al. (2010) reported two-year protection with emamectin benzoate based on canopy ratings. McCullough et al. (2011) felled and debarked 175 entire ash trees to assess larval densities. Compared to controls in the same block, they found minimal larval densities in ash trees treated with emamectin benzoate. MSU began using emamectin benzoate in 2008 at a cost of $1.04 per cm DBH, but in 2011 this cost increased to $1.32 per cm DBH as the cost of the emamectin benzoate increased. The cost of a single application can be reduced one third due to recent research showing nearly complete control for three years (McCullough et al. 2018). For example, the most expensive tree to treat had an initial cost of $316.62 in 2012. If this tree were treated biennially, the annual cost would be $158.31, but when spread across three years the cost drops to $105.54. Newer, cheaper emamectin benzoate products, such as Arbormectin and TREE-äge® R10, are now available for use. The availability of these products can help reduce costs as well as improve uptake times.

My results showed that it was more economical to treat the MSU ash trees with emamectin benzoate than to remove and replace the trees, which aligns with simulations such as Kovacs et al. (2010), Sadof et al. (2011), and Van Atta et al (2012). Removal and replacement of MSU's ash population was the most expensive option in terms of direct costs, plus ecosystem services and structural benefits were lost. Treating the ash population with emamectin benzoate on a three -year rotation was the least expensive and does not incur any loss in ecosystem services or structural loss. Sydnor et al. (2007, 2011) estimated that although the removal and replacement of ash populations would be cheaper, $3.4 billion in structural value would be lost in Ohio communities; however, it was assumed that ash trees to be removed would be easily accessible and not encumbered by obstacles such as buildings. McKenney et al. (2012) estimated potential costs of EAB in Canadian municipalities. They found that treating 50% of the medium (5-10 m tall) to large (>10 m tall) street and private trees with azadirachtin over a 30-year period would cost less than removing the trees but provide economic justification for managing EAB. Using an economic model, McKenney and Pedlar (2012) found it took 19 years for costs of biennial applications of TreeAzin® (azadirachtin) to exceed removal and replacement costs. Kovacs et al. (2010) simulated four management options (do nothing, remove, remove and replace, treat with emamectin benzoate) and found that homeowners and communities could spend $150 - $200 to treat a single ash tree > 61 cm DBH and receive $1,259 in annual benefits. Vanatta et al. (2012) simulated three management options (remove, remove and replace, treat with emamectin benzoate) to determine the most economical option to retain a high net urban forest value over 20 years. The authors found the treatment option to be the most economical as it retained the most ash trees, which would provide numerous ecosystem services, easily outweighing the treatment costs. The remove only option, which was the cheapest option, had the lowest urban forest value as ecosystem services are eliminated. Kovacs et al. (2014) found it was more economical to treat ash trees with insecticide and to share the cost amongst municipal jurisdictions, allowing ash trees to continue providing ecosystem services. McCullough and Mercader (2012) simulated EAB growth and dispersal under varying scenarios. The authors found trees, when treated on a two-year rotation, could be protected for at least 30 years before treatment costs approached removal costs.

The alternative management option of removing and replacing all ash trees is the costliest option for MSU. This option would eliminate treatment costs along with ecosystem services the ash population provides, including carbon storage and structural value. Approximately 77% of the ash population have values and benefits totaling at least $1,000. Several years would be required for small planted trees to match the benefits and values provided by the current ash population. Carbon storage would be reduced as ash trees are removed while carbon and pollution emissions would increase due to the use of equipment for removals. Canopy cover would be reduced impacting the amount of rainfall interception, thus increasing the amount of runoff going into storm drains. Energy usage in buildings would increase as the removal of nearby ash would increase the amount of sunlight exposure to buildings.

Removing small ash trees while treating the larger ash would be the second costliest option. Mature trees would be treated and maintained, reducing annual treatment costs. Some ecosystem services would remain with the mature trees; however, the removal of the smaller ash trees, which accounts for 70% of the total cost for this option, eliminates future ecosystem services. Both options 1 and 2 would also result in removal of three unique ash species (*Fraxinus chinensis* ssp. *rhynchophylla*, *Fraxinus ornus*, *Fraxinus latifolia*) as well as any future educational and research topics that the ash population may provide.

The current and third alternative management options, which are trunk injections of emamectin benzoate on a two to three-year rotation and four-year rotation, respectively, are the cheapest to either continue or implement. Carbon emissions would be minimal since basic tree maintenance and insecticide applications would continue to occur. Both options allow the ash tree population to provide current and future ecosystem services, carbon storage and canopy cover, which will increase as smaller ash trees grow. Although ash trees are highly sectorial, xylem follows a zig zag pattern of ascent (Tanis et al. 2012), which allows for low densities of EAB larvae to have little effect on ash trees and suggests a four year treatment is feasible. Treating on a four-year rotation could extend how long it would take for treatment costs to surpass removal costs. Ecological services would be retained, and carbon emissions would not increase with the constant use of equipment needed for removals. There is no research supporting the 4-year protection from emamectin benzoate, which suggests that studies need to be done to see if this is feasible in areas where EAB population densities are low. These options allow for the ash population to remain and provide continued education, social and health benefits, and added beauty to the campus community.

APPENDIX

Table 1 - Number of ash trees treated with insecticide compounds and products, including total cm DBH treated; application rates to apply active ingredient; method of application; total costs of treatments, which includes costs of insecticides, labor to apply product, and travel time to reach trees; and MSU's costs per cm DBH, total cm DBH treated, and total cost of treatments.

Active Ingredient	Product			Distributor	Rate per 2.5 cm DBH	Application Method
Imidacloprid	Imicide®	No. of trees	22	JJ Mauget Co., Arcadia, CA	0.15 g	Trunk micro-injection; 3mL capsules
		Total cm DBH	1,289			
		Mean (±SE) DBH	59 ± 6.2			
		Total cost (all	$1,916			
		Cost per cm DBH	$1.49			
	Merit® 75 WSP	No. of trees	417	Bayer CropScience, Research Triangle, NC	1.42 g	Soil injection
		Total cm DBH	6,538			
		Mean (±SE) DBH	15.7 ±			
		Total cost (all	$10,982			
		Cost per cm DBH	$1.68			
	Quali-Pro® 75 WSP	No. of trees	244	Makhteshim Agan of North America, Inc., Raleigh, NC	1.42 g	Soil injection
		Total cm DBH	3,847			
		Mean (±SE) DBH	15.8 ±			
		Total cost (all	$6,291			
		Cost per cm DBH	$1.64			
	IMA-jet®	No. of trees	30	Arborjet, Inc. Woburn, MA	0.2 g	Trunk micro-injection; TREE IV
		Total cm DBH	1,809			
		Mean (±SE) DBH	60 ± 5.0			
		Total cost (all	$2,178			
		Cost per cm DBH	$1.20			
Emamectin benzoate	TREE-äge®	No. of trees	313	Arborjet, Inc. Woburn, MA	0.2 g	Trunk micro-injection; TREE IV
		Total cm DBH	13,098			
		Mean (±SE) DBH	42 ± 1.3			
		Total cost (all	$26,966			
		Cost per cm DBH	$2.06			

Table 2 – Potential removal costs for ash trees by size class estimated by MSU arborists.

DBH Class	Labor Cost	Equipment Cost	Stump Grinding	Total Cost
< 20 cm	$138	$34	N/A	$172
20 - 40 cm	$253	$67	$34	$354
40 - 60 cm	$644	$308	$45	$997
> 60 cm	$1,196	$334	$68	$1,598

Table 3 – Estimated planting costs for balled and burlaped deciduous trees provided by MSU Landscape Services' Beaumont Nursery. Post planting maintenance includes watering and any necessary fertilization and pruning.

Tree diameter (cm)	Cost of tree	Post planting maintenance cost	Installation Cost	Total cost
5.1	$256	$125	$125	$506
6.4	$297	$125	$125	$547
7.6	$345	$125	$125	$595
8.9	$402	$125	$125	$652
10.2	$419	$125	$125	$669

Table 4 – Number of ash trees on the Michigan State University campus; mean, minimum, maximum, and total cm of DBH; location; and number of trees exhibiting signs of emerald ash borer infestation by species.

		F. americana	***F. pennsylvanica***	***F. nigra***	***F. quadranulata***	***F. rhynchophylla***	***F. ornus***	***F. latifolia***	**Overall**
No. of trees		*104*	33	11	8	2	2	1	161
DBH (cm)	Mean ± SE	40.1 ± 2.3	44.4 ± 3.8	24.7 ± 3.8	36.6 ± 5.2	13.2 ± 1.5	50.8 ± 5.1	N/A	39.6 ± 1.76
	Minimum; Maximum	15.8:30.8	22.6:129.5	18.3:62.7	19.3:65.3	11.7:14.7	45.7:55.9	N/A	11.8:130.8
	Total	4,172	1,465	272	293	26	102	47	6377
Location	Near Building	2	13				2		17
	Lawn	39	8	1	2	2		1	53
	Street	39	7	10					56
	Parking lot	24	5		6				35
EAB Signs	Woodpecker damage	67	4	3	1		1		75
	Adult exit holes	26	4	3	3		1		37
	Old larval gallery	69	26	10	3		2	1	102
	Epicormic sprouts	99	29	11	8	1	2	1	151

Table 5 - Annual number of trees, total diameter (cm) treated, and total treatment costs for imidacloprid insecticides applied to MSU ash trees from 2005 to 2014. Costs included labor and travel time to apply product and costs of the insecticide.

Products		**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
Mauget® Imicide® 3mL	No. of trees	21	1						
	cm DBH	1,254	35						
	Cost	$1,790	$127						
IMA-Jet®	No. of trees		30						
	cm DBH		1,809						
	Cost		$2,178						
Merit® 75 WSP	No. of trees	108	114	101	94				
	cm DBH	1,639	1,843	1,537	1,519				
	Cost	$2,832	$3,007	$2,654	$2,489				
QualiPro®	No. of trees					71	67	53	53
	cm DBH					1,042	1,055	841	908
	Cost					$1,822	$1,729	$1,368	$1,372
Total	**No. of trees**	**129**	**145**	**101**	**94**	**71**	**67**	**53**	**53**
	cm DBH	**2,893**	**3,687**	**1,537**	**4,833**	**1,064**	**4,561**	**1,806**	**951**
	Total cost	**$4,622**	**$5,312**	**$2,654**	**$2,489**	**$1,822**	**$1,729**	**$1,368**	**$1,372**

Table 6 - Annual number of trees, total diameter (cm) treated, and total treatment costs for emamectin benzoate applied to MSU ash trees from 2008 to 2014. Costs included labor and travel time to apply product and costs of the insecticide. Trees are protected 2-3 years after treatment. Total cost indicates cost for number of trees treated for indicated year. Annualized costs indicate cost when spread across 2-3 years.

Product		**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
Emamectin benzoate	No. of trees treated	65	22	67	36	43	74	6
	No. of trees protected	0	65	22	67	60	82	113
	cm DBH	3,314	608	3,506	965	2,787	1,752	192
	Total cost	**$5,613**	**$1,614**	**$6,250**	**$3,121**	**$6,507**	**$5,600**	**$557**
	Annualized cost	**$2,806**	**$795**	**$2,869**	**$1,113**	**$2,169**	**$1,867**	**$186**

Table 7 – Annual removal and monetary values of pollutants removed by MSU's ash population. Monetary value of each pollutant is based on local incidence of adverse health effects and national median externality costs.

Pollutant	**$/kg**	**Removal (kg/year)**	**Value ($/year)**
Carbon monoxide (CO)	1.62	1.6	2.53
Ozone (O_3)	11.40	47.3	540.58
Nitrogen dioxide (NO_2)	11.40	4.5	51.12
Sulfur dioxide (SO_2)	2.79	2.4	6.62
Fine particulate matter ($PM_{2.5}$)	7.61	1.6	12.32
Total		**57.4 kg^{-1}**	**$612.17**

Table 8 - iTree Eco data information on canopy cover, leaf area, and annual environmental benefits MSU’s ash population provides to campus, including total monetary value of each ash species. Carbon sequestration, avoided runoff, pollution removal and energy savings are annual, functional values. Carbon storage and structural value represent one point in time and are not annual values.

		F. americana	***F. pennsylvanica***	***F. nigra***	***F. quadranulata***	***F. rhynchophylla***	***F. ornus***	***F. latifolia***	**Total**
No. of trees		*104*	33	11	8	2	2	1	161
Canopy Cover (m^3)		*8,626*	2,926	517	437	36	351	104	12,997
Leaf Area (m^3)		*33,245*	10,802	1,684	1,961	137	854	330	49,013
Structural Value		*$314,256*	$109,755	$14,967	$20,972	$547	$7,649	$3,559	$471,705
Carbon Storage	Kg	68,716	10,955	1,517	2,307	47	1,038	476	85,056
	$	$10,078	$1,607	$222	$338	$7	$152	$70	$12,474
Carbon sequestration	Kg yr^{-1}	1,955	218	60	100	7	21	10	2,371
	$ yr^{-1}	$287	$32	$9	$1	$0.96	$3	$2	$348
Avoided runoff	m^3 yr^{-1}	66.9	22.1	3.5	4.0	0.3	1.8	0.7	32.4
	$ yr^{-1}	$159	$52	$8	$9	$0.66	$4	$2	$235
Pollution removal	g yr^{-1}	38,835	12,705	1,980	2,306	161	1,004	388	57,379
	$ yr^{-1}	$414	$136	$21	$25	$2	$11	$4	$612
Energy savings	No. of trees	2	13				2		17
	$ yr^{-1}	$25	$169				$3.22		$198
Total		$325,219	$111,751	$15,227	$21,359	$557	$7,822	$3,636	$485,572

Table 9 - Comparisons between annual treatment costs and benefits for MSU’s current management plan. Functional services included pollution removal, avoided runoff, energy savings, and carbon sequestration. Carbon storage and structural value were estimated using 2016 DBH. Annual values represent DBH recorded at the time of treatment.

	2005	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
Total Treatment Cost	$4,622	$5,312	$2,654	$5295	$5,390	$5,393	$5,350	$5,056	$5,040	$4,221
Functional Services	$1,393	$1,393	$1,393	$1,393	$1,393	$1,393	$1,393	$1,393	$1,393	$1,393
Carbon Storage	$9,770	$10,022	$10,249	$10,451	$10,758	$11,054	$11,251	$11,488	$11,703	$11,929
Structural Value	$345,671	$357,381	$368,199	$378,237	$392,277	$405,645	$415,248	$425,871	$436,421	$446,934

Table 10 - Summary of costs and benefits for 2005-2014 for the alternative management options and the actual management plan. This includes total treatment costs, remove and replace costs, monetary value of annual services and carbon storage present.

	Costs		**Benefits**	
	Total Treatment	**Remove & Replace**	**Annual Services**	**Carbon Storage**
Actual	$48,320	$0	$13,926	$12,474
Option 1 Remove & Replace	$0	$179,465	$6,289	$0
Option 2 Treat ≥ 20 cm; Remove < 20 cm	$27,689	$65,023	$11,346	$9,988
Option 3 TREE-äge®	$32,989	$0	$13,926	$12,474

Table 11 –Summary of costs and benefits for 2005-2014 for alternative management option 1, which was removing and replacing all ash trees. This includes annual costs of removing and replacing ash trees and monetary value of annual services and carbon storage lost each year.

		2005 - 2007	**2008**	**2009**	**2010**	**2011**	**2012**	**2013 - 2014**
No. of trees		161	161	121	81	41	1	0
Benefits	**Current**	$1,393	$1,393	$1,058	$693	$347	$21	0
	Lost		$335	$364	$346	$326	$2	
Carbon Storage	**Current**	$12,474	$12,474	$9,649	$7,114	$3,672	$332	0
	Lost		$2,825	$2,535	$3,442	$3,340	$332	
Remove & Replace			$42,618	$44,626	$47,637	$43,041	$1,544	0

Table 12 – Value of ecological services between the actual treatment applied to 161 ash trees on the MSU campus and alternative option 2, which involved treating only trees ≥ 20 cm DBH beginning in 2005 and removing smaller trees beginning in 2008. Carbon storage and structural value represent one point in time and are not annual values.

	No. of trees	**Canopy Cover (m^3)**	**Leaf area (m^3)**	**Structural Value**	**Carbon Storage**		**Carbon Sequestration**		**Avoided Runoff**		**Pollution Removal**		**Energy Savings**	
					Kg	**$**	**Kg yr^{-1}**	**$ yr^{-1}**	**m^3 yr^{-1}**	**$ yr^{-1}**	**g yr^{-1}**	**$ yr^{-1}**	**No. of trees**	**$ yr^{-1}**
Total (original)	161	12,997	49,013	$471,705	85,056	$12,474	2,371	$348	99	$235	57,379	$612	17	$198
Total (≥ 20 cm)	76	9,651	33,897	$360,604	70,408	$10,326	1,603	$235	69	$162	39,639	$422	17	$198

Table 13 – Potential removal costs for ash trees by diameter class estimated by MSU arborists for alternative management options 1 and 2. Costs based on number of people and equipment needed for each size class.

DBH Class	Labor Cost	Equipment Cost	Stump Grinding	Total Cost
< 20 cm	$138	$34	N/A	$172
20 - 40 cm	$253	$67	$34	$354
40 - 60 cm	$644	$308	$45	$997
> 60 cm	$1,196	$334	$68	$1,598

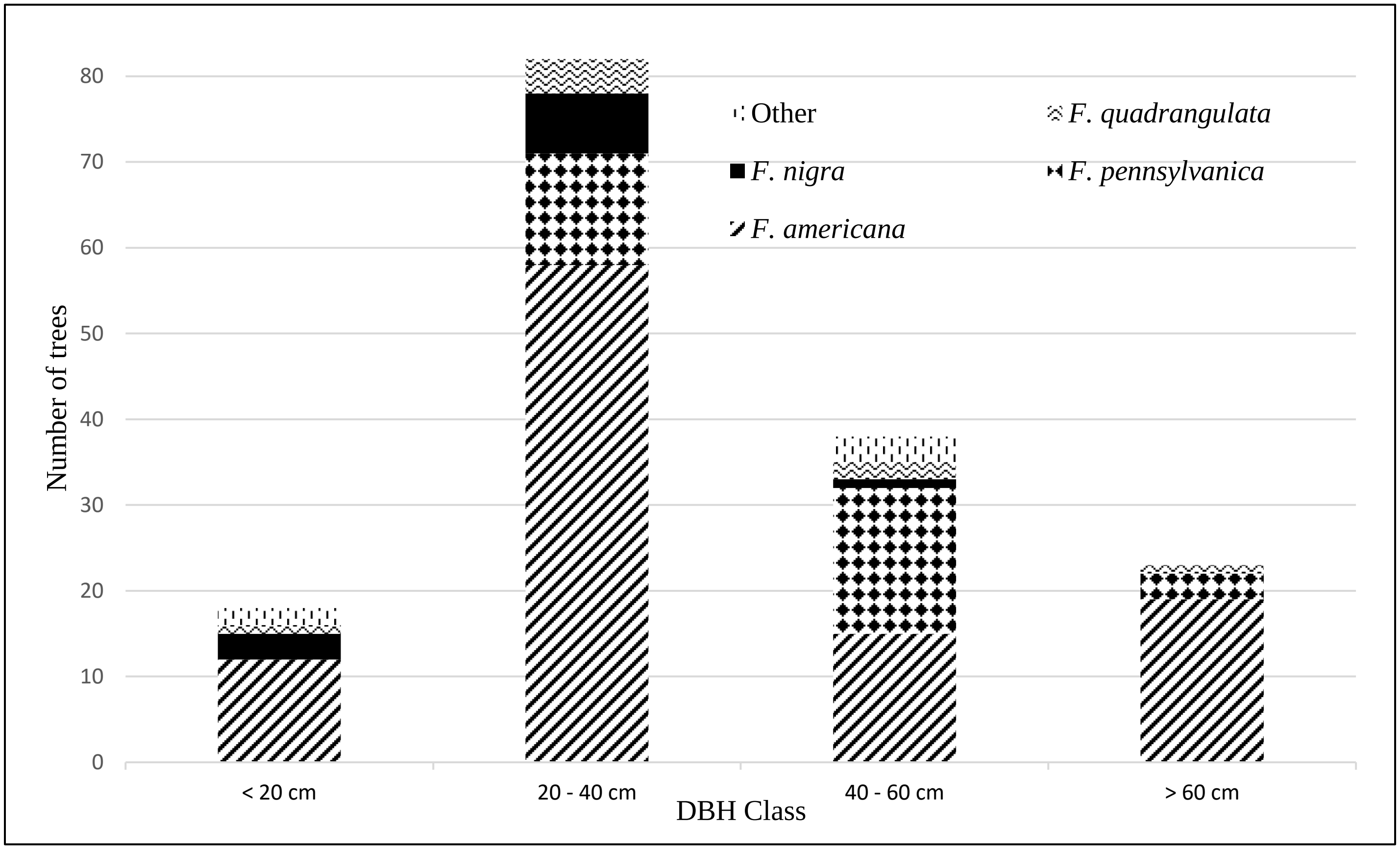

Figure 1 - Ash population on the MSU campus grouped by diameter classes: < 20 cm, 20-40 cm, 40-60 cm, and > 60 cm.

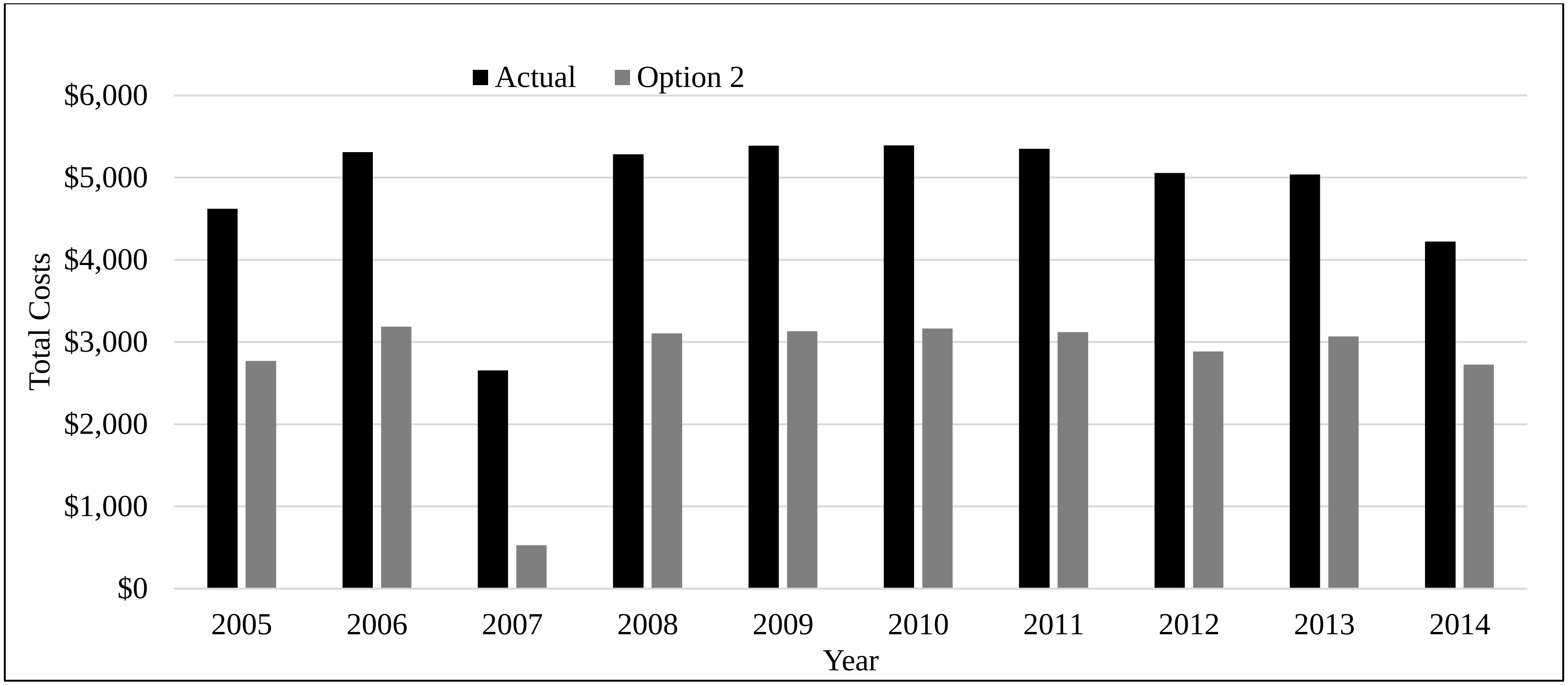

Figure 2 – Comparison of annual treatment cost of treating ash trees on MSU campus. In option 2, trees ≥ 20 cm are treated, reducing annual and total treatment costs. Trees < 20 cm DBH would be removed and replaced beginning in 2008.

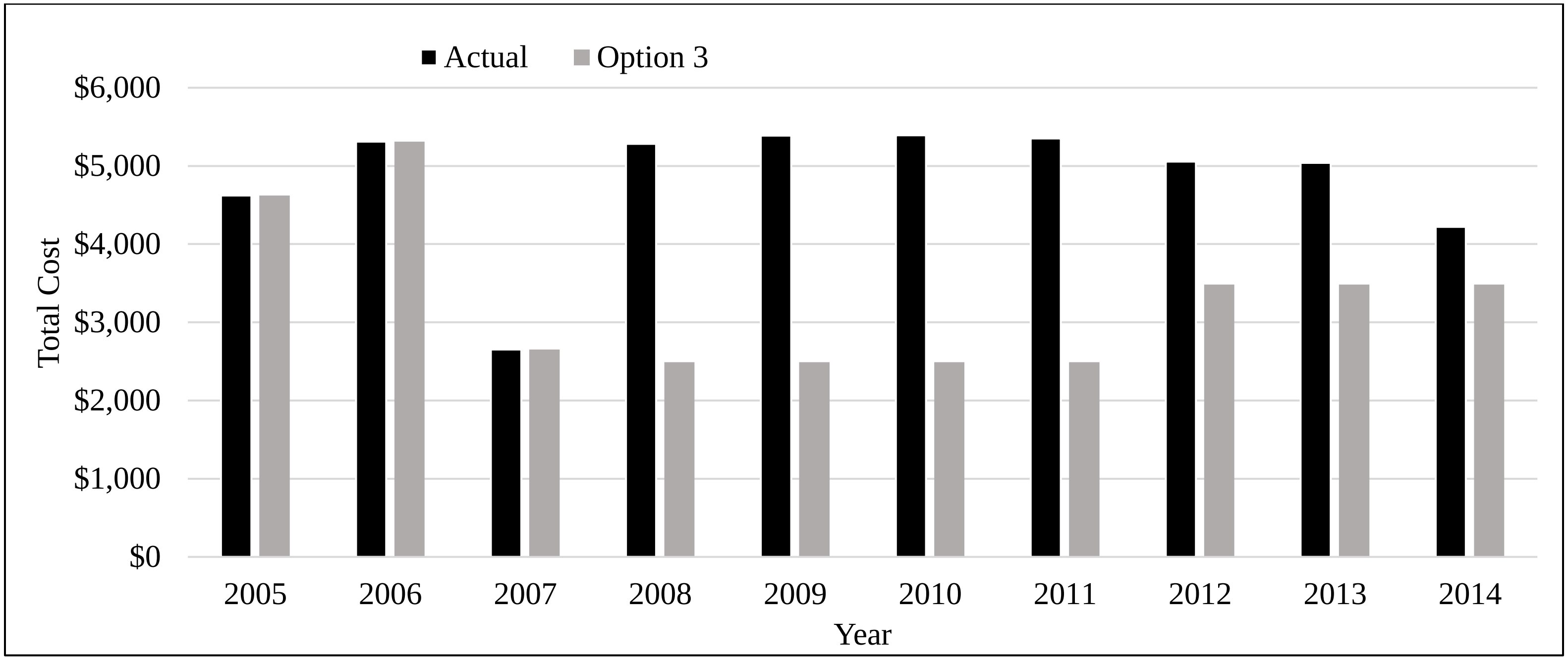

Figure 3- Comparison of annual treatment cost of treating ash trees on MSU campus. In option 3, all trees are treated with TREE-äge® beginning in 2008 and treated on a four year rotation, with treatments remaining the same from 2005-2007. No trees would be removed or replaced.

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