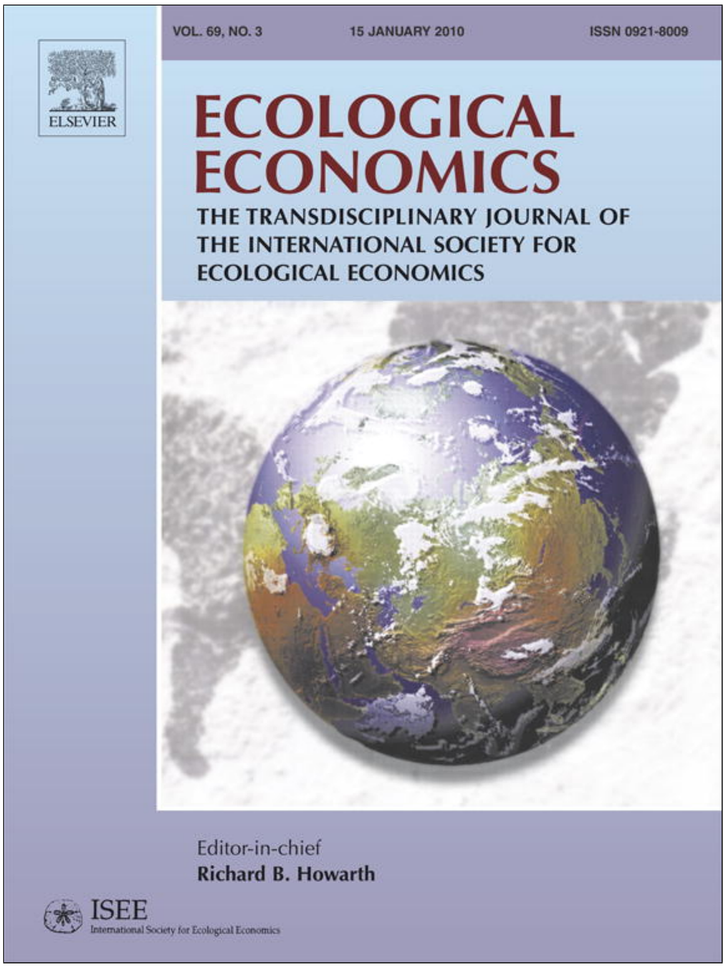
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Analysis

# Cost of potential emerald ash borer damage in U.S. communities, 2009–2019

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ABSTRACT

Emerald ash borer (*Agrilus planipennis* Fairmaire), a phloem-feeding beetle native to Asia, was discovered near Detroit, Michigan and Windsor, Ontario in 2002. As of March 2009, isolated populations of emerald ash borer (EAB) have been detected in nine additional states and Quebec. EAB is a highly invasive forest pest that has the potential to spread and kill native ash trees (*Fraxinus* sp.) throughout the United States. We estimate the discounted cost of ash treatment, removal, and replacement on developed land within communities in a 25-state study area centered on Detroit using simulations of EAB spread and infestation over the next decade (2009–2019). An estimated 38 million ash trees occur on this land base. The simulations predict an expanding EAB infestation that will likely encompass most of the 25 states and warrant treatment, removal, and replacement of more than 17 million ash trees with mean discounted cost of $10.7 billion. Expanding the land base to include developed land outside, as well as inside, communities nearly double the estimates of the number of ash trees treated or removed and replaced, and the associated cost. The estimates of discounted cost suggest that a substantial investment might be efficiently spent to slow the expansion of isolated EAB infestations and postpone the ultimate costs of ash treatment, removal, and replacement.


## 1. Introduction

Emerald ash borer (*Agrilus planipennis* Fairmaire) (Coleoptera: Buprestidae), a phloem-feeding beetle native to Asia, was discovered near Detroit, Michigan and Windsor, Ontario in the summer of 2002. Increased awareness of emerald ash borer (EAB) and ongoing survey efforts have led to the detection of numerous EAB populations throughout Michigan, Ohio and Indiana. Estimates indicate that more than 53 million native ash (*Fraxinus* sp.) trees had been killed by EAB in those states by 2007 (Smith et al., submitted for publication). By March 2009, EAB infestations had been found in a total of ten states and two Canadian provinces (Fig. 1).

Emerald ash borer has the potential to spread and kill ash trees throughout the United States. Much of the damage caused by EAB occurs on developed land since ash trees have been a popular street tree for decades. The low genetic diversity of planted ash in the cities of the United States, predominantly white and green ash (*F. americana*, *F. pennsylvanica*), enhances the risk to the urban forest resource (MacFarlane and Meyer, 2005). Most EAB in North America develop in a year, although at very low densities some larvae require two years to develop (Tluczek et al., 2008). Adult beetles feed on small patches of ash foliage from late May through September and cause negligible damage. Individual eggs are laid on the bark of ash trees at least 5 cm in diameter at breast height (1.4 m above ground) and hatch in 1–2 wks. Larvae feed under the bark on phloem and cambium, typically from mid summer through fall. Larval galleries effectively girdle the phloem and score the outer sapwood, disrupting nutrient and water transport within the tree (Cappaert et al., 2005). As EAB densities build over time, tree health declines until the tree dies.

Trees with low densities of larvae typically exhibit few or no external symptoms (McCullough et al., 2009) and infestations are rarely discovered before canopy dieback or tree mortality occurs. Intensive analysis of trees in localized outlier sites has indicated that trees typically must be infested by EAB for 3–4 years before they succumb (Siegert et al., 2006). Flight mill studies indicate that mated females may be physiologically able to fly 5 km (Taylor et al., 2006); however, most adults fly less than 100 m when ash trees are near. Long distance dispersal of EAB can also occur when humans inadvertently transport infested ash nursery trees, logs, firewood or related material. Because visual detection of eggs, larvae, and adult beetles is difficult, multiple cohorts are likely to have dispersed before the first sign of infestation is detected.

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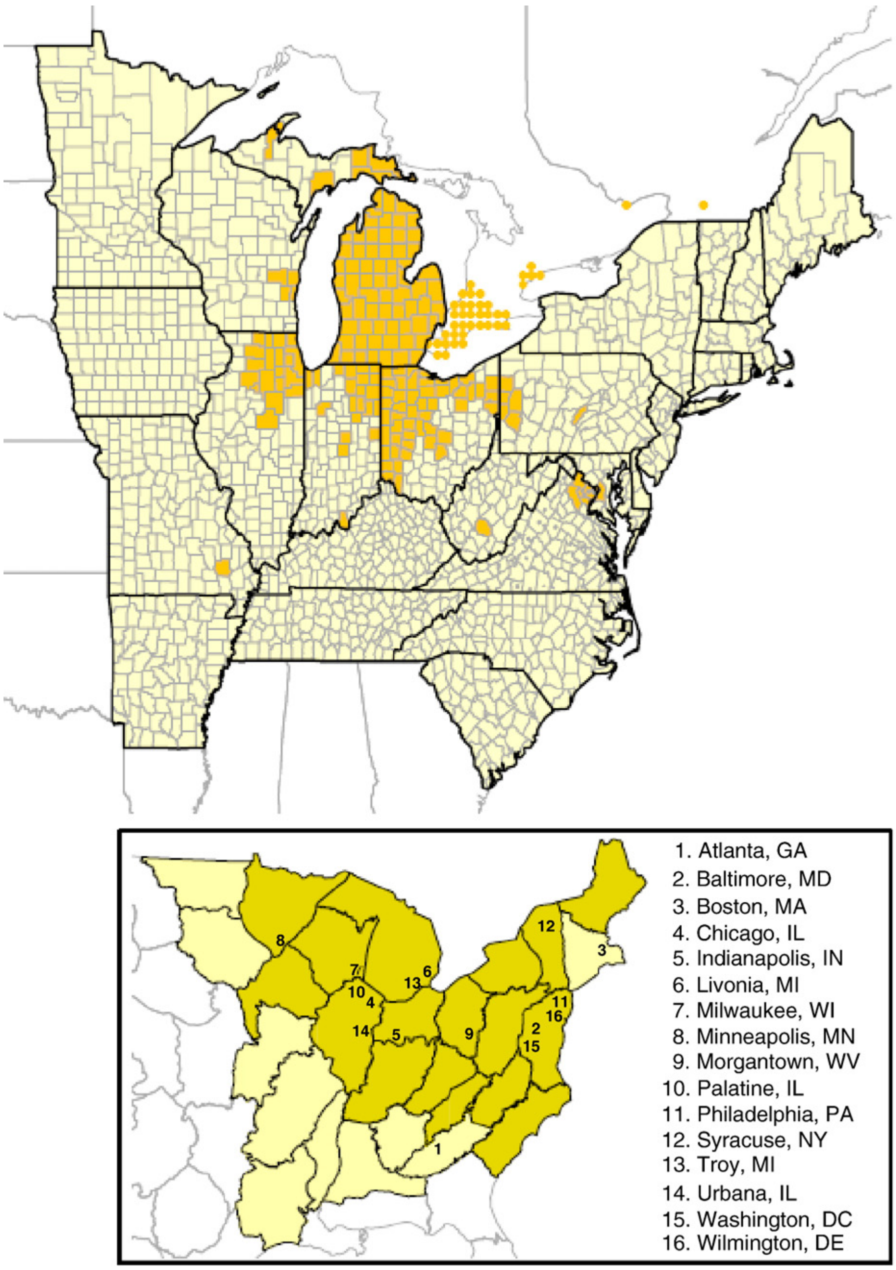


**Fig. 1.** Study area with U.S. counties known to be infested (shaded) by emerald ash borer in March 2009. Dots outside the study area represent locations in Canada with known EAB infestations in March 2009. Inset shows cities with tree inventory information and mapping zones we used to estimate ash density. Lighter shaded mapping zones are only partially covered by our study area. Note: Rhode Island is not part of the study area because, according to the spread model, no county of Rhode Island becomes infested during the study period.

In response to the threat posed by EAB, federal, state and provincial agencies impose quarantines to restrict the movement of ash from infested counties, conduct surveys to detect new infestations, and support research on EAB biology and management. These programs are expensive, yet there is little economic literature on the cost of EAB management and loss from EAB damage, especially in developed areas. In one example, Sydnor et al. (2007) estimates EAB could result in the removal and replacement costs of $1.0–$4.2 billion in Ohio communities. Assessing the potential economic impacts of EAB is important for evaluating the benefits of efforts to slow the range expansion of EAB, as well as investments in research on EAB biology and management. To help address this gap, we estimate the discounted cost of ash treatment, removal, and replacement in communities in a 25-state study area centered on Detroit (Fig. 1) by simulating EAB infestation over the next decade (2009–2019) and calculating the costs associated with ash treatment, removal, and replacement.

Our estimate of the discounted cost of treatment, removal, and replacement in response to EAB infestation over the 10-yr horizon, $10.7 billion, indicates nearly $1 billion per year in tree treatment, removal, and replacement costs.[1] Additional investments could

[1] For comparison, the 2008 regulatory, survey and detection, outreach and education, biocontrol, and method development investment by the Animal and Plant Health Inspection Service (APHIS) for EAB was $32 million (Chaloux, 2009).

**Table 1**
Developed land and canopy cover in U.S. Census Communities and in all land in the study area.

| State | U.S. Census Communities | | All land | |
|---|---|---|---|---|
| | Developed land (ha) | Canopy cover (ha) | Developed land (ha) | Canopy cover (ha) |
| Arkansas | 223,000 | 33,500 | 776,000 | 177,000 |
| Connecticut | 136,000 | 34,000 | 297,000 | 96,000 |
| Delaware | 19,600 | 962 | 51,400 | 2,870 |
| Illinois | 753,000 | 47,400 | 1,690,000 | 87,800 |
| Indiana | 368,000 | 27,800 | 965,000 | 54,000 |
| Iowa | 251,000 | 18,500 | 1,060,000 | 41,000 |
| Kentucky | 180,000 | 8980 | 739,000 | 89,700 |
| Maine | 74,300 | 8360 | 292,000 | 20,900 |
| Maryland | 203,000 | 21,400 | 308,000 | 37,700 |
| Massachusetts | 252,000 | 49,700 | 496,000 | 134,000 |
| Michigan | 528,000 | 53,900 | 1,590,000 | 237,000 |
| Minnesota | 361,000 | 27,500 | 1,110,000 | 64,100 |
| Missouri | 394,000 | 39,700 | 1,210,000 | 159,000 |
| New Hampshire | 53,100 | 9910 | 180,000 | 40,200 |
| New Jersey | 276,000 | 55,900 | 474,000 | 93,600 |
| New York | 537,000 | 137,000 | 1,130,000 | 296,000 |
| North Carolina | 500,000 | 88,700 | 1,220,000 | 228,000 |
| Ohio | 673,000 | 59,900 | 1,510,000 | 156,000 |
| Pennsylvania | 397,000 | 54,100 | 1,260,000 | 254,000 |
| South Carolina | 206,000 | 45,100 | 663,000 | 147,000 |
| Tennessee | 395,000 | 50,800 | 938,000 | 134,000 |
| Vermont | 19,600 | 2410 | 132,000 | 23,700 |
| Virginia and District of Columbia | 316,400 | 35,080 | 801,400 | 147,980 |
| West Virginia | 75,300 | 11,700 | 429,000 | 148,000 |
| Wisconsin | 307,000 | 19,700 | 970,000 | 121,000 |
| Total | 7,498,300 | 942,002 | 20,291,800 | 2,990,550 |

Note: Rhode Island is not part of the study area because, according to the spread model, no county of Rhode Island becomes infested during the study period.

include continued enforcement of quarantines to restrict transport movement of ash material, surveys to detect new infestations, and outreach to increase public awareness. Enhanced investments in research on effective control, containment and management strategies, survey methodology and related avenues that could slow EAB expansion are also warranted.

## 2. Methods

The study area (Fig. 1) includes 25 states that we predict will have EAB infestations by 2019. The next decade (2009–2019) was chosen for our analysis because this is a logical time frame for the purpose of planning a policy response to the EAB invasion. Projecting the EAB infestation and costs further than a decade would require assumptions that are difficult to justify. Our approach to estimate the discounted cost of ash treatment, removal, and replacement has three primary components. First, we estimate the number of ash trees on developed land. Next, we predict the counties that will be infested with EAB over a 10-yr horizon. Finally, we predict the number of trees that will be treated or removed and replaced in response to infestation and compute the total discounted cost of these activities.

### *2.1. Estimating the number of ash trees*

We estimate the number of ash trees on developed land in U.S. Census-defined communities, which are geographic areas defined by jurisdictional or political boundaries and included in the U.S. Census definitions of places (census-designated place, consolidated city, and incorporated place).[2] We use a digital map of communities developed from the 2000 U.S. Census by the U.S. Forest Service for an assessment of urban and community forests as part of the Forest and Rangeland Renewable Resources Planning Act of 1974 (Nowak and Greenfield, 2008). Communities cover 14.8 million ha in our 226 million ha study area.

Communities are defined as places of established human settlement and may include both developed and undeveloped land within their boundaries. We estimate numbers of ash trees on developed land within communities because these ash trees will likely be the highest priority to treat, remove, and replace. We identify developed land using the 2001 National Land Cover Database (NLCD, 2001). The NLCD 2001 is a raster-based land cover classification derived from satellite imagery and consistently applied with a $30 \times 30$ m$^2$ resolution over the United States (Homer et al., 2007). The NLCD 2001 has four developed land cover classes based on the percentage of impervious surface and vegetation cover (Homer et al., 2004), and these four land classes cover 7.5 million ha of the 14.8 million ha of community land in our study area (Table 1).[3] We also report the area of tree canopy cover in the developed portions of communities based on NLCD 2001. Tree canopy covers about 13% (942,002 ha) of developed land.

It is important to note that the U.S. Census contains a geographic definition of urban area based on population density in census blocks and block groups, which differs from our earlier definition of community. U.S. Census-defined urban areas and communities may overlap but they are not congruent (see Nowak and Greenfield, 2008 for examples in the northeastern U.S.). We use communities and not urban areas as geographic units in this study because communities have geopolitical boundaries and people within these jurisdictions are likely to organize and manage their ash trees in response to EAB infestation as a group.[4]

The numbers of ash trees on developed land in communities are estimated using forest inventory information for 16 cities and three regions (Table 2) that we obtained from web sites, publications, and personal communication with city foresters (Nowak et al., 2001;

[2] For detailed definitions, see http://www.census.gov/geo/www/cob/pl_metadata.html.

[3] For detailed information, see http://www.mrlc.gov/nlcd.php.

[4] A small number of "communities" may be historical or special-use districts that no longer have formal geopolitical boundaries.

**Table 2**
Developed land, canopy cover, and ash (*Fraxinus* sp.) density for selected cities and regions in the eastern United States.

| Areas | Developed land (ha) | Canopy cover (ha) | Ash trees per ha developed land | Ash trees per ha canopy cover |
|---|---|---|---|---|
| Cities | | | | |
| Atlanta, GA | 24,846 | 8418 | 1.57 | 4.62 |
| Baltimore, MD | 18,593 | 1219 | 16.03 | 244.44 |
| Boston, MA | 11,357 | 663 | 2.35 | 40.18 |
| Chicago, IL | 57,162 | 1338 | 6.77 | 289.37 |
| Indianapolis, IN | 72,360 | 8417 | 2.05 | 17.65 |
| Livonia, MI | 8859 | 981 | 2.61 | 23.58 |
| Milwaukee, WI | 23,142 | 822 | 4.08 | 114.92 |
| Minneapolis, MN | 13,733 | 1243 | 14.58 | 161.06 |
| Morgantown, WV | 1745 | 309 | 22.01 | 124.22 |
| Palatine, IL | 3300 | 303 | 7.94 | 86.47 |
| Philadelphia, PA | 29,854 | 1310 | 4.36 | 99.27 |
| Syracuse, NY | 5912 | 467 | 1.13 | 14.24 |
| Troy, MI | 8273 | 940 | 7.03 | 61.83 |
| Urbana, IL | 2477 | 145 | 3.40 | 58.13 |
| Washington, DC | 13,362 | 9797 | 2.40 | 3.27 |
| Wilmington, DE | 2522 | 99 | 1.62 | 41.20 |
| Mean | 18,594 | 2279 | 6.25 | 86.53 |
| Regions | | | | |
| MI, OH, IN[a] | 919,470 | 85,139 | 6.60 | 71.28 |
| MI[b] | 339,773 | 35,118 | 11.06 | 107.04 |
| OH[c] | 673,000 | 59,900 | 6.41 | 72.03 |

[a] Counties of Michigan: Gladwin, Arenac, Midland, Gratiot, Saginaw, Tuscola, Huron, Sanilac, Lapeer, Genesse, St. Clair, Shiawassee, Clinton, Eaton, Ingham, Livingston, Oakland, Macomb, Kalamazoo, Calhoun, Jackson, Washtenaw, Wayne, Branch, Hillsdale, Lenawee, Monroe. Counties of Indiana: Lagrange, Steuben. Counties of Ohio: Williams, Fulton, Lucas. (Smith et al., submitted for publication).

[b] Counties include Gratiot, Mecosta, Montcalm, Newaygo, Barry, Calhoun, Clinton, Eaton, Ionia, Jackson, Shiawassee, Ingham, Livingston, Washtenaw, Kent. (MacFarlane et al., submitted for publication).

[c] Urban areas of Ohio (Sydnor et al., 2007).

**Table 3**
Ash (*Fraxinus* sp.) density by land use and diameter class for the city of Chicago.

| Land use | Percent of urban land | Ash trees per ha cover | Ash trees per ha cover by diameter class | | |
|---|---|---|---|---|---|
| | | | 2.5–30 cm | 30–61 cm | >61 cm |
| Residential | 0.64 | 141.7 | 47.5 | 34.6 | 8.6 |
| Non-residential | 0.36 | 551.9 | 177.1 | 17.3 | 4.3 |

Smith et al., submitted for publication; Sydnor et al., 2007). For the 16 cities, the inventory information includes estimates of the total number of ash trees within city boundaries, including trees on public and private lands. For each city, we divide the number of ash trees by the area of canopy cover on developed land to obtain an estimate of ash density (Table 2, right-hand column). Across the 16 cities, average ash density is 87 trees per ha of tree cover with a range of three trees per ha in Washington DC to 289 trees per ha in Chicago. The significant variation of the ash densities is because of the wide range in the ecological, cultural, and historical differences of the cities across the study area.

We also use forest inventory information from three regional studies of ash resources. Smith et al. (submitted for publication) recorded the species, size, and damage of trees in 249 circular 900 $m^2$ plots in a core area of EAB infestation in Michigan, Ohio, and Indiana in 2007. Of the 249 plots, 67 were located in NLCD 2001 developed land types. From these 67 plots, we estimate an ash density of 71 trees per ha cover for the 33-county core area (Table 2). MacFarlane et al. (submitted for publication) developed and implemented a large-scale forest inventory to determine the abundance and spatial distribution of ash trees in 1335 plots in southern Lower Michigan in 2004. For the 324 plots on the developed land types of IFMAP, a land classification developed from satellite imagery for the state of Michigan, we estimate an ash density of 107 trees per ha cover for southern Lower Michigan. Additionally, Sydnor et al. (2007) surveyed 67 communities in Ohio in 2005 to determine the size of the ash resource. Based on their estimate of 4.3 million ash trees in communities of Ohio, we estimate an average ash density of 72 trees per ha cover in Ohio communities.

The forest inventory information for cities and regions is the basis for estimating numbers of ash trees on developed land within communities. First, we divide the study area into mapping zones (Fig. 1, inset). The mapping zones are from the NLCD 2001 and represent areas of relatively homogenous landform, soil, vegetation and spectral reflectance (Homer et al., 2004). Then, we assign each city or region to a mapping zone and compute average ash density (trees per ha cover) for the zone.[5] Finally, we multiply the average ash density times the area of tree cover on developed lands in communities to estimate number of ash trees in the mapping zone. If we did not have inventory information for a particular zone, we use the ash density of the nearest zone.

Since the cost of managing ash trees in areas of EAB infestation depends on tree size and land use, we also estimate the number of ash trees by size class and land use in the developed portion of communities in each mapping zone. The extensive tree inventory for the city of Chicago includes estimates of all trees within the urban boundary for seven land uses and several diameter classes. From this detailed inventory information, we compute ash density (trees per ha cover) for residential areas (single-family, multi-unit, and planned development), non-residential areas (downtown, industrial, open space, and commercial) and three tree diameter classes (2.5–30 cm, 30–61 cm, and >61 cm) (Table 3).[6] Street trees are the responsibility of the community, and we include street trees in the category of non-residential areas. We reallocate 10% of trees from residential areas to the non-residential areas to account for the street trees, based on estimates of the number of street trees in Indianapolis (Peper et al., 2008). Because most of the city tree inventories only include estimates of numbers of ash trees, we use the relative ash tree densities across land use and size classes in Chicago to estimate ash tree densities by land use and size class in each of the other cities.

### 2.2. Predicting EAB infestation

We use a probabilistic model of EAB spread to compute 100 scenarios of EAB infestation across the study area over the next decade, 2009–2019. The model is run on a 7046 equidistant point grid extending from 30.25 to 49.64 °N and 61.12 to 98.22 °W, excluding major bodies of water. This effectively divides the study area into cells approximately $23 \times 25$ $km^2$ in size. The model uses a negative exponential function to predict the annual probability that EAB in an infested cell will spread and cause an infestation in a vacant cell at a detectable level. The probability of spread, $p$, depends on the distance, $d$ (km), between cell midpoints:[7]

$$p = 0.94e^{-0.06d} \quad (1)$$

In each scenario, the model begins with the locations of known EAB infestations in the U.S. and Canada in March 2009 (Fig. 1) and predicts the spread of the infestations for 10 years to March 2019. During each year, each vacant cell is tested to see whether it becomes infested at a

[5] For example, if forest inventory information is available for three cities in a mapping zone, the average ash density of the three cities is the ash density for the zone.

[6] Seven land uses (separated into residential and non-residential areas) and three tree diameter classes are chosen because this is how the most detailed forest inventory, from Chicago, categorizes trees. The ash densities for residential and non-residential areas and the three diameter classes for all the cities and regions in Table 2 are based on the ash distribution across these categories from Chicago. For the lower bound of the smallest tree diameter class, a tree less than 1″ (2.54 cm), is considered a shrub and is not part of the inventory.

[7] The spread model does not include population dynamic processes, simply the rate at which infestations are detected.

detectable level.[8] The test is a series of Bernoulli trials using the probabilities of movement from all of the infested cells at the beginning of the year. If at least one trial is positive, then the vacant cell becomes infested. The two parameters of the probability model were selected by contrasting the predictions from simulations starting with a single infestation near the initial infestation in Wayne County, Michigan, in 1994 (Siegert et al., 2006) to the observed infestations as of March 2009. In particular, 500 simulations of the model were performed for each of the 500 permutations of the two parameters (ranging from 0.5–1.5 and 0.01–0.1) and the results were summarized by distance from the epicenter into 80.5 km intervals. Subsequently, the mean square difference between the actual proportion of infested counties and the predicted proportion of counties infested by distance class was determined for each model permutation and used to identify the best fitting parameters.

Muirhead et al. (2006) estimated a negative exponential function to predict the annual probability of EAB spread based on known sites of infestation between 2002 and 2004. Since that model was developed, many more sites have been discovered that were infested between 2002 and 2004. Further, dendrochronological evidence suggests that many of the sites discovered between 2002 and 2004 were already infested before 2002 (Siegert et al. unpublished data). Therefore, many of the infestations discovered between 2002 and 2004 represented improvements in detection abilities rather than new infestations. Not surprisingly, the parameters of the two negative exponential models differ. We do not attempt to mechanistically model long distance movement of EAB mediated by humans and leave that to future work.

We overlay a map of counties on the center points of the grid to predict whether each county is infested each year. A county is considered infested when EAB is detected in at least one grid point within the county. In cases where a county does not have a grid point within its boundaries,[9] the county is considered infested when EAB is present at the point nearest a boundary. Once an infestation has been detected in a county, it takes time for EAB to spread and infest all of the ash trees in the county. Smitley et al. (2008) estimated that ash decline moved outward from a point of infestation at a rate of 10.6 km per year. Evidence from U.S. Forest Service Forest Inventory and Analysis plots suggests that catastrophic ash mortality in a county becomes apparent about five years after an infestation has been detected there (Liebhold et al. unpublished data). From this evidence, we assume that the percent of the ash that is infested in a county increases linearly from 0–100% in five years following the detection of the initial infestation.

### 2.3. Estimating the cost of EAB damage

When EAB infests a community, we assume that a homeowner or tree manager maximizes the present value of a stream of benefits and costs associated with each tree by choosing among four actions—1) do nothing, 2) remove, 3) remove and replace, or 4) treat with an insecticide that prevents injury from EAB.[10] The annual benefit of a tree represents a premium to the property value and depends on tree size (Table 4). Anderson and Cordell (1985) show that the presence of one medium size hardwood tree on the front of a property increases the property value of single-family home by 0.8%, and we use the price of an average home in Ohio to compute the premium (American Community Survey, 2006). The costs of removal and replacement depend on tree size, with community managers paying slightly less than homeowners (Table 4). Removal and replacement costs come from an EAB cost calculator for Indiana (http://www.entm.purdue.edu/EAB/) and represent the costs of managing 15 cm, 45 cm, and 76 cm diameter trees.[11]

**Table 4**
Management costs and annual benefits estimated for homeowners and community managers based on ash tree diameter at breast height (DBH; 1.4 m aboveground).

| Landowner | Costs and benefits ($/tree) | | | |
|---|---|---|---|---|
| | Remove | Remove and replace | Treat | Annual benefit |
| *Tree size = 2.5–30 cm in DBH* | | | | |
| Homeowner | 200 | 600 | 54 | 289 |
| Community | 150 | 450 | 50 | 289 |
| *Tree size = 30–61 cm in DBH* | | | | |
| Homeowner | 400 | 800 | 120 | 723 |
| Community | 300 | 600 | 100 | 723 |
| *Tree size = >61 cm in DBH* | | | | |
| Homeowner | 1100 | 1500 | 200 | 1259 |
| Community | 900 | 1200 | 150 | 1259 |

Costs estimates come from the EAB Cost Calculator (http://www.entm.purdue.edu/EAB/).

Treatment to prevent injury from EAB commonly involves injecting a systemic insecticide directly into the base of the tree. An insecticide with emamectin benzoate as an active ingredient prevents colonization and injury from EAB for two years (McCullough et al., in press). We use insecticide treatment costs (Table 4) from the EAB cost calculator for Indiana (http://www.entm.purdue.edu/EAB/) and assume that treatment is required every two years.

We formulate a discrete-time dynamic-programming model to determine the optimal action depending on tree size (see Appendix A). Given our assumptions of tree benefits and management costs, the optimal action, from an economic perspective, is to remove and replace smaller trees (<45 cm diameter for homeowners and <61 cm diameter for tree managers) and treat larger trees. Larger trees have high value that can be sustained through time with treatment. Conversely, it is better to remove and replace small ash trees to hasten the benefits of longer-living replacement trees and avoid the cost of treatment.

For each of the 100 scenarios of EAB infestation, we sum the annual discounted treatment, removal and replacement costs that take place over the 10-yr horizon. When a county becomes infested, we assume that all larger trees (>45 cm diameter for homeowners and >61 cm diameter for tree managers) are treated with an insecticide immediately and then every two years until the end of the 10-yr horizon. Smaller trees (<45 cm diameter for homeowners and <61 cm diameter for tree managers) are removed and replaced at the time of infestation, assuming that 20% of the ash trees are infested each year following the county's initial infestation.[12] For homeowners, half the ash trees in the tree diameter size class 30–61 cm are treated, and the other half are removed and replaced. For tree managers, all the ash trees in the tree diameter class 30–61 cm are removed and replaced. Once the discounted cost is computed for each infestation scenario, we compute the mean and standard deviation for total discounted cost over the 100 simulations.

The annual costs of treatment, removal, and replacement are discounted to the present with a 2% real discount rate. Howarth (2009) observes that the future benefits of a public good, such as the removal and replacement of a dead ash tree, should be discounted at a rate close to the market rate of return for risk-free financial assets. This holds true even when the public good has risk characteristics equivalent to those of risky forms of wealth such as corporate stocks.

[8] There is no information available on the level of the infestation. The model only describes when an infestation is detected.
[9] This is the case for some counties in Virginia, for instance.
[10] The homeowner and tree manager models assume that the insecticide is 100% effective at preventing ash trees from being infested.
[11] The City of Westland began a major ash tree removal in 2002 and finished in late 2004 with a median removal and replacement cost of $635 per tree (Michigan Department of Natural Resources, 2007).
[12] The decisions are optimal according to the model, but a number of factors, for example sentimental attachment or uncertainty surrounding the effectiveness of the treatment, could result in a different decision by homeowner or tree manager.

**Table 5**
Estimated number of ash trees in developed areas of communities and number of ash trees that are either treated with insecticide or removed under one scenario of EAB infestation (base case).

| State | Base case | | | Sensitivity analysis | | |
|---|---|---|---|---|---|---|
| | Ash trees (1000s) | Ash trees treated or removed (1000s) | Cost (2009 $ millions) | Ash trees (1000s) | Ash trees treated or removed (1000s) | Cost (2009 $ millions) |
| Arkansas | 3299 | 492 | 240 | 18,300 | 1246 | 546 |
| Connecticut | 556 | 11 | 4 | 1568 | 23 | 8 |
| Delaware | 42 | 41 | 22 | 125 | 60 | 33 |
| Illinois | 5474 | 3497 | 2120 | 10,100 | 4511 | 2740 |
| Indiana | 944 | 527 | 333 | 1820 | 786 | 503 |
| Iowa | 1149 | 611 | 321 | 2455 | 815 | 423 |
| Kentucky | 263 | 228 | 127 | 2626 | 743 | 409 |
| Maine | 968 | 531 | 255 | 2424 | 811 | 381 |
| Maryland | 940 | 883 | 533 | 1700 | 939 | 570 |
| Massachusetts | 811 | 46 | 18 | 2189 | 82 | 29 |
| Michigan | 1719 | 353 | 230 | 7591 | 2507 | 1590 |
| Minnesota | 1842 | 583 | 260 | 4236 | 638 | 270 |
| Missouri | 4449 | 3111 | 1680 | 17,900 | 5766 | 3120 |
| New Hampshire | 518 | 259 | 121 | 1812 | 541 | 251 |
| New Jersey | 1435 | 630 | 286 | 2576 | 749 | 333 |
| New York | 2047 | 419 | 203 | 4187 | 749 | 378 |
| North Carolina | 662 | 185 | 84 | 3042 | 349 | 158 |
| Ohio | 1428 | 598 | 376 | 3985 | 1146 | 735 |
| Pennsylvania | 1850 | 1347 | 786 | 9325 | 3222 | 1940 |
| South Carolina | 85 | 2 | 1 | 276 | 5 | 2 |
| Tennessee | 4485 | 811 | 336 | 9280 | 1113 | 451 |
| Vermont | 101 | 93 | 52 | 693 | 236 | 130 |
| Virginia and District of Columbia | 1334 | 1126 | 641 | 5369 | 2026 | 1182 |
| West Virginia | 409 | 405 | 237 | 5516 | 1732 | 1070 |
| Wisconsin | 1092 | 988 | 566 | 6171 | 2164 | 1200 |
| Total | 37,902 | 17,777 | 9832 | 125,266 | 32,959 | 18,452 |

Note: Rhode Island is not part of the study area because, according to the spread model, no county of Rhode Island becomes infested during the study period.
The sensitivity analysis shows the result of expanding the land base to include all developed land as defined by the National Land Cover Database 2001.

### *2.4. Sensitivity analysis*

U.S Census-defined communities are places of established human settlement, yet urban development also exists outside community boundaries (Nowak and Greenfield, 2008). To account for development outside communities, we expand the land base to include all developed land as defined by the NLCD 2001. The developed land classes in the NLCD 2001 have been used extensively to estimate land cover associated with urban development (e.g., Brown et al., 2005; Burchfield et al., 2006). In the sensitivity analysis, we estimate the number of ash trees on developed land both inside and outside communities. We assume that ash trees on developed, residential land outside communities will be treated or removed and replaced in response to EAB infestation in the same fashion as trees inside communities; however, trees on developed, non-residential land[13] will not be managed in response to EAB and incur no cost. The proportions of trees in residential and non-residential areas are assumed to be the same as for the city of Chicago (Table 3) because we do not have further information on the breakdown of trees by land use. With these assumptions, we determine how the increased land base affects the estimate of discounted cost of ash treatment, removal, and replacement in response to EAB.

## 3. Results

We estimate that 37.9 million ash trees grow on developed land within communities in the study area (Table 5), ranging from 42,000 ash trees in Delaware to 5.5 million ash trees in Illinois. The state with the largest ash population (Illinois) has a large amount of canopy cover on developed land (47,460 ha) and high ash density (289 trees per ha cover). Our estimate of the number of ash trees on developed land in Minnesota communities (1.8 million) is comparable to a recent estimate made by the Minnesota Department of Natural Resources (2007). From a sample of residential and commercial areas in 750 Minnesota communities in 2006, the Minnesota DNR estimated 2.9 million ash trees. Their estimate is larger than our figure because in the Minnesota DNR survey, boundaries of residential and commercial areas included undeveloped lands that are not included in our NLCD 2001 estimate of the developed land base.

### *3.1. EAB infestation*

We predict that the area of EAB infestation will steadily expand from its current distribution in 2009. Newly infested counties occur primarily on the perimeter of the existing area of infestation. By 2019, however, the infestation is predicted to cover most of the states in our study area.[14] An example of the simulated progression of the EAB infestation is shown in Fig. 2. Note that the infestations predicted to occur in upstate New York and northern Vermont in 2011 result from expansion of existing EAB infestations near Montreal, Canada.[15]

### *3.2. Cost of EAB damage*

The mean discounted cost of treating, removing, and replacing ash trees on developed land in communities is $10.7 billion (Table 6). A majority of the cost is incurred by removing and replacing small ash

[13] This is the 2001 National Land Cover Class for "Developed, Open Space". These are areas where impervious surfaces account for less than 20% of total cover. This includes large-lot single-family housing units, parks, and golf courses (MRLC, 2009).

[14] Between March and July 2009, new EAB infestations have been found in cities distant from the frontier (e.g., St. Paul, MN). These outlier populations change the initial EAB footprint and projection of EAB infestation. Modeling the discovery of outlier populations is problematic because of the large uncertainty, and modifying the projection to include the latest discoveries may not better reflect the EAB infestation because in a few months a new set of latest discoveries may further alter the forecast. We are planning to analyze the impact of the outlier populations on the progression of the infestation in upcoming work.

[15] Based on Fig. 2, the only state without an infestation in the northeast at the end of the study period is Rhode Island.

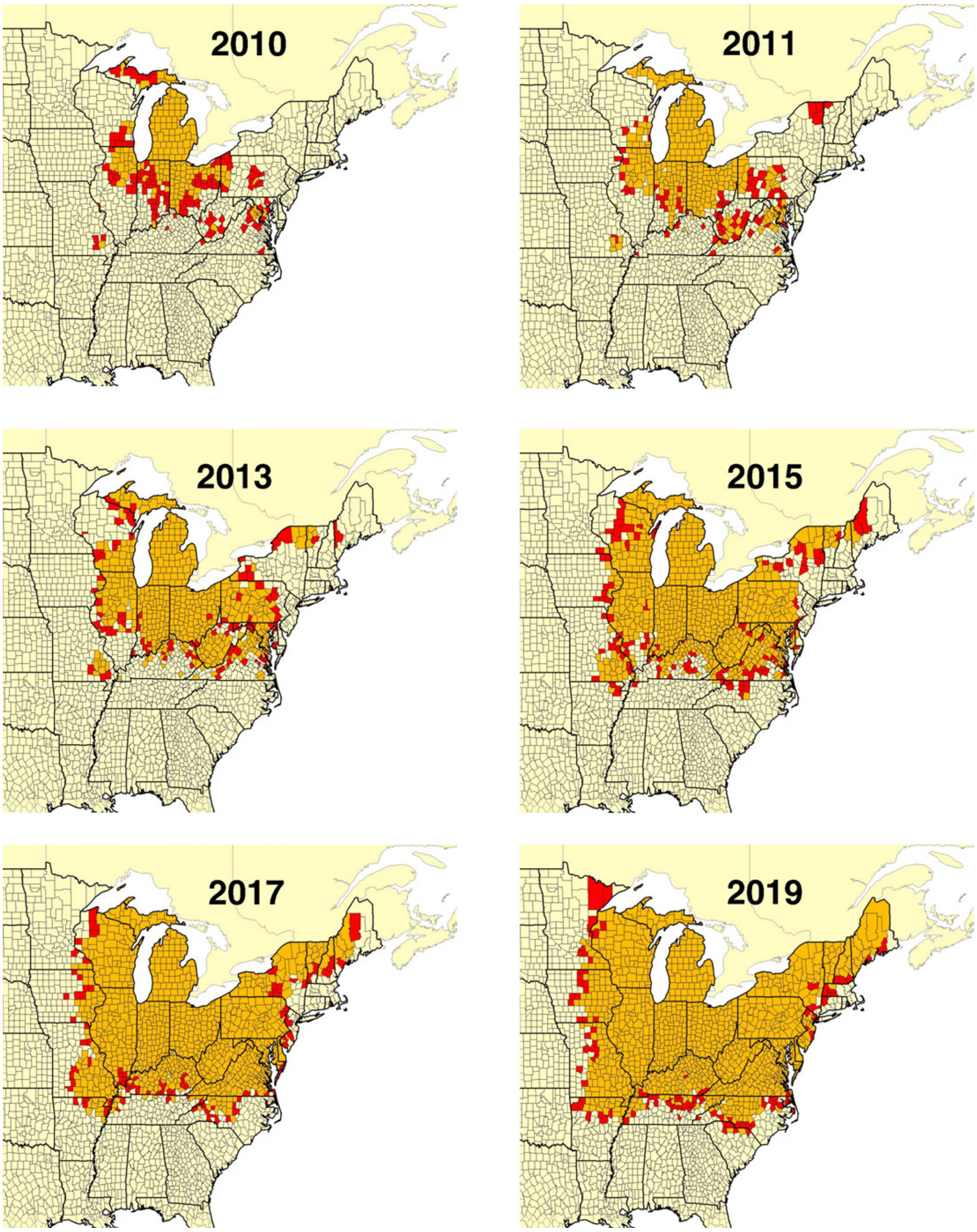


**Fig. 2.** A simulation of emerald ash borer distribution in counties from March 2010 to March 2019. Darker counties are newly invaded while lighter counties became infested in prior years. These maps represent only a single realization of 100 stochastic simulations.

trees on non-residential land. If all 37.9 million ash trees on developed land in communities are assumed to be removed and replaced at once, a common assumption in other studies (e.g., Sydnor et al., 2007), the total cost is $25.0 billion, more than double our estimate. The difference reflects our prediction that fewer than half of the 37.9 million ash trees will be treated or removed and replaced in the 10-yr horizon and our assumption that costs incurred later in the horizon are discounted.

The discounted costs in Table 6 represent averages computed from 100 simulations of EAB spread across the study area. For the simulation illustrated in Fig. 2, slightly less than half of the ash trees on developed land in communities (17.7 million) are treated or removed and replaced over the 10-yr horizon (Table 5). States with the highest proportion of ash trees removed and replaced (>90%)

**Table 6**
Mean (± standard deviations in parentheses) discounted treatment, removal, and replacement cost ($billion) computed over 100 simulations of EAB infestation.

| Land use | Diameter class (cm) | | | Total |
|---|---|---|---|---|
| | 2.5–30 | 30–61 | >61 | |
| Residential | 1.45<br>(0.09) | 1.32<br>(0.08) | 0.30<br>(0.02) | 3.07<br>(0.13) |
| Non-residential | 6.14<br>(0.42) | 1.04<br>(0.07) | 0.43<br>(0.02) | 7.61<br>(0.43) |
| Total | 7.59<br>(0.44) | 2.36<br>(0.10) | 0.73<br>(0.02) | 10.68<br>(0.69) |

have outlier populations in 2009 that expand across the entire state during the 10-yr horizon (West Virginia, Maryland, Delaware, Wisconsin, and Vermont). In Michigan and Ohio, small proportions of ash are removed and replaced (0.21 and 0.42, respectively) because many counties were infested prior to 2009 and we assume that much of the ash has already been removed and replaced.[16] The total discounted cost of treatment, removal, and replacement in the simulation in Fig. 2 is $9.8 billion, slightly less than the average cost computed from the 100 simulations of potential EAB spread.

### 3.3. Sensitivity analysis

Expanding the land base to include all developed land as defined by the NLCD 2001 more than triples the estimate of number of ash trees from 37.9 million to 125.3 million (Table 5). Three regional ash inventories have estimates that are comparable to our state-wide estimates of ash on developed land. Using inventory plots located in NLCD 2001 developed land cover types, Smith et al. (submitted for publication) estimated 6.1 million ash trees in a core area of EAB infestation in Michigan, Indiana and Illinois. We estimate 7.6 million ash trees on developed land for the entire state of Michigan. Based on a survey of community foresters in 67 Ohio communities, Sydnor et al. (2007) estimated 3.8 ash trees per capita in those communities. That figure was multiplied by the total Ohio population to obtain their estimate of 4.3 million urban ash trees in the state. Assuming this estimate represents the number of ash trees on developed land, it is comparable to our estimate of 4.0 million ash trees on developed land in Ohio. From 111 plots located in U.S. Census-defined urban areas in Wisconsin, Cumming et al. (2007) estimated 5.2 million urban ash trees compared with our estimate of 6.2 million ash trees on developed land in Wisconsin. The main reason for the difference is that U.S. Census-defined urban areas are based on population density in county subdivisions and do not include small areas of developed land that do not meet the population density requirements.

Using the larger land base, we estimate that the number of ash trees treated or removed and replaced in response to one scenario of EAB infestation (32.9 million) is almost twice as many as we estimated using developed land within U.S. Census-defined communities (17.7 million). Similarly, the discounted cost of treatment, removal and replacement ($18.5 billion) is almost twice as much as our estimate of the discounted cost ($9.8 billion) of treatment, removal and replacement on developed land within communities. We note that the proportion of ash trees that are treated or removed and replaced (0.26) in the sensitivity analysis is less than the proportion of ash trees treated or removed and replaced in the base case (0.47). The difference is caused by our assumption in the sensitivity analysis that non-residential trees on developed land outside communities are not treated or removed and replaced in response to infestation.[17] The sensitivity analysis demonstrates that estimates of the number of ash and cost of EAB damage are dependent on the data source and definition of the land base.

## 4. Conclusions

Our estimate of the discounted cost of treatment, removal, and replacement in response to EAB infestation over a 10-yr horizon from 2009–2019 is $10.7 billion. Since the cost of treating, removing, and replacing all the 37.9 million ash trees on developed land in communities at once is $25 billion, this indicates a justification for substantial investment to slow the spread of EAB and postpone treatment, removal, and replacement costs if feasible. These investments could include continued enforcement of quarantines to restrict transport movement of ash material, surveys to detect additional infestations, and outreach to increase public awareness. Enhanced investments in research on effective control, containment and management strategies, survey methodology and related avenues that could slow the rate at which EAB populations build and expand are also warranted.

In addition to the land base assumption that we tested in the sensitivity analysis, other assumptions may affect our estimates of treatment, removal, and replacement costs. Our cost estimates are based on the assumption that homeowners and community foresters manage ash trees to maximize present value of tree benefit net management cost, and the best actions are either treatment or removal and replacement. If homeowners or community foresters have cost constraints or place lower values on ash trees than we assume, fewer ash trees than we predict will be treated or removed and replaced, and we overestimate management costs. Treating rather than removing and replacing trees larger than 30 cm in diameter is economically beneficial, assuming that treatment effectively prevents EAB damage. Very large trees (> 61 cm diameter) can be difficult to treat effectively with systemic insecticides because of the difficulty of ensuring that the product is well distributed within the tree (Herms et al., 2009). Accounting for a reduction in effectiveness would narrow the range of tree sizes for which it is better to treat, which will increase the overall estimate of management cost because tree removal and replacement is more expensive.

USDA Plant Protection and Quarantine (PPQ) within the Animal and Plant Health Inspection Service (APHIS) and the state plant pest regulatory agencies monitor and regulate potential pathways for artificial movement.[18] We did not attempt to specifically model long distance dispersal of EAB caused by humans, and as a result, we do not predict the establishment of outlier populations. To the extent that the establishment of outlier EAB populations increases the rate at which counties become infested, our model underestimates the progression of spread and the discounted cost of treatment, removal, and replacement.

Two other issues need further attention to improve estimates of the economic impacts of EAB. A systematic sample of community forests throughout the study area is needed to obtain statistically sound estimates of the number and size of ash trees on residential and non-residential lands. While estimates of ash abundance in communities for which tree inventory data are available appear robust, expanding those numbers to places without tree inventories, as we do here, should be viewed with some caution because inventories are only available from a limited number of communities and do not represent a random sample. Our estimate of the discounted cost of treatment, removal, and replacement in response to EAB infestation is only a management cost and represents an income transfer from homeowners and communities to the tree-care industry. There are also net losses to society from the invasion of EAB (e.g., losses in market and non-market values of ash trees) that need to be counted, including losses of forest landowners and the wood products industry.

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[16] Evidence of removal rates from Michigan and Ohio of ash trees on developed land would be useful for calibrating the removal of trees in the simulation model. A systematic sample of ash tree removals in developed areas infested prior to 2009 is needed to obtain statistically sound estimates of the removal rates of urban ash.

[17] We assume that ash on non-residential land outside of communities does not influence property values since the trees are not sufficiently close to dwelling structures to have an amenity effect on property values. The optimal action is “do nothing” since any other actions yields no benefit and is costly.

[18] There are no outlier populations found that post-date when these regulatory programs were fully operational. The regulatory program investments are assumed to be effective and necessary to maintain. We thank an anonymous reviewer for pointing this out.

inventory information for cities and regions. This work was conducted as part of the Ecological and Economic Impacts of Non-native Forest Pests and Pathogens in North America Working Group, supported by The Nature Conservancy and The National Center for Ecological Analysis and Synthesis, a Center funded by NSF (Grant #DEB-0553768), the University of California, Santa Barbara, and the State of California. The authors also acknowledge the support of the U.S. Forest Service Northern Research Station.

## Appendix A

We suppose an infestation of the emerald ash borer has reached a particular city. A homeowner or manager has four options for each ash tree: 1) do nothing, 2) remove the ash tree, 3) remove the ash tree and replace it with another tree resistant to the emerald ash borer (e.g., a maple tree), or 4) treat the ash tree with a chemical that prevents infestation. We formulate a discrete-time dynamic-programming model to determine the optimal action depending on tree age, from which we calculate tree size using equations for predicting the diameter of street trees (Peper et al., 2001).

We assume that the landowner chooses the action that maximizes the present value of tree benefit net the cost of treatment, removal, or removal and replacement. The annual benefit of a tree represents a premium to the property value and depends on tree age. The tree may also cause a reduction in property value if it dies and is left standing (Holmes and Smith, 2007).[19] We define an optimal value function $V(a)$ as the present value of the optimal sequence of actions applied to an ash tree age $a$. If the landowner does nothing, the dead tree results in an annual loss of property value, $c_{\mathrm{dn}}(a)$, that diminishes over time as the tree decomposes. The landowner may remove the ash tree with cost $c_{\mathrm{rm}}(a)$. Removing and replacing the ash tree produce a present value of a stream of benefits associated with the replacement tree, $p_{\mathrm{maple}}$, net removal and replacement cost $c_{\mathrm{rp}}(a)$. Treating the ash produces a benefit $p_{\mathrm{ash}}(a)$ during the year net cost of treatment $c_{\mathrm{treat}}(a)$ plus the discounted value of the optimal policy for the ash tree one year older, $V(a+1)$. The optimal value function is:

$$V(a) = \max \begin{cases} -c_{\mathrm{dn}}(a) & \text{do nothing} \\ -c_{\mathrm{rm}}(a) & \text{remove} \\ p_{\mathrm{maple}} - c_{\mathrm{rp}}(a) & \text{remove and replace} \\ p_{\mathrm{ash}}(a) - c_{\mathrm{treat}}(a) + \delta V(a+1) & \text{treat} \end{cases}$$

where $\delta$ is the discount factor. The optimal value function is solved backward from a maximum age $n$ when we assume that the ash tree is either removed or replaced:

$$V(n) = \max \begin{cases} -c_{\mathrm{rm}}(n) & \text{remove} \\ p_{\mathrm{maple}} - c_{\mathrm{rp}}(n) & \text{remove and replace} \end{cases}.$$

We solve this dynamic-programming model with the management costs and benefits in Table 4, a real discount rate of 2%, and a maximum tree age of 85 years. The optimal action is to remove and replace trees less than 30 cm diameter and treat larger trees. It is better to treat trees larger than 30 cm diameter because they have high value which can be sustained through time with the treatment. Likewise, it is better to remove and replace small ash trees to hasten the attainment of the benefits of longer-living replacement trees.

[19] Note though, that unless the homeowner has their home on the market, this loss may not be an immediate concern.

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