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The influence of satellite populations of emerald ash borer on projected economic costs in U.S. communities, 2010–2020

Kent F. Kovacs [a,*], Rodrigo J. Mercader [b], Robert G. Haight [c], Nathan W. Siegert [d], Deborah G. McCullough [b,e], Andrew M. Liebhold [f]

[a] *Department of Applied Economics, University of Minnesota, 1994 Buford Avenue, St. Paul, MN 55108-6040, United States*
[b] *Department of Entomology, Michigan State University, East Lansing, MI 48824, United States*
[c] *U.S. Forest Service, Northern Research Station, 1992 Folwell Ave., St. Paul, MN 55108, United States*
[d] *U.S. Forest Service, Northeastern Area State and Private Forestry, 271 Mast Road, Durham, NH 03824, United States*
[e] *Department of Forestry, Michigan State University, East Lansing, MI 48824, United States*
[f] *U.S. Forest Service, Northern Research Station, 180 Canfield Street, Morgantown, WV 26505, United States*

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ABSTRACT

The invasion spread of the emerald ash borer (*Agrilus planipennis* Fairmaire) (Coleoptera: Buprestidae) is characterized by the formation of satellite populations that expand and coalesce with the continuously invading population front. As of January 2010, satellite infestations have been detected in 13 states and two Canadian provinces. Understanding how newly established satellite populations may affect economic costs can help program managers to justify and design prevention and control strategies. We estimate the economic costs caused by EAB for the 10-yr period from 2010 to 2020 for scenarios of fewer EAB satellite populations than those found from 2005 to 2010 and slower expansion of satellite populations found in 2009. We measure the projected discounted cost of treatment, removal, and replacement of ash trees (*Fraxinus* spp.) growing in managed landscapes in U.S. communities. Estimated costs for the base scenario with the full complement of satellites in 2005–2010 and no program to mitigate spread is $12.5 billion. Fewer EAB satellites from 2005 to 2010 delay economic costs of $1.0 to 7.4 billion. Slower expansion of 2009 satellite populations delays economic costs of $0.1 to 0.7 billion. Satellite populations that are both distant from the core EAB infestation and close to large urban areas caused more economic costs in our simulations than did other satellites. Our estimates of delayed economic costs suggest that spending on activities that prevent establishment of new satellite EAB populations or slow expansion of existing populations can be cost-effective and that continued research on the cost and effectiveness of prevention and control activities is warranted.

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. As of January 2010, emerald ash borer (EAB) infestations had been detected in a total of 13 states and two Canadian provinces (Fig. 1a). The natural spread of EAB is gradual because the median distance that adults can fly is <3 km (Taylor et al., 2010) and females lay most eggs within 100 m when ash trees are in the immediate vicinity of the emergence point (Mercader et al., 2009). Satellite populations of EAB become established when humans inadvertently transport infested ash nursery trees, logs, firewood or related material. Because visual detection of EAB life stages or infested trees is difficult when densities are low (Cappaert et al., 2005; McCullough et al., 2009a), multiple cohorts likely disperse from infested trees before new infestations are detected (e.g., Siegert et al., 2010).

EAB is a highly invasive forest pest that could potentially spread, colonize and kill native ash trees (*Fraxinus* spp.) throughout the U.S. (Anulewicz et al., 2008), costing homeowners and local governments billions of dollars for treatment or removal and replacement of landscape ash trees (Kovacs et al., 2010). To prevent the artificial spread of EAB, federal, state and provincial agencies regulate transport of ash firewood, logs, nursery stock and related materials in quarantined areas. The U.S. Dept. of Agriculture Animal and Plant

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* Corresponding author.
E-mail addresses: kova0090@umn.edu (K.F. Kovacs), mercade2@msu.edu (R.J. Mercader), rhaight@fs.fed.us (R.G. Haight), nwsiegert@fs.fed.us (N.W. Siegert), mccullo6@msu.edu (D.G. McCullough), aliebhold@fs.fed.us (A.M. Liebhold).

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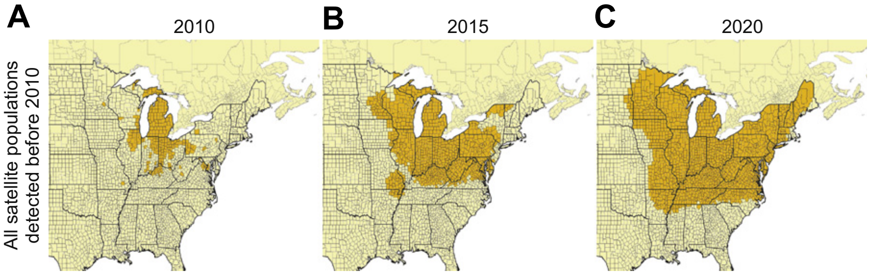

Fig. 1. Simulation of the emerald ash borer spread in counties from March 2010 to March 2020 (base case). The maps represent the rounded average of 200 stochastic simulations.

Health Inspection Service (APHIS) have spent more than $30 million annually since 2008 on the national EAB program. Funds are allocated to regulatory activities to support the quarantine, as well as survey and detection efforts, public education and outreach (Chaloux, 2009).

As more infestations are identified and additional states, municipalities and property owners are affected by EAB, the need to prioritize allocation of limited resources rises. Understanding how newly established satellite populations of EAB affect overall spread and economic costs can help program managers efficiently and effectively allocate resources. Here, we simulate the effect of satellite populations (initiated by long-distance human transport) detected from 2005 to 2010 on the projected economic costs caused by EAB over the next decade (2010–2020). We measure the discounted cost of treatment, removal, and replacement of landscape ash trees within communities. While ecological effects of widespread mortality of ash trees in forested or riparian settings will likely be substantial (Poland and McCullough, 2006), impacts of EAB on ecosystem services or forest products are not included in our analysis. Ecosystem services and forest products generally involve ecological and economic processes not strongly related to costs incurred by communities and thus are beyond the scope of this study.

Tactics to reduce the natural rate at which EAB populations build and expand should slow the progression of ash mortality in outlier sites (McCullough et al., 2009b). Such tactics could include intensive surveys with girdled trees to delineate EAB density and distribution, systemic insecticides to control EAB adults or larvae, girdled trees that are used as sinks to attract egg-laying adult EAB and then destroyed before larvae can complete development, and targeted removal of ash trees to reduce the availability of phloem for larval development. These tactics are likely to be effectively applied only in satellite populations that are localized and relatively recently established rather than in the core infested area (the area within the main infestation front) where the massive spatial extent and densities of EAB populations preclude large-scale management efforts (e.g., McCullough et al., 2009b). Efforts to implement and evaluate a strategy to slow the onset and progression of widespread ash mortality by integrating these tactics are currently underway at selected sites in the U.S. While these tactics may successfully reduce local EAB population growth and the rate of ash mortality, reducing the rate of EAB spread would also be highly desirable and any management strategies must be economically viable at a larger scale. Here, we estimate the potential reduction in economic costs to landscape trees that could result from hypothetical programs focused on slowing the expansion of satellite EAB populations and delaying the period when ash treatment or removal costs are incurred in surrounding areas.

Previous studies of the spatial management of invasive species have examined the allocation of control efforts between core and satellite populations (Epanchin-Niell and Hastings, 2010). Moody and Mack (1988) modeled the spread of an invasion consisting of a main core and multiple smaller satellites, each exhibiting constant radial growth. They found prioritizing satellites for management increased the time before the total area of the satellites exceeded the total area of the core. If control costs increase with invasion density (Higgins et al., 2000) or if low-density infestations have higher rates of spread (Taylor and Hastings, 2004), then prioritizing satellites remains the best approach. On the other hand, if high-density infestations spread faster (Taylor and Hastings, 2004) or there are lower marginal costs of control and detection for high-density infestations (Menz et al., 1980), then prioritizing the core should be preferred. Whittle et al. (2007) and Blackwood et al. (2010) suggested that control efforts should be allocated to both the core and satellite populations. However, Whittle et al. (2007) assumed costs only accrue at the end of the management horizon and Blackwood et al. (2010) assumed that costs, while dependent on the spatial connectivity of infestation, did not vary over space. The assumption of homogeneous damages over space simply means the optimal strategy is to minimize the total area invaded.

Our study examines EAB costs likely to be sustained in human communities spread heterogeneously over the U.S. The spatial heterogeneity of costs refers to the spatial concentration of the costs (i.e., the area of a community and the number of landscape ash trees) and the distance of satellite costs from costs that occur within the core (i.e., how long it takes for the core and satellite infestations to coalesce). Our results suggest substantial savings accrue from prioritizing the location of prevention and control activities.

2. Methods

The study area was comprised of 30 states that we predict will have EAB infestations by 2020 (Table 1), based on the EAB spread model. The next decade (2010–2020) was chosen to balance the need for a long-term programmatic response to the EAB invasion and the problem of forecasting too far into the future when significant changes in actual spread and abundance or location of satellites may have occurred. Estimating the effect of satellite populations on EAB costs has three primary components. First, in the base case, we predict the discounted cost of treatment, removal, and replacement of landscape ash trees in communities over the 10-yr horizon beginning with the EAB infestations known as of January 2010 (EAB.info, 2010). Second, we estimate the effect of the satellite EAB populations detected in 2005–2010 on economic costs by comparing the base case with i) scenarios including fewer satellites than found in previous years, and ii) scenarios for hypothetical programs to prevent spread applied to 2009 satellites. The programs to prevent spread are applied only to satellites in 2009 because the earlier satellites have expanded too much to now prevent spread. Scenarios in i) are used to study how the locations

Table 1
Estimated discounted cost of landscape ash treatment, removal and replacement (shown for 2-yr intervals and the total for 2010–2020) for the simulation of EAB spread from all known January 2010 infestations (base case). Standard deviation of the total based on the 200 simulations of the spread model is shown in parentheses.

State	Cost of treatment, removal, and replacement ($ millions)					
	2012	2014	2016	2018	2020	Total
Alabama	0	0	0	0	9	9
Arkansas	0	4	46	71	186	471
Connecticut	0	0	0	22	56	148
Delaware	0	2	4	4	1	23
Georgia	0	0	0	0	0	0
Illinois	483	136	169	150	102	2110
Indiana	91	28	13	8	7	329
Iowa	3	23	47	51	64	344
Kentucky	16	14	20	12	6	132
Maine	0	0	0	2	82	119
Maryland	74	105	54	11	5	538
Massachusetts	0	0	0	2	27	32
Michigan	25	20	16	13	12	230
Minnesota	112	149	131	75	52	974
Mississippi	0	0	0	19	47	87
Missouri	8	31	305	308	320	1670
New Hampshire	0	0	4	6	52	85
New Jersey	0	2	74	152	143	658
New York	5	11	43	104	185	659
North Carolina	0	0	0	2	61	100
North Dakota	0	0	0	0	5	5
Ohio	56	40	27	12	11	366
Pennsylvania	85	87	81	63	38	766
South Carolina	0	0	0	0	0	0
South Dakota	0	0	0	0	13	13
Tennessee	0	0	6	324	447	1160
Vermont	0	5	9	9	3	50
Virginia and District of Columbia	48	62	71	97	61	655
West Virginia	18	44	40	12	3	238
Wisconsin	90	61	53	35	11	492
Total	1114	825	1211	1562	2008	12,462 (152)

Note: The results are the mean of 200 iterations of the spread model.

on the landscape where satellites are found affect the 10-yr horizon costs, and scenarios in ii) are used to study how effective programs to prevent spread would need to be to reduce the 10-yr horizon costs. Finally, we analyze the sensitivity of the effects in relation to increases and decreases in ash density and per tree costs of removal, replacement, or treatment. In each scenario, the projected reduction in economic cost over the period 2010–2020 relative to the base case is called a delayed cost because damages are postponed and likely to occur in later years as EAB expands its range.

2.1. *Predicting EAB costs in the base case*

We estimate the economic costs associated with insecticide treatment or removal and replacement of landscape ash trees by following the approach in Kovacs et al. (2010). First, we estimate the number of landscape ash trees on developed land within communities.[1] Next, we predict the counties that will be infested with EAB over a 10-yr horizon. Finally, we predict the number of landscape ash trees that will be treated or removed and replaced in response to the infestation and compute the discounted cost of these activities in the next ten years.

2.1.1. *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). Communities cover 14.8 million ha of our 226 million ha study area. We estimate numbers of ash trees on developed land within communities because these trees will likely receive the highest priority for treatment or removal and replacement. We identify developed land using the 2001 National Land Cover Database. The NLCD 2001 has four developed land cover classes (Open Space, Low Intensity, Medium Intensity, High Intensity) based on the percentage of impervious surface and vegetation cover (Homer et al., 2007). These four land classes cover 7.5 million ha of the 14.8 million ha of community land in our study area. 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.

The numbers of ash trees on developed land in communities are estimated using forest inventory information for 16 cities and two regions that we obtained from web sites, publications, and personal communication with city foresters (Nowak et al., 2001; Smith et al., 2009; Sydnor et al., 2007). First, we divide the study area into 28 mapping zones. The mapping zones are from the NLCD 2001 and represent areas of relatively homogenous landform, soil, vegetation and spectral reflectance (Homer et al., 2007). Then, we assign each city or region to a mapping zone and compute the average ash density (trees per ha cover) for the zone.[2] Finally, we multiply the average ash density by 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.

2.1.2. *Predicting EAB infestation*

We use a probabilistic model of EAB spread to estimate EAB infestations across the 226 million ha study area for the decade spanning January 2010 to January 2020. 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 × 25 km 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 (Fig. 2)[3]:

$$p = 0.94\, e^{-0.06d} \tag{1}$$

The model begins with the locations of known EAB infestation in the U.S. and Canada in January 2010 and predicts the spread of infestations over a 10-yr period ending in January 2020. Additional infestations likely exist but have not yet been identified because of the detection difficulties associated with EAB (McCullough et al., 2009a). During each year, each vacant cell is tested to determine whether it becomes infested at a detectable level. 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.

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[1] Landscape ash trees are ash trees found on or near developed land. Forest ash trees are not part of this analysis.

[2] 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. Forest inventory data by tree size is available for Chicago, and the same proportions of tree sizes from Chicago are applied to the other mapping zones (Kovacs et al., 2010).

[3] The spread model does not include population dynamic processes, simply the rate at which infestations are detected. The negative exponential function used here was parameterized to fit the spread observed in this grid, and its use is therefore limited to studies of this resolution.

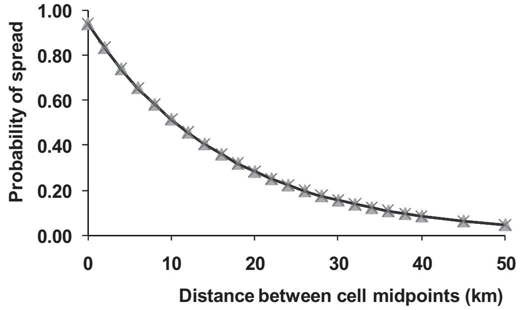

Fig. 2. A graph of the negative exponential function to predict the annual probability that EAB in an infested cell will spread and cause an infestation in a vacant cell at a detectable level.

The two parameters of the probability model were selected by contrasting the predictions from simulations starting with a single infestation near the EAB origin in Wayne County, Michigan, in 1994 (Siegert et al., 2006) to the known infestations as of March 2009 (as per Kovacs et al., 2010). In particular, 500 simulations of the model were performed for each of the 500 permutations of the two parameters (ranging from 0.5 to 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 infested counties by distance class was determined for each model permutation and used to identify the best fitting parameters.

Two other studies have developed probabilistic cell-based models of EAB spread. Muirhead et al. (2006) estimated a negative exponential function to predict the annual probability of EAB spread based on the distribution of known infestations between 2002 and 2004. Prasad et al. (2010) developed a probabilistic model of EAB spread as a function of current EAB abundance, ash abundance, and geographic variables (e.g., road density, human population density) that may affect human transport of EAB. Here, we use a simple, empirically based spread function and leave the use of a mechanistic model of EAB spread through the use of gravity-based, stratified, and/or pathway models 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. 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. Evidence from U.S. Forest Service Forest Inventory and Analysis plots indicates 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 percentage of the ash that is infested in a county increases linearly from 0 to 100% in five years following the detection of the initial infestation.[4] Our model assumes infested ash trees will eventually die.

2.1.3. Estimating economic costs

Costs of treatment or removal and replacement of landscape ash trees depend on tree size and ownership. Municipalities pay slightly less than homeowners because larger jobs reduce per unit tree costs. Removal, replacement, and treatment costs were derived from an EAB cost calculator for Indiana (http://www.entm.purdue.edu/EAB/) and represent the costs of managing trees with a diameter at breast height (DBH) of 15 cm, 45 cm, and 76 cm. The City of Westland in Michigan had a median removal and replacement cost of $635 per tree (Michigan Department of Natural Resources, 2007), which is comparable to the cost estimates from the EAB cost calculator for Indiana. We assumed treatment to prevent injury from EAB would consist of a trunk injection of a systemic insecticide containing emamectin benzoate, which provides highly effective EAB control for at least two years (Herms et al., 2009; McCullough et al., 2010).

The treatment and removal assumptions are based on a dynamic programming model of homeowner and tree manager behavior in which the decision maker chooses the activity that maximizes discounted net benefits over time (Kovacs et al., 2010). When a county becomes infested, larger trees (>45 cm DBH for homeowners and >61 cm DBH for municipalities) are treated with an insecticide immediately and re-treated at 2-yr intervals 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.[5] We calculate the annual discounted costs of treatment or removal and replacement that take place over the 10-yr horizon with a 2% real discount rate (Howarth, 2009; OMB Memo, 2009).

Howarth (2009) observed 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. The OMB Memo (2009) indicates the real interest rate on treasury notes and bonds with 10-yr maturity is 2.2%. A sensitivity analysis of the base case to the discount rate finds the 10-yr discounted costs are 5% higher with a 1% real discount rate and 10% lower with a 4% real discount rate.

2.2. Predicting the effect of fewer satellite populations in 2005–2010

We define a satellite EAB population as an isolated colony in the continental U.S.[6] more than 150 km from the main body of the EAB infestation. A threshold distance of 150 km was used because the majority of recently detected infestations during the 2005–2010 time period were either located in close proximity to an infested county or were beyond 150 km. In addition, cells in our simulations at these distances had a <0.01% probability of becoming infested from the closest infested cell. Because EAB beetles appear to be incapable of flying >20 km from an existing infestation (Taylor et al., 2010), satellite populations do not result from natural range expansion and are presumably established by human transport of EAB-infested ash material. Distribution of EAB outlier infestations in the U.S. mapped by APHIS (e.g., EAB.info, 2010) were used to locate the satellites detected each year from 2005 to 2010.[7]

To estimate the effects of EAB satellite populations detected in 2005–2010, we created a set of counterfactual scenarios, first of no discoveries of satellites prior to 2010, and then of no satellites after January 2005, 2006, 2007, 2008 and 2009, for comparison with the

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[4] This 5-yr average approach for mortality works well for a model, but mortality is likely to be lower in the initial year and greater in the later years.

[5] These 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. For the short term, a homeowner or municipality may do nothing about an infected tree (e.g., because of budget constraints), but a dead tree poses a hazard to people and property and eventually must be removed and replaced.

[6] Canadian satellites are excluded from the scenarios of fewer satellites since the data are not available for the economic model to calculate Canadian costs. However, Canadian satellites that eventually spread into the U.S. do affect the U.S. costs in all the scenarios.

[7] http://www.emeraldashborer.info/map.cfm

base case. This could be equivalently thought of as scenarios only including satellites discovered as of 2005, 2006, 2007, 2008, and 2009. The scenario of no satellite populations begins by excluding all of the satellites from the January 2005 footprint of EAB infestation. Next, EAB spread is simulated from 2005 to 2010 using only the main body of the EAB infestation. Finally, EAB spread is simulated from 2010 to 2020 for the calculation of economic costs. The scenarios of no satellites after January 2005, 2006, 2007, 2008, and 2009 each begin with the 2005 footprint of the EAB infestation. Satellites are then added during the course of the simulation in the year in which the satellites were detected, but no further satellites are added after the year associated with the counterfactual scenario. The infestation spreads from the main body and the satellites found in the respective years until 2020. Economic costs are tabulated for the period from 2010 to 2020. Each scenario assumes that every grid cell in a county where there has been an EAB discovery, either a satellite or part of the main body, is infested and contributes to the spread of EAB.

It is important to note here that the method used to calculate function (1) relies on the EAB footprint observed in 2009, and therefore is influenced by the presence of satellites prior to this point. For this reason, we re-estimated function (1) to account for the presence of satellites discovered before 2009. Using the re-estimated function, we predicted the EAB footprint for January 2010 with and without satellites. Results are qualitatively identical to the scenarios described below (see Appendix).

Simulations using the re-estimated function (1) predicted a lower spread between 2005 and 2010 than what was mapped by APHIS. In particular, the spread east was greatly diminished. In contrast, when we run the spread between 2005 and 2010 using function (1), the spread east was adequately predicted, but the spread south was slightly greater than observed in the APHIS maps. The cause of this inconsistency is that the spread model presented here considers the spread of EAB to be anisotropic, while the detected EAB populations are not symmetrical. The cause of the asymmetry in spread may be due to either a true spread bias toward the east, differences in detection efforts, asymmetrical distribution of habitat characters affecting establishment (e.g., the distribution of host trees) or a combination of these factors. In the future, as more information is gathered, the use of more complex EAB spread models (e.g., Prasad et al., 2010) may enable us to move from a symmetrical spread pattern to one that more closely resembles the actual pattern of spread.

2.3. Predicting the effect of tactics to slow the spread from satellite populations

We created four scenarios of hypothetical programs to prevent spread applied to EAB satellite populations detected in 2009. Each scenario represents a different level of effectiveness of the program to prevent spread. The spread model (function 1) relates the probability of spread from an infested cell to an insect-free cell based on the distance between the cell midpoints. To represent different levels of effectiveness of preventing spread, the probability of spread from a cell in which the management program has been applied is uniformly reduced for any distance between cells by 25%, 50%, 75%, and 100%.[8] To achieve greater reduction in the probability of spread, the expense of the program to prevent spread would likely increase, but the rate of this increase is unknown. The reduced probability is applied to a 5 × 5 square of cells centered on each satellite population detected in 2009. In each scenario, we simulated the expansion of the EAB infestation present in 2010 using a reduced spread probability in the satellites detected in 2009. The economic costs of the EAB infestation are tabulated for the period from 2010 to 2020.

2.4. Simulation design

We report the mean discounted cost, computed from 200 simulations of the EAB spread model, for the base case and each scenario. Also, for the base case, the standard deviation of the total mean discounted cost is reported. We report the mean delayed cost (and the standard deviation of the mean delayed cost) associated with each scenario. The mean delayed cost of a scenario is the mean of the differences of discounted cost between 200 corresponding simulations of the base case and the scenario. To lower the standard deviation of the mean delayed cost, we employ the method of common random numbers (e.g., Law and Kelton, 2000). The method maintains the consistency of random numbers across the base case and the scenarios. Consistency of random numbers was accomplished by using a common seed to test whether a cell became infested in a given year across the base case and scenarios. In this manner, the random numbers used for the 200 simulations within the base case and each scenario remained independent, but were identical between scenarios.

2.5. Sensitivity analyses

The influence of uncertainty in the estimates of ash density and costs of tree removal, replacement, and treatment on the delayed costs of the scenarios is examined since these parameters heavily influence the magnitude of the delayed costs. To quantify uncertainty about the density of ash in communities, we computed the standard deviation among the urban forest inventories for the four cities in the mapping zone containing Chicago, IL.[9] This standard deviation is meant to represent the variability in ash density among communities with similar climate, topography, and history. The Chicago mapping zone is chosen because the urban forest inventories in this zone represent a handful of suburban, urban, and rural communities near Chicago. The standard deviation of ash densities for the mapping zone is 66% of the average ash density. The delayed cost is recalculated when the ash density in every mapping zone is increased or decreased by this standard deviation.[10]

There is also uncertainty about the costs of tree removal, replacement, and treatment. A 2009 survey of seven arborists (Alexander et al., 2009) collected per tree costs of removal, replacement, and treatment of oaks in response to the forest pathogen that causes sudden oak death.[11] Based on the survey of seven arborists, the standard deviation of the cost of removal and replacement is 50% of the average removal and replacement cost, and the standard deviation of the cost of treatment is 30% of the average treatment cost. This variation is likely attributable to how quickly the affected tree requires removal or treatment, the region of the country, and the accessibility of the tree to the arborists. The delayed cost is recalculated when the cost per tree for removal and replacement is increased and decreased by 50% and the cost per tree for treatment is increased and decreased by 30%.

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[8] The rate of ash mortality within infected counties is unchanged. A reduction in mortality may occur for the limited cells where management tactics are applied.

[9] The cities are Palatine, Park Ridge, Urbana, and Chicago, IL.

[10] This approach for assessing the effect of parameter uncertainty on economic damages is similar to a recent paper by Koch et al. (2009) for assessing the effect of parameter uncertainty on risk mapping.

[11] The level of the costs in California is not representative of costs in the Midwest because of differences in regional price levels. However, the variability of the costs may be similar across regions assuming the market structure of the tree care industries is similar.

Table 2
Estimated discounted cost of landscape ash treatment, removal, and replacement (the total for 2010–2020) for the scenarios of no satellites and no satellites found after January 2005, 2006, 2007, 2008, and 2009.

State	Cost of treatment, removal, and replacement ($ millions)						
	No Satellites	No Satellites					Base case
		2005–2010	2006–2010	2007–2010	2008–2010	2009–2010	
Alabama	0	0	0	0	0	9	9
Arkansas	0	0	0	0	0	493	471
Connecticut	0	0	0	21	21	34	148
Delaware	0	0	0	25	25	25	23
Georgia	0	0	0	0	3	0	0
Illinois	2480	2510	2810	1960	1980	2120	2110
Indiana	432	299	267	263	263	263	329
Iowa	51	62	80	273	269	280	344
Kentucky	78	74	125	126	137	138	132
Maine	122	147	78	108	138	153	119
Maryland	8	8	16	492	492	491	538
Massachusetts	10	10	4	4	10	19	32
Michigan	215	223	225	225	225	228	230
Minnesota	0	3	10	15	26	229	974
Mississippi	0	0	0	0	0	121	87
Missouri	1	181	492	704	759	1750	1670
New Hampshire	85	87	85	85	85	102	85
New Jersey	0	0	0	517	505	520	658
New York	117	113	117	317	315	355	659
North Carolina	0	0	1	17	180	180	100
North Dakota	0	0	0	0	0	0	5
Ohio	652	653	476	438	316	319	366
Pennsylvania	556	558	582	1020	752	751	766
South Carolina	0	0	0	0	4	4	0
South Dakota	0	0	0	0	0	0	13
Tennessee	1	0	144	171	325	1080	1160
Vermont	50	50	49	50	49	53	50
Virginia and District of Columbia	10	9	65	613	719	732	655
West Virginia	131	127	202	218	215	214	238
Wisconsin	267	448	474	547	556	598	492
Total	5263	5562	6301	8209	8368	11,261	12,462

Note: The results are the mean of 200 iterations of the spread model.

3. Results

3.1. EAB costs in base case

The discounted costs of ash treatment or removal and replacement by year total $12.5 billion from 2010 to 2020 (Table 1) and the simulated progression of the EAB infestation is shown in Fig. 1. Costs in Midwest states such as Illinois and Minnesota are largest initially, but by the end, costs in the southern (Tennessee and Missouri) and northeastern states (New Jersey and New York) are the most prominent. Many southern and northeastern states do not sustain costs until 2018[12]; promptly afterward those states have the most costs. Costs in the Midwest states subside over time, but remain substantial to the end of the study period because large trees continue to be treated (at 2-yr intervals) after the smaller trees are removed.

Economic costs sustained within the total study area rise each year, except in 2014 when the infestation has not yet reached southern and northeastern cities and most of the costs have already been sustained in the Midwestern cities. The states projected to experience the highest costs are Illinois, Missouri, Tennessee, and Minnesota. Illinois and Minnesota sustain high costs because the infestation reaches these states early in the 10-yr period and the states have a substantial amount of developed land with canopy. Missouri and Tennessee also sustain high costs because of the area of developed land with canopy and because ash density is high (Kovacs et al., 2010).

3.2. EAB costs for scenarios of fewer satellites found from 2005 to 2010

The economic costs sustained when fewer or no satellites are discovered prior to 2010 are shown by state in Table 2. In states neighboring the core infestation, simulations with fewer satellites appear to have an increased economic cost for the state compared to the base case scenario. This apparent inconsistency is due primarily to a smaller footprint in 2010 for simulations with fewer or no satellites. The economic costs the states would have experienced prior to the time frame of 2010–2020 under the base case scenario are experienced during the 2010–2020 time period in simulations with fewer satellites. The progression of the infestation depends on how many fewer satellites are discovered each year, but where those satellites are located has an even greater effect (Fig. 3). When the 10-yr costs of scenarios with no satellites were compared to costs associated with no satellites from 2005 to 2010, results show the satellites identified before 2005 contributed only about $300 million to the 10-yr total, and costs are similar across the states. The satellites before 2005 include only a few counties to the north of the EAB core infestation and just south of the Upper Peninsula of Michigan. Because the satellites bring the infestation closer to Wisconsin, the 10-yr costs increase for Wisconsin.

The satellites identified in 2005 have a stronger effect, increasing costs for the 10-yr total by approximately $740 million. The southern states of Kentucky, Missouri, Tennessee, and West Virginia are most affected by the 2005 satellites, which are further from the core and appear for the first time in the South. A year later, the 2006 satellites have a stronger effect on the 10-yr total, increasing costs by more than $1.90 billion. The 2006 satellites

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[12] The July 2010 discoveries of EAB in eastern New York and Tennessee mean that damages will likely occur sooner in these regions.

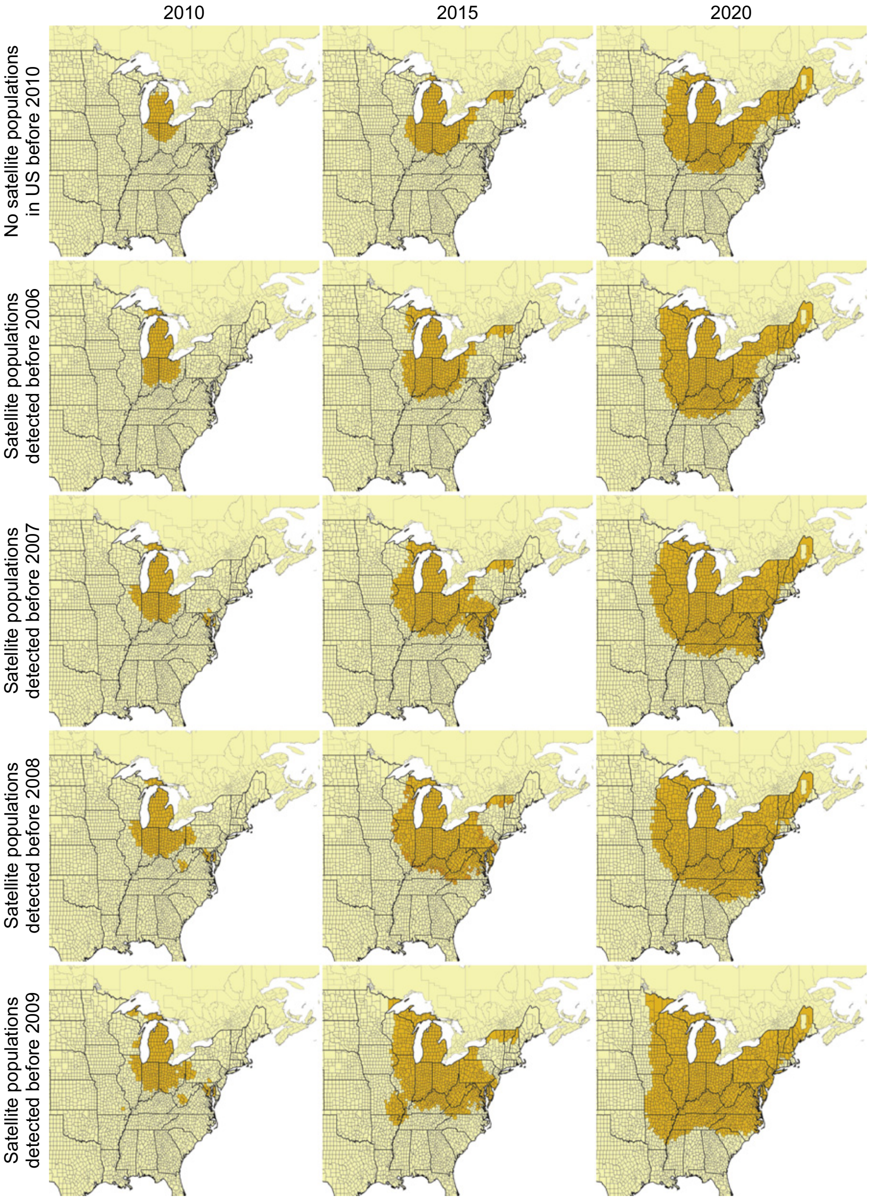

Fig. 3. A simulation of emerald ash borer distribution in counties from March 2010 to March 2020 for the scenarios of no satellites and no satellites found after January 2005, 2006, 2007 and 2008. The maps represent the rounded average of 200 stochastic simulations.

influence costs in the Midwestern states of Wisconsin and Iowa, the northeastern states of Pennsylvania, New York, New Jersey, Connecticut, Delaware, and the southern states of Virginia, Maryland, and Missouri. Most of the additional costs are attributable to the satellite found in Maryland, near Washington D.C., which is more than 480 km from the core. Satellites distant from the core cause more economic costs than satellites near the core because the distant satellites cause costs that would not occur in the study period through the advance of the infestation along the core. Also, the satellite in Maryland puts large cities on the East Coast at high risk of EAB invasion, although it takes ten years for the satellite to grow large enough to spread to the east coast cities.

In 2007, costs associated with the new EAB satellite populations increase the 10-yr total by only $160 million. Both the Tennessee and North Carolina costs are greater because of proximity to a satellite population found in West Virginia, more than 300 km south of the core infested area. However, because the satellite grows slowly, the core's momentum southward does not increase appreciably.

The 2008 satellites generate the largest increase of additional costs to the 10-yr total, amounting to $2.89 billion. This occurs largely in Missouri, Tennessee, and Arkansas in the South, but also in Minnesota in the Midwest. The satellite in Missouri is more than 450 km from the core of the invasion and exposes large cities in the south to the EAB invasion. The satellites in Wisconsin and the Upper Peninsula of Michigan contribute to the additional costs sustained by Minnesota.

Finally, the 2009 satellites increase the costs sustained over the 10-yr period by more than $1.20 billion. Most of this results from satellites in Minnesota that are more than 300 km from previously known infestations. A big difference from the earlier Missouri and Maryland satellites is that the Minnesota satellites did not expose many other large cities to the EAB invasion. Additional costs in New York, New Jersey, and Connecticut occur because of the Pennsylvania satellites identified a few counties east of the core and closer to the large cities on the Northeast coast. The marginally greater proximity to the high cost area adds significant additional costs to the 10-yr total.

Table 3
Estimated discounted cost of landscape ash treatment, removal, and replacement (the total for 2010–2020) for the scenarios of hypothetical programs to prevent spread applied to satellites found in 2009 with 25, 50, 75 and 100% effectiveness of preventing EAB spread to adjacent uninfected cells.

State	Cost of treatment, removal, and replacement ($ millions)				
	Base case	25% effective	50% effective	75% effective	100% effective
Alabama	9	30	6	9	9
Arkansas	471	382	434	345	437
Connecticut	148	148	144	149	128
Delaware	23	23	23	23	23
Georgia	0	0	0	0	0
Illinois	2110	2120	2120	2120	2120
Indiana	329	328	329	328	328
Iowa	344	339	321	307	293
Kentucky	132	132	132	131	131
Maine	119	109	78	100	115
Maryland	538	536	537	536	535
Massachusetts	32	38	25	41	23
Michigan	230	230	230	230	230
Minnesota	974	944	886	741	264
Mississippi	87	68	92	67	72
Missouri	1670	1690	1690	1680	1690
New Hampshire	85	86	87	87	85
New Jersey	658	664	670	669	606
New York	659	757	772	780	693
North Carolina	100	104	98	99	98
North Dakota	5	0	0	0	0
Ohio	366	365	365	365	365
Pennsylvania	766	782	781	751	739
South Carolina	0	1	0	0	0
South Dakota	13	13	1	0	0
Tennessee	1160	1030	947	962	973
Vermont	50	50	50	51	50
Virginia and District of Columbia	655	663	665	660	661
West Virginia	238	235	235	233	232
Wisconsin	492	490	488	472	448
Total	12,462	12,356	12,206	11,935	11,347

Note: The results are the mean of 200 iterations of the spread model.

General conclusions about the additional costs associated with the satellites identified from 2005 to 2010 may help program managers identify priorities for resource allocation in urban areas. Satellites distant from the core and near large cities put large numbers of urban ash trees at risk of EAB infestation and are most costly. The least costly satellites in our simulations are both near the core and distant from large cities. The satellites that add an intermediate level of cost are associated with two categories: i) those distant from the core and from large cities; ii) satellites near the core and near large cities.

3.3. Economic costs from EAB associated with scenarios of the effectiveness of programs to prevent spread applied to 2009 satellites

The economic costs for the scenarios of programs to prevent spread applied to 2009 satellites with 25, 50, 75, and 100% effectiveness are shown by state in Table 3. The progression of the EAB infestation depends on the effectiveness of the efforts to prevent spread (Fig. 4). If programs reduce EAB spread by 25%, the 10-yr total costs are delayed by about $100 million (or 1% less than the base case costs). States with the greatest differences between the base case and the 25% effectiveness occur at the edge of the study area: Alabama, Arkansas, Minnesota, Mississippi, Missouri, New York, and Tennessee. The delayed costs in Minnesota likely reflect the effort to prevent spread while the delayed costs in Tennessee, Arkansas, and Mississippi where no nearby 2009 satellites occur are due to the stochastic differences of the spread model. The unexpected increase in costs with programs to prevent spread in states such as Alabama and New York is due to the stochastic differences of the spread model. Minnesota is the only place in the 2020 maps of Fig. 4 where there is a visually distinguishable difference in the number of counties infested because of the treatment of the Minnesota satellite found in 2009.

Programs to prevent spread that are 50% effective delay the 10-yr total by an additional $150 million for a total delay from the base case of about $250 million (or 2% less than the base case costs). Increasingly effective efforts to prevent spread delay the total costs over the 10-yr period at an increasing rate, although this is not always evident for particular states due to the stochastic nature of the spread model. Delayed costs from the 50% effectiveness scenario are realized in Alabama, Iowa, Maine, Massachusetts, Minnesota, South Dakota, and Tennessee. The highest reduction in costs resulting from the programs occurs in Iowa, Minnesota, and South Dakota.

If efforts to prevent spread are 75% effective, the total economic costs over the 10-yr period drop by an additional $270 million for a total reduction from the base case of about $530 million (or 4% less than the base case costs). Iowa, Minnesota, Pennsylvania, and Wisconsin sustain lower costs likely because of the efforts to prevent spread.

If efforts are 100% effective in slowing EAB spread from satellite populations, the 10-yr total costs are delayed by an additional $590 million, for a total delay from the base case of more than $1 billion (or 9% less than the base case costs). A program to prevent spread that is 100% effective continues to delay the 10-yr total costs at an increasing rate, although not always for particular states. Even if the marginal cost of more effective programs to prevent spread is increasing at an increasing rate, 100% effective programs may still be optimal. Delayed costs from a program to prevent spread that is 100% effective in the simulation are most apparent in Connecticut, Iowa, Massachusetts, Minnesota, New Jersey, New York, Pennsylvania, and Wisconsin. Even with 100% effectiveness, however, the projected economic costs are still $11 billion.

If the programs to prevent spread have limited effectiveness, only the programs applied to satellites distant from the core, like Minnesota, will result in appreciably delayed costs. A program to prevent spread would need to be 75% effective before delayed costs would be observed in Pennsylvania and Wisconsin, where satellites occur close to the main body of the EAB infestation. A program that is 100% effective delays costs in the surrounding states, even when applied to satellites close to the core and distant from cities. Unless the program to prevent spread is highly effective, only the treatment of satellites distant from the core and near large cities will result in substantially delayed costs for landscape ash trees. Also, investments to improve the effectiveness of tactics to prevent spread will likely be cost-effective; increasingly effective programs delay costs at an increasing rate.

3.4. Summary of delayed EAB costs

Total and regional mean values of delayed economic costs (and the standard deviations of the means) associated with both sets of scenarios are presented in Table 4. This summary of the previous sections examines how the delayed costs from fewer satellites or the efforts to prevent spread compare to each other. The delay in economic costs increases as more EAB satellite populations are removed. Especially large increases in delayed costs occur with the removal of the 2008 (Missouri) and 2006 (Maryland) satellites. The delayed costs in the Northeast region are largely unaffected by the removal of the satellites except for the 2006 (Maryland) satellites. Delayed costs in the southern region are significantly affected by the removal of the 2008 (Missouri) and 2006 (Maryland)

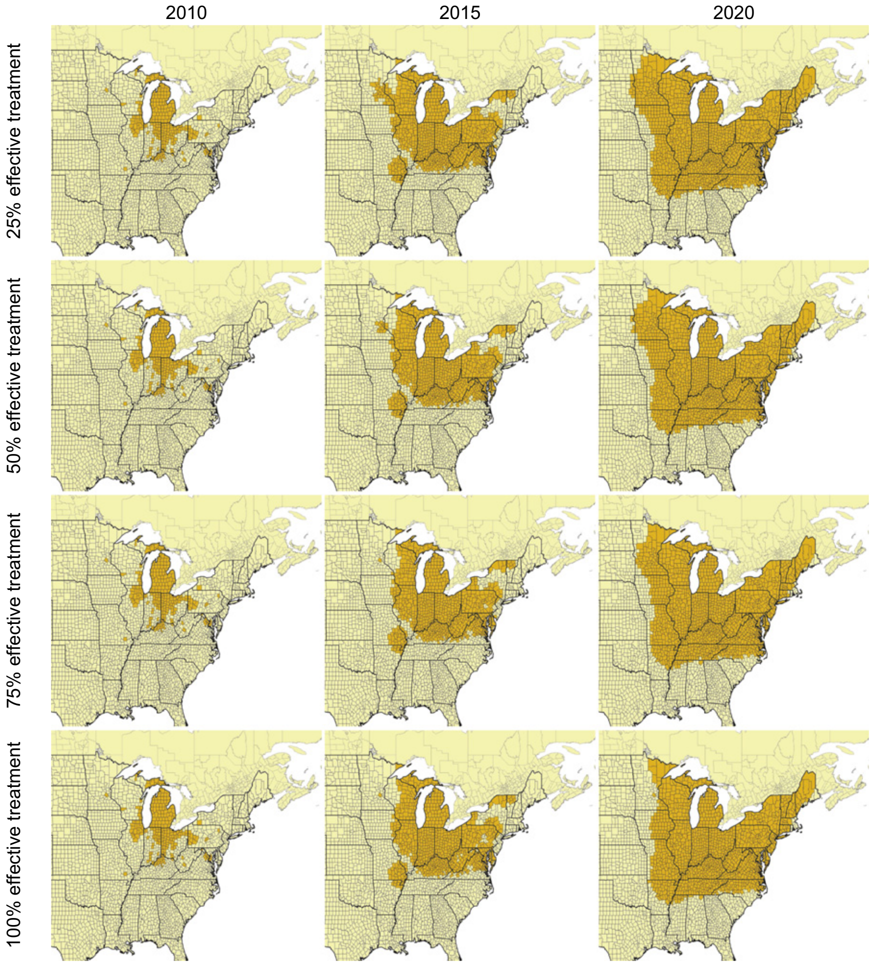

Fig. 4. A simulation of emerald ash borer distribution in counties from March 2010 to March 2020 for the scenarios of hypothetical programs to prevent spread applied to satellites found in 2009 with 25, 50, 75 and 100% effectiveness of preventing EAB spread to adjacent uninfected cells. The maps represent the rounded average of 200 stochastic simulations.

satellites, while delayed costs in the Midwest region are strongly affected by 2009 (Minnesota) and 2008 (Missouri) satellites and less strongly by the 2005 (Indiana and Ohio) satellites.

The delays in costs generated by applying programs to prevent spread are similar for the 25% and 50% effectiveness levels and not significantly distinguishable from zero. The 75% effectiveness significantly delays costs, and the 100% effectiveness nearly doubles the delay in costs from the previous 75% level. Programs to prevent spread have no significant influence on the delay of costs in the South and the Northeast regions, and all of the delay in costs comes from the Midwest region. This is expected since only the Minnesota satellite is capable of incurring serious costs.

3.5. *Sensitivity analyses for the delayed EAB costs*

Delays in economic costs are sensitive to uncertainty about the density of ash and the costs of tree care (Table 5). The parameters for ash density and cost of tree care are critical for assessing the economic costs and thus for influencing the decisions about control efforts for pest program managers. Results of the sensitivity analysis follow the same trend as the previous results, except the trend is softened for the lower bound and sharpened for the upper bound.

Examining the upper bound of the sensitivity analysis for the removal of the satellites detected in 2005 shows the delayed costs are greater in absolute magnitude than in the base case. Depending

Table 4

Estimated delayed costs calculated as the difference between the estimated cost of landscape ash treatment, removal, and replacement (shown for three regions and the total for 2010–2020) for 200 simulations of the fewer satellites (Table 2) and programs to prevent spread effectiveness (Table 3) from the base case (Table 1).

	Delayed costs ($ millions)			
	Midwest	South	Northeast	Total
Fewer satellites				
No satellites	2895 (42)	3275 (37)	1206 (32)	7387 (67)
No satellites 2005–2010	2621 (38)	3287 (37)	1180 (30)	7099 (65)
No satellites 2006–2010	2001 (44)	2886 (41)	1160 (31)	6058 (69)
No satellites 2007–2010	2251 (39)	1805 (39)	26 (36)	4092 (66)
No satellites 2008–2010	2331 (38)	1505 (40)	255 (36)	4099 (75)
No satellites 2009–2010	1004 (24)	−54 (47)	71 (34)	1025 (63)
Effectiveness of programs to prevent spread				
100%	768 (26)	−70 (52)	7 (38)	705 (69)
75%	386 (26)	5 (42)	−11 (30)	378 (58)
50%	157 (24)	−6 (44)	23 (32)	171 (59)
25%	74 (21)	49 (44)	−2 (31)	123 (58)

Note: Standard deviation of the average of 200 simulations of reduced costs shown in parentheses. Midwest includes the states of Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, North Dakota, Ohio, South Dakota and Wisconsin. South includes the states of Alabama, Arkansas, Delaware, District of Columbia, Georgia, Kentucky, Maryland, Mississippi, North Carolina, Tennessee, Virginia and West Virginia. Northeast includes the states of Connecticut, Maine, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania and Vermont.

Table 5

Sensitivity analyses of the estimated delayed costs calculated as the difference between the estimated cost of landscape ash treatment, removal and replacement for 200 simulations of the fewer satellites (Table 2) and programs to prevent spread effectiveness (Table 3) from the base case (Table 1).

	Delayed costs ($ millions)				
	Baseline	Ash density		Per tree cost	
		Low	High	Low	High
Fewer satellites					
No satellites	7387 (67)	2955 (27)	11,821 (108)	3880 (35)	11,082 (101)
No satellites 2005–2010	7099 (65)	2840 (26)	11,360 (104)	3725 (33)	10,650 (97)
No satellites 2006–2010	6058 (69)	2423 (28)	9694 (112)	3183 (36)	9091 (104)
No satellites 2007–2010	4092 (66)	1637 (26)	6551 (107)	2139 (34)	6139 (101)
No satellites 2008–2010	4099 (75)	1639 (30)	6557 (121)	2128 (39)	6146 (113)
No satellites 2009–2010	1025 (63)	407 (25)	1631 (103)	535 (33)	1530 (96)
Effectiveness of programs to prevent spread					
100%	705 (69)	281 (27)	1121 (111)	368 (36)	1056 (104)
75%	378 (58)	151 (23)	599 (93)	198 (30)	566 (87)
50%	171 (59)	69 (23)	274 (94)	91 (30)	264 (88)
25%	123 (58)	49 (23)	195 (93)	64 (30)	189 (87)

Note: Standard deviation of the average of 200 simulations of reduced costs shown in parentheses.

on the program managers' confidence about estimates of ash density or per tree cost of treatment, removal or replacement, prevention of satellites, such as those observed in 2005, may become economically beneficial. If programs to prevent spread are 25 and 50% effective, upper bound estimates indicate that delayed costs are significantly different from zero, and the programs may then be worth implementing if the control costs do not exceed the delayed economic costs. On the other hand, lower bound estimates indicate that delayed costs are not different from zero; efforts to prevent spread may not appreciatively delay economic costs.

4. Conclusions

We estimated the economic costs caused by EAB, measured by the discounted cost of landscape ash removal, replacement, and treatment for the 10-yr period from 2010–2020, for scenarios of fewer EAB satellite populations in 2005–2010 and slower expansion of satellite populations detected in 2009. The base case cost with the full complement of satellites detected in 2005–2010 and no program to prevent spread is $12.5 billion. This does not include the satellites discovered in July 2010 in eastern New York and Tennessee. These new discoveries put several large cities at risk much sooner than currently modeled and would significantly increase the 10-yr discounted costs. Fewer EAB satellites in 2005–2010 delay economic costs by $1.0 to 7.4 billion. Slower expansion of 2009 satellite populations delays economic costs by $0.1 to 0.7 billion. The prevention of satellites delays economic costs much more than programs to prevent the spread of established satellite populations, but more research is needed on the effectiveness and cost of the regulatory activities before decisions about investment in the programs can be made.

Our estimates of delayed economic costs suggest that spending on programs that prevent the establishment of new satellite EAB populations or slow the expansion of existing satellites could be cost-effective. Currently, we lack adequate information to make firm conclusions about the cost-effectiveness of regulatory, management, and outreach activities. Also, more information is needed about the formation of satellite EAB populations, which may be influenced by biological, atmospheric and climatological (e.g., weather patterns and temperature), economic (e.g., the cyclical state of the economy), and social factors, as well as the public's awareness of EAB, to better predict economic costs. Nevertheless, the potential for significant delays in economic costs identified here should prove useful to decision makers interested in the overall scale and scope of the problem.

Our results show that the spatial distribution of EAB infestations has implications for the management and resource allocation. In our simulations, satellite populations that are both distant from the core EAB infestation and close to large urban areas increase economic costs more than satellites in other places. Consequently, activities that prevent the establishment or slow the expansion of satellites in places such as Wayne County, Missouri or Maryland could yield substantial savings if programs to prevent spread are highly effective or moderate savings if the effectiveness of the programs is relatively low. For satellites close to the core infestation or distant from large urban areas, programs to prevent spread only yield savings if they are highly effective. Although more effective programs to prevent spread yield greater savings, these may not be the best to implement if the cost of the programs is much higher. Given the 10-yr period in our analysis, programs to slow the expansion of satellite populations mostly benefit the state where the satellite occurs and the surrounding states.

Our analysis focused on one component of the economic damage caused by EAB: the cost of treatment, removal, and replacement of landscape ash trees in urban areas. As such, our analysis provides a lower bound estimate of the total economic damage. In addition to these costs, forest product and ecosystem service losses occur from ash trees that are killed by EAB in a wide range of forest, riparian and urban settings. Ecosystem service and forest product losses will likely be greatest far away from urban areas and in the invaded areas where EAB density is highest. An estimate of the value of the loss of these services requires accurate information about ecological impacts of widespread ash mortality. Another consideration is how EAB programs to prevent spread in one state influence neighboring states. We do not explore the incentives for collaboration or free riding among the multiple states affected by EAB. Even if the reduction in economic costs from programs to slow the spread of EAB in the projected time period exceeds the control costs, other projects available to the state may be economically preferred because of higher benefit-cost ratios.

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Appendix. Supplementary material.

The method used to calculate the spread for simulations in the main text relies on the EAB footprint observed in January 2010, and is therefore influenced by the presence of satellites prior to this time. To control for this effect the spread function was recalculated to account for the presence of satellites discovered before January 2010. This was accomplished by contrasting predictions from simulations run from 2005 to 2010 starting with the 2005 footprint and incorporating known outliers the year they were discovered to the observed infestations present in 2010. Fit was assessed as described for function (1) in the main text. The recalculated spread function is:

$$p = 1.04\, e^{-0.073d} \tag{A1}$$

Results from identical simulations to the ones described using adjusted 2010 footprints (Table A-I) indicated that the overall costs for the simulations are lower. However, the differences between the scenarios are qualitatively identical to those described in the main text.

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Table A-I

Alternative estimate of cost of landscape ash treatment, removal and replacement (the total for 2010–2020) for the simulation of slower eastern spread of EAB for the scenarios of no satellites and no satellites found after January 2005, 2006, 2007, 2008 and 2009.

State	Cost of treatment, removal, and replacement ($ millions)						
	No Satellites	No Satellites					Base case
		2005–2010	2006–2010	2007–2010	2008–2010	2009–2010	
Alabama	0	0	0	0	0	0	0
Arkansas	0	0	0	0	0	206	205
Connecticut	0	0	0	0	0	0	0
Delaware	0	0	0	0	0	22	22
Georgia	0	0	0	0	0	0	0
Illinois	0	0	0	985	984	1840	1880
Indiana	22	37	72	236	236	265	265
Iowa	0	0	0	0	0	111	242
Kentucky	0	0	0	2	2	104	103
Maine	0	0	0	0	0	3	4
Maryland	0	0	0	243	243	509	509
Massachusetts	0	0	0	0	0	0	0
Michigan	161	186	186	186	186	228	228
Minnesota	0	0	0	0	0	25	931
Mississippi	0	0	0	0	0	18	21
Missouri	0	0	0	0	0	979	1030
New Hampshire	0	0	0	0	0	26	19
New Jersey	0	0	0	0	0	119	136
New York	0	3	0	0	7	70	82
North Carolina	0	0	0	0	0	14	14
North Dakota	0	0	0	0	0	0	0
Ohio	5	16	45	92	121	628	627
Pennsylvania	0	0	0	0	194	555	621
South Carolina	0	0	0	0	0	0	0
South Dakota	0	0	0	0	0	0	0
Tennessee	0	0	0	0	0	243	242
Vermont	0	0	0	0	0	45	43
Virginia and District of Columbia	0	0	0	151	151	522	530
West Virginia	0	0	0	0	4	214	214
Wisconsin	0	0	0	0	0	530	595
Total	188	243	303	1894	2129	7275	8563

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