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Evaluating Restoration Capacity and Costs of Managing the Emerald Ash Borer with a Web-based Cost Calculator in Urban Forests

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Abstract. Described here is the development of a web-based cost calculator for projecting management costs and restoration, during a planned response to an emerald ash borer invasion in the City of Indianapolis, IN, U.S. Forest sizes, measured as the sum of tree diameters, and costs of managing urban ash trees were projected under various management scenarios over a 25-year period. The study authors illustrate how a city can use local information to compare management plans. Although the simple strategy of treating all ash trees provided the lowest annual cost and produced the largest forest, this option was ultimately the most expensive. Simply removing ash trees and replacing them with resistant trees restored the forest to its initial size after 25 years. However, after taking five years to complete tree removal and replacement, the initial ash forest was reduced to a mere 27% of its original size. When this management plan was modified, by protecting trees in the median size class with insecticides, the restoration forest was below 50% of the initial size for two years but at a discounted cost that was only 6% greater than replacing all trees. The authors of the study describe how the cost calculator can be used to address the unique local attributes of urban forests.

Key Words. Emerald Ash Borer; Forest Restoration; Management Costs.

Emerald ash borer (EAB), *Agrilus planipennis*, is a highly aggressive metallic wood boring beetle that attacks and kills otherwise healthy ash trees in the genus *Fraxinus* (Cappaert et al. 2005). Adult females lay eggs in cracks and crevices of tree bark that hatch into larvae which bore beneath the bark to feed on and destroy phloem and other adjacent vascular tissues. Ash trees native to North America are particularly susceptible to beetle attack (Anulewicz et al. 2008). Since its detection in 2002 near Detroit, MI, U.S., it has now been reported in 15 U.S. states and two Canadian provinces (Cappaert et al. 2005). EAB spreads by both natural and artificial means (Poland and McCullough 2006). In the presence of abundant hosts, natural spread from a colonization site is less than 400 m/yr (Mercader et al. 2009). In southeast Michigan, movement of infested ash material including nursery stock, firewood, and ash debris dramatically increased the rate of spread to 20 km/yr (Siegert et al. 2007). Prasad et al. (2010) found that outlier infestations are often located in the vicinity of highways, further emphasizing human-aided dispersal in long-distance spread of EAB.

As a significant component of the urban forest canopy, ash trees provide substantial benefits to cities (McPherson et al. 2006). Approximately 38 million ash trees are estimated to be in urban areas located in 25 states in the northeastern United States surrounding the initial Detroit detection (Kovacs et al. 2010). Spread of emerald ash borer is expected to affect nearly 17 million urban trees in this area from 2009–2019. The discounted cost in today's dollars of removing, replacing, and protecting these trees with insecticides during this 10-year period is predicted to be USD $10.7 billion (Kovacs et al. 2010).

Individual ash trees can be protected with repeated applications of systemic insecticides that diffuse toxicant from their ring porous xylem to leaves where the insecticide kills adults (Mota-Sanchez et al. 2009). The ability of an insecticide to diffuse through the tree in sufficient concentration to kill beetles is influenced by its solubility, toxicity, dose, application method, the infestation status, and the size of the tree (Herms et al. 2009; Smitley et al. 2010). Trees with most of their functional xylem intact have the best chance of taking up and distributing the insecticide. Trees whose canopies have been thinned by more than 50% from a combination of EAB infestation and other stressors are not likely to be saved by insecticide application. Longevity of protection provided by a single insecticide application ranges from one to three years and depends on the compound, dose, and the solubility of the insecticide formulation.

Benefits and costs of removing and treating trees with insecticide are driven by tree size (McPherson et al. 2006, McPherson 2007; Herms et al. 2009). This study includes a report on the development of a web-based tool called the Emerald Ash Borer Cost Calculator (Sadof 2009a), which uses a size class based tree inventory to project forest size, costs of insecticide treatment, and removal and replacement of ash trees over a 25-year period from local bids for any combination of these strategies. Using the City of Indianapolis, IN, U.S. as a case study, the study authors demonstrate how output from the calculator can be used with local information to discuss tradeoffs between costs and reforestation during the development of a community EAB response plan.

MATERIALS AND METHODS

Development of the EAB Cost Calculator

To estimate costs of removal and treatment for an urban forest, the EAB Cost Calculator uses a range of input variables to define initial forest composition, fee schedules for treating, removing, and replacing ash trees, and a time schedule for applying insecticides, tree removal, and replacement. Input data used for the current case study of the City of Indianapolis is presented in Table 1. The size of the ash forest at risk is based on a street tree inventory (Peper et al. 2008), and indicated by the numbers of trees present within a user defined set of size classes expressed as diameters of trunk at breast height (DBH). Treatment costs are expressed as dollars per centimeter. Treatment fees are structured to increase with tree size to account for research findings that indicate higher doses of insecticides per DBH are required to control EAB in larger trees (Herms et al. 2009; Smitley et al. 2010). This gives an average cost, not adjusted for inflation, of $2.42/cm DBH of treating all Indianapolis trees in the first year.

Cost of tree removal is also based on DBH and increases with tree size to account for the increased labor, equipment, and difficulties encountered in removing larger trees. Actual rates used in the Indianapolis case study (Table 1) were estimates provided by the City Forester of Indianapolis (LP). The price for removing trees includes the cost of removing a tree and grinding the stump. Replacement costs ($300) include the cost of tree removal plus the cost of obtaining, planting, staking, and mulching a tree. Annual maintenance costs for new or existing ash trees are not included in the simulation model because the goal of the study was to focus on additional costs incurred by the arrival of EAB. Costs for removing and replacing trees are spread over five years under the assumption that target numbers of trees designated for this activity will be spread over five years.

Tree Growth Model

In order to predict the costs of treatment, removal, and the size of the managed forest 25 years into the future a growth model accounting for tree growth over time needed to be developed. The model was developed from data collected on DBH and time elapsed after planting white and green ash in Indianapolis (Peper et al. 2008). For ease of programming, the midpoint of each ash size category was regressed as a linear function of the average time after planting for a tree to reach this size class, rather than using a second order polynomial which gave a slightly better fit (R^2 = 0.999). The slope the line is biased in that it [$y = 1.16x + 3.73$; R^2 = 0.994; where y = tree size (cm) DBH, and x = time in years] overestimates the growth of young and old trees but underestimates the growth of middle aged trees. For Indianapolis, this would underestimate the growth of a median sized tree (age = 15 yrs; DBH = 19.1 cm) by 5.1% (2.38 cm) over the 25-year simulation. Clearly, many other factors such as transplant shock, tree condition, and site conditions, are likely to cause individual tree growth to deviate from the actual growth rate predicted by this model. However, because forest size was estimated from the numbers of trees in size categories, the study authors lacked the necessary information to make this model more realistic. Thus, this simple linear model as is used as the best estimate of tree growth over time.

Using Tree Inventory Data to Project Forest Size

To approximate the growth of ash trees present in an actual urban forest, the calculator estimates the starting size of each tree from the initial tally of trees grouped by size class. Potential starting sizes are determined by dividing the total number of trees in a size class by the number of trees in the category. Each tree is assigned to the midpoint of each of those size ranges.

For example, if 100 ash trees in an inventory have a DBH between 15 and 30 cm, trees are assigned to one of 100 size classes, 0.152 cm apart, with starting values of anywhere from 15.32 to 30.40 cm. For computational efficiency, this algorithm was used for up to 500 trees. When more than 500 trees were in a category, the additional trees were assigned to one of the existing starting size categories until there are no trees remaining. Every surviving ash tree grows from its starting size, accumulating 1.16 cm per year. The size of remaining ash forest is determined as the sum of the DBH for all living trees in a given year. The study authors specified each replacement tree to have a 5 cm caliper at planting. To simplify the model it was assumed that trees designated as ash replacements will grow at the same annual rate as ash trees.

Calculating Discount Rates

To account for the time value of money, the calculator allows the user to define a discount rate to discount all current expenses into the future by the following formula Vn = Vo (1 + i)n,

Table 1. Inventory of Indianapolis ash trees under care by the City of Indianapolis in 2007. Fee schedule used to estimate costs of a single application of insecticide for emerald ash borer, and removing an ash tree and grinding the stump.

Tree size DBH (cm)	Ash trees (count)	Insecticide application cost ($) / cm DBH	Tree removal and stump grinding cost ($)/cm DBH
0–7	1310	1.57	3.62
7–15	1783	1.57	3.62
15–30	3275	1.57	3.62[z]
30–45	2020	2.36	5.22
45–61	1140	2.36	5.22
61–76	626	3.15	7.28
76–91	340	3.15	7.28
91–107	152	3.94	7.28[z]
>107	122	3.94	9.84
Ash Trees (% of total)	10,768 (9.2)		
Initial Total DBH	3,401 m		
Average Cost /cm DBH for treating all trees in first year	$2.42		

[z] Rates per DBH for tree removal and stump grinding used in the EAB calculator simulation between 25 and 30 cm were $13.25. Similarly, rates for trees with DBH between 102 cm and 107 cm were $25.00.

where Vn = the value at the end of the investment period, Vo = value at the beginning of the investment, i = interest rate, and n = number of periods (years) (Rose et al. 1988).

Evaluating Cost and Reforestation Capacity

Projections of costs and tree size of 11 management strategies (Appendix), were compared under an arbitrary assumption that the discount rate would be 3%. Effects of the discount rate on strategy costs are explored in a sensitivity analysis that will be described later. Trees were treated every three years in anticipation that insecticide applications are likely to be effective for three years (Herms et al. 2009). The first three management scenarios—remove all ash trees, replace all ash trees, treat all ash trees—are the simplest cases. The next four management strategies are based on recent research that indicates ash trees with a DBH of up to 63.5 cm can be protected with insecticides. Under the assumption of the normal growth, trees with a DBH > 30 cm in 25 years are likely to grow beyond the point where protection has been demonstrated (Herms et al. 2009; Sadof 2009b). The first two of these strategies protect all trees smaller than this critical size and remove or replace the larger ash trees. The next two strategies only protect trees with an initial DBH between 15 and 30 cm while removing or replacing the rest. In these strategies, recently planted trees with a DBH < 15 cm are removed in attempt to take advantage of their ease of removal and relatively low investment in maintenance. This size class also happens to be the median size of ash trees in Indianapolis.

The last four strategies have been contrived under the optimistic scenario that technology will be developed to compensate for trees with a DBH > 61 cm. Examined here is the cost of protecting the historical investment in larger trees and replacing the smaller trees. The first two strategies compare using a minimum size of 30 cm to select trees that will be treated with insecticides with the remainder being removed or replaced. The last two strategies were selected from a recent study of urban ash trees in North America that suggest protecting trees with a minimum DBH of 61 cm would optimize the value of the standing forest and minimize control and removal costs for city managers (Kovacs et al. 2010).

Reforestation capacity of each management strategy was evaluated by calculating the size of the resulting forest relative to the initial size of the ash forest. The projected forest size in any year is expressed as the sum of the DBH of all trees. The initial size of ash forest was estimated from inventory data by multiplying the midpoint value of each size range by the number of trees in each size class, and calculating the sum (Table 1). Reforestation capacity at each time step was expressed as a percentage of the initial forest size and plotted over time.

The relative cost of each management strategy was evaluated by comparison to the strategy of removing all ash trees and replacing them with a resistant tree. In this way, each strategy was compared to a simple approach toward reforestation that would eventually eliminate the need for managing trees for EAB. Relative cost of each management strategy was expressed as a percentage of the cost of replacing all ash trees and plotted over time.

To demonstrate graphics provided by the calculator, the calculator was used to construct plots of annual and cumulative costs, and forest size over time for the three simple management strategies of treating, removing and replacing all trees. Plots that evaluate reforestation capacity and relative costs of each management strategy were obtained from tabular values of cost and forest size provided by the calculator for each year of the simulation.

Impacts of Variable Factors on 25-year Strategy Projections

Later compared were the expected variations in treatment cost, discount rates, median tree size, and cost of tree removal, and their impact on the 25-year costs of each of the seven default strategies on the EAB calculator website. Treatment costs were reduced by extending the number of years between insecticide treatments from one to four years. Discount rates were varied between zero and 6% to determine effects of the variable cost of money. Median tree size of the Indianapolis data set was shifted one size class up or down to determine projected costs for an urban forest with younger trees (median size tree size 7–15 cm DBH) or older trees (median tree size 15–30 cm DBH). Finally, to determine how the price of ash removal costs could alter future costs, the program was run with initial removal costs as well as at two, four, and eight times the rate.

Tradeoffs Between Insecticide Treatment and Tree Replacement

In order to generalize beyond the 11 strategies, alterations to the proportion of ash trees replaced or treated with insecticide affects forest regeneration after 25 years were examined. Two approaches were used to reduce the proportion of trees treated with insecticide. The first gradually increased the percentage of trees in each size category that would be treated with insecticide rather than to be replaced. The second specified a maximum caliper size to select trees that would be protected with insecticide and not replaced. According to this scheme, if the maximum DBH is 0 cm, then all trees would be replaced and no trees would be treated; whereas if the minimum was 107 cm, then all trees would be treated. Forest regeneration was measured as a percentage change from the initial size of the ash forest. Results were plotted and curves fit to a linear model for comparisons.

RESULTS

Comparison of simple management programs for the City of Indianapolis based on single tactics indicate that treating each ash tree every third year had the lowest annual cost, but the highest total cost in current dollars after 25 years (Figure 1). Cumulative costs for treatment reached the costs of removing all ash trees in seven years, and replacing all trees in 17 years. As expected, successfully protecting standing trees with insecticide produced a forest larger than what would be expected if all ash trees were removed and replaced with 5 cm trees. The size of the replacement forest was at its minimum in year five but reached the size of the initial Indianapolis ash forest after 25 years.

Examination of reforestation capacity of each of the 11 strategies indicate that at its minimum, the size of the forest produced by replacing all Indianapolis ash trees was 27% the initial size of the initial ash forest (Figure 2). Growth of these replacement trees produced a forest that was 50% the initial size by year twelve, 75% by year eighteen, and 100% after 25 years (Figure 2a). Those strategies which combined the replacement and treating of ash trees produced a forest that was intermediate in size when compared to that of simply treating or replacing all

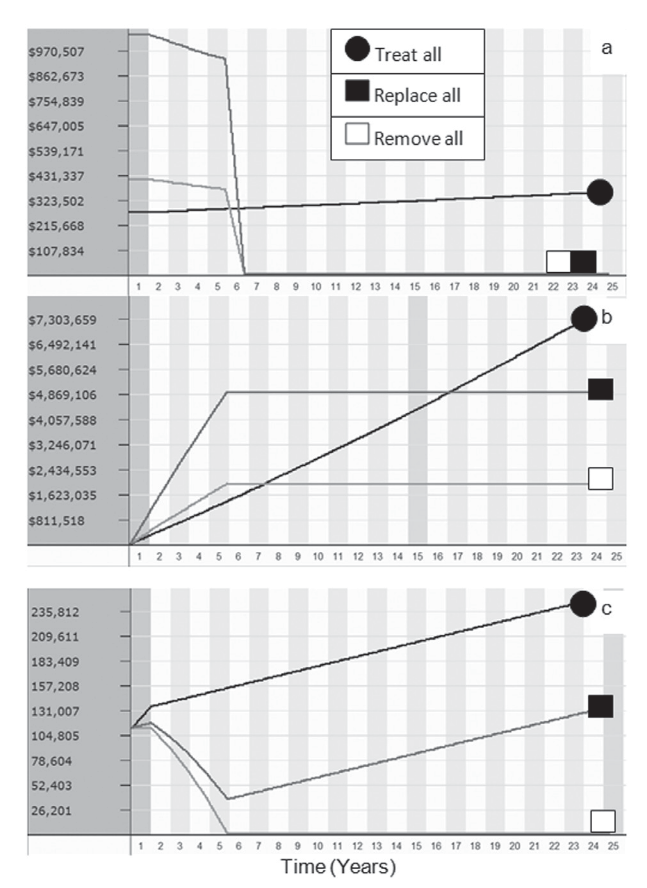

Figure 1. Sample graphic display of EAB Cost Calculator showing effects of three single tactic emerald ash borer management strategies on projected a) annual, b) cumulative costs, and c) size of the ash forest in Indianapolis, assuming pesticide treatments are applied every three years.

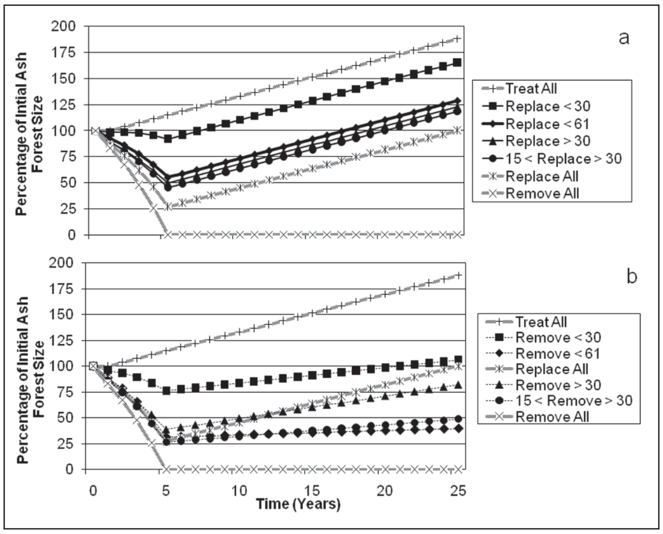

Figure 2. Predicted reforestation capacity of different management scenarios for Indianapolis with tree removals and replacement occurring in the first five years. Treat all = all ash trees treated with insecticide, Remove all = all ash trees removed, Replace all = all ash trees replaced with a resistant tree. a) Mixed strategies that replace ash trees based on critical trunk DBH (cm). b) Mixed strategies that remove trees without replacement, and treating the remainder of trees with insecticides based on critical trunk DBH (cm). Values obtained from EAB Cost Calculator as described in text.

trees. When, based on the optimization model, the largest trees were protected (Replace < 61 cm DBH), the forest was only 55% of the replacement forest in year five but reached the original size of the forest in 14 years and 128% in 25 years. When larger trees were protected (Replace < 30), the forest was never less than 92% of its original size. When smaller trees were protected (Replace > 30), the minimum size was 50% of the initial forest and reaching a size of 118% after 25 years. Protecting ash trees in the median size class (15 < Replace > 30) produced a restoration forest that was less than half the original size for only two years, but reached a size of 106% after 25 years.

In contrast, those strategies which removed larger ash trees without replacement (Remove > 30), all but the median sized tree (15 < Remove > 30), or those that saved the largest trees (Remove < 61) initiated growth trajectories that produced forests which were smaller than those produced by replacing all ash trees (Figure 2b). The forest resulting from just removing the small trees and saving the larger ones (Remove < 30) created a forest that was always larger than one produced by replacing all trees.

The comparison of cumulative costs for managing EAB in Indianapolis indicate that replacing all the ash trees over a five-year period is initially the most expensive option with the cost of treating all ash trees reaching this level after 17 years (Figure 3a). During the first five years, the cumulative costs of the mixed strategies were intermediate between the cost of replacing and removing all ash trees. Saving the larger trees (Replace < 30) reached the cost of replacing all the ash trees in 13 years. After 25 years, these costs approached those of treating all the ash trees. In contrast, the optimal approach of saving the largest trees (Replace < 61) was initially most expensive. By year six, after all trees were removed and replaced, costs increased at a slower rate and was less expensive than saving the larger trees (Replace < 30) after 25 years. Saving just the median size trees (15 < Replace > 30) had initially higher costs than saving all the smaller trees (Replace > 30) due to the cost of removing more trees.

Cumulative costs of strategies that removed Indianapolis ash trees without replacement were less expensive than those that also replaced trees (Figure 3b). During the first five years all three of these strategies were less expensive than removing all ash trees. The strategy of protecting the large trees (Remove < 30) exceeded the cost of replacing all trees in 21 years. Neither of the remaining two strategies exceeded the cost of replacing all the trees during the simulation period.

In year twenty-five, the predicted annual pesticide costs of a management plan that treated all Indianapolis trees were an estimated $356,827. The cost was reduced to 65% of this value when trees with DBH larger than 30 cm were saved, to 35% when trees smaller than 30 cm were saved. Saving the largest trees (DBH > 61 cm) incurred a cost of 28% of treating all trees; whereas the cost saving only the median sized trees was 21% of the cost of treating all trees.

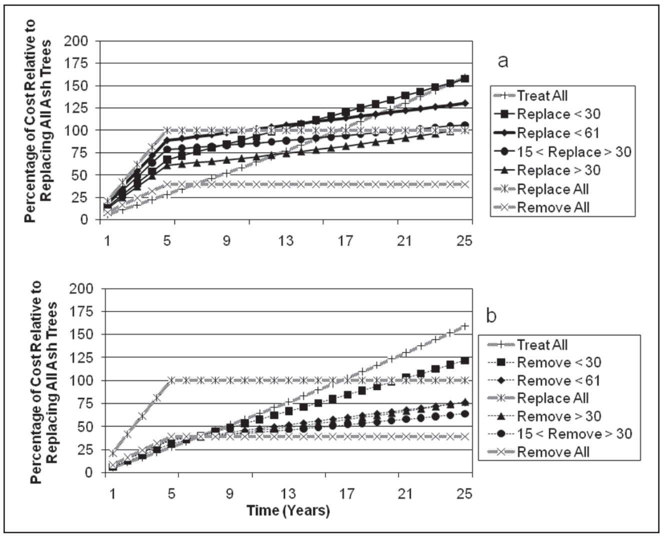

Figure 3. Cost predictions of management plans relative to the cost of replacing all ash trees for Indianapolis. All removals and replacements occur over first five years. Treat all = all ash trees treated with insecticide, Remove all= all ash trees removed, Replace all = all ash trees replaced with a resistant tree. a) Mixed strategies that replace ash trees based on critical trunk DBH (cm). b) Mixed strategies that remove trees without replacement and treating the remainder of trees with insecticides based on critical trunk DBH (cm). Values obtained from EAB Cost Calculator as described in text.

Impacts of Variable Factors on Projected Costs

Of the seven default management strategies, the option of treating all Indianapolis ash trees was most sensitive to factors that influence costs of pesticide application (Figure 4). Decreasing the cost of insecticides by reducing insecticide application frequency from yearly to every two, three, or four years, cut the 25-year costs respectively by a half, one-third, and one-quarter of the full cost (Figure 4a). Similarly, because of the relatively higher 25-year costs, the accumulated cost of treating all trees was most influenced by the cost of money as determined by a 44% decrease in costs when the discount rate rose from zero to 6% (Figure 4b). Changing the forest composition by shifting the median tree size up one class elevated the cost of treating all trees by 3% because of the greater costs needed to protect larger trees (Figure 4c). Changing the removal costs had no effect on the cost of treating all ash trees because, in the absence of tree mortality, this cost is unrelated to the cost of treatment (Figure 4d).

In contrast to the strategy of treating all trees, strategies of removing or replacing all ash trees were relatively unaffected by all but factors that influence the cost of tree removal (Figure 4). A small overall decrease (15%) in cost occurred over the range of discount rates (Figure 4b). In contrast small increases (10% and 12%) in costs resulted when the initial forest size was augmented by increasing the median size class of urban trees (Figure 4d). Increasing the cost of removing ash trees by a factor of 8 elevated the costs of the strategies of removing all ashes with and without replacement by $14.7 million.

The four strategies that relied on mixed tactics were intermediate in their responses to the factors that most greatly affected the single tactic strategies in Indianapolis. The cost of the mixed tactic strategy that saved large trees with pesticide applications (Replace < 30), tracked changes in the costs of treating all trees more closely than those which saved only smaller trees with pesticide applications (Replace > 30) (Figure 4b; Figure 4c). Similarly, increases in the costs of ash removal that propelled costs of removing and replacing all ash trees were reflected as increases in the mixed tactic strategies (Figure 4d). A shift in the forest composition from one size class away from the median size class decreased the differences among the 25 year costs of the mixed strategies (Figure 4c) because they included the removal of fewer or smaller trees.

Tradeoffs Between Insecticide Treatment and Tree Replacement

When the number of protected trees is spread evenly through the distribution of canopy sizes, the size of the restored forest gains 0.88% of the initial Indianapolis forest size after 25 years for each percent of forest protected (Figure 5a). The size of the forest after 25 years relative to the initial ash forest is projected to increase by 0.83% for each cm added to the maximum size of a trees to be treated with insecticides (Figure 5b).

DISCUSSION

The capacity of any management strategy to produce trees that follow growth trajectories predicted by the EAB Cost Calculator is contingent on the capacities of insecticides to protect trees and urban foresters to grow replacement trees. Strategies that rely only on pesticides, or tree removal and pesticides to regenerate an urban forest will only be successful as long as the pesticide continues to protect trees. As trees increase in size, it may become more difficult to distribute the insecticide effectively and provide adequate protection (Smitley et al. 2010). Although studies clearly indicate the potential to protect ash trees up to 63.5 cm DBH (Herms et al. 2009), the capacity to protect trees beyond that point has yet to be demonstrated. Nevertheless the capability of insecticides to prolong the life of ash trees at least for a limited time make them important tools for EAB response programs.

Extending tree life under adverse conditions conserves the value of trees and provides time for the development of new technologies that could eventually be used against EAB. This has been the case for other responses to invasive species, like gypsy moth, where a national program designed to slow its spread has seen pest control tactics change from applications of broad spectrum carbamate insecticides to the use of biological controls and mating disruption (Leuschner et al. 1996; Liebhold and McManus 1999). However, under the current state of knowledge, ash trees in infested areas must be protected from EAB to keep them alive (Anulewicz et al. 2008). The EAB Cost Calculator can help communities use their local tree inventory and local price structures to compare the projected costs and forest regeneration capacities of multiple management strategies. This Indianapolis case study shows how these projections can be used to guide comparisons of proposed local responses to EAB.

Cities can vary widely in the composition of urban forests and in the sizes of their ash component. The ash forest of Indianapolis is similar in some ways to that of other U.S. cities in that its 9.2% ash composition is similar to that of Toledo, OH, and Kansas City, MO (Raupp et al. 2006; Peper et al. 2008). Yet on the basis of ash trees per hectare of canopy cover, Indianapolis has relatively few ash trees, ranking thirteenth of sixteen cities surveyed in the area likely to be infested with EAB in the

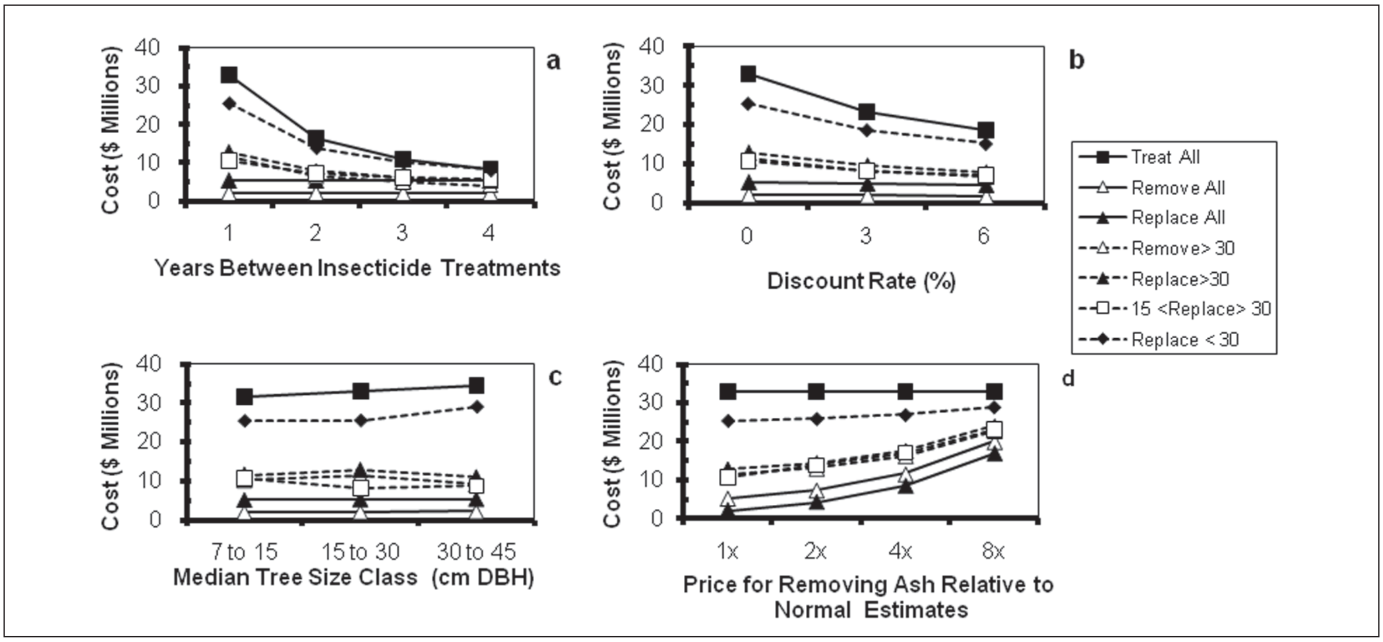

Figure 4. Effects of a) years between insecticide application and the b) discount rate, c) median size class of ash trees in the urban forest, and d) price for removing ash on the 25-year costs for managing the urban ash forest in Indianapolis for each of seven management strategies after 25 years. Values obtained from EAB Cost Calculator as described in text.

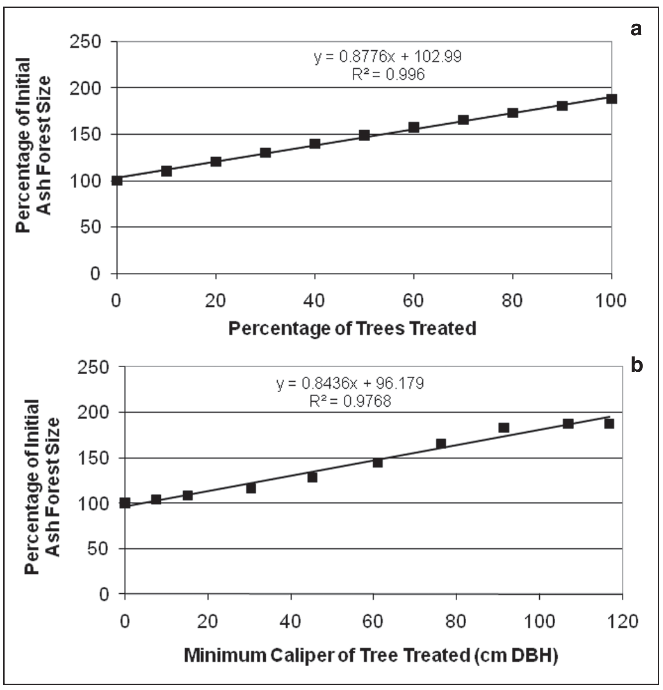

Figure 5. Effects of treating ash trees with insecticides rather than replacing trees on reforestation relative to the initial size of the Indianapolis ash forest after 25 years. a) percentage of trees treated (n = 11), b) Maximum caliper of tree treated (n = 10).

next 10 years (Kovacs et al. 2010). The median size of its ash trees (15–30 cm) is similar to New York City, NY, but smaller than for Minneapolis, MN (MacPherson et al. 2005; MacPherson 2007). Therefore, in deference to the singular nature of any urban forest, the relative differences found among strategies are not necessarily applicable to other cities and would need to be validated by using the EAB Cost Calculator with local data.

This comparison of simple management approaches for Indianapolis indicated that initial annual costs for treating all ash trees with insecticides are relatively low in comparison with the cost of removing or replacing trees (Figure 1). Although this strategy can be attractive to a city with a dwindling forestry budget, the accumulated cost of annual treatment with insecticides eventually exceeds the cost of tree removal or replacement. The strategy of removing all trees had the lowest accumulated cost, but left behind the smallest remaining forest. After 25 years, simply replacing the ash trees in Indianapolis would result in a forest that is 100% of the original forest size. Treating all the trees with insecticides every three years yielded a forest that was 188% the initial size at 158% the cost of simply replacing all trees (Figure 2; Figure 3).

Evaluation of the reforestation potential of each strategy is closely linked to the original size of the Indianapolis ash forest (Figure 2). If the same number of trees were planted to replace a forest of larger ash trees, then it would take longer to replace the forest and the benefits the trees provide. For example, if the size of the initial ash forest was increased from 3401 m to 3592 m DBH by shifting the median trees up one size class to between 30 and 45 cm, the replacement forest would only be 95% of its original size in 25 years. Shifting the median tree size class in the other direction to create a smaller forest (3230 m) would result in replacement forest being 6% larger than the initial forest in 25 years. For these reasons, when using the EAB calculator to compare strategies for a particular forest, it is better to compare relative differences than the absolute values.

Using the trajectories of forest size for single strategies as guideposts to explore the consequence of mixed management strategies, it was found that strategies that used tree replacement and insecticides will regenerate forests more quickly than those that simply replace all ash trees (Figure 2a). By whatever method, strategies that increase the number of treated trees will increase the size of the regenerated forest (Figure 2; Figure 5). Thus, the optimal strategy (Kovacs et al. 2010) of protecting only the largest trees (DBH > 61 cm) produces a forest that is smaller than when trees with a DBH as small as 30 cm are also protected (Figure 2).

Strategies that rely on treating and removing ash trees without replacement generally produce a smaller regeneration forest than those reliant upon replanting (Figure 2b). Nevertheless, among options that remove trees without replacement, the size of the forest increases as the number and/or size of the trees treated gets larger. Interestingly, the strategy of protecting the larger trees (DBH > 30 cm) and removing the small trees kept the relative forest size relatively static with its lowest point (71%) at the completion of tree removal and its highest point at 106%, during the 25-year simulation.

Initially the cumulative costs of strategies that mix insecticide use and tree replacement relative to the cost of replacing all trees have a tendency of being more expensive than treating all ash trees with insecticide (Figure 3). Strategies that rely on replacement of trees are more expensive than those strategies that simply remove ash trees. Among removal or replacement strategies, the highest costs are for those strategies that protect the largest trees because of the expense of repeatedly treating larger trees with insecticides. Strategies that involve replacement of median size trees and or smaller have cost trajectories that surpass the cost of replacing trees near the end of the 25-year projection. In contrast, the strategies of saving larger trees (DBH > 30 or 61 cm) exceed the cumulative cost of replacing trees by 30% or 58%. The optimal strategy (Replace DBH < 61) has the lower of these two costs because the size of the forest it protects with insecticide (Figure 2) is much smaller than the strategy that also protects smaller trees (Replace DBH < 30).

The cumulative cost of any strategy relative to the cost of replacing the initial ash forest will vary with local differences in ash forest size and the cost of insecticide treatments, money, and tree removal (Figure 4). Indianapolis provides a good example of how a municipality can influence tree removal and planting costs. Historically, annual planting and maintenance costs in Indianapolis are reported to be $8 per tree, a value that is less than one-third of the average expenditures for 19 cities ($25/year) studied in U.S. Forest Service Municipal Forest Resource Assessments (Peper et al. 2008). Very large cities are often capable of reducing costs of pesticides below the EAB default values due to the competitive bidding process. In Fort Wayne, IN, during 2010, the bids received for annual soil injection of trees with a high enough rate of imidacloprid to kill EAB on large trees ranged between $0.41 and $1.08 per centimeter DBH (C. Tinkel pers. comm.). These rates are between 17% and 44% of the annualized application cost per tree used in this simulation, where trees would be treated only once every three years. As such, the yearly cost per centimeter DBH ($0.81) is a reasonable approximation of what a city could expect to pay to treat all ash trees with insecticides (Table 1). Further reductions in the cost of tree removal may also be achieved by developing a tree removal plan that removes ash trees before EAB has killed them. This is especially important for large trees where limb breakage during tree removals increase the need to use specialized and more expensive procedures that reduce hazards to people and property.

In summary, the study authors conclude that although some ash trees can be protected from EAB with insecticides, the long-term expense of this strategy is likely to drive some communities to rely heavily on tree replacement in their EAB response plans. From gypsy moths to Asian longhorned beetles, the development of an effective response to exotic invasive pests has required urban forestry professionals to work with their communities to set mutually agreed upon objectives (Antipin and Dilly 2004; Lensing et al. 2008; Nealis 2009). Local opposition to the removal of live trees and the cost of a management program can derail attempts to implement even the most well-meaning of restoration plans (Vining et al. 2000). The EAB Cost Calculator can be used to evaluate approaches a community can take to selecting trees for treatment based on DBH, ranging from maximizing treatment effectiveness (DBH < 30 cm) to optimizing costs and benefits (DBH > 61 cm). As such, the current research demonstrates how the cost calculator can be used as a tool to help urban foresters engage their communities in the decision-making process by helping them discuss the consequences of management plans in terms of budgets and rates of restoration.

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Résumé. Dans cet article se trouve décrit le développement sur le web d'un système de calcul de la projection des coûts de gestion et de restauration dans le cadre d'un plan établi en réponse à une invasion par l'agrile du frêne dans la ville d'Indianapolis en Indiana aux États-Unis. Les dimensions de la forêt, mesurée par la somme des diamètres de tronc des arbres, et les coûts de gestion des frênes ont été projetés sous divers scénarios sur une période 25 ans. Les auteurs de cette étude illustrent comment une ville peut utiliser de l'information locale pour comparer les plans de gestion. Même si la simple stratégie de traiter tous les frênes donnent les coûts annuels les plus faibles et résulte en la forêt la plus vaste, cette option devient ultimement la plus dispendieuse. Éliminer simplement les frênes et les remplacer par des arbres résistants à cet insecte permet de restaurer la forêt à son état initial en 25 ans. Néanmoins, après avoir pris cinq ans pour compléter l'élimination et le remplacement des frênes, on se retrouve après 25 ans avec une forêt d'arbres réduite à près de 27% par rapport à la dimension initiale de celle en frênes. Lorsque ce plan de gestion a été modifié en protégeant les frênes de la classe médiane de dimensions au moyen d'insecticides, la restauration de la forêt se trouvait sous la barre des 50% par rapport à sa dimension initiale durant deux ans, le tout à un coût qui était de seulement 6% plus élevé que le remplacement de tous les arbres. Les auteurs de cette étude décrivent comment le calculateur de coûts peut être employé pour répondre spécifiquement aux attributs locaux de chacune des forêts urbaines.

Zusammenfassung. Hier ist die Entwicklung eines web-basierenden Kostenkalkulators für die Kosten von Projektmanagement und Restauration während einer geplanten Antwort aus die Invasion des Eschenprachtkäfers in der Innenstadt von Indianapolis, IN, beschrieben. Die Forstgröße, gemessen als Summe der Baumdurchmesser und die Kosten der Pflege urbaner Eschenbäume wurden unter verschiedenen Management-Szenarien über eine Periode von 25 Jahren erfasst. Die Autoren dieser Studie illustrieren, wie eine Stadt lokale Informationen nutzen kann, um Managementpläne zu vergleichen. Obwohl die simple Strategie der Behandlung aller Eschenbäume die geringsten jährlichen Kosten verursacht und die größten Forste produziert, war diese Methode schlussendlich die teuerste Variante. Einfaches Entfernen und Ersetzen von Eschenbäumen durch resistente Bäume erhielt die Forstflächen nach 25 Jahren in ihrer ursprunlichen Größe.Dennoch reduzierte sich die ursprüngliche Forstfläche um ca. 27 %, nachdem fünf Jahre für die komplette Baumentfernung und Nachpflanzung verwendet wurden. Als dieser Managementplan modifiziert wurde, indem die Bäume der mittleren Klasse durch Insektizide geschützt wurden, war die Forstgröße für einen Zeitraum von zwei Jahren unter 50 % der ursprünglichen Größe, und das bei anfallenden Kosten, die nur 6 % über denen der Nachpflanzung aller Bäume gelegen haben. Die Autoren der vorliegenden Studie beschreiben, wie der Kostenkalkulator angewendet werden kann, die einzigartigen Attribute urbaner Forste einzubeziehen.

Resumen. Se describe el desarrollo de un calculador web para el costo de un proyecto de manejo y restauración, durante un respuesta planeada a la invasión del barrenador esmeralda del fresno en la Ciudad de Indianapolis, IN, USA. Se proyectaron tamaños de los bosques, medidos como la suma de diámetros de los árboles, y costos de árboles urbanos de fresno bajo varios escenarios de manejo en un período de 25 años. Los autores del estudio ilustraron cómo una ciudad puede usar información local para comparar los planes de manejo. A pesar que la estrategia simple de tratar todos los fresnos proporcionó los costos anuales más bajos y produjo los bosques más grandes, esta opción fue al final la mas costosa. La simple remoción de los fresnos y remplazo con árboles resistentes restauró el bosque a su tamaño inicial después de 25 años. Sin embargo, después de cinco años de remoción y remplazo completo, el bosque inicial de fresno fue reducido a un mero 27% de su tamaño original. Cuando este plan de manejo fue modificado, con la protección de los árboles en la clase de tamaño medio con insecticidas, la restauración del bosque fue abajo del 50% del tamaño inicial por dos años a un coso de descuento que fue solamente 6% mayor que el remplazo de todos los árboles. Los autores del estudio describen cómo el calculador del costo puede ser usado para dirigir los atributos locales de los bosques urbanos.

APPENDIX. DEFAULT STRATEGIES OF THE EMERALD ASH BORER COST CALCULATOR EVALUATED FOR THE CITY OF INDIANAPOLIS.

Management plan	Description	Reason
Remove all[z]	All ash trees will be removed. No trees will be replanted.	After the EAB comes to a city, the city will have to remove the ash trees in order to prevent dead trees from falling on people or property and causing harm. This plan has the lowest out of pocket expense.
Replace all[z]	All ash trees will be removed and replaced with a new tree.	This option replaces every ash tree with a new tree that won't get emerald ash borer. No pesticides are applied. In time, the ash forest will be replaced with a different forest.
Treat all[z]	All ash trees will be treated with insecticides to kill the EAB.	Initially, this plan has the lowest annual out of pocket cost, but the greatest accumulated cost for managing EAB over time.
Remove trees with DBH > 30 cm[z]	All large trees (DBH > 30 cm) will be removed and none will be replaced. Smaller trees (DBH < 30.5 cm) will be protected from EAB with insecticides.	This plan examines the cost of simply removing trees that are larger than what can be expected to be protected with insecticides for the next 25 years if tree caliper (DBH) increases normally (1.16 cm /year).
Replace trees with DBH > 30 cm[z]	All large trees (DBH > 30 cm) will be removed and replaced with a resistant tree. Smaller trees (DBH < 30 cm) will be protected from EAB with insecticides.	Examines the cost of removing and replacing trees that are larger than what can be expected to be protected with insecticides for the next 25 years if tree caliper (DBH) increases normally (1.16 cm /year).
Remove trees with DBH < 15 cm or > 30 cm	All large trees (DBH > 30 cm) and very small trees (DBH < 15 cm) will be removed without replacement.	This plan charts the costs of removing ash trees that are too large to protect for 25 years (DBH > 30 cm) and those small trees (DBH < 30 cm) that are relatively inexpensive to remove.
Replace trees with DBH < 15 cm or > 30 cm[z]	All large trees (DBH > 30 cm) and very small trees (DBH < 15.2 cm) will be removed will be replaced with a resistant tree.	This plan charts the costs of replacing ash trees that are too large to protect for 25 years (DBH > 30 cm) and those small trees (DBH < 30 cm) that are relatively inexpensive to remove.
Remove trees with DBH < 30 cm	All small trees (DBH < 30 cm) will be removed without replacement. Larger trees (DBH >30 cm) will be protected from EAB with insecticides.	Examines the cost of protecting the historical investment in larger trees with insecticides and removing smaller trees. It assumes insecticide treatment is effective on larger trees.
Replace trees with DBH < 30 cm[z]	All small trees (DBH < 30 cm) will be removed and replaced with a resistant tree. Larger trees (DBH > 30 cm) will be protected from EAB with insecticides.	This plan examines the cost of protecting the historical investment in larger trees with insecticides and replacing smaller trees. It assumes insecticide treatment is effective on larger trees.
Remove trees with DBH < 61 cm	All smaller trees (DBH < 61 cm) will be removed without replacement. The largest trees (DBH > 61 cm) will be protected from EAB with insecticides.	This strategy is based on a dynamic programming model that optimizes value of the standing ash forest by saving the largest trees (Kovacs et al. 2010). It assumes insecticides are effective.
Replace trees with DBH < 61 cm	All small trees (DBH < 61 cm) will be removed and replaced with a resistant tree. The largest trees (DBH > 61 cm) will be protected from EAB with insecticides.	This option uses the dynamic programming model that optimizes value of the standing ash forest by saving the largest trees and replacing others (Kovacs et al. 2010). It assumes insecticides are effective.

[z] This is one of the seven default strategies on the EAB Cost Calculator website.