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Economic Analysis of Emerald Ash Borer (Coleoptera: Buprestidae) Management Options

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ABSTRACT Emerald ash borer, *Agrilus planipennis* (Fairmaire) (Coleoptera: Buprestidae), plays a significant role in the health and extent of management of native North American ash species in urban forests. An economic analysis of management options was performed to aid decision makers in preparing for likely future infestations. Separate ash tree population valuations were derived from the i-Tree Streets program and the Council of Tree and Landscape Appraisers (CTLA) methodology. A relative economic analysis was used to compare a control option (do-nothing approach, only removing ash trees as they die) to three distinct management options: 1) preemptive removal of all ash trees over a 5 yr period, 2) preemptive removal of all ash trees and replacement with comparable nonash trees, or 3) treating the entire population of ash trees with insecticides to minimize mortality. For each valuation and management option, an annual analysis was performed for both the remaining ash tree population and those lost to emerald ash borer. Retention of ash trees using insecticide treatments typically retained greater urban forest value, followed by doing nothing (control), which was better than preemptive removal and replacement. Preemptive removal without tree replacement, which was the least expensive management option, also provided the lowest net urban forest value over the 20-yr simulation. A "no emerald ash borer" scenario was modeled to further serve as a benchmark for each management option and provide a level of economic justification for regulatory programs aimed at slowing the movement of emerald ash borer.

KEY WORDS economic analysis, emerald ash borer, preemptive removal, urban forest management

Emerald ash borer, *Agrilus planipennis* (Fairmaire) (Coleoptera: Buprestidae), was first discovered near Detroit, MI and Windsor, Ontario in 2002 (Poland and McCullough 2006, Kovacs et al. 2010). It has since spread to include parts of 15 U.S. states (Illinois, Indiana, Iowa, Kentucky, Maryland, Michigan, Minnesota, Missouri, New York, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia, and Wisconsin) and two Canadian provinces (Ontario and Quebec). It was most likely introduced from Asia in the 1990s (Poland and McCullough 2006). Development of active management approaches is desirable to reduce the financial impact of pests such as emerald ash borer (Miller 1997).

Ash trees are one of the most common genera in urban settings. For example, in Wisconsin, 5.2 million urban ash trees exist and represent 20% of the urban forest (Cumming et al. 2007). Emerald ash borer larva feed in the phloem and outer xylem tissue, causing decline and eventually ash tree mortality (McCullough et al. 2009). Under sufficient larva numbers, ash trees become girdled and may die within 1 to 4 yr (Poland and McCullough 2006). All ash trees native to the eastern United States are considered susceptible to emerald ash borer (Rebek et al. 2008, Herms et al. 2009).

Emerald ash borer moves naturally at a slow rate, however, its long distance spread is exacerbated through the movement of infested wood products and ash nursery stock (Raupp 2010, Sargent et al. 2010). Without human induced spread, most emerald ash borer disperse <100 m (325 feet) with a reported physiological capability of 5 km (3.1 mile) based on flight studies (Cappaert et al. 2005). Flight distances of 0.3 km (0.2 miles) to 19.3 km (12 miles) per year have been reported, with a maximum dispersal of 1.37 km (0.9 miles) per year in an intensive quarantine zone (Raupp 2010, Sargent et al. 2010).

The cost of lost urban ash trees and management activities for emerald ash borer can be substantial for communities, states, and federal agencies (Sydnor et al. 2007, 2011; Kovacs et al. 2010). Estimates vary depending on location (urban, metropolitan, or rural land areas); however, tens of millions of urban ash trees are likely impacted (Kovacs et al. 2010). It is estimated that if emerald ash borer is left to take its course, by 2019 a discounted $10.7 billion cost could accrue from emerald ash borer in 25 states in the eastern United States (Kovacs et al. 2010). Sydnor et al. (2011) estimated a $13.4–26.0 billion cost for lost tree value, tree removal, and tree replacement in four

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midwestern U.S. states. In the State of Ohio alone, the loss of all urban ash trees from emerald ash borer is estimated to cost 1.8–7.6 billion dollars (Sydnor et al. 2007). To date, over 50 million ash trees in the U.S. states of Michigan, Ohio, and Indiana have been killed from emerald ash borer in urban and rural forests (McCullough et al. 2009, Kovacs et al. 2010). This insect has the potential to kill an estimated seven billion ash trees in urban and rural forests. This will induce costs from regulation, inspection, prevention, removal, disposal, and replacement, not to mention the social and environmental impacts.

The management of emerald ash borer, like other urban forest health problems, should consider the costs associated with different management objectives, what efficacy they provide, and what alternatives are available to develop the most cost-effective approaches (Sherwood and Betters 1981, Baughman 1985, Herms et al. 2009). Currently, an emerald ash borer cost calculator is one tool that models the costs associated with removal, replacement, and treatment of ash (Sadof 2008, Sadof et al. 2011). One limitation of this model is it does not include the net value of trees. The net value is the functional or compensatory value of a tree minus management costs needed to retain and maintain it to a level that meets management goals and objectives (Miller 1997). Discounted cash-flow models have been used to evaluate Dutch elm disease (*Ophiostoma ulmi*) management options and can be used to develop community urban forestry management plans for this disease and other forest health problems (Miller and Schuman 1981, Sherwood and Betters 1981, Baughman 1985). Likewise, historical methods used to model other insect and disease problems can potentially be applied when comparing emerald ash borer management options.

Knowing the economic outcomes of commonly reported management options such as treating living ash trees to prevent their death, preemptively removing ash before infestation, preemptive removal and replacement, and doing nothing is critical to help guide sound and science-based urban forest management. This study created an economic model using an existing ash population on the University of Wisconsin–Stevens Point (UWSP) campus to quantify the net value of an urban ash population under several management options. The study compared preemptive removal, preemptive removal and replacement, and insecticide treatment as options to control emerald ash borer infestations and retain ash trees. All management options were compared with doing nothing (control) to calculate a relative ratio. An additional option was modeled to determine the net value of the UWSP ash population should emerald ash borer not arrive. Two valuation methods were used to quantify the net value of the remaining ash population and lost ash trees over time.

Materials and Methods

Field Data Collection. Tree data were collected using a hand-held PDA (HP iPAQ110) loaded with Wachtel Tree Science inventory software. A diameter-tape was used to measure trunk diameter at breast height (DBH) (1.37 m) and visual evaluations were used to assess tree species, planting depth, percent deadwood in the canopy, and maintenance requirements of spatially located trees. Tree value in the trunk formula method was derived from tree diameter, tree species, tree condition, and tree location using Council of Tree and Landscape Appraisers methods (CTLA 2000). With this approach, larger trees are worth more than smaller trees as they provide greater property value contributions. Trees in poorer condition are worth less than trees with greater condition, which is a reflection of plant health and structural integrity. Tree location places emphasis on the site a tree occurs at, its contribution to a site, and the placement in the landscape. Finally, tree species percentage rating reflects the suitability of a species to grow at a location. Values for these parameters in this study were based on the mean values from the assessed tree population. The existing 155 ash trees were a mean 20.6 cm (8.1 in) in diameter (DBH), mean 75% condition rating, 70% species rating, and 70% location rating (CTLA 2000).

Tree information was uploaded from field units to a desktop computer. From there it was transferred into a Microsoft Access database, where it was formatted to be compatible with the USDA i-Tree Streets version three software (Anonymous undated). The CTLA approach was conducted with a simulation model developed in Microsoft Excel. The simulation model grows trees, kills trees, accounts for management costs, establishes an annual tree value, and further compares management options using parameters described below.

Mortality and Growth. An assumption was made that emerald ash borer was introduced to the tree population at the start of the model simulation. For the control option (do nothing), annual mortality was set at 20% after 7 yr, an emerald ash borer population "tipping point" (Knight et al. 2007). Before this 7 yr tipping point, a logistic function was used to model the annual mortality rate:

$$1 - \left[\frac{(R_n - R_e)}{1 + e^{(4-Y_n)}}\right] + N_a$$

where:

R_n = ash survival rate (%) without emerald ash borer present

R_e = ash survival rate (%) after tipping point with emerald ash borer present

Y_n = years from present

N_a = normal ash mortality rate without emerald ash borer present

e = natural log

The denominator is written such that the step function reaches 20% mortality by year seven (i.e., the four in the exponent shifts the curve to the right 4 yr). Mortality begins at the point of infection and rises eventually to 20%.

For the preemptive removal and replacement option, 20% of the ash were removed each year for 5 yr and it was assumed that after each year's removal an equal amount (31 trees per year for a period of 5 yr) of comparable new trees (nonash) were planted. For the remove only option, it was assumed these trees were not replaced. For the insecticide treatment option using emamectin benzoate (Tree-äge), a mortality rate of 3% (2% natural mortality plus 1% emerald ash borer mortality) was used after the 7 yr tipping point (Herms et al. 2010). Two percent natural mortality was modeled for the preceding years. An average growth rate of 1.02 cm (0.4 in) DBH/yr was applied for all planted trees based on urban tree growth studies from Wisconsin (Churack et al. 1994, Walsh 2001).

Economic Model Development. The management options were analyzed in annual increments for a period of 20 yr to determine their net annual value and then compared with the control population using a relative ratio. Twenty years was used as a timeframe as it is consistent with the guidelines in Wisconsin's comprehensive planning legislation (s. 66.1001 Wisconsin Municipal Law) and this timeframe is consistent with other emerald ash borer management models (Sadof 2008). Accounting for management options began on 1 July with all values in U.S. dollars. Net annual value was calculated for both the net remaining (retained and living) ash trees and the lost ash trees each year by accounting for the value of each ash tree and costs associated with their management. Annual costs and tree value were discounted by 6% for all options to obtain a net present value. Net tree value for the remaining ash trees was calculated using two valuation approaches (CTLA and i-Tree Streets program) minus tree costs from each management option (Miller and Schuman 1981; Sherwood and Betters 1981; Miller 1997; CTLA 2000; Anonymous, undated). For the analysis of value lost, tree management costs were added to the value of lost trees. The following equations were used to calculate the net value of remaining and lost ash trees:

$$VR_i = \left\langle \sum_{t=1}^{n} \left[\frac{V_c}{(1+d)^t} - \frac{C_m}{(1+d)^t} - \frac{C_t}{(1+d)^t} - \frac{C_r}{(1+d)^t} - \frac{C_p}{(1+d)^t} \right] \right\rangle$$

$$VR_i = \left\langle \sum_{t=1}^{n} \left[\frac{V_i}{(1+d)^t} - \frac{C_m}{(1+d)^t} - \frac{C_t}{(1+d)^t} - \frac{C_r}{(1+d)^t} - \frac{C_p}{(1+d)^t} \right] \right\rangle$$

$$VL_i = \left\langle \sum_{t=1}^{n} \left[\frac{V_c}{(1+d)^t} + \frac{C_m}{(1+d)^t} + \frac{C_t}{(1+d)^t} + \frac{C_r}{(1+d)^t} + \frac{C_p}{(1+d)^t} \right] \right\rangle$$

$$VL_i = \left\langle \sum_{t=1}^{n} \left[\frac{V_i}{(1+d)^t} + \frac{C_m}{(1+d)^t} + \frac{C_t}{(1+d)^t} + \frac{C_r}{(1+d)^t} + \frac{C_p}{(1+d)^t} \right] \right\rangle$$

Where

VR_i = Net annual value remaining for management option i

VL_i = Net annual value lost for management option i

V_c = CTLA value

V_i = i-Tree value

C_m = Management costs

C_t = Treatment costs

C_r = Removal costs

C_p = Planting costs

d = Discount interest rate

The CTLA method used a replacement cost of \$4.93/cm^2 (\$31.82/in^2), a mean 75% condition rating, 70% location factor, and 70% species percentage for ash and nonash replacements during the analysis. The i-Tree Streets method used default values except for electrical (\$0.1198/kWh) and natural gas (\$0.306/therm) that were the standard utility rates during the study. Management costs were determined for tree removal (\$3.94/cm DBH, \$10/in DBH, based on UWSP, municipal removal contract), tree maintenance (\$1.27/cm DBH, \$3.23/in DBH, based on UWSP annual tree management costs), and tree planting costs (\$100 wholesale tree cost, 5.08 cm caliper or two in caliper, and \$200 planting and establishment cost). Insecticide application costs were based on the assumption of bi-annual treatments (\$5.51/diameter cm, \$14.00/diameter in) using the chemical emamectin benzoate for the cost that private tree care companies would charge for private residential tree care. A public municipal treatment cost (\$1.48/diameter cm, \$3.75/diameter in) also using emamectin benzoate was modeled using the same bi-annual treatment protocol (Herms et al. 2009). Finally, the net value of each management option was divided by the net value of the control option to calculate the relative ratio for the remaining population. The lost tree relative ratio was derived by dividing the control option by the management option. In addition to a relative ratio, a benefit-cost analysis was performed within each management option. The average yearly net present value of trees retained was divided by the total costs within each management option. As with all models, input variables may have significant implications with outcomes, so a one-way sensitivity analysis was used to test for this. One-factor-at-a-time was either increased or decreased to a point that the insecticide treatment outcome was similar to doing nothing.

Summarization of Data. To clearly and concisely present the study's results, a Goeller scorecard was developed (Goeller 1988). Potential urban forest goals and objectives were listed along the vertical axis of the scorecard and each management option listed across the top of the score card. Values for each management option were linked to the appropriate goal or objective and Microsoft Excel's con-

GOELLER SCORECARD					
Goals & Objectives	Options				NO EAB
	CONTROL	TREATMENT	REMOVAL	REMOVE/REPLANT	
RETAINED TREE ANALYSIS					
CTLA Relative Ratio	◑ 1.00	● 1.88	○ 0.32	○ 0.62	2.10
i-Tree Relative Ratio	● 1.00	○ -3.67	◕ -0.17	◑ -1.28	3.48
Mean Net Value Per Tree	● 706	● 688	○ 154	○ 208	739
Net Per Tree Value at Year 20	● 733	● 711	○ 0	◔ 234	749
Mean Net Value Per Year	◑ 44,913	● 84,610	○ 14,174	○ 27,984	94,289
Net Value at Year 20	○ 3,338	● 64,563	○ 0	◔ 25,777	77,533
LOST TREE ANALYSIS					
CTLA Relative Ratio	○ 1.00	● 2.24	○ 1.01	○ 0.74	2.95
i-Tree Relative Ratio	◑ 1.00	● 1.79	◔ 0.89	○ 0.32	2.97
Mean Net Value Per Tree	○ 864	○ 906	● 198	○ 876	857
Net Per Tree Value at Year 20	○ 832	○ 867	● 0	◕ 280	832
Mean Net Value Per Year	◔ 6,193	● 2,769	◔ 6,128	○ 8,344	2,102
Net Value at Year 20	◕ 947	○ 2,418	● 0	◕ 629	1,757
POPULATION CHARACTERISTICS					
Mean DBH Per Year	● 10.1	● 11.7	○ 2.1	◔ 5.8	11.8
Mean DBH at Year 20	● 16.1	● 16.1	○ 0.0	◑ 8.8	16.1
Mean # of Trees Lost Per Year	◔ 7.2	● 3.1	◔ 7.4	○ 9.5	2.5
Total Trees Lost After 20 Years	◔ 150.4	● 64.2	◔ 155.0	○ 200.0	51.5
Mean # of Trees Retained Per Year	◔ 63.6	● 122.9	○ 22.1	● 134.5	127.6
Trees Retained at Year 20	○ 4.6	● 90.8	○ 0.0	● 110.0	103.5
MAINTENANCE and REMOVAL COSTS					
Total Maintenance Cost	◑ 35,691	○ 58,460	● 15,882	◑ 35,712	60,036
Mean Per Year Maintenance Cost	◑ 1,700	○ 2,784	● 756	◑ 1,701	2,859
Maintenance Cost at Year 20	● 92	○ 1,518	● 0	◔ 993	1,712
Total Removal Cost	◔ 10,554	● 4,251	○ 12,083	○ 13,259	3,466
Mean Per Year Removal Cost	◔ 503	● 202	○ 575	○ 631	165
Removal Cost at Year 20	◑ 57	○ 140	● 0	◑ 61	106
PLANTING and TREATMENT COSTS					
Total Planting Cost	● 0	● 0	● 0	○ 39,175	0
Mean Per Year Planting Cost	● 0	● 0	● 0	○ 1,865	0
Planting Cost at Year 20	● 0	● 0	● 0	● 0	0
Total Treatment Cost	● 0	○ 126,693	● 0	● 0	0
Mean Per Year Treatment Cost	● 0	○ 6,033	● 0	● 0	0
Treatment Cost at Year 20	● 0	○ 3,289	● 0	● 0	0
OVERALL MANAGEMENT COSTS					
Total Cost	● 46,244	○ 189,404	● 27,966	◕ 88,146	63,502
Mean Per Year Cost	● 2,202	○ 9,019	● 1,332	◕ 4,197	3,024
Total Cost at Year 20	● 150	○ 4,947	● 0	◕ 1,054	1,818
Mean Per Tree Cost	◕ 31	○ 70	● 10	◕ 27	23
Per Tree Cost at Year 20	◑ 26	○ 53	● 0	● 9	17
BENEFIT-COST ANALYSIS					
Average Annual PV : Total Cost	● 1.02	○ 0.49	◔ 0.55	○ 0.37	1.53

Fig. 1. Goeller scorecard output from emerald ash borer management option analysis using default values. Least grey shading and most darkened circle rated as most desirable to most grey shading and least darkened circle rated as least desirable. Shading of circles represents a 20% frequency between upper and lower value in any row.

ditional formatting function was used to rank each option from most desirable (lightest gray color, signifying the highest or lowest value, depending on the goal) to least desirable (darkest gray color, converse of the most desirable option). Values between the most and least desirable were ranked and colored according to the conditional formatting rule of mean equals 50%. The conditional formatting function also allows for the inclusion of symbols to rank each management option, where a filled circle represents the best option, a three-quarters-filled circle an option in the 75th percentile, a half-filled circle in the 50th percentile, a quarter-filled circle in the 25th percentile, and an open circle the least desirable management option, based on the individual goal or objective.

Results

After 20 yr, the remove only option had no ash and no replacement trees, the do nothing approach had five (3% of original) ash remaining, the treatment option had 91 (59%) ash left, and remove and replace had the most with 110 (71%) nonash trees (Figs. 1 and 2). Under natural mortality rates used in this study and without emerald ash borer, 103 trees were modeled to remain (66.5% of original) after 20 yr. The treatment option had the largest mean weighted DBH (29.7 cm,

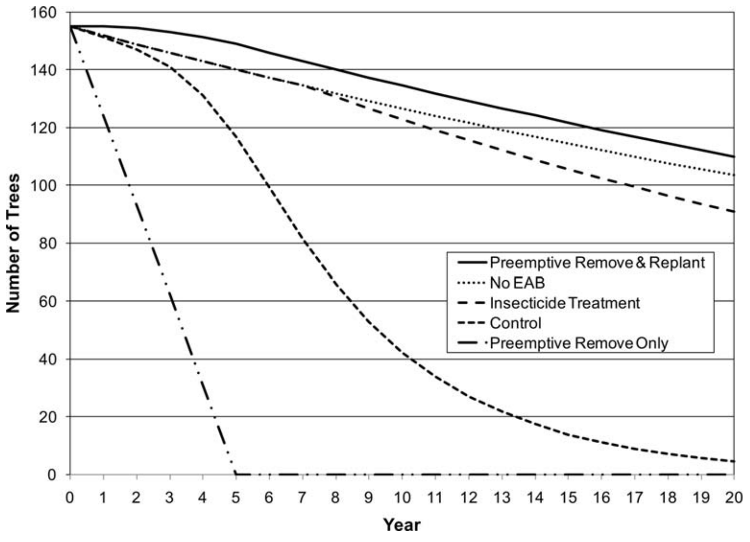

Fig. 2. Mortality of ash trees over a 20 yr-time period for the management options used in this study.

11.7 in), followed by the control (25.7 cm, 10.1 in), remove and replace (14.7 cm, 5.8 in), and finally remove only (5.3 cm, 2.1 in) option. At year 20 of the simulation, the treatment and control options had the largest trees (40.9 cm, 16.1 in mean DBH), followed by remove and replace (22.4 cm, 8.8 in) and remove only (0 cm, 0 in). The simulation of a healthy population showed a mean DBH of 30.0 cm (11.8 in) and an ending DBH of 40.9 cm (16.1 in) in year 20. The remove and replace option averaged 135 trees remaining per year, followed by insecticide treatment (123), control (64), and remove only (22). If emerald ash borer had not entered the population, 104 trees would remain in year 20, with a mean of 128 remaining per year.

Value Remaining Analysis. Over a 20 yr period, the mean annual net present value of remaining trees in the treatment option was higher ($84,610) than the remove and replace ($27,984) and the remove only ($14,174) options for the CTLA method for tree valuation (Table 1). The do nothing (control approach) had a $44,913 net present value. For comparison, the ash population would have a mean value of $94,289 if emerald ash borer was not present during the 20 yr simulation. The i-Tree Streets method for tree valuation of remaining trees projected a different trend. The mean discounted net present value for treatment using i-Tree was the lowest ($−3,189), followed by removal and replacement ($−1,110), and remove only ($−149). In comparison, the control ($868) and no emerald ash borer options ($3,018) provided net positive value. Using CTLA as a value method, treatment (1.88) was the only option with a relative ratio >1.0, meaning that under the given assumptions, removal (0.32) and removal plus replacement (0.62) provided less mean net value than doing nothing (Fig. 3; Table 1). Using i-Tree to value the remaining population, no options (except emerald ash borer not present) were above a 1.0 relative ratio. This suggests the costs associated with emerald ash borer management are greater than the functional values of the ash cohort. In comparison, the compensatory value of the ash trees was greater than management costs.

Another way to evaluate options is comparing the mean annual per tree net value (weighted mean) and net value remaining after 20 yr. Although the control (do nothing) option exhibited the highest mean net remaining annual tree value ($706) compared with treatment ($688), remove and replace ($208), and remove only ($154), the control (do nothing) option had the second lowest net value remaining at year 20 of the simulation ($3,338), after treatment ($64,563),

Table 1. Mean remaining (retained) values and lost value comparisons of CTLA and i-Tree Streets valuation approaches over a 20-yr time period for all management options, including relative ratio comparisons

Management options	Mean net remaining				Mean net lost			
	CTLA		i-Tree		CTLA		i-Tree	
	Value (US$)	Relative ratio	Value (US$)	Relative Ratio	Value (US$)	Relative ratio	Value (US$)	Relative ratio
Control	44,913	1.00	868	1.00	6,193	1.00	994	1.00
Insecticide treatment	84,610	1.88	−3,189	−3.67	2,769	2.24	555	1.79
Preemptive removal	14,174	0.32	−149	−0.17	6,128	1.01	1,119	0.89
Remove and replant	27,984	0.62	−1,110	−1.28	8,344	0.74	3,106	0.32
No emerald ash borers	94,289	2.10	3,018	3.48	2,102	2.95	334	2.97

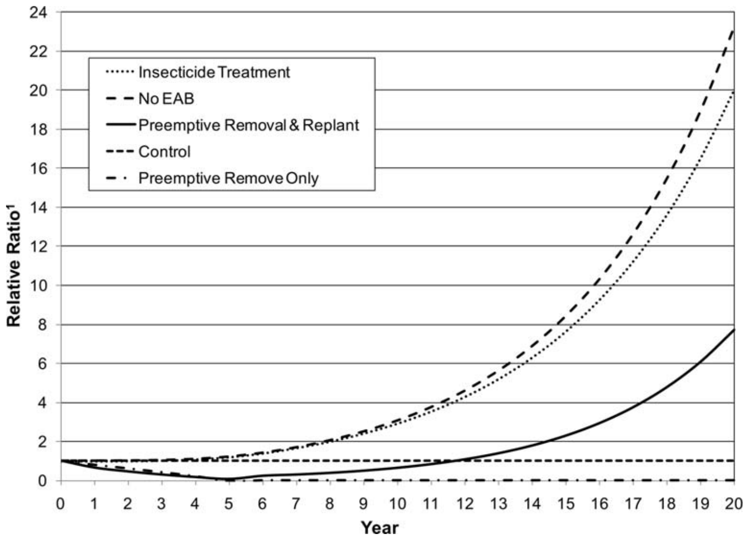

Fig. 3. Annual relative ratio of the remaining ash population using the CTLA valuation method. ([1]Relative ratio = control option/management option; management options include treatment, preemptive removal, preemptive removal and replacement, and no emerald ash borer).

and removal plus replacement ($25,777). Only the removal option ($0) was lower with no urban forest value at year 20. The no emerald ash borer scenario had a mean $739 per tree value and $77,533 ash tree value remaining at year 20.

Using the benefit-cost analysis within each management option, the control option was 1.02:1. The removal (0.55:1), treatment (0.49:1), and remove and replace options (0.37:1) were lower. By comparison, the no emerald ash borer scenario had a benefit-cost ratio of 1.53:1.

Value Lost Analysis. Over a 20 yr period, the mean discounted net value lost per year for the treatment option was lower ($2,769) than the remove only ($6,128) and the remove and replace ($8,344) options for the CTLA method for tree valuation (Table 1). The do nothing option had a $6,193 mean net present value lost. For comparison, a healthy population not infested with emerald ash borer would have a mean annual lost value of $2,102 because of natural attrition. The i-Tree Streets valuation model showed a similar trend. The mean discounted net value lost per year for the treatment option was the lowest ($555), followed by control ($994), removal ($1,119), and remove and replace ($3,106). Without emerald ash borer, the net loss per year was lowest ($334). When compared with the control option in a relative ratio, treatment was the most cost effective approach to retain net urban forest value to minimize net loss of value using both the i-Tree (1.79) and CTLA (2.24) valuation methods (Fig. 3, Table 1). Under the simulation's basic assumptions, the remove option (i-Tree = 0.89, CTLA = 1.01) was comparable to doing nothing (control) and remove and replace (i-Tree = 0.32, CTLA = 0.74) was least favorable during the 20 yr horizon.

Cost of Management Options. Examining only tree management costs over 20 yr, treatment was the highest at $189,404 ($9,019 mean per year), followed by removal plus replacement ($88,146 total, $4,197 mean), control ($46,244 total, $2,202 mean), and remove only ($27,966 total, $1,332 mean) options (Fig. 1). Expressed in per tree numbers, these mean annual costs were $70 for treatment, $31 for control, $27 for removal plus replacement, and $10 per tree for the remove only option. A no emerald ash borer scenario would have $63,502 in total management costs, $3,024 mean per year, and $23 per tree annual costs. Removing urban trees is the least costly, at the loss of the value that urban trees provide. Likewise, maintaining an ash tree population with insecticides was the most costly and subsequently provided the greatest net present value for the urban forest.

Sensitivity Analysis. A one-way sensitivity analysis of variables associated with our model algorithm was conducted (Table 2). Changing the cost of these values had no significant effect on our study findings (e.g., treatment > control > preemptive removal and replacement > preemptive removal). By example, if a 5 cm (2 in) caliper replacement tree cost $11, treatment and doing nothing were comparable. It is highly unlikely you could purchase a nonash tree of that size for that price. Likewise in the CTLA approach, if ash tree survival rates with emerald ash borer present were 96%, interest rates were 50%, injection costs were $20.9/cm DBH/yr ($53.1/in DBH/yr), or injection survival was 70.2%, treatment and doing nothing are comparable.

Discussion

As urban and community forest managers, arborists, and others prepare to undertake emerald ash borer management options, they should base decisions upon their intended goals and objectives and consider re-

Table 2. A one-way sensitivity analysis of model input variables, default study input values, and input value from CTLA valuation method when the relative ratio of treatment compared with control (do nothing) = 1 for the remaining ash pop value and net lost value

Model input variables	Unit	Default value	Value relative ratio = 1.00	
			Ash trees remaining	Ash trees lost to emerald ash borers
Maintenance cost	\$/yr/cm (in)	1.27 (3.23)	Undefined	−47.2 (−120.0)
Injection cost	\$/yr/cm (in)	2.76 (7)	20.9 (53.1)	69.4 (176.2)
Removal cost	\$/yr/cm (in)	3.94 (10)	Undefined	−44.6 (−113.2)
Replacement cost	\$/cm (in)	39.37 (100)	4.21 (10.7)	−6.10 (−15.5)
Injection survival	%	99	70.2	85.3
Natural survival	%	98	92.8	91.2
Emerald ash borer survival	%	80	96.1	96.9
Species rating	%	70	10.3	Undefined
Condition rating	%	75	10.0	Undefined
Location rating	%	70	10.3	Undefined
Preemptive years	yr	5	Undefined	Undefined
Interest rate	%	6	50	Undefined
Growth rate	cm/yr (in/yr)	1.016 (0.4)	Undefined	Undefined

Undefined, no value within reasonable limits would cause the relative ratio to equal 1.00.

source requirements. Several approaches have been suggested as options to manage emerald ash borer (Herms et al. 2009). Doing nothing is one approach with dead ash trees removed as the end product. The preemptive removal approach suggests ash will die anyway, so orderly removal of a fixed percentage of trees annually will spread the cost of management over several years. Another version of preemptive removal involves a likewise replacement of removed ash trees. Retention of existing ash through chemical treatment is another approach with the desired goal to retain ash as long as possible and the value they provide. This study does not say one approach is better or worse, considering different management goals and objectives exist. Rather, the results from this study can be used to incorporate the economic comparison of management alternatives into an informed decision making process. In addition, this analysis does not examine management actions in populations of trees in which emerald ash borer is known to be present for some time, nor does it attempt to estimate when emerald ash borer will first become a concern. By assuming that emerald ash borer enters the population in year 0, this study takes an "insurance policy" approach. By example, if one could predict the next big hail storm, a home or auto insurance policy would not be necessary until the day before the event. Similarly, one cannot take out a policy after the fact. In the same way, an urban forest manager's decisions would change if the arrival of emerald ash borer could be known, but no such accurate prediction model yet exists. One recommendation is to start preventative ash tree treatments when emerald ash borer has been detected within 10–15 miles (Herms et al. 2009).

Economic and aesthetics thresholds are used to guide decision making (Pedigo et al. 1986, Ball et al. 1999). Both approaches can be used to manage urban tree populations. Economic thresholds are more easily applied to commodities with a defined monetary value (such as in agriculture), making urban forests (and their aesthetic values) a more complex management issue (Ball and Marsan 1991, Ball et al. 1999). The science based management of insect pests, however, is evolving and progressing, providing for more advanced management options, such as the application of preventative as well as responsive tactics (Pedigo et al. 1986). Aside from emerald ash borer, past urban forest health challenges, such as Dutch elm disease (DED), provide examples of the evolution of science, planning, and resource needs for effective management (Cannon et al. 1982, Miller and Schumann 1981, Sherwood and Betters 1981). Sanitation, for example, works very well with the control of DED. The success of ash sanitation is less known; however, removing the phloem area from an infested ash population should reduce emerald ash borer populations (McCullough and Siegert 2007). Chemical treatment costs are an important consideration with application of that management strategy. If the net value of treated trees is less than doing nothing, then active treatment would not be economically justified and retention of a tree not economically warranted. Early DED literature, for instance, found sanitation was highly cost effective (Cannon et al. 1982, Kostichka and Cannon 1984). Chemical treatment of elms to prevent DED, however, was more costly.

In this study, insecticide treatment of all ash was supported by all but one analysis method at recommended application rates and the costs for commercial application. The i-Tree Streets valuation method for the remaining trees analysis returned a negative value for the treatment option. Subsequently, the relative ratio for treatment for this analysis method only was the lowest of the four options. Management costs, primarily associated with chemical purchase and application, were greater than the tree values resulting from the i-Tree model. This was not the case for the CTLA analysis, however, as the CTLA value is compensatory and includes the replacement value for the tree. The i-Tree value, however, is functional, comparing only the benefits the tree provides and not its replacement value. The chemical cost and application rates used in this study assumed commercial application, which was \$2.76 annually/cm DBH (\$7.00/in

DBH). Reducing the chemical treatment cost to $0.90 annually/cm DBH ($2.29/in DBH) gives the i-Tree remaining tree valuation approach a 1.0 relative ratio. The city of Milwaukee, WI, has calculated their mean per tree in-house municipal cost is $0.74 annually/cm DBH ($1.88/in DBH) for an emerald ash borer treatment program. Subsequently, using the model in this study, the Milwaukee emerald ash borer treatment program is justified by the compensatory CTLA (1.98 relative ratio) approach and the functional i-Tree (1.42 relative ratio) approach for remaining ash trees. Using the municipal costs for chemical treatment from Milwaukee greatly reduces the mean annual cost to treat the ash population in this study from $126,693 ($189,404 total cost) to $33,936 ($96,646 total cost) over the 20 yr period.

The benefit-cost analysis performed within each management option further demonstrates the effects of management costs in our assessment of emerald ash borer control options. At the assumed commercial application rates, the chemical treatment option was the fourth most cost-effective at managing for emerald ash borer. If chemical treatment proves effective at controlling emerald ash borer for three as opposed to 2 yr, treatment becomes the second most cost-effective management option (0.64:1 benefit-cost ratio). Likewise, if the municipal chemical application rate is used at the 2 yr rate, treatment (0.97:1 benefit-cost ratio) becomes more comparable to the control option. If both municipal application rates and 3 yr of effectiveness are modeled together, chemical treatment becomes the most cost-effective option, with a benefit-cost ratio of 1.10:1. The benefit-cost ratios of the control (1.02:1), preemptive removal (0.55:1), and preemptive remove and replace (0.37:1.00) options remained the same throughout this analysis. Other costs associated with the benefit-cost analysis were also analyzed. The maintenance costs used in this model were consistent with McPherson et al. 2006. Their research found tree removal costs of $11.81/cm DBH ($30/in DBH) reflected typical values for the tree type in this study. At $3.94/cm DBH ($10/in DBH) our assumed removal costs are lower but based on a contract price. Raising the removal cost in this study to $11.81/cm DBH makes treatment an even better proposition with the control or preemptive removal options becoming much more expense with lower benefit cost and relative ratios. The results from this model have real-world applications. The type of chemical used, the dosage level, and time of application are important factors in the efficacy of emerald ash borer management (Herms et al. 2009, Smitley et al. 2010b). Larva densities and canopy decline are often used as a parameter to measure effectiveness of emerald ash borer insecticide treatment (Smitley et al. 2010a,b). The chemical emamectin benzoate used in this study has a reported efficacy of >99% at reducing larva density when used biannually (Herms et al. 2009). In this study, a 1% mortality rate was used, assuming an effectiveness of 2 yr per treatment. Field evidence suggests emamectin benzoate injections may be effective for a period of 3 yr, which further reduces the cost of this management option. The injection survival rate could be decreased to 85.3% for the lost ash analysis and 70.2% for the remaining ash analysis before the relative ratio of treatment was one. Thus, with current chemical label rates, application timing, and application technique it is likely that treatment of urban ash trees in park-like and residential settings is economically justified based on this study if you use net value as an evaluation approach. Ash in nonlandscape settings have lower value than landscape trees and the insecticide treatment of these trees would likely be difficult to economically justify; however, this was not investigated.

When looking at the effectiveness and cost of chemical treatments, it is also important to consider other available products and methods of application. In addition to emamectin benzoate, which is applied via tree injection, urban managers have other options (Herms et al. 2009). Dinotefuran and imidacloprid are the active ingredients in two additional products marketed for emerald ash borer treatment, the latter being available for homeowners to purchase. Imidacloprid has shown good success for smaller trees with larger trees showing decline when used at labeled rates (Smitley et al. 2010b). For this study, emamectin benzoate was modeled (Herms et al. 2009). Regardless of insecticide selected, if tree survival exceeds 85.4%, and costs are the same, then treatment was economically justified.

It is imperative to recognize the health of individual trees when managing a tree population for emerald ash borer. Treating ash trees in this study makes economic sense as a whole, but managers will need to decide which trees are worth saving to maximize economic potential. The city of Milwaukee, WI, for instance, is currently treating most street trees >20.32 cm DBH (eight in DBH). The management goals are to reduce initial costs incurred from an emerald ash borer infestation, remove trees at a more normal rate, retain benefits of street trees, and prolong the time period to reforest with nonash trees. Decisions to treat or not treat trees should also be based on tree condition. First, trees in poor to fair condition would have lower priority than good to excellent condition trees. Recent research on imidacloprid suggests that declining trees (>60% canopy thinning) not be treated, as the survival rate of such trees is significantly less than that of healthy trees (Smitley et al. 2010b). Ash trees with poor conditions, at high risk for failure, and in locations with limited aesthetic and ecological benefits could be removed before healthier trees with greater structural fitness and higher aesthetic and ecological benefit.

Preemptive removal is one management option proposed to manage ash populations in light of emerald ash borer. For example, The Three Rivers Park District in Hennepin County, Minnesota, has chosen to preemptively remove their entire ash tree population over a period of 10 yr, citing labor costs as a driving factor (Blake 2010). This approach does provide for an orderly transformation from ash. From this study, however, preemptive removal led to the lowest net urban forest value. This results as the benefits that ash trees provide are forgone after tree removal. However, the district will eventually recapture net tree benefits through the growth of replacement trees (Miller and Schuman 1981, McPherson et al. 1997, McPherson 2004). Preemptive removal has been suggested as a means to avoid high levels of ash mortality as emerald ash borer populations increase, having to then remove large quantities of trees and debris. While a reasonable fear, one could argue that application of debris management principles and approaches associated with storms is one way to handle large pulses of debris associated with dead and dying ash trees (FEMA 2007, Escobedo et al. 2009, Hauer et al. 2011).

Management costs are an important part of developing the most cost effective approaches to emerald ash borer management. Investigating ways to minimize tree removal, treatment, and replanting costs associated with emerald ash borer management (as with any urban forest management option) is vital to reduce the costs associated with this urban forest problem. In addition, understanding the underlying reasons for management costs and values is important. For example, the preemptive removal option had the lowest cost to implement because after trees were removed there was no maintenance cost. This study assumed that tree maintenance (primarily pruning) would occur similar to that without an emerald ash borer concern. If maintenance was not implemented in any option, the cost of ash tree management decreases. For example, total costs were decreased in the control ($35,691, 77% of total costs), treatment ($58,460, 31%), preemptive removal ($15,882, 57%), preemptive removal and replacement ($15,882, 57%), and no emerald ash borer ($60,036, 95%) options when maintenance was removed. Thus, options that retain trees for longer periods will require consideration of how much maintenance is needed. Providing no maintenance to the urban forest could produce potentially unsafe conditions (i.e., falling limbs); however, to economically justify treatment of ash trees, the intensity of pruning could potentially be decreased (Miller 1997).

The mortality of ash trees is an important component of modeling the economics of emerald ash borer and ash populations. This paper modeled the mortality in the control population based on a buildup of ash mortality between the initial infestation (2% normal mortality) to year 7 (20% annual mortality). After that we modeled a constant 20% mortality. If mortality is greater than this, then retention of ash through protection strategies such as insecticide treatment becomes even more favorable. If mortality is less than this, treatment becomes less beneficial and is closer to the control option.

A Goeller scorecard was developed to compare a list of many common urban and community forestry goals and objectives against the results of each management option (Fig. 1). This analysis presumes that different communities will have differing goals relating to their ash population. The scorecard allows decision-makers to quickly and easily view trends in the data and weigh decisions against individually defined goals and objectives. For instance, if a community's goals were to reduce the mean number of trees lost per year the Goeller scorecard shows insecticide treatment to be the best option. Likewise, if the goal is to maximize net urban forest value, treatment is the better option. However, if the goal is to reduce the mean total costs per year, insecticide treatment is the worst option. This example shows the complexity of the issue. Should managers consider goals and objectives individually, or can the Goeller scorecard be read as a whole? One way of dealing with this is to assign a weight to each goal based on local feasibility or desirability. Weights can then be multiplied by each option's rank (i.e., the best of the four management options gets a "four" rank and the worst a "one") and summed for a total score. When decision-making becomes difficult or contentious, weighting and ranking in a Goeller scorecard allows managers to objectively make effective decisions based on available data and according to local needs and desires. Most communities will need to find a balance between effectiveness and efficiency. That is to say, the most cost-effective solution may not be the most effective at addressing emerald ash borer infestations, and vice versa. By example, a community with a limited budget may weigh per year costs higher or set limits on yearly spending to come to a management decision. The "best" decision, per se for one community, may not be the right decision for another community.

Managers need also anticipate future developments in the fight against emerald ash borer: as management options evolve, so too must a community's goals and objectives. For instance, if the effectiveness of parasitic wasps becomes more evident, managers must evolve in their application of management options (Ulyshen et al. 2011). Screening, selecting, and breeding for emerald ash borer-resistant ash trees may also be an important future consideration for managers, much as the use of hybrid elms has become more common in communities once decimated by DED (Rebek 2008). One must also note that although this analysis looked at each management option separately, implementing an integrated approach for emerald ash borer management is a useful option. Through the treatment of ash, the preemptive replacement (underplanting) of nonash before ash trees die, the removal of the worst condition ash first, and the development of an emerald ash borer management plan in advance, communities can prepare for emerald ash borer and attempt to minimize a significant loss in canopy in a narrow window of time.

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