CHAPTER NINE

Evaluating the Economic Costs and Benefits of Slowing the Spread of Emerald Ash Borer

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Introduction

The emerald ash borer (*Agrilus planipennis;* EAB) is poised to wipe out native ashes (*Fraxinus* spp.) in North America with expected catastrophic losses to ash tree forestry (MacFarlane and Meyer 2005). EAB was first discovered in Detroit in 2002. Most scientists hypothesize that it entered the United States through solid wood packing material transported in cargo ships and on planes. The beetles have continued their spread through firewood, wooden packing materials, and infested nursery trees. In only a few years, EAB has destroyed most ash trees within the Detroit Metropolitan area and spread through Michigan's lower peninsula and into Ohio, Indiana, and other states (Fig. 9–1). For the foreseeable future, EAB will continue to destroy urban and forested ash trees, causing substantial economic impacts.

Given this threat, immediate action is crucial for the preservation of ash trees. The US Department of Agriculture (USDA) and state and local agencies are already urgently attempting to prevent further spread of the EAB but are constrained by agency budgets, and little guidance exists about how best to allocate scarce funds to alternative methods of prevention and control. For government or private institutions, the allocation of

FIG. 9–1. Distribution of EAB as of May 1, 2012, based on data from the USDA and Canadian Food Inspection Agency (modified from http://www.emeraldashborer.info/files/Multi State_EABpos.pdf).

funding would address the level of investment in prevention provided the benefits outweigh the costs. Equally essential are analyses about which kinds of prevention methods—education and quarantine efforts, for example—are most cost-effective. Specifically, hard numbers are needed on the likely financial impacts of the emerald ash borer on urban areas and the ash industry, as well as benefits of possible alternative prevention and control options.

Our project has two basic objectives: first, to provide estimates of the regional economic impact emerald ash borer will potentially inflict upon the ash forestry in Ohio and Michigan; and second, to provide policy makers with quantitative guidance for cost-effective alternative strategies to control, prevent, or slow the spread of emerald ash borer.

Methods and Results

1) Current and Potential Distribution of Ash Trees and Emerald Ash Borer

The only known limiting factor in the potential distribution of EAB is the presence of ash trees. The insect is host specific to the genus *Fraxinus* and infests all North American ash species, though different species have different susceptibilities to becoming infested (Poland and McCullough 2006). Thus, to understand the potential distribution of the emerald ash borer requires knowing the distribution of ash at local and regional scales. We estimated the distribution of ash trees in Ohio and Michigan in three ways—a coarse-level analysis of the eastern United States, a fine-scale analysis of Ohio and Michigan, and an assessment of ash in urban areas.

We first used Forest Inventory and Analysis data (USDA Forest Service, Miles et al. 2001) to map and quantify the four species of ash that account for the vast majority of ash in rural settings in the eastern states (Fig. 9–2). The four species are *Fraxinus americana* (white ash), *F. pennsylvanica* (green ash), *F. nigra* (black ash), and *F. quadrangulata* (blue ash). A detailed estimate of ash resource availability in Ohio and Michigan was developed by combining estimates of ash basal area per Forest Inventory and Analysis (FIA) plot with a Landsat Thematic Mapper (TM)-based classification of forest types.

We also assessed the abundance of ash in private and public areas within cities, where it is a common landscaping tree. Sydnor et al. (2007) surveyed 200 communities in Ohio and found, for every 1,000 residents, an average of 20.5 ash street trees, 38.3 park trees, and 320.9 ash trees on personal property. Thus, EAB has had and will continue to have a large impact, not only on native forests but also on urban and suburban communities.

2) Risk of the Spread of Emerald Ash Borer

As ash trees occupy much of the eastern United States, the second step of our study was to predict how quickly EAB spreads in both forests and cities. Modeling the insect's spread requires the integration of several models and data layers because EAB disperses by multiple mechanisms. Flight is their natural mode of dispersal, but they also spread by way of human transport of goods and services (BenDor et al. 2006), especially firewood and wood products.

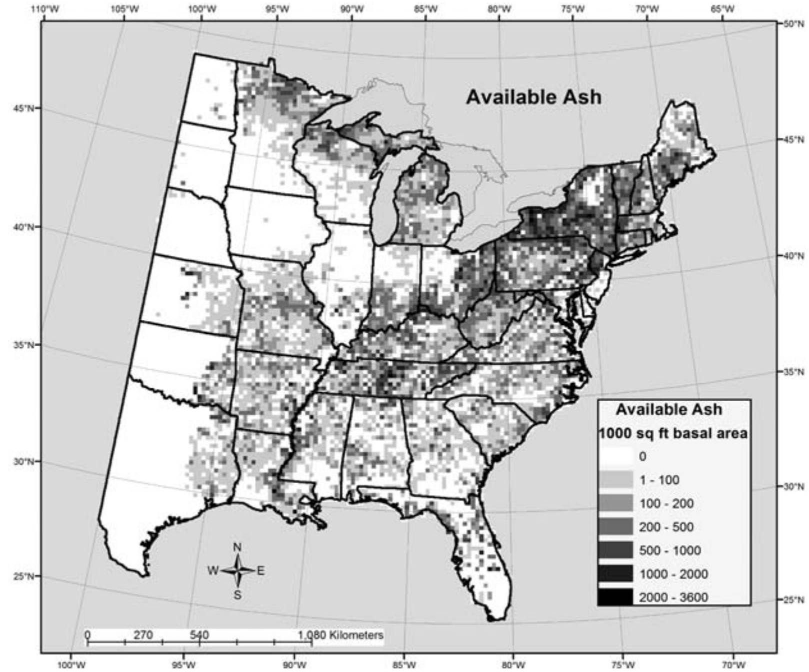


FIG. 9–2. Amount of ash available to the EAB. It is the product of the basal area of ash and percent forest (from Iverson et al. 2010).

Our model of movement comprised a "flight" model and an "insect-ride" model (Prasad et al. 2010). The flight component was based on the SHIFT model, a spatially explicit cell-based model designed to estimate the potential migration of trees under current fragmented landscapes, and including the northward climatic pressure shown to exist now and increasingly so into the future (Iverson et al. 1999, 2004; Schwartz et al. 2001). This model was adapted to match the "front" of the spread of EAB, based on the known front location in 2006, the abundance of EAB behind the front, and the quantity of ash ahead of the front (based on step 1). The flight component was based on state and federal data documenting the spread of EAB during 1998–2006, along with several assumptions (see Prasad et al. 2010).

The flight model simulated local-scale movements, which includes the flight capabilities of EAB and human-assisted local movements. The movement of firewood and wood products are typically thought of as long-distance vectors; however, they also play a role in spread at local scales. To examine the importance of human-mediated dispersal at the local scale, we developed a diffusion model to fit the spread of the "wave front" through Lucas County, Ohio. Two components drive the velocity of a diffusion model: r, the intrinsic rate of increase of a population, and D, a distance coefficient. Because specific population growth parameters are unknown for EAB, the intrinsic growth rate was tested over several orders of magnitude. To test the hypothesis that natural dispersal is not a major factor of the invasion, we adjusted the model parameter values to generate dispersal patterns similar to those observed in Lucas County. These parameter values were then assessed for their validity, namely whether these values were consistent with known life history traits of EAB or other similar species. On the basis of the diffusion model, we estimated mean values for the intrinsic growth rate (r) of 76 and a distance coefficient (D) of 803 km. The value of r estimated by our model for EAB is substantially higher than for other insects, including long-horned beetle (0.02; Akbulut et al. 2007) and Mexican rice borer (0.11; Sétamou et al. 2003). Also, the furthest recorded flight of an individual borer is 20 km (Taylor et al. 2006), which is much lower than the rate estimated by our model. Thus, our analysis suggests that local dispersal, even at a small scale, is driven primarily by human-mediated movement rather than natural diffusion.

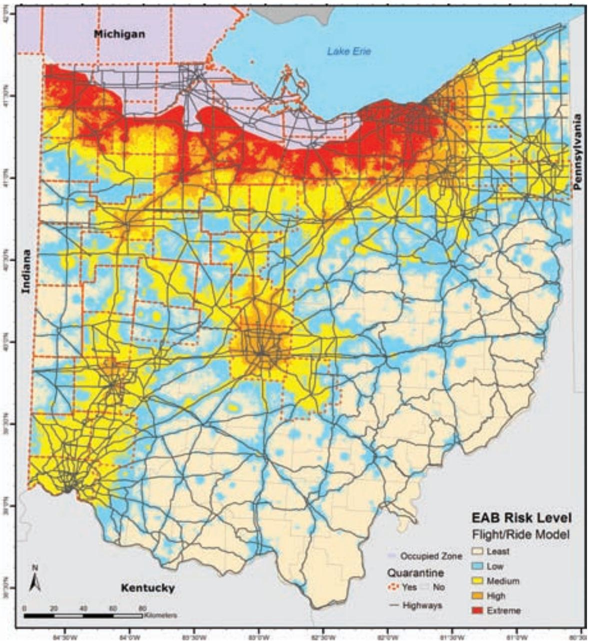
Though the flight model was based on the empirical pattern of spread, the insect-ride model incorporated the mechanisms of long-distance dispersal that are known to move EAB. We modified the SHIFT model by weighting factors related to potential human-assisted movements of infested wood or just hitchhiking insects: traffic on roads, urban areas, various wood products industries (including nurseries), population density, and campgrounds. To register the increased probability of insects invading areas adjacent to highways by somehow attaching to vehicles moving down the road, we assigned higher weights to two widths of major road corridors and weighted the risk on the basis of data obtained from Annual Average Daily Traffic volumes for Michigan and Ohio (National Highway Planning Network). Wood products industries were responsible for some outlier EAB invasions, so a scheme was developed to weight buffers around individual businesses dealing in wood products (data from the listing of Standard Industrial Classification [SIC] codes from Dunn and Bradstreet).

Finally, campgrounds are likely destinations of human-assisted EAB transport (Muirhead et al. 2006), primarily through the (mostly illegal) movement of firewood. First, we used a gravity model to identify the relative risk of different campgrounds becoming infested with the insect. Gravity models use distance and attraction of a destination to determine where people choose to travel (Bossenbroek et al. 2001). Thus, the relative risk of a campground becoming infested is based on campground attractiveness, which was estimated on the basis of the number of campsites and distance to the current distribution of EAB. Our results provided a relative rate of propagule pressure for each campground within the study area. Campgrounds with high rates of propagule pressure were predicted to exist throughout the study area and not just close to the current range of EAB. By combining the insect-ride and insect-flight models, we could predict the relative risk of EAB introduction in Ohio and Michigan (Fig. 9–3; Fig. 9–4).

To verify our model, we compared the output of our model to confirmed EAB observations as of 2007. The EAB data we used for verification was from a survey by the Ohio Department of Agriculture during 2003–2007 wherein they used girdled trees to monitor for EAB presence. Trees in the survey that were found to have EAB are called "detection trees." As of 2007, 255 detection trees were outside the occupied zone (Fig. 9–3). Of these locations, 32% fell in our highest-risk class, which primarily captured zones very near the core with high risk from both ride and flight models. Among the other detection trees, 30% fell in the high-risk class, 35% in the medium classes, 3% in the low classes, and 0 in the least class. This comparison suggests that our modeling efforts are capturing key aspects of the spread of EAB.

The detection tree data also provided insights about the importance of the different anthropogenic dispersal vectors in explaining the observed pattern of spread. Detection trees within Ohio were not randomly placed, so we compared the portion of total detection trees with the proportion of positive trees within particular distances of roads, campgrounds, and wood products industries. Most likely for convenience of sampling, ~50% (depending on year) of detection trees were within 2 km of a highway. However, ~75% of the positive detection trees were within 2 km of a highway, suggesting that highways are an important vector for the spread of EAB. We also found that roads with positive trees are generally nearer campgrounds and especially wood product industries. Thus, we conclude that roads, more than other anthropogenic factors, are the best predictors of long-distance dispersal by EAB.

Our model, by combining the insect's flight characteristics and human-facilitated movement, results in a map of spread that we believe estimated



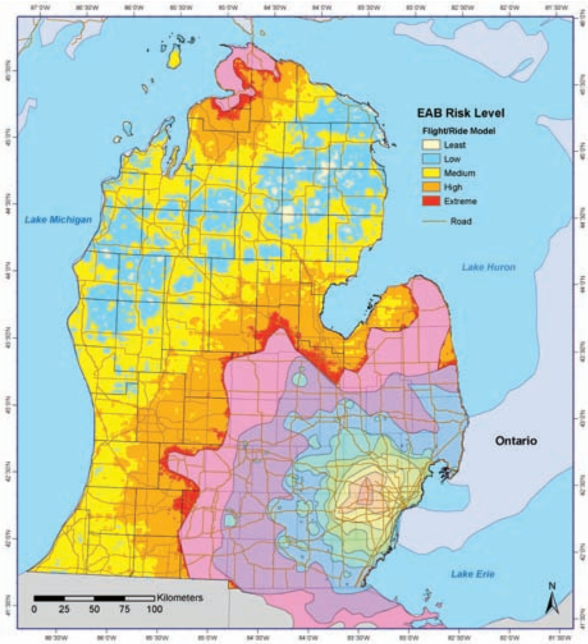


FIG. 9–3. Risk map for EAB in Ohio (based on Prasad et. al 2010). See also color plate.

FIG. 9–4. Risk map for EAB in Michigan. See also color plate.

risk areas for the next 2–4 years with much better accuracy than simple imputed statistical maps. We are able to outline degrees of risk in our maps that agree reasonably well with positive EAB locations. Our mapping effort should help managers better anticipate future risk from EAB, despite uncertain information, by locating areas of higher risk, thereby allowing managers to focus where infestations are most likely to occur. It may also help state and county agencies in the placement of traps or detection trees, or in sample plot design for researchers.

3) *Spatially Explicit Estimation of Ash Tree Value*

Estimating the value of ash trees in a spatially explicit manner required an inventory of ash stocks from across Ohio, both on forested land and in urban settings, as well as an estimate of losses to the overall economy. We focused on two primary elements of the economic impact of EAB. First, we assessed the value and potential costs of replacing ash trees in urban settings, including households, parks, and streets. Second, we developed a computable general equilibrium (CGE) model to estimate overall losses to the state economies of Ohio and Michigan in the case of a complete loss of ash stock.

To examine the local impact of an EAB invasion on urban and suburban communities Sydnor et al. (2007) used a survey of 200 Ohio Tree Cities. The costs assessed by these surveys included loss of landscape value, stump removal, and tree replacement. Total costs per 1,000 residents ranged from $157,600 to $664,800. When these values were extrapolated to the entire state of Ohio, Sydnor et al. (2007) estimated that the potential costs or losses from EAB-killed ash could range from $1.8 billion to $7.6 billion.

We recognize that assessing “costs” to individuals does not accurately convey how the EAB invasion impacts the larger statewide economy. To determine the annual regional economic consequences for Ohio and Michigan, a CGE model for the region was developed. CGE models are appropriate for determining the economic consequences of EAB outbreaks because they account for the fact that ash trees are inputs into many consumer goods. Seemingly local impacts of the invasion create ripple effects throughout the statewide economy owing to input interactions between industries. Our multisector, general equilibrium method for determining these complex regional economic consequences involves inter-industry linkages, production inputs (including labor and capital), households, government receipts and expenditures, and trade. Impacts to households occur when the spreading beetle causes prices and incomes to adjust to changing market conditions, and are calculated by measuring how much consumers are hurt by the resulting price changes.

The loss of ash tree harvests affects the Ohio and Michigan economies in four ways (Fig. 9–5). First, ash-dependent industries (e.g., logging operations, sawmills, processed wood firms) experience an input shortage along the supply chain, where a loss of ash trees in the logging sector trickles down to sawmills and processed wood firms. For this study, the loss of ash as an input was modeled by reducing the amount of final goods that could be produced by each industry. Second, parks, and consequently recreation activities, are impacted by a loss of ash trees, modeled as an increase in operating costs due to the removal and replacement of dead ash trees. Third, the demise of ash trees in residential yards means households must spend money to remove the trees. To incorporate these fees, household income was reduced by the average cost of ash removal. In addition, household expenditures on the removal of ash trees by landscaping businesses that remove and replace ash trees were taken into account. Fourth, state and local governments must remove ash trees, mainly along streets, which diverts funds from other public services. Government expenditures also lead to an additional increase in demand for landscaping businesses that provide ash tree replacement and removal. Given limited time and money, removal impacts affecting households, parks and recreation activities, and the state government would persist for 10 years until 100% of the ash were replaced, assuming that 10% of the trees would be removed annually. In the event that all ash trees would be destroyed, the impact on the logging sector would persist for upwards of 40 years.[1]

IMPLAN (Impact Analysis for Planning; MIG) data from 2003 provided detailed economic information for the CGE model. In addition, we aggregated 509 industry sectors into 14 categories. The logging, sawmill, and processed wood sectors were designated following Hushak (2005). The 11 remaining sectors (finished wood products, building, business services, transportation and storage, furniture manufacturing, consumer wood goods, recreation, paper products manufacturing, garden supply stores, parks, and miscellaneous) were grouped according to Iverson and Sydnor's research, which sorted through Ohio's industries and ranked each company's chance of using ash products from 1 (lowest) to 6 (highest), on the basis of the company's Standard Industrial Classification (SIC) number provided by the US Department of Commerce. Finally, we allowed

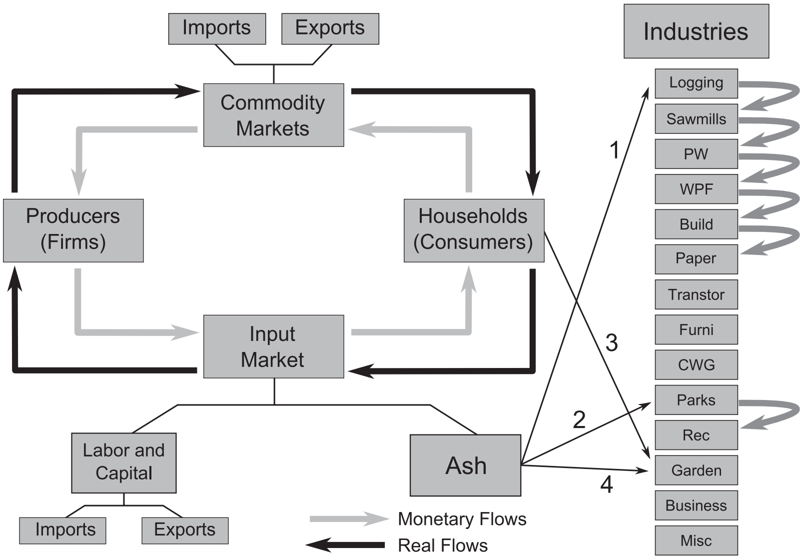


FIG. 9–5. The Ohio economy in terms of the sectors expected to be impacted by EAB. Arrow 1 represents the vertically integrated impacts from a loss of ash beginning with the logging sector. Arrow 2 represents the cost impact to parks and recreation sectors. Arrow 3 portrays the removal fee and consequent increase in demand of the garden sector. Arrow 4 represents the state governments' replacement fee and increase in demand for the garden sector. CWG, consumer wood goods; PW, processed wood; Transtor, transportation and storage; WPF, wood products finished. (Image from McDermott 2011.)

industries the ability to substitute other wood (e.g., maple) for ash. As ease of substitution for ash decreased, loss of productivity increased. The minimum impact occurred when the logging sector was affected, while the maximum impact occurred when all industries were unable to substitute for ash. In total, the model accounts for 7,776 combinations of substitution possibilities.

On the basis of the CGE model, the median impact from a complete loss of ash trees would result in an annual loss of $58.20 million in Ohio and $57.96 million in Michigan (Table 9–1). The maximum impact would result in an annual loss of $59.25 million in Ohio and $59.39 million in Michigan. On average, the states of Ohio and Michigan would experience an annual loss of 0.01% and 0.02% of their 2003 GDP, respectively. The sectors in which prices are projected to increase in the future are logging, sawmills, processed wood, finished wood products, paper, parks, and recreation. All other sectors' domestic prices would decrease.

TABLE 9–1. **Summary of annual median welfare impact from complete loss of ash harvest.**

Mode of Imapct	Ohio Impact	Michigan Impact
Vertically integrated production (excluding parks and recreation sectors)	–$2.85 million	–$3.81 million
Parks and recreation cost impacts	–$2.95 million	–$3.70 million
Household income reduction	–$51.92 million	–$49.93 million
Garden sector demand increase (household)	$5,924.00	$6,665.00
State cost impact	–$492,363.00	–$537,459.00
Garden sector demand increase (state)	$847.00	$1,032.00
Total average impact	–$58.20 million	–$57.96 million

The loss of ash affects households differently. For both Ohio and Michigan, the household income bracket of $25–$35K per year was the most heavily impacted. The results for the two states were similar, so we provide details on Ohio only here. On average, a household in the $25–$35K income bracket lost $14.32 annually (Table 9–2). Households in this income bracket yield the largest percentage of their income to removal of dead ash trees, which made the biggest impact on welfare in this model. Since the <$10K and $10–$15K household brackets own the lowest shares of labor and capital, they are impacted slightly differently from other household brackets. The <$10K bracket decreased consumption from all sectors with increased prices, and increased its consumption in all other sectors except for logging and sawmills, of which it purchased nothing. The $10–$15K bracket decreased consumption in sectors for which the price increased and decreased consumption in the building and consumer wood goods sectors. Household income brackets above $25K decreased their consumption of all commodities but decreased their consumption proportionally less in sectors whose prices decreased. On average, commodity prices for logging, processed wood, finished wood products, paper, recreation, and parks all increased. The IMPLAN data show that higher-income households consumed the most recreation and parks services and lost a higher amount of income to the removal of ash trees. These results imply that the mid- and higher-income brackets are the most impacted by EAB outbreaks.

The group with the largest annual welfare impact ($51.92 million in Ohio) is households faced with the removal of ash trees. In contrast, the average industry and parks/recreation impacts from an EAB invasion in Ohio result in an annual loss of $2.85 million and $2.95 million, respectively.

TABLE 9–2. **Annual Ohio impacts per individual households.**

Household Income	Minimum Impact ($\varepsilon_{LOG} = 1$)	Maximum Impact (*all* ε*'s* = 1)	Average Impact (over 7,776 scenarios)
<$10K	$1.13	$0.69	$0.91
$10-$15K	$0.31	$0.20	$0.26
$15-$25K	–$0.42	–$0.37	–$0.40
$25-$35K	–$14.31	–$14.32	–$14.32
$35-$50K	–$15.11	–$15.32	–$15.21
$50-$75K	–$16.81	–$17.36	–$17.08
$75-$100K	–$17.34	–$18.28	–$17.81
$100-$150K	–$19.19	–$20.49	–$19.84
>$150K	–$21.48	–$23.22	–$22.35

4) *Cost and Effectiveness of Different Prevention and Control Strategies*

Slowing or stopping the spread of an invasive species, such as EAB, is often a goal of local, state and federal managers. Different strategies can be utilized, such as EAB eradication at the edge of the expanding population, increasing outreach and education efforts to reduce human-mediated spread, or preventing the establishment of new long-distance/outlier populations. To evaluate the appropriate investment in prevention strategies, we assessed the cost and effectiveness of postinvasion control approaches in two ways. First, we collected data on the costs of removing outlier populations. Second, we modeled the effectiveness of eradicating outlier populations to slow the spread of EAB in Ohio (Croskey 2009).

Early in the invasion of EAB, when an outlier population was detected, the typical response in both Michigan and Ohio was to quarantine the area and attempt to eradicate the population through tree removal. Invaded trees and all host trees within a minimum half-mile buffer zone were removed. Removal was subsequently followed by herbicide treatment of stumps in woodlots and grinding of landscape stumps. For thirteen outlier sites in Michigan, removal cost nearly $6 million for more than 216,000 trees. However, despite the amount of money spent on these efforts, there was very little assessment of their effectiveness. Over time the eradication efforts have proved largely ineffectual, as new populations of the borer emerged. Likewise, managers in Ontario, Canada, cut down all ash trees within a 10-km radius of an infestation in 2003, which also proved to be ineffective, as additional populations were discovered just outside the ash-free zone in 2004 (Muirhead et al. 2006).

To assess the ability of eradication programs of outlier populations to slow the spread of EAB, we developed a spread model based on the risk map of Ohio from Prasad et al. (2010; Fig. 9–3). The spread model predicted the infested status of a location on the basis of two factors: the distance to a known source of EAB and the risk level from the aforementioned map. In order to run multiple trials of our stochastic model in a timely manner, we increased the cell size of the Prasad et al. (2010) model by a factor of ten for the long-distance risk map, resulting in cells measuring 2,700 m by 2,700 m. In addition, we randomly pre-seeded long-distance infestations into the map; this reflected the long-distance observations observed in Ohio the same year the wave front reached the state (i.e., the first "year" of this model). The local spread component of the model was developed to mimic the wave front of the invasion known thus far, which occurred at about 20 km per year between 1998 and 2006 (Prasad et al. 2010).

To test the hypothesis that eradication would significantly slow the invasion spread and therefore lower annual costs, eradication events were built into the model. To simulate an eradication program, a certain percentage of infested cells were randomly returned to uninfested after each year of the model. Several levels of eradication were analyzed—5%, 10%, 15%, 20%, 25%, 50%, 75%, and 95%. Model simulations for each level of eradication were run for 30 years, 20 times. The locations of infested cells were plotted on a census map, allowing us to calculate the number of humans impacted and therefore potential costs incurred by the infestation each year. The census values obtained were averaged for each year across all trials.

The statewide spread model without any eradication events predicted complete infestation of the state within 26 years. However, the last seven years of the infestation under this strategy show little increase in the number of people affected—99% of the state of Ohio is infested at year 19. The various eradication strategies postponed EAB infestation by 2–4 years. With 95% eradication occurring each year, the state was completely infested in 26 years. The halfway point of the infestation in Ohio, 5.5 million people, occurred after eight years under the no-eradication strategy, and eleven years into the infestation under the 95%-eradication strategy. In sum, while eradication programs can slow the spread of EAB, whether such efforts are economically beneficial is questionable.

5) *Optimizing Resources by Linking Distribution and Spread Models with Estimates of Potential Damages*

To link models of spread, impact, and effectiveness of control efforts we used Stochastic Dynamic Programming (SDP) to optimize inputs from the various models. In the absence of well-defined dose-response relationships over strategies of prevention and control we narrowed the focus to an implementation of public policy early in the invasion, when the beetle was first spreading from Detroit, MI. We also focused the SDP framework on the optimal timing and stringency (or aggressiveness) of strategies to control the spread. In our model, optimal timing depends on the extent of the spread, current damages, expected future damages, cost of the strategy, impact of the strategy, and stochastic dynamic spread of EAB.

Policies to control an invasive species like EAB are investments of scarce resources in the face of uncertainty. Natural variability in factors like weather and biological processes of the species (growth, mortality, movement) as well as uncertainty arising from human interactions can randomly alter the dynamics of spread. This variability in spread dynamics translates into uncertain costs and benefits of control actions. Controlling EAB can also be postponed and requires the consideration of two kinds of irreversibilities that work in opposition and determine the effect of uncertainty on the optimal control decision. First, environmental damage due to EAB can be partially or totally irreversible. On the basis of a precautionary principle argument, this irreversibility calls for more immediate control actions than suggested by traditional cost-benefit analysis. Second, policies aimed at controlling the spread of the beetle impose sunk costs on society that may prove to be undesirable as more information on the invasion is revealed over time, causing decision makers to be more cautious about allocating scarce resources to control (an economic precautionary principle). This "fear of regret" delays control action beyond what would be suggested by traditional cost-benefit analysis. There is also a tradeoff between the timing and stringency of EAB policy strategies in terms of whether spread is slowed, stopped, or reversed. More stringent policies commit decision makers to larger sunk costs, which cause more cautious behavior by decision makers. Thus more stringent EAB policies will be delayed further into the future.

An alternative to cost-benefit analysis that incorporates irreversibility and uncertainty is the real options examined by Dixit and Pindyck (1994). Real options analysis specifies a stochastic process for the asset of interest (here, uninvaded area) and solves for the total value of the investment opportunity in order to determine an optimal threshold below which investment is optimal and above which investment should be postponed. However, our analysis extends the existing literature in three important ways. First, the costs and benefits of EAB control imply the existence of an optimal degree of control in addition to an optimal time to control that are linked and must be considered jointly. Second, the cost of stopping EAB spread is likely to increase over time as the invasion progresses, which differs from the traditional assumption of a fixed investment cost. Finally, we incorporate upper bounds on the stochastic process that correspond to physical barriers (Great Lakes) to EAB spread. Since decision makers may consider benefits of control that accrue within their jurisdiction only, we also allow for the possibility of perceived barriers (state and federal boundaries). When faced with these barriers, decision makers will optimally engage in a significantly lower amount of control.

CONTROLLING A BOUNDED EAB INVASION. The model assumes EAB was introduced into Detroit, MI, in 1998, became established in a new habitat, is spreading from the point of introduction, and is causing damage in the areas it is spreading. We assume that the rate of spread can be permanently reduced from the current rate to some lower rate through a control policy at a particular cost. A risk-neutral social planner must optimally select 1) the rate to which invasive species spread should be reduced, and 2) the socially optimal time to do so, in order to minimize the expected present value of EAB damages and control costs.

An optimization problem such as this must be solved in two steps (Saphores and Carr 2000): 1) the optimal stringency of the policy to be adopted based on current known damage and 2) whether a policy with that level of stringency should be adopted immediately. At each instant in time optimal stringency minimizes expected damage and cost from that point forward by lowering the spread rate at a sunk cost (control cost that cannot be recovered). Immediate policy adoption lowers the growth in expected damage but incurs the sunk cost and forfeits the option value (a conditional value of information regarding the characteristics of the invasion). Otherwise policy adoption is postponed until the next instant in time where the decision maker determines a new spread rate reduction on the basis of current damage and is faced with the same binary choice concerning policy adoption. Thus possible outcomes for the EAB control policy are: 1) immediate slowing of spread, 2) delayed slowing of spread, 3) immediate reversal of spread, or 4) delayed reversal of spread.

For our model, management was conducted in ten different zones (Fig. 9–6). As EAB spreads outward from the introduction point, damages are incurred by ecosystems and by industries that rely on these ecosystems. The optimal timing of EAB control relies on comparing termination and continuation values. The termination value is the minimum of the precontrol or postcontrol damage position and represents the payoff received by controlling immediately. The precontrol damage position is equal to the value of all precontrol future damages. The postcontrol damage position is equal to the sum of the postcontrol future damages and the control cost. The continuation value represents what one would receive by abstaining from invasive species control and the value of being able to postpone the control decision. The value of being able to postpone control efforts in order to gain more information about EAB spread is known as the option or time value. This option value is an additional cost that must be overcome in order to trigger an investment in EAB control and arises as a result of the uncertainty inherent in the spread of the beetle.

For the dispersal of EAB through the management zones we parameterized a geometric Brownian motion (GBM) process with the known dispersal patterns from 1998 and 2006. The spread data provided in step 2 is used to calculate maximum likelihood estimates of the drift and volatility parameters for the GBM spread process. According to Sharov and Liebhold (1998), the cost of eradicating a similar invasive forest insect, gypsy moth, was $31,000 per square kilometer. Given the estimated 175-km length of the EAB population front in 2002, and assuming all control activities take place in a barrier zone along the population front that is 1 kilometer wide, a plausible upper bound for the cost of stopping EAB spread in 2002 would be $31,000 * 175 = $5 billion, which implies that the total cost of stopping EAB spread in 2002 would have been approximately $3.6 billion. Actual values will vary depending on the control method (tree removal, pesticide application, biological control, quarantines) and could be adjusted as needed.

Since most invasive species policies are formulated at the state and federal level, control policies are presented from the perspective of the federal government as well as individual states. In our scenario, the barrier in several management zones is marked by a natural feature like a lake, while in other cases barrier location depends on who makes the decision to invest in EAB control. If the decision is made at the state level, state boundaries mark the upper absorbing barrier, whereas national boundaries delineate that barrier in decisions made by federal policy makers. This implies that our results will be most applicable to state and federal governments developing isolated EAB policies, but could easily be extended to allow for cooperation among government entities. Any decision to control spread at the federal level instead of the state level would sig-

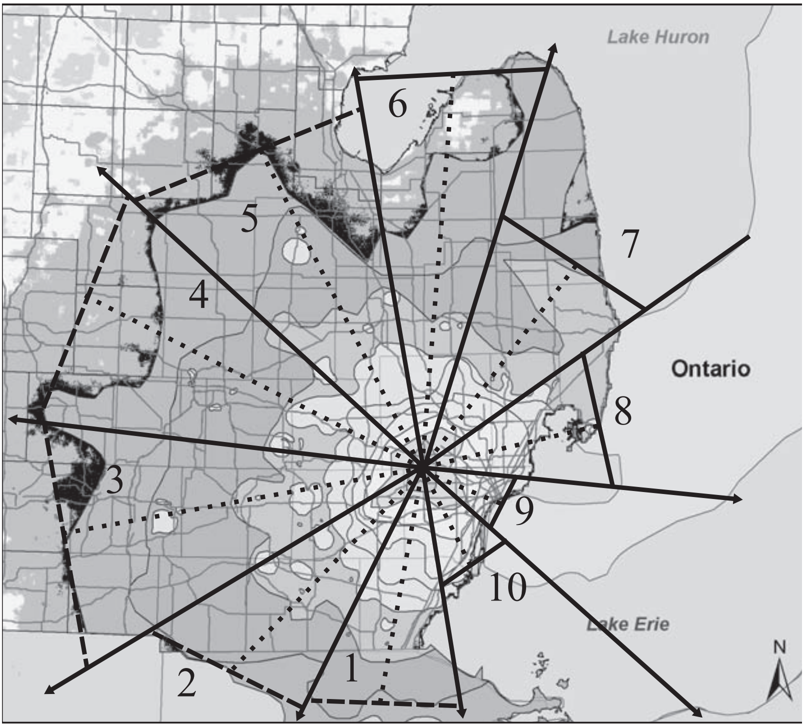


FIG. 9–6. Hypothetical management zones for EAB in the Detroit, MI, region (from Sims 2009).

nificantly increase the upper absorbing barrier in zones 1, 2, and 3. Spread in these zones will largely be responsible for invasion of the rest of the country.

OPTIMAL EAB CONTROL STRATEGY. The optimal EAB control strategy as predicted by our real options model depends on whether the decision making is based on a federal or state perspective. Table 9–3 presents characteristics of the optimal policy to control EAB at the federal level and the state level for Michigan. The total expected present value of EAB damages within the United States under this optimal control policy is $647 million and $726 million for the federal and state scenarios respectively. The optimal investment in EAB control in the state of Michigan by the federal government is over $2 billion, while it would only be $1.1 billion

TABLE 9–3. **Optimal control of EAB by the federal government or state of Michigan.**

		Management zone						
	Manager	1	2	3	4	5	6	7
Upper barrier (km)	Federal	1600	2100	3200	273	627	167	122
	State	80	108	278	273	627	167	122
Time to reach upper barrier (yrs)	Federal	334.55	294.54	219.76	48.18	129.97	3.57	2.15
	State	1.04	3.90	62.23	48.18	129.97	3.57	2.15
% reduction in spread rate	Federal	95.5%	91.7%	90.6%	86.40%	92.1%	0.4%	0.03%
	State	0.00%	0.30%	85.8%	86.4%	92.1%	0.40%	0.02%
Optimal spread rate (%/yr)	Federal	0.02	0.02	0.03	0.06	0.04	0.49	0.48
	State	0.46	0.23	0.04	0.06	0.04	0.49	0.48
Present Value cost (millions $)	Federal	672.60	214.74	247.96	390.22	509.54	0.14	0.00
	State	0.00	0.05	228.40	390.56	509.54	0.14	0.00
Expected Present Value damages (millions $)	Federal	68.23	47.19	33.15	74.43	50.96	227.04	145.87
	State	73.64	108.42	46.13	74.09	50.96	227.04	145.87

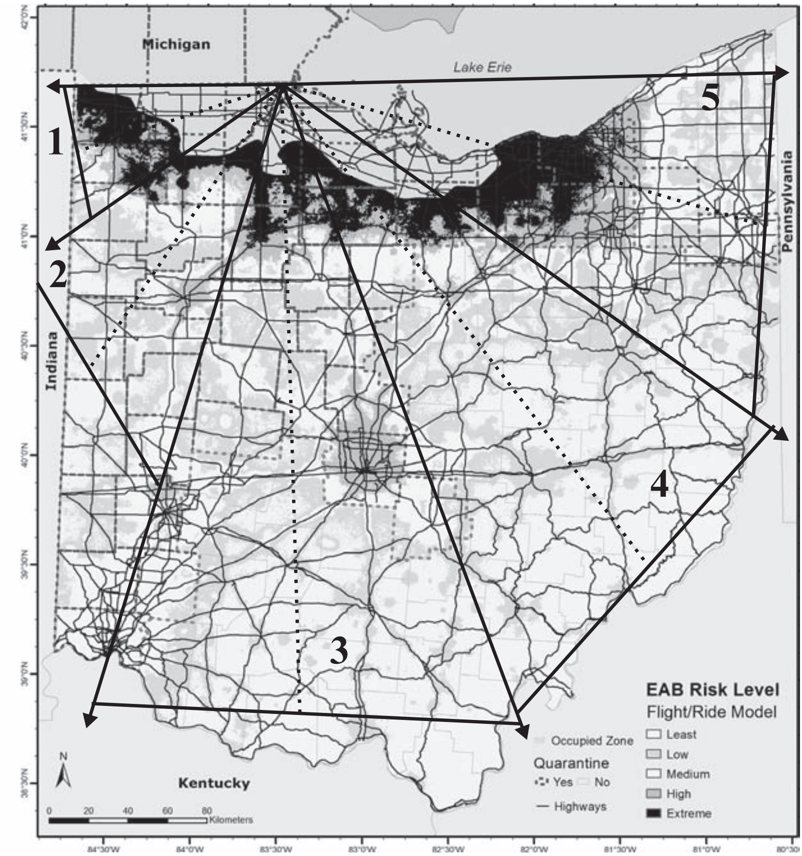


FIG. 9–7. Hypothetical management zones for EAB in Ohio (from Sims 2009).

by the state of Michigan. Because of the lower level of control, expected damages within Michigan under state-level control are greater than under the federal policy.

Given the optimal response to EAB by the state of Michigan in 2002, Ohio would become the next state to consider the option to control the borer. Specifically, the EAB population front would have reached Ohio in 2004 somewhere near the city of Toledo. Because the control problem facing Ohio is fundamentally different than the problem facing Michigan, five new management zones are created that encompass Ohio (Fig. 9–7). Characteristics of the optimal policy to control the invasion by Ohio are presented in Table 9–4. Given the parameters selected to represent EAB

TABLE 9–4. **Optimal control of EAB by the state of Ohio.**

	Management zone				
	1	2	3	4	5
Upper barrier (km)	112.59	200.16	341.94	321.09	258.54
Time to reach upper barrier (yrs)	11.92	34.78	58.75	64.39	44.56
% reduction in spread rate	10.50%	71.00%	81.50%	72.10%	78.50%
Optimal spread rate (%/yr)	0.27	0.12	0.08	0.07	0.10
Present Value cost (millions $)	4.02	109.18	160.19	55.22	166.90
Expected Present Value damages (millions $)	54.45	28.64	17.72	9.79	25.91

spread in Ohio, state officials would find it optimal to spend nearly $496 million on EAB control within the state. As a result EAB damages in Ohio would total approximately $147 million.

A full comparison of EAB control policies formulated at the state and federal levels would require that the control option be evaluated in each potentially invaded state starting when that state is expected to become invaded. However, data limitations become an even bigger issue as an invasion progresses. For that reason we limited our analysis to the control decisions of two states: Michigan and Ohio. Even with this limited analysis EAB will clearly spread much faster under state-level control compared with federal EAB policies. If the federal government had optimally responded to the EAB invasion in 2002, $2 billion would have been spent on control and EAB might still be contained within the state of Michigan. However, if EAB control had been relegated to individual states, over $1.5 billion would have been optimally spent by Michigan and Ohio to control EAB and the invaded area would be much larger.

Conclusions

Our analyses suggest it would have been optimal to spend over $1 billion at the beginning of the EAB invasion to slow or stop its progress. Considering we addressed only Ohio and Michigan, however, we cannot say to what extent it is worth investing in eradication events now or in the future without further analysis. Nonetheless, each step of our project contributed important results that will benefit managers of EAB and invasive species generally:

Step 1: Currently there is no known limit to the range of EAB except the distribution of ash trees themselves. Our efforts, however, showed that for an economic analysis trees grown for harvest and for recreation/landscaping are important to consider.

Step 2: EAB dispersal is a result of both human-mediated and natural spread. Even at the local scale, human-mediated dispersal is important. At the state scale, roads are the primary human factor associated with EAB spread compared with campgrounds or the wood products industry.

Step 3: The financial impact of EAB invasion will be substantial to individual members of a community, involving the costs of removal and replacement of dead trees. Using a CGE, we estimate that the welfare loss to the states of Ohio and Michigan will exceed $110 million annually. These losses will affect mostly individuals earning over $25,000.

Step 4: Eradication efforts for EAB were expensive and rarely successful, though formal evaluation of the effectiveness of eradication programs has been minimal. Eradication of long-distance outbreaks in Ohio would have slowed the spread by several years, yet the entire state is expected to be infested within 20 years.

Step 5: Slowing the spread of EAB at the beginning of its invasion would have been worth more than $1 billion. The total amount it is worth for management actions is also dependent on the agency (federal vs. state in this case) making the decision.

Emerald ash borer will continue to spread regardless of human intervention. However, we have demonstrated that slowing its spread can reduce the rate of impact and eventual welfare loss.

Policy Implications

Our analysis of the emerald ash borer invasion addresses several complex issues in generating invasive species policy, such as coordinating uncertainty in ecological processes and uncertainty in the timing and magnitude of control investment or effort. Addressing each of these issues highlights several implications for policy makers. First, policy makers should encourage investment in models of long-distance spread. The spread of invasive species is often a result of multiple vectors, including natural and anthropogenic mechanisms as well as an understanding of potential habitat. The anthropogenic forces that move invasive species frequently result in long-distance jumps, ultimately causing the overall rate of spread to rapidly increase. These vectors are often similar for multiple species, so any understanding of how one pathway, such as movement of firewood, affects the spread of a species will aid in predictions of other related species that have yet to be introduced into nonnative areas.

Second, understanding how resources that are impacted by invasive species are integrated into larger regional economies can influence policy decisions. Our analyses highlight that the damages of invasive species are probably not restricted to specific localities or limited demographic groups. Rather, because our economy is a complex network of sectors, the impact to one sector of the economy is likely to influence many other sectors, with some sectors perhaps benefitting even though the economy has an overall loss in welfare. Likewise, households with disparate income categories may be impacted differently. Thus, policy makers may need to balance their response because of how these different constituencies are impacted.

Third, our economic analyses highlight the importance for policy makers to recognize the temporal dynamics of an invasion. The real options framework employed in this work emphasizes the importance of timing for slowing or stopping the spread of invasive species. Policy decisions and their subsequent implementation occur at specific times and are subject to uncertainty and changes in damages. By responding quickly to an invasion, policy makers sacrifice the option of gaining more knowledge about a species and how to control it, which may reduce the cost of control. On the other hand if implementation is delayed, the damages incurred due to the invasive species are likely to increase.

Finally, prevention of invasive species in the first place should be a primary policy goal. We predict EAB will cause an annual loss of welfare of several million dollars for Michigan and Ohio. Although a focus on prevention and early eradication is not a new idea (see Simberloff 2003), our findings about the long-term economic impacts of EAB will hopefully help convince policy makers that prevention, monitoring, and early detection are well worth the cost (Leung et al. 2002).

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Notes

1. Using an average growth rate for ash trees as 22.5 inches a year and an average maturity height of 885 inches leads to a rotation period of 40 years (Arbor Day 2009; Ohioline 2009; Treehelp.com 2009).

Literature Cited

Akbulut, S., A. Keten, I. Baysal, and B. Yüksel. 2007. Effect of seasonality on the reproductive potential of *Monochamus galloprovincialis* (Coleoptera: Cerambycidae) reared in black pine logs under lab conditions. *Phytoparasitica* 36:187–198.

BenDor, T. K., S. S. Metcalf, L. E. Fontenot, B. Sangunett, and B. Hannon. 2006. Modeling the spread of the emerald ash borer. *Ecological Modeling* 197:221–236.

Bossenbroek, J. M., C. E. Kraft, and J. C. Nekola. 2001. Prediction of long-distance dispersal using gravity models: zebra mussel invasion of inland lakes. *Ecological Applications* 11:1778–1788.

Croskey, A. K. 2009. Evaluating the costs of the emerald ash borer invasion in Ohio. Master's thesis, University of Toledo.

Dixit, A. K., and R. S. Pindyck. 1994. *Investment under Uncertainty*. Princeton, NJ: Princeton University Press.

Hushak, L. 2005. Economics of the forest products industry in Ohio. Unpublished manuscript.

Iverson, L. R., A. Prasad, J. Bossenbroek, D. Sydnor, and M. W. Schwartz. 2010. Modeling potential movements of the emerald ash borer: the model framework. In *Advances in Threat Assessment and Their Application to Forest and Rangeland Management*, edited by J. M. R. Pye, H. Michael, Y. Sands, D. C. Lee, and J. S. Beatty, 581–597. Portland, OR: US Department of Agriculture, Forest Service, Pacific Northwest and Southern Research Stations.

Iverson, L. R., A. Prasad, and M. W. Schwartz. 1999. Modeling potential future individual tree-species distributions in the eastern United States under a climate change scenario: a case study with *Pinus virginiana*. *Ecological Modelling* 115:77–93.

Iverson, L. R., M. W. Schwartz, and A. M. Prasad. 2004. How fast and far might tree species migrate in the eastern United States due to climate change? *Global Ecology and Biogeography* 13:209–219.

Leung B., D. M. Lodge, D. Finnoff, J. F. Shogren, M. A. Lewis, G. Lamberti. 2002. An ounce of prevention or a pound of cure: bioeconomic risk analysis of invasive species. *Proceedings of the Royal Society B* 269:2407–2413.

MacFarlane, D. W., and S. P. Meyer. 2005. Characteristics and distribution of potential ash tree hosts for emerald ash borer. *Forest Ecology and Management* 213:15–24.

McDermott, S. M. 2011. Economics with a view: invasive species ecosystem externalities. PhD diss., University of Wyoming.

Miles, P. D., G. J. Brand, C. L. Alerich, S. W. Woudenberg, J. F. Glover, and E. N. Ezzell. 2001. The forest inventory and analysis database: database description and users manual, version 1.0. GTR NC-218. St. Paul, MN: North Central Research Station, USDA Forest Service.

Muirhead, J. R., B. Leung, C. Overdijk, D. W. Kelly, K. Nandakumar, K. R. Marchant, and H. J. MacIsaac. 2006. Modeling local and long-distance dispersal of invasive emerald ash borer *Agrilus planipennis* (Coleoptera) in North America. *Diversity and Distributions* 12:71–79.

Poland, T. M., and D. G. McCullough. 2006. Emerald ash borer: invasion of the urban forest and the threat to north Americas ash resource. *Journal of Forestry* 104:118–124.

Prasad, A. M., L. Iverson, M. Peters, J. Bossenbroek, S. N. Matthews, D. Sydnor, and M. Schwartz. 2010. Modeling the invasive emerald ash borer risk of spread using a spatially explicit cellular model. *Landscape Ecology* 25:353–369.

Saphores, J. D., and P. Carr. 2000. Real options and the timing of implementation of emissions limits under ecological uncertainty. In *Project Flexibility, Agency, and Competition: New Developments in the Theory and Application of Real Options*, edited by M. J. Brennan and L. Trigeorgis. New York: Oxford University Press.

Schwartz, M. W., L. R. Iverson, and A. M. Prasad. 2001. Predicting the potential future distribution of four tree species in Ohio, USA, using current habitat availability and climatic forcing. *Ecosystems* 4:568–581.

Sétamou, M., J. S. Bernal, T. E. Mirkov, and J. C. Legaspi. 2003. Effects of snowdrop lectin on Mexican rice borer (Lepidoptera: Pyralidae) life history parameters. *Journal of Economic Entomology* 96:950–956.

Sharov, A. A., and A. M. Liebhold. 1998. Bioeconomics of managing the spread of exotic pest species with barrier zones. *Ecological Applications* 8:833–845.

Simberloff, D. 2003. How much information on population biology is needed to manage introduced species? *Conservation Biology* 17:83–92.

Sims, C. 2009. Essays on the bioeconomic control of invasive species and forest pests. PhD diss., University of Wyoming.

Sydnor, T. D., M. Bumgardner, and A. Todd. 2007. The potential economic impacts of emerald ash borer (*Agrilus planipennis*) on Ohio, U.S., communities. *Arboriculture and Urban Forestry* 33:48–54.

Taylor, R. A., T. M. Poland, L. S. Bauer, K. N. Windell, and J. L. Kautz. 2006. Emerald ash borer flight estimates revised [abstract]. In Emerald Ash Borer and Asian Longhorned Beetle Research and Development Review Meeting, October 29–November 2, 2006; Cincinnati, OH, FHTET 2007–04, edited by V. Mastro, D. Lance, R. Reardon, and G. Parra, 10–12. Morgantown, WV: US Forest Service, Forest Health Technology Enterprise Team.