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Abstract

Detection of emerald ash borer, *Agrilus planipennis* Fairmaire (Coleoptera: Buprestidae), an invasive forest pest, is difficult in low density populations warranting continual development of various trapping techniques and protocols. Understanding and predicting landing behavior of *A. planipennis* may assist in the further development of trapping techniques and improvement of trapping protocols for widespread survey programs in North America. Three multiple regression models were developed using ash tree vigor and crown light exposure to predict the landing behavior of *A. planipennis*. These models were then used to predict the landing density of *A. planipennis* at separate sites and in separate years. Successful prediction of *A. planipennis* capture density at the test sites was limited. Even though the multiple regression models were not effective at predicting landing behavior of *A. planipennis*, tree characteristics were used to predict the likelihood of *A. planipennis* landing. Trees predicted as having high likelihood of landing had 3.5 times as many *A. planipennis* adults/m^2 on stem traps than trees predicted as having low likelihood of landing. While the landing density of *A. planipennis* may not be efficiently predicted, the utility of these predictions may be in the form of identifying trees with a high likelihood of *A. planipennis* landing. Those high likelihood trees may assist in improving existing detection programs and techniques in North American forests.

Since its discovery in North America in 2002, *Agrilus planipennis* Fairmaire (Coleoptera: Buprestidae, emerald ash borer) has caused significant mortality of ash (*Fraxinus* spp.) in numerous U.S. states and Canadian provinces, especially in black, green, and white ash (*F. nigra* Marsh., *F. pennsylvanica* Marsh., and *F. americana* L., respectively) (Poland and McCullough 2006, Poland 2007). Originally introduced from Asia, there is evidence that *A. planipennis* may have been present in North America since the mid-1990s (Siegert et al. 2007). Establishment of outlier, incipient populations of *A. planipennis* typically occur through human movement of ash wood products and ash nursery stock (Cappaert et al. 2005). Movement of ash commodities accounts for the vast majority of long-distance spread for this beetle; however, natural spread does occur and there is evidence of minor secondary spread of adults (Buck and Marshall 2008).

Detection techniques for *A. planipennis* have included visual surveys for symptoms in ash trees, artificially stressed trap trees, and lured traps for adults (e.g., Cappaert et al. 2005, de Groot et al. 2006, Storer et al. 2007, Crook et al. 2008, Francese et al. 2008). Harvesting ash trees artificially stressed

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with a girdle, peeling the entire tree of bark, and inspecting for larval occurrence is considered the most effective detection technique. However, peeling of girdled ash trees is time consuming and expensive to establish and examine, and girdled trees can be hazards in the forest (Crook and Mastro 2010, USDA APHIS PPQ 2010).

Previous studies have presented mixed results regarding larval and adult *A. planipennis* densities and the effectiveness of unwounded ash trees relative to other detection techniques. Marshall et al. (2009, 2010) found no difference in larval density or adult landing between unwounded ash and girdled trees. However, Anulewicz et al. (2008) and Porter (2009) reported that girdled ash resulted in greater adult landing and higher larval densities than unwounded ash. In addition, McCullough et al. (2009 a,b) found differences in both larval and adult densities of girdled and unwounded ash at study sites with low population densities but differences were less pronounced at sites with moderate to high population densities. Although there isn't a clear differentiation in capture rates of *A. planipennis* adults on girdled and unwounded ash, trapping of this pest on unwounded trees may still be an important addition to a survey program along with other detection techniques. The objectives of this study were to 1) model the landing density of *A. planipennis* adults on ash trees without an artificial wound at sites with different population densities, 2) to test the models by predicting landing rates of *A. planipennis* adults, and 3) test the hypothesis that trees identified as having a high likelihood of *A. planipennis* adults landing do have more adults land on traps than low likelihood trees.

Materials and Methods

Model development. During spring 2008, 374 ash trees were identified at Burt Lake and Harrisville State Parks, MI, and during spring 2009, 42 total ash trees were identified at Farnsworth and Providence Metroparks, OH, for development of *A. planipennis* landing behavior models (Fig. 1). All trees were left unwounded with no artificial stress applied. Each tree was wrapped with a 0.5 m wide plastic band centered at breast height and coated with Tangle-Trap Coating (The Tanglefoot Co., Grand Rapids, MI). Traps were checked every two weeks and adult *A. planipennis* were collected. Trapping surface area was calculated and used to determine landing density of *A. planipennis* adults (adults/m^2). At Burt Lake and Harrisville State Parks, categorical assessments of crown class/position (1 = superstory, 2 = overstory, 3 = understory, 4 = open canopy), crown light exposure (CLE, 0-5, where each category is a count of sides and top receiving direct sunlight), and tree vigor (1-5, where 1 = healthy and 5 = standing dead) were made following USDA (2005) and Millers et al. (1991). Based on the 2008 results of multiple regression with step-wise variable selection (Porter 2009), categorical crown assessment variables were chosen for subsequent model development at Farnsworth and Providence Metroparks.

Median tests for independent samples (Sheskin, 1997) were used to test for differences in categorical tree assessment variables used to develop the models between trees with *A. planipennis* landing and those without. Three individual multiple regression models were fit using data from the 2008 state parks (2008 model), 2009 metroparks (2009 model), and a pooling of the 2008 and 2009 data (combined model) for adults/m^2 (dependent) using the categorical variables (independents) of the crown assessments. Akaike Information Criterion with a correction (AICc) was used to compare the relative fit of the three models in relation to subsequent residual sum of squares between observed and predicted values (Johnson and Omland 2004, Murtaugh 2009).

Model testing. During spring 2009, 40 trees at each of Deford and Shiawassee State Game Areas, MI, were identified for testing the *A. planipennis* landing behavior models (Fig. 1). Trees were left unwounded, wrapped with Tangle-Trap coated plastic, and checked using the same technique described in model development. The data sets from 2009 at Deford and Shiawassee were used to test model validation and gauge the efficacy of those models to predict adults/m^2. Predicted values of adults/m^2 for each tree at Deford and Shiawassee were calculated using the categorical crown assessments with the three previously developed models. AICc was used to compare the relative fit of the three models in relation to subsequent residual sum of squares between observed and predicted values at each of Deford and Shiawassee. Paired *t*-tests were used to compare observed and predicted values. Pearson correlation was used to test the relationships between the predicted and observed values, as well as predicted and residual values.

Landing prediction. During spring 2010, 30 trees at each of Deford State Game Area and Young State Park, MI, were identified for predicting the likelihood of adult *A. planipennis* landing (Fig. 1). Trees were left unwounded, wrapped with Tangle-Trap coated plastic, and checked using the same technique described in model development and model testing. Trees were selected with a range of crown assessment categories in an effort to provide different likelihoods of adult *A. planipennis* landing. Using the models developed, selected trees were then placed into two categories of high and low likelihood of adult *A. planipennis* landing. Proportions of trees with *A. planipennis* detection (1, 0) within each vigor and CLE combination were calculated. Those vigor and CLE combinations with proportions ≥ the median proportion were categorized as high likelihood and those combinations with proportions < the median were categorized as low likelihood. Trees were pooled across the two sites for analysis. One-tailed *t*-tests were used to compare the number of adult *A. planipennis* landing on high and low likelihood trees. Chi-squared was used to test if detection (1,0) was independent of the likelihood category assigned to a tree.

Results

Model development. Of the 374 trees wrapped at Burt Lake and Harrisville State Parks, 47 trees had a total of 210 adult *A. planipennis* landing. In these parks, ash accounted for 15.1 percent of basal area. Using step-wise variable selection, total *A. planipennis* adults captured and adults/m^2 was positively related to CLE at the state parks. In addition, total *A. planipennis* captured was positively related to tree vigor. Crown class/position was not significantly related to the total *A. planipennis* captured. Since using CLE and tree vigor to produce a model for adults/m^2 resulted in a significant model (Porter 2009), these two categorical variables were used for further model development, testing, and landing predictions. Trees wrapped at Burt Lake and Harrisville resulted in a mean landing rate of 1.19 adults/m^2 (SD 5.98) with a median vigor and CLE of 1 and 3, respectively. The probability of trees being greater than the overall median vigor value of 1 and CLE value of 3 was not the same between trees with *A. planipennis* landing and without (χ^2 = 11.98, df = 1, $P < 0.001$; χ^2 = 12.66, df = 1, $P < 0.001$, respectively). This result suggested that trees without adult *A. planipennis* landing were more likely to be healthier, with a median vigor rating of 1, and had less exposure of the crown to direct sunlight, with a median CLE value of 2.5, than trees with adult landing. Conversely, trees with vigor ratings greater than 1 or more crown exposure to direct sunlight were more likely to have adult *A. planipennis* captures.

Of the 42 trees wrapped at Farnsworth and Providence Metroparks, 33 trees had a total of 587 adult *A. planipennis* landing. In these parks, ash accounted for 27.7 percent of basal area. Wrapped trees resulted in a mean of 45.72 adults/m^2 (SD 78.00), with median vigor and CLE values of 1 and 3, respectively. The probability of trees being greater than the overall median CLE value of 3 was not the same between trees with *A. planipennis* landing and without (χ^2 = 5.14, df = 1, P = 0.023); trees without adult landing were more likely to have less exposure of the crown to direct sunlight with a median CLE value of 2. However, the probability

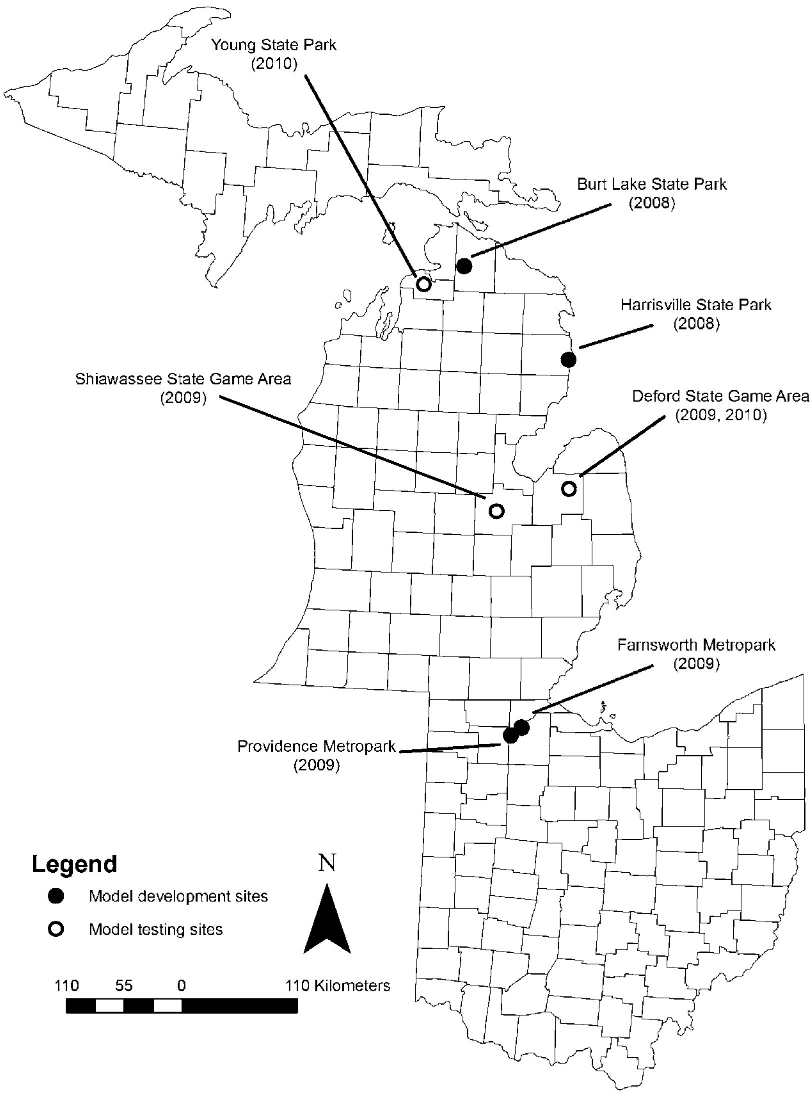

Figure 1. Distribution of sites in Michigan and Ohio, USA (with trapping year).

of being greater than the median vigor value of 1 was not different between trees with *A. planipennis* landing and without (χ^2 = 3.54, df = 1, *P* = 0.060).

The 2008 data from Burt Lake and Harrisville State Parks, the 2009 data from Farnsworth and Providence Metroparks, and the combined model (both 2008 and 2009 data) all resulted in a significant multiple regression models (Table 1). The fit of the multiple regression equations, however, were variable across the data sets used. The combined model resulted in the lowest AICc value (Table 1). Overall using the combined 2008 and 2009 data, the probability of being greater than the overall median vigor value of 1 and CLE value of 3 was not the same between trees with *A. planipennis* landing and without (χ^2 = 12.0, df = 1, *P* = 0.001; χ^2 = 13.5, df = 1, *P* < 0.001, respectively); similar to that of the 2008 data separately.

Model testing. At Deford, 3 trees had a total of 3 adults captured. At Shiawassee, 40 trees captured a total of 991 adults. Ash accounted for 30.0 and 40.5 percent of the basal area at test sites of Deford and Shiawassee State Game Areas, respectively. When predicted *A. planipennis* adults/m^2 values were calculated, negative density values were converted to zeros. Predicted and observed adults/m^2 didn't differ at Deford using the 2008 model and at Shiawassee using the 2009 model (Table 2). Also, the 2008 model resulted in the lowest AICc value for Deford, and the 2009 model resulted in the lowest AICc value for Shiawassee, suggesting these are the better models for these two sites because the resulting residual sum of squares was smallest for those models and the 2009 model had fewer parameters (Table 3). Only the 2008 and 2009 models predicted values correlated to the observed values when Deford and Shiawassee data were pooled (Fig. 2). Correlations between the predicted adults/m^2 and the residuals for the 2008 and combined models were not significant when the two test sites were pooled (Fig. 3A, C). However, the 2009 model had a significant relationship between the predicted values and the residuals (Fig. 3B). Separating the sites resulted in significant correlations between predicted and residual values for all three models at Deford (Fig. 3D-F) and the 2009 model at Shiawassee (Fig. 3H).

Landing prediction. Even though the 2008 model fit well at Deford, the correlation between the predicted values and residuals was significant with an increase in the residual size with increases in predicted values. Similarly, a prediction bias did occur at Shiawassee with the 2009 model with increased residual size in response to increased prediction values (Fig. 3H). Because of these prediction biases, we used only the Farnsworth and Providence Metropark (model development sites) data to develop a decision model for predicting the likelihood of *A. planipennis* adults (Table 4). Of the 60 trees at Deford State Game Area and Young State Park in 2010, 21 were categorized as high and 39 as low likelihood. Trees that were categorized as high likelihood of *A. planipennis* adult landing had significantly higher landing density (44.5 adults/m^2 ± SE 9.1) than trees categorized as low likelihood (12.7 adults/m^2 ± SE 4.6) (*t* = 3.17, df = 58, *P* = 0.001). Detection of adult *A. planipennis* was not independent of the likelihood category assigned to a tree based on vigor rating and CLE (χ^2 = 15.20, df = 1, *P* < 0.001), with 71.9 percent of detections occurring on trees categorized as high likelihood of *A. planipennis* landing and 78.6 percent of trees categorized as low likelihood were without *A. planipennis* detection.

Discussion

Population size variability of *A. planipennis* and available ash resources most likely added considerable difficulties to effectively modeling and predicting the actual density of adults per m^2. Population variations are evidenced by the major differences in the intercepts and parameter estimates in the 2008, 2009, and combined years models, as well as the total number of adult *A. planipennis* captured. Also, ash resources were variable between the sites used in

Table 1. Multiple regression models for 2008, 2009, and combined years using crown light exposure (CLE) and vigor ratings to predict *Agrilus planipennis* adults per m² of trapping surface, including Akaike Information Criterion with correction (AICc) values.

Model	**Equation**	R^2	F	**df**	P	**AICc**
2008	adults/m² = 6.77 + 0.62×CLE0 - 1.06×CLE1 - 0.33×CLE2 - 0.51×CLE3 + 0.83×CLE4 - 5.97×vigor1 - 6.18×vigor2 - 2.21×vigor3 - 0.18×vigor4	0.08	3.61	9, 363	< 0.001	1.79
2009	adults/m² = 334.09 + 26.48×CLE0 - 2.11×CLE1 + 7.00×CLE2 + 26.13×CLE3 + 34.30×CLE4 - 333.52×vigor1 - 305.33×vigor2 - 65.25×vigor3	0.72	10.46	10,33	< 0.001	1.30
Combined	adults/m2 = 44.08 + 2.17×CLE0 - 1.74×CLE1 + 3.11×CLE2 + 1.19×CLE3 + 11.45×CLE4 - 44.20×vigor1 - 40.20×vigor2 - 32.37×vigor3 - 38.36×vigor4	0.07	3.90	9, 405	< 0.001	4.75

Note: CLE# and vigor# are categorical 1, 0

Table 2. Two-tailed paired *t*-test values between predicted (2008, 2009, and combined years models) and observed *Agrilus planipennis* adults per m² at Deford and Shiawassee State Game Areas, as well as pooled Deford and Shiawassee sites.

Model	**Deford**		**Shiawassee**		**Pooled Sites**	
	$t_{df=39}$	P	$t_{df=39}$	P	$t_{df=79}$	P
2008	-2.01	0.051	7.09	< 0.001	5.52	< 0.001
2009	-4.70	< 0.001	-1.37	0.178	-3.06	0.003
Combined	-7.08	< 0.001	6.80	< 0.001	5.02	< 0.001

Table 3. Akaike Information Criterion with correction (AICc) values for 2008, 2009, and combined model years for predicted *Agrilus planipennis* adults per m^2 of trapping surface at testing sites Deford and Shiawassee State Game Areas, MI.

Model	Test Site	AICc Value
2008	Deford	14.99
2009	Deford	23.34
Combined	Deford	18.84
2008	Shiawassee	26.97
2009	Shiawassee	25.19
Combined	Shiawassee	26.91

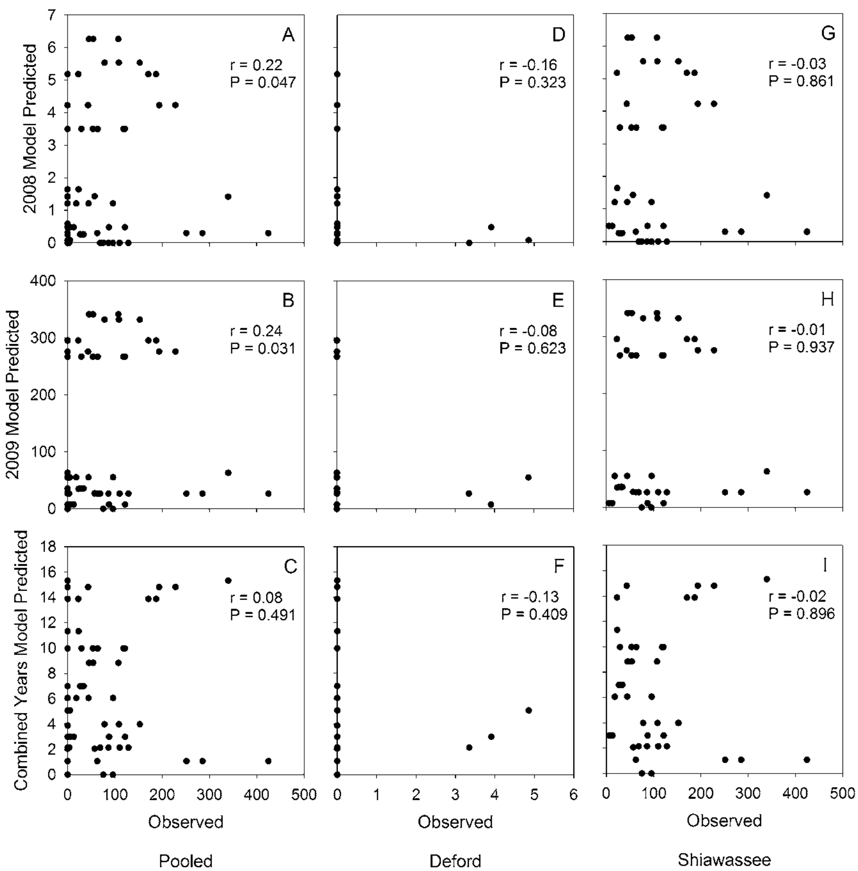

Figure 2. Correlation plots between 2008, 2009, and combined year models at the pooled test sites (A-C), at Deford State Game Area (D-F), and at Shiawassee State Game Area (G-I).

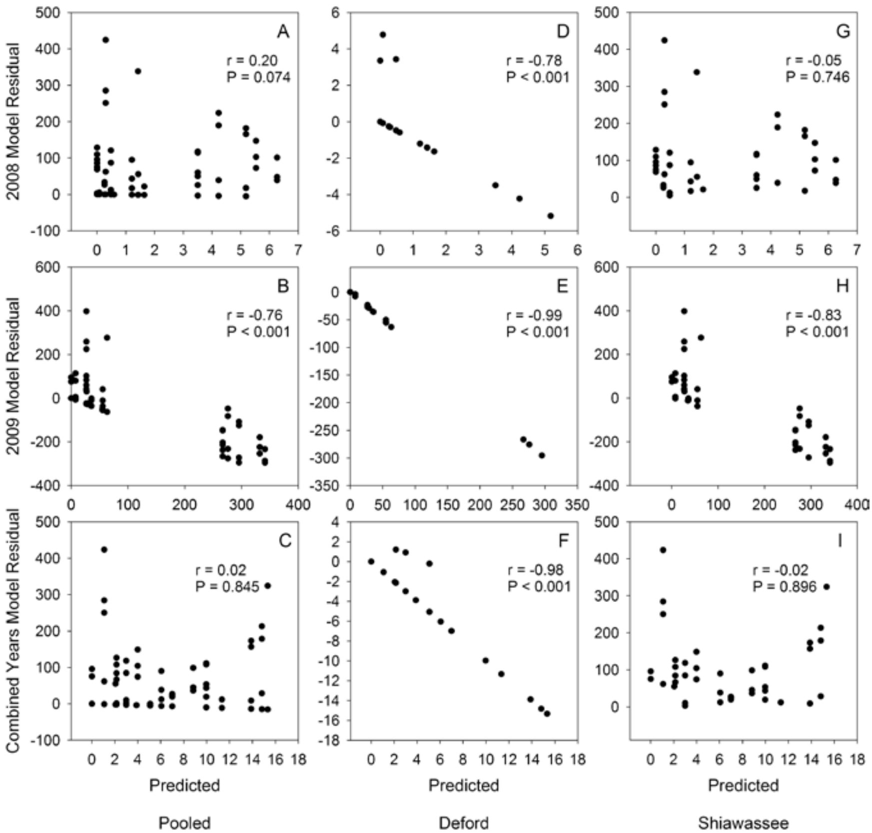

Figure 3. Correlation plots between 2008, 2009, and combined year models at the pooled test sites (A-C), at Deford State Game Area (D-F), and at Shiawassee State Game Area (G-I).

Table 4. Decision model matrix for categorizing trees as low or high likelihood of adult *Agrilus planipennis* landing based on vigor rating and crown light exposure from trees at Providence and Farnsworth Metroparks, OH.

Crown Light Exposure	Vigor Rating 1	2	3	4	5
0	Low	Low	Low	Low	Low
1	High	High	Low	Low	Low
2	Low	High	High	Low	Low
3	Low	High	Low	High	Low
4	High	High	Low	High	High
5	Low	High	Low	Low	Low

both model development and model testing (range 15.1 to 40.5 percent of basal area). The AICc values for models tested at Deford were lowest for the 2008 model, while they were lowest for the 2009 model at Shiawassee. Because of population size variability at the model development sites and testing sites, only select models would be appropriate for any given site with *A. planipennis* infestation. Without clear population size estimations, it becomes difficult to then select the appropriate model.

The strong negative correlations between predicted and residual values for all three models at Deford suggested that it would be appropriate to exclude that site from the subsequent decision model matrix development. This exclusion was done with the assumption that the population dynamics at Deford may not provide a clear differentiation between high and low likelihood trees. Since the 2009 model fit the development data well (R^2 = 0.72, AICc = 1.30) as compared to 2008 and combined years models, trees from Farnsworth and Providence Metroparks were used to construct the decision model matrix. Like Deford, predicted values for the 2009 model from Shiawassee were correlated with the resulting residuals and this prediction bias also suggested appropriate exclusion of this data from the decision model.

While the actual adults/m^2 value may not be successfully predicted for a single tree at a given site, the utility of the models may come in the form of selecting trees that will have the greatest likelihood of adult *A. planipennis* landing. The decision model matrix resulted in many of the high likelihood vigor and CLE combinations having medium vigor ratings (2-4) with some portion of the crown receiving direct sunlight. The relationship between vigor rating, likelihood of *A. planipennis* landing on the tree, and subsequent greater number of adults landing on high likelihood trees, is most likely a result of attraction to the tree. As with other *Agrilus* spp. (Dunn et al. 1986), *A. planipennis* has an increased attraction to stressed trees, while healthy and nearly dead trees are less attractive (Katovich et al. 2001, McCullough et al. 2009a, Crook and Mastro 2010). While healthy trees may not be as attractive to *A. planipennis*, increases in sunlight increase beetle activity and may account for the addition of healthy trees with vigor rating of 1 being included in the high likelihood category within the decision matrix (McCullough et al. 2009a).

Girdling, harvesting, and peeling ash trees may be the most effective method for detecting *A. planipennis*, but it is cited as being expensive to establish and evaluate, as well as hazardous to workers and the public (Crook and Mastro 2010, USDA APHIS PPQ 2010). However, this is when the tree is then felled, peeled, and inspected for *A. planipennis* larvae (Crook and Mastro 2010). By leaving the tree ungirdled and standing, the expense and hazard can be greatly reduced or essentially eliminated. Illustrated previously, an unwounded ash tree may be as effective for adult detection as a girdled trap tree, depending on surrounding forest resources (Marshall et al. 2009, McCullough et al. 2009a,b). An unwounded tree is a less expensive and simpler alternative to a girdled trap tree. Effectiveness of different trap types for capture and detection of *A. planipennis* is highly variable most likely due to population size and density, as well as forest structure and composition. As such, increasing the available number of techniques for use in *A. planipennis* detection may decrease the probability that incipient populations will go undetected. Placing plastic wrap as traps on trees with the highest likelihood of *A. planipennis* landing may add to detection efficiency, but there is a need to identify which trees have the highest likelihood of *A. planipennis* detection when standard plastic prism traps are used.

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