Journal of Economic Entomology, XX(X), 2018, 1–9
doi: 10.1093/jee/toy018
Research

Forest Entomology

Seven-Year Evaluation of Insecticide Tools for Emerald Ash Borer in *Fraxinus pennsylvanica* (Lamiales: Oleaceae) Trees

Emily N. Bick,[1,6] Nora J. Forbes,[2] Christopher Haugen,[3] Grant Jones,[4] Shawn Bernick,[3] and Fredric Miller[5]

[1]Department of Entomology and Nematology, University of California, Davis, 71 Briggs Hall, Davis, CA 95616, [2]Division of Biostatistics, University of Minnesota, 420 Delaware St SE MMC 303, Minneapolis, MN 55455, [3]Department of Research & Development, Rainbow Treecare Scientific Advancements, 11571 K-Tel Dr., Minnetonka, MN 55343, [4]Department of IPM, Longwood Gardens, Kennett Square, PA, [5]Department of Horticulture Science, Joliet Junior College, 1215 Houbolt Rd, Joliet, IL 60431-8938, and [6]Corresponding author, e-mail: enbick@ucdavis.edu

Subject Editor: Brian Sullivan

Received 28 July 2016; Editorial decision 11 January 2018

Abstract

Emerald ash borer (EAB), *Agrilus planipennis* (Fairmaire; Coleoptera: Buprestidae), is decimating ash trees (*Fraxinus* spp.) in North America. Combatting EAB includes the use of insecticides; however, reported insecticide efficacy varies among published studies. This study assessed the effects of season of application, insecticide active ingredient, and insecticide application rate on green ash (*Fraxinus pennsylvanica* Marsh.) (Lamiales: Oleaceae) canopy decline caused by EAB over a 5- to 7-yr interval. Data suggested that spring treatments were generally more effective in reducing canopy decline than fall treatments, but this difference was not statistically significant. Lowest rates of decline (<5% over 5 yr) were observed in trees treated with imidacloprid injected annually in the soil during spring (at the higher of two tested application rates; 1.12 g/cm diameter at 1.3 m height) and emamectin benzoate injected biennially into the stem. All tested insecticides (dinotefuran, emamectin benzoate, and imidacloprid) under all tested conditions significantly reduced the rate of increase of dieback.

Key words: emerald ash borer, *Fraxinus*, management, systemic insecticide

Emerald ash borer (EAB), *Agrilus planipennis* (Fairmaire; Coleoptera: Buprestidae), is a wood-boring beetle native to Asia that is devastating North American and European ash (*Fraxinus* L.) species. Unlike native *Agrilus* species in Northern America such as the bronze birch borer (*Agrilus anxius* Gory) (Coleoptera: Buprestidae) and two-lined chestnut borer (*Agrilus bilineatus* Weber) (Coleoptera: Buprestidae), EAB is a primary pest, and larval feeding causes mortality regardless of initial tree health (Poland and McCullough 2006, McCullough et al. 2009). As of March 2017, EAB was established in 28 U.S. states (http://www.emeraldashborer.info).

Prompt treatment or removal of EAB-infested ash trees is recommended (Herms and McCullough 2014) since trees die 3- to 4 yr post-infestation (Siegert et al. 2005) and dead trees pose a physical hazard due to falling limbs (Knight et al. 2013). EAB population control strategies target larvae through the removal of infested trees, release of larval parasitoids, and restriction of pest movement by establishment of quarantine areas (Herms et al. 2009, Duan et al. 2012, Jennings et al. 2016). Insecticide treatments are a viable option for controlling EAB infestations in individual trees (Poland and McCullough 2006).

Pest management protocols for controlling wood-boring insects include trunk injections of emamectin benzoate as well as soil applications, trunk sprays, and trunk injections of the neonicotinoid class insecticides imidacloprid and dinotefuran (Cregg et al. 2005, Mota-Sanchez et al. 2009). In laboratory feeding studies, adult EAB feeding on foliage from imidacloprid-treated trees experienced more than 70% mortality (Cregg et al. 2005, Mota-Sanchez et al. 2009). Dinotefuran sprayed on the bases of trunks resulted in 57 to 68% mortality against feeding EAB adults in field studies (McCullough et al. 2011). Although soil applications of dinotefuran are less effective at decreasing fecundity and causing mortality in foliage-feeding adult beetles when applied to large trees, they are recommended as a management tool for small trees

(Herms et al. 2009, McCullough et al. 2011). In contrast, imidacloprid is effective on all sizes of ash trees (Smitley et al. 2007b). Trees with up to 60% canopy dieback recovered following imidacloprid treatments (Smitley et al. 2007b).

Trunk injections of emamectin benzoate produce 95% larval mortality (McCullough et al. 2011). A 2-yr retreatment interval is recommended by all manufacturers and is effective at preventing tree mortality from EAB (McCullough et al. 2011). Studies report that the active ingredient emamectin benzoate results in the most effective EAB control (Herms 2010, Smitley et al. 2010, McCullough et al. 2011, McCullough and Mercader 2012, Sadof et al. 2017). Unlike soil-applied insecticides, tree injection requires drilling into the tree (Smitley et al. 2007b).

High variation in insecticide efficacy has been reported among active ingredients, among individual trees, and across treatment sites (Smitley et al. 2007a). Identical active ingredients showed efficacy in some trials but failed in others (McCullough et al. 2005, Herms et al. 2009). Multiple studies have demonstrated that the cost of tree removal commonly exceeds the cost of insecticide treatment (Herms 2010, Smitley et al. 2010, McCullough et al. 2011, McCullough and Mercader 2012). Therefore, there is a need for effective insecticide treatment options.

This study was intended to address gaps in the EAB literature regarding long-term survival of ash trees treated with insecticides. Specifically, our objectives were to determine: 1) the multi-year efficacy of dinotefuran, imidacloprid, dinotefuran + imidacloprid, and emamectin benzoate for EAB control, 2) the multi-year impact of seasonal treatment timing on the efficacy of soil-applied insecticides for EAB control, and 3) the effective dose of imidacloprid.

Materials and Methods

In January 2008, a single EAB-infested tree was found in Hazel Crest, IL by the Illinois Department of Agriculture EAB Trap Tree Program (Fig. 1). A study site was established within an ongoing EAB infestation discovered in proximity to the trap tree, centered at approximately 41°33′25.2″N 87°42′10.8″W, and with a total of 205 green ash (*F. pennsylvanica*) trees growing across a 0.728 km^2 area. A wide boulevard and set of buildings in the center of the research plot created a 340-m-wide division of the area into two subplots. The 90 trees in the southern (S) subplot were dispersed over 750 m along Village Drive, while the 115 trees in the northern (N) subplot were dispersed over 610 m along Fountainbleau Drive. The trees in the two subplots differed significantly in their average DBH and

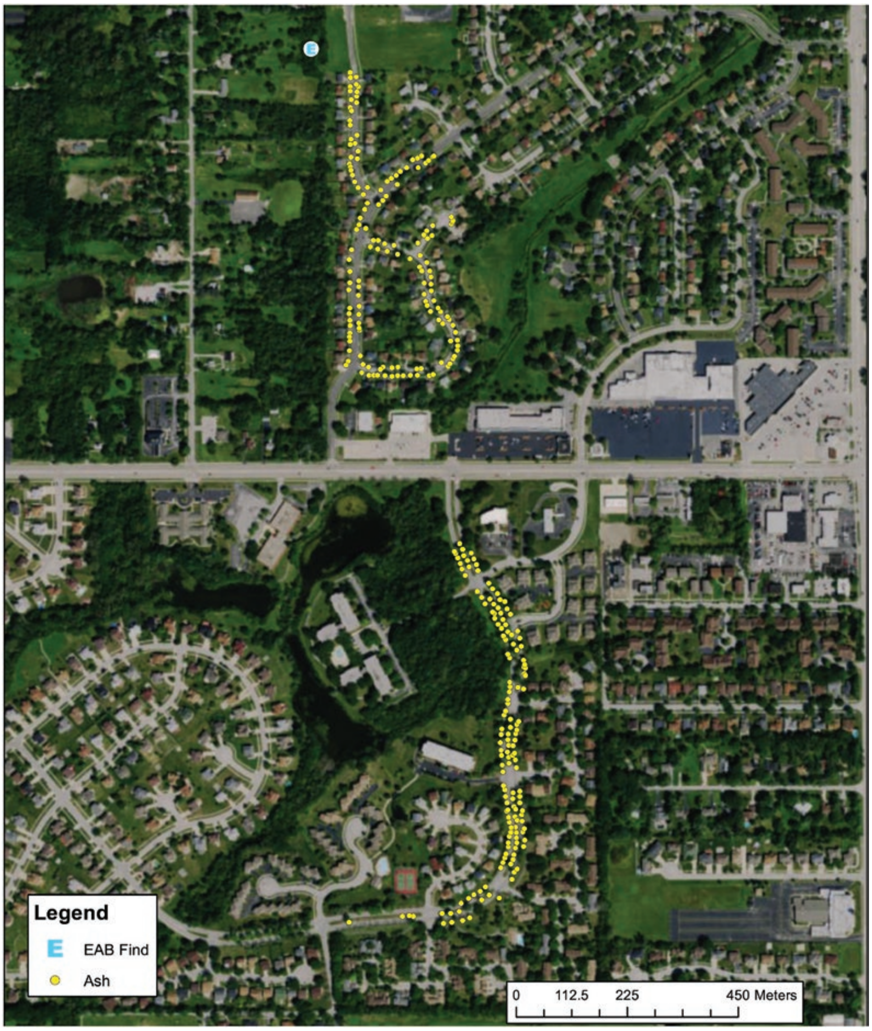

Fig. 1. Map of Hazel Crest, IL study site indicating location of green ash trees included in the study and the trap tree in which EAB was originally detected in the area.

Table 1. Insecticide treatments applied to green ash in Hazel Crest, IL (2008–2013)

Treatment number	Treatment name	Treatment abbreviaion	Doseage rate (active ingredient per cm tree DBH)
1	Untreated control	Ctl	NA
2	Spring imidacloprid[a]	Sp. Im.	0.56 g
3	Fall imidacloprid[b]	Fa. Im.	0.56 g
4	Spring dinotefuran[a]	Sp. Din.	1.34 g
5	Fall dinotefuran[b]	Fa. Din.	1.34 g
6	Spring imidacloprid + dinotefuran[a]	Sp. Im. Din.	0.56 g and 1.34 g, respectively
7	Fall imidacloprid + dinotefuran[b]	Fa. Im. Din.	0.56 g and1.34 g, respectively
8	Spring 2× imidacloprid[c]	Sp. 2× Im.	1.12 g
9	Fall 2× imidacloprid[d]	Fa. 2× Im.	1.12 g
10	Emamectin benzoate[e]	Em. Ben.	0.26 g

[a] Applied 15 May 2008, 20 May 2009, 11 May 2010, 6 May 2011, 5 May 2012, and 24 April 2013.

[b] Applied 20 November 2008, 12 November 2009, 9 November 2010, 10 November 2011, 1 November 2012, and 14 November 2013.

[c] Applied 20 May 2009, 11 May 2010, 6 May 2011, 5 May 2012, and 24 April 2013.

[d] Applied 12 November 2009, 9 November 2010, 10 November 2011, 1 November 2012, and 14 November 2013.

[e] Applied 6 September 2008, 10 June 2010, and 5 May 2012.

the treatments applied in each (Table 1) and therefore, in addition to analyzing data as a whole, we also analyzed data by N and S subplots.

Branches were sampled in 2008 on trees with conspicuous canopy decline to confirm that the decline was a result of EAB activity. Eleven trees were sampled in the N subplot and ten in the S subplot. An aerial bucket truck was used to collect four branches, one from each cardinal direction. Branch samples were 5 to 10 cm in diameter and 91 cm (3 ft) long. Branches were peeled with draw knives and examined for EAB presence. In 2012, one randomly selected tree per treatment group per subplot was sampled.

Seven treatments were initially included in trials from May 2008 through August 2014: 1) untreated control (18 in N, nine in S); 2) spring imidacloprid (15 in N, seven in S); 3) fall imidacloprid (16 in N, seven in S); 4) spring dinotefuran (14 in N, seven in S); 5) fall dinotefuran (15 in N, seven in S); 6) spring imidacloprid plus dinotefuran (15 in N, seven in S); 7) fall imidacloprid plus dinotefuran (15 in N and seven in S) (Table 1). Insecticide was applied at the label rate: for imidacloprid, 0.56 g/cm diameter at breast height (DBH); for dinotefuran, 1.34 g/cm DBH. Spring treatments were applied in May and fall treatments in November. Within each subplot, treatments were assigned to each tree using simple randomization with equal probabilities.

In March 2009 the Environmental Protection Agency changed its regulations allowing for the application of imidacloprid at 1.12 g/cm DBH on ash trees. Additionally, tree injections of emamectin benzoate had recently been determined to be a promising technology for the control of EAB (McCullough 2008). Therefore beginning in Fall 2009 three additional treatments were included which used this rate of imidacloprid: 8) Spring 2× imidacloprid (applied annually beginning May 2010; seven in N and six in S); 9) Fall 2× imidacloprid (applied annually beginning November 2009; 23 in S); 10) Emamectin benzoate (0.255 gm/cm DBH applied September 2008, June 2010, and May 2012; 10 in S) (Table 1). Due to limited availability of trees at the time of treatment initiation, fall 2× imidacloprid and emamectin benzoate treatments were exclusively applied to the S subplot. Annual applications of treatments 1–9 were continued through the date of the final dieback assessment.

All treatments of imidacloprid (Xytect 75 WSP) and dinotefuran (Transtect 70 WSP) insecticide formulations (Rainbow Treecare Scientific Advancements, Minnetonka, MN) were applied by using an HTI 2000 soil injection probe (Rainbow Treecare Scientific Advancements), and 98.4 ml of aqueous insecticide solution per cm DBH of the tree was injected into the mineral soil matrix adjacent to the root flare, 15 cm below the soil surface, with one injection site per 2.54 cm DBH (i.e., 250 ml per injection). Emamectin benzoate in a 4% aqueous solution was applied by using the Tree IV micro-infusion system (TREE-äge, Arborjet, Woburn, MA) using one arborplug for every 5 cm DBH per manufacturer specifications.

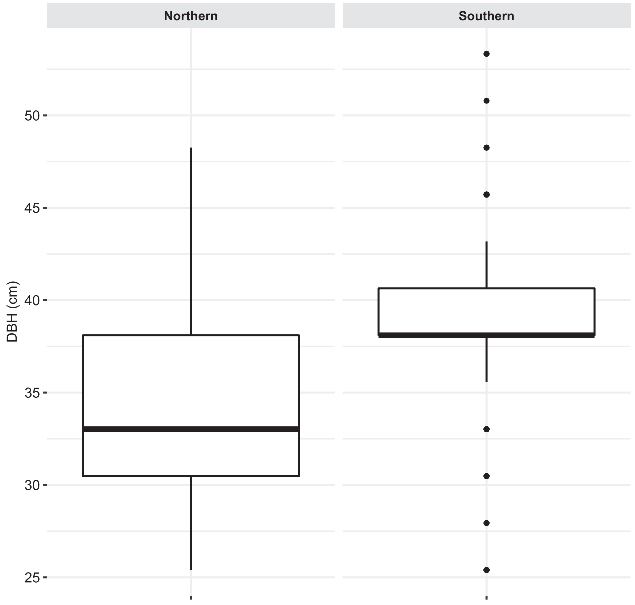

Fig. 2. Boxplot of initial diameter at breast height (cm DBH) in the northern and southern subplots.

Treatment efficacy was evaluated independently by two researchers using the Ash Canopy Thinning and Dieback Scale developed by Smitley et al. (2008). The scale pictorially quantifies the percentage of canopy dieback in 10% increments. Canopies of trees in treatments 1–7 were rated for dieback in August of 2008 and bi-annually thereafter in June and August from 2009 through 2014. Baseline canopy dieback ratings for treatments 8–10 (fall and spring 2× imidacloprid and emamectin benzoate) were made in 2009.

Table 2. Mean ± SD canopy thinning ratings by year and treatment for green ash trees in Hazel Crest, IL

Treatment	2008	2009	2010	2011	2012	2013	2014
Ctl (*n* = 27)	10 ± 19.8	14 ± 7.0	20 ± 23.6 *P* = 0.044	34 ± 28.1	37 ± 32.9 *P* < 0.001	91 ± 12.8	93 ± 10.5 *P* < 0.001
Sp. Im. (*n* = 22)	10 ± 10.7	12 ± 8.3	15 ± 19.3 *P* = 1.000	35 ± 31.9	32 ± 19.8 *P* < 0.001	36 ± 17.7	55 ± 17.6 *P* < 0.001
Fa. Im. (*n* = 23)	9 ± 9.6	17 ± 6.8	18 ± 19.6 *P* = 0.156	31 ± 21.6	34 ± 31.2 *P* = 0.003	48 ± 26.8	56 ± 22.2 *P* < 0.001
Sp. Din. (*n* = 21)	10 ± 10.3	16 ± 5.6	14 ± 11.7 *P* = 0.686	37 ± 27.2	42 ± 34.1 *P* = 0.001	40 ± 22.5	51 ± 20.0 *P* < 0.001
Fa. Din. (*n* = 22)	9 ± 14.1	15 ± 7.0	20 ± 22.6 *P* = 0.258	32 ± 24.4	38 ± 28.1 *P* = 0.002	60 ± 24.1	62 ± 17.9 *P* < 0.001
Sp. Im. Din. (*n* = 22)	8 ± 8.4	9 ± 6.1	15 ± 13.9 *P* = 0.340	32 ± 27.6	42 ± 35.3 *P* = 0.002	43 ± 23.1	51 ± 20.8 *P* < 0.001
Fa. Im. Din. (*n* = 22)	9 ± 11.5	13 ± 4.4	16 ± 13.8 *P* = 0.159	41 ± 25.7	40 ± 33.3 *P* < 0.001	55 ± 28.5	60 ± 26.6 *P* < 0.001
Sp. 2× Im. (*n* = 13)	-	-	25 ± 27.2	20 ± 16.2	25 ± 28.8 *P* = 1.000	37 ± 19.0	41 ± 17.9 *P* = 0.129
Fa. 2× Im. (*n* = 23)	-	-	8 ± 8.4	1 ± 8.1	19 ± 16.7 *P* = 0.065	33 ± 19.4	47 ± 24.5 *P* < 0.001
Em. Ben. (*n* = 10)	-	-	15 ± 14.5	5 ± 0.0	11 ± 9.9 *P* = 1.000	16 ± 9.7	21 ± 18.8 *P* = 1.000

P-values based on Mann-Whitney U-Tests (with Bonferroni correction) comparing canopy thinning from levels at first assessment (2008 or 2010).

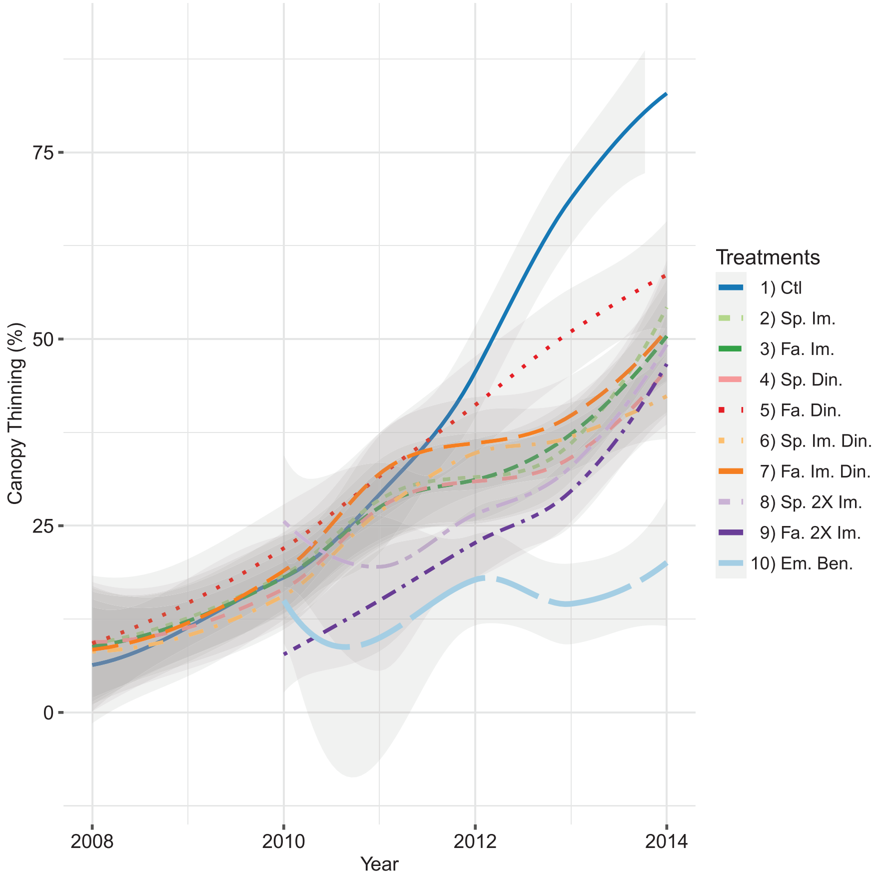

Fig. 3. Plot of mean annual canopy thinning by year for all treatments from 2008 to 2014, with Loess smoothing and 95% confidence intervals.

Statistical Methodology

Data were analyzed using R Statistical Software (R Core Development Team 2008). Tree size (DBH) at trial initiation was compared between the two subplots using a Welch's two sample *t*-test. Annual changes in canopy dieback were calculated both from the beginning of the study (2008) and from the time when all treatments were included (2010).

Significant changes in canopy dieback were determined by contrasting dieback at each reassessment against the 2008 and

2010 'baseline' assessments by using non-parametric Mann-Whitney U-tests within treatment. Specifically, for treatments 1–7, canopy dieback was compared between spring 2008 and years 2010, 2012, and 2014. For treatments 8–10, canopy dieback was compared between 2010 and years 2012 and 2014. These analyses were conducted both with subplots combined and separate. Bonferroni correction was applied to control for experiment-wise error across years within each treatment. Additionally, Mann-Whitney U-tests were applied to determine the difference in outcomes between equivalent fall and spring treatments in 2014.

Mean canopy dieback, mean canopy dieback since 2008, and mean canopy dieback since 2010 were compared across treatments by using ANCOVA with type III sums of squares to address unequal sample sizes and potential interaction among independent variables. All ANCOVAs included treatment as the main effect controlled for DBH, year, and subplot. This analysis was performed using the 'Anova' function in the 'car' package, which allows for type determination of the sum of squares (Fox 2011). To determine pairwise differences between treatments in canopy dieback and canopy change, post-hoc comparisons were performed by using Tukey's Honest Significant Difference (HSD) method. This analysis was performed with the 'HSD.test' function in the 'agricolae' package (De Mendiburu 2014). This method was utilized to account for unequal sample sizes across groups and type 1 error rate. Statistical significance was defined at an alpha level of 0.05. Plots of trends were created using 'ggplot2' and 95% confidence bands were computed by a non-parametric loess method using 'geom_smooth' (Wickham 2009).

Results

In the N and S subplots in 2008 (the initiation of the study), 36 and 40%, respectively, of sampled trees with conspicuous dieback were positive for EAB. In 2012, 100% of branches sampled (from one randomly selected tree per treatment and subplot) were positive for EAB. Welch's two sample *t*-tests revealed a significant difference in DBH between subplots at the initiation of the study ($P < 0.001$). Mean DBH was 35.0 cm and 38.9 cm for N and S subplots, respectively (Fig. 2)

Canopy Dieback Across Subplots

Canopy dieback increased significantly for untreated control trees between 2008 and 2014, from 10 to 93%, respectively ($P < 0.001$) (Table 2). Spring applied and fall applied imidacloprid, dinotefuran, and imidacloprid plus dinotefuran treatments demonstrated a significant increase in percent canopy dieback over the 7-yr trial ($P < 0.001$) (Table 2; Figs. 3 and 4). By 2014, all fall applied treatment trees had higher mean canopy dieback ratings than the spring applied equivalents, however these differences were not significant ($P > 0.05$).

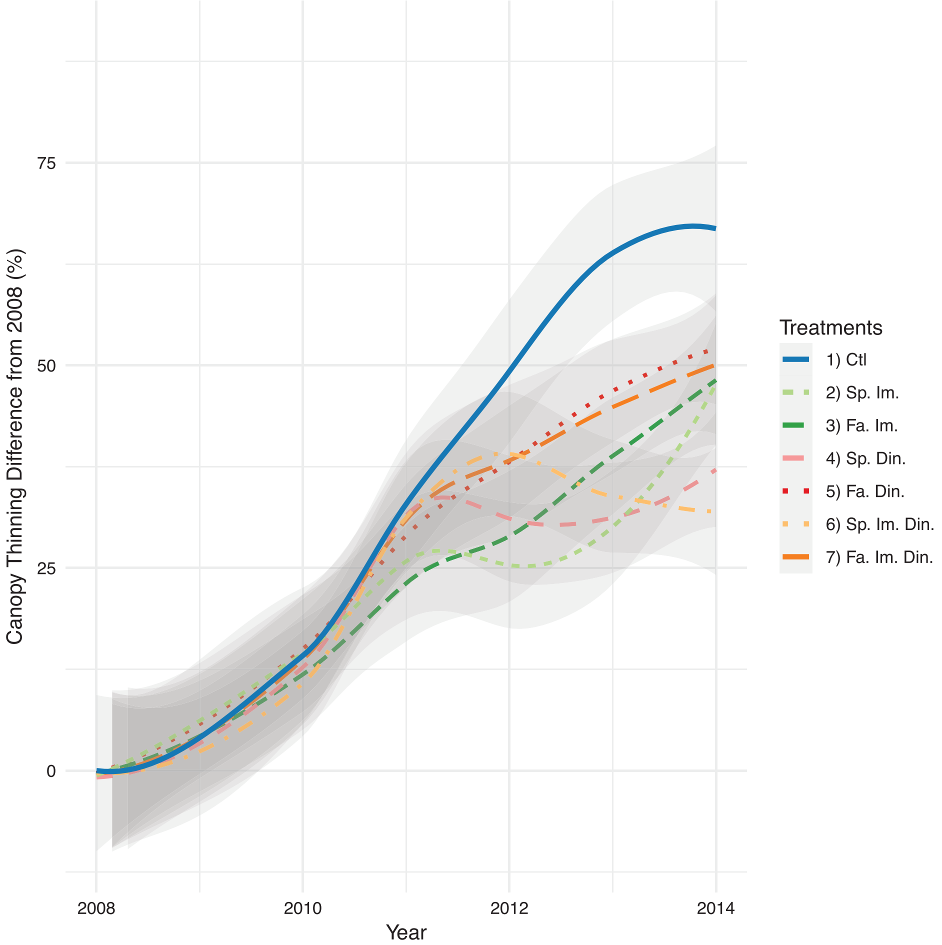

Fig. 4. Plot of mean annual difference in canopy thinning since 2008 for all seven original northern region treatments from 2008 to 2014, with Loess smoothing and 95% confidence intervals.

For treatments applied in 2010, there were no significant changes in dieback ratings for spring applied 2× imidacloprid (from 25 to 41%; $P = 0.129$) or emamectin benzoate (from 15 to 21%; $P = 1.0$) between 2010 and 2014 (Table 2; Figs. 3 and 5B). Fall applied treatments of 2× imidacloprid had a significant difference in canopy ratings, from 8 to 47% dieback ($P < 0.001$).

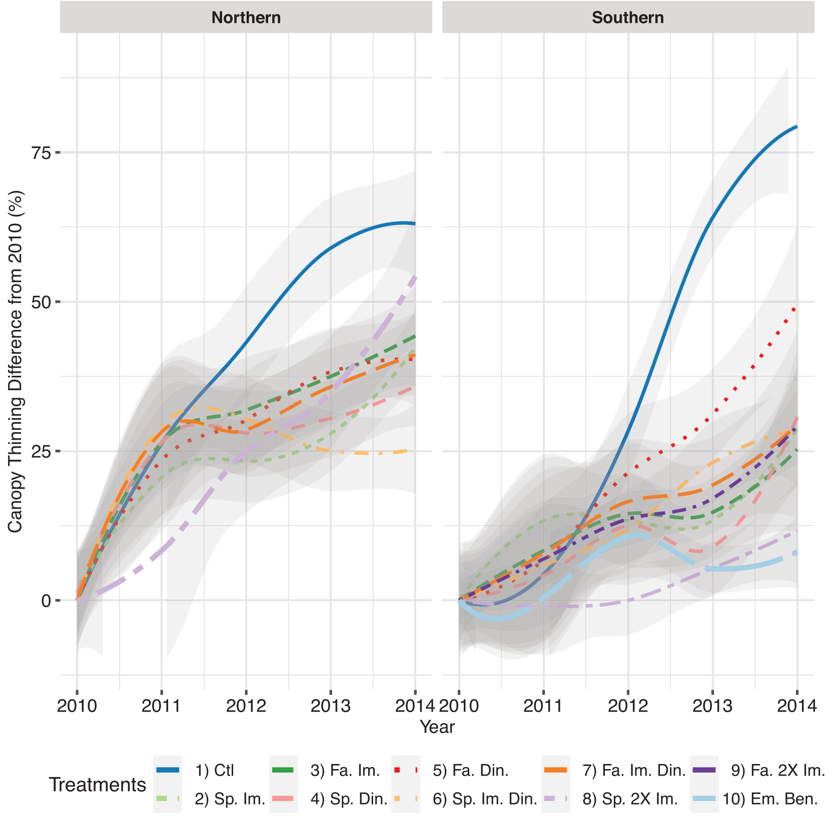

Fig. 5. Plot of mean annual difference in canopy thinning since 2010 separated for the northern and southern subplots, for all treatments from 2010 to 2014, with Loess smoothing and 95% confidence intervals.

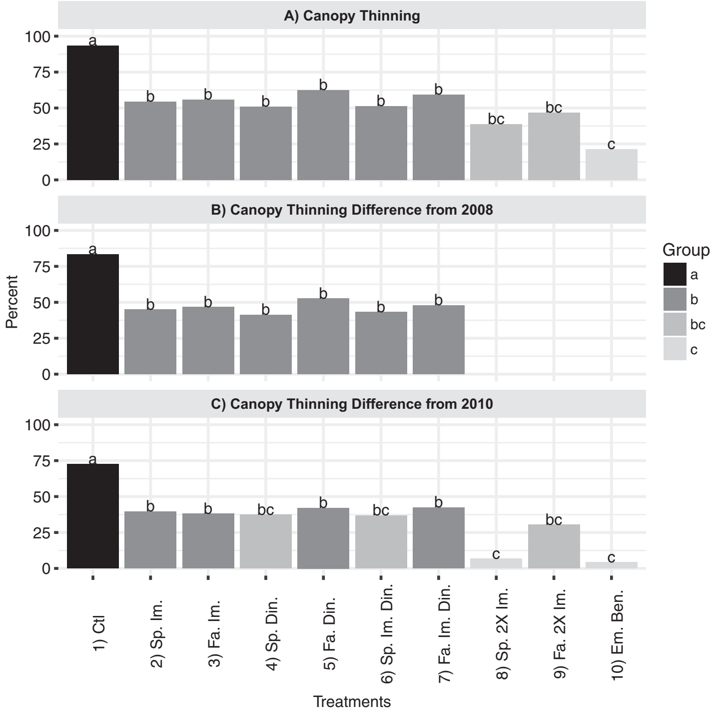

Fig. 6. Results of post-hoc pair-wise comparisons among insecticide treatments for A) mean canopy thinning in 2014, B) mean difference in canopy thinning from 2008 to 2014, and C) mean difference in canopy thinning from 2010 to 2014 (Tukey's HSD test, $P \leq 0.05$).

Canopy Dieback Accounting for Subplot

There was a significant effect ($P < 0.001$) of year, subplot, and treatment in predicting canopy dieback in 2014, change in canopy dieback from 2008 to 2014, and change in canopy dieback from 2010 to 2014, whereas DBH did not have a significant effect on any of these measures ($P > 0.1$; Table 5). Post-hoc analysis revealed significant pair-wise differences in mean canopy dieback between the untreated trees and all other treatments (Fig. 6A). Additionally, mean canopy dieback was significantly less for emamectin benzoate, compared to all other treatments, except fall 2× imidacloprid and spring 2× imidacloprid (Fig. 6A). From 2008 to 2014, mean increase in canopy dieback for the untreated trees was significantly higher than for all other treatments tested over this entire interval (Fig. 6B). From 2010 to 2014, mean increase in canopy dieback was significantly higher for the untreated trees than for all other treatments. Additionally, emamectin benzoate and spring 2× imidacloprid trees experienced significantly less change in canopy dieback compared to spring and fall imidacloprid, fall dinotefuran, and fall imidacloprid plus dinotefuran (Fig. 6C).

By 2014, all trees in the southern subplot, except spring 2× imidacloprid and emamectin benzoate treated trees, had significant increases in canopy dieback ($P = 0.316$ and 1.0, respectively) (Table 4). In the northern subplot, all trees except spring 2× imidacloprid had significant increases in canopy dieback by 2014 ($P = 0.443$). The absence of a detectable increase in dieback for spring 2× imidacloprid and emamectin benzoate treatments (begun in 2010), which was not detected in any of the treatments begun in 2008, could be attributed to the relatively shorter treatment and monitoring period for the former.

Discussion

Branch sampling indicated that canopy dieback could be attributed to the EAB infestation. Trees in the N subplot tended to be smaller than those in the S subplot (Fig. 2), however, the difference

Table 3. Mean (±SD) canopy thinning ratings by year and treatment for green ash trees in the northern subplot (*n* = 115)

Treatment	2008	2009	2010	2011	2012	2013	2014
Ctl (*n* = 18)	14 ± 23.3	17 ± 6.5	25 ± 27.4 *P* = 0.306	45 ± 28.7	47 ± 35.3 *P* = 0.001	94 ± 11.3	94 ± 11.9 *P* < 0.001
Sp. Im. (*n* = 15)	9 ± 10.2	16 ± 5.0	14 ± 20.3 *P* = 1.000	39 ± 33.3	33 ± 23.3 *P* = 0.006	39 ± 16.6	58 ± 10.3 *P* < 0.001
Fa. Im. (*n* = 16)	10 ± 10.4	15 ± 5.5	18 ± 23.2 *P* = 0.658	35 ± 20.6	41 ± 34.5 *P* = 0.006	56 ± 26.0	62 ± 18.6 *P* < 0.001
Sp. Din. (*n* = 14)	9 ± 11.6	14 ± 3.5	13 ± 13.0 *P* = 0.934	45 ± 28.4	50 ± 34.3 *P* = 0.001	46 ± 24.4	54 ± 19.5 *P* < 0.001
Fa. Din. (*n* = 15)	10 ± 15.5	13 ± 7.6	22 ± 23.1 *P* = 0.477	38 ± 25.1	43 ± 26.2 *P* = 0.003	63 ± 21.7	61 ± 16.7 *P* < 0.001
Sp. Im. Din. (*n* = 15)	10 ± 9.1	11 ± 4.0	18 ± 15.4 *P* = 0.388	39 ± 29.4	55 ± 33.9 *P* = 0.001	46 ± 24.7	59 ± 19.2 *P* < 0.001
Fa. Im. Din. (*n* = 15)	10 ± 13.0	12 ± 4.5	18 ± 15.3 *P* = 0.527	50 ± 25.9	49 ± 33.8 *P* = 0.002	60 ± 27.5	60 ± 25.8 *P* < 0.001
Sp. 2× Im. (*n* = 7)	-	-	30 ± 32.9	26 ± 22.9	33 ± 25.0 *P* = 1.000	47 ± 19.1	45 ± 18.7 *P* = 0.443

P-values based on Mann-Whitney U-Tests (with Bonferroni correction) comparing canopy thinning from levels at first assessment (2008 or 2010).

Table 4. Mean (±SD) canopy thinning ratings by year and treatment for green ash trees in the southern subplot (*n* = 90)

Treatment	2008	2009	2010	2011	2012	2013	2014
Ctl (*n* = 9)	2 ± 4.4	9 ± 4.5	12 ± 11.5 *P* = 0.053	13 ± 9.0	18 ± 15.8 *P* = 0.053	83 ± 13.2	92 ± 7.1 *P* = 0.001
Sp. Im. (*n* = 7)	11 ± 12.4	4 ± 8.0	16 ± 18.4 *P* = 1.000	26 ± 29.1	29 ± 11.0 *P* = 0.071	29 ± 19.1	46 ± 26.9 *P* = 0.024
Fa. Im. (*n* = 7)	8 ± 8.1	22 ± 7.0	16 ± 7.5 *P* = 0.239	21 ± 22.3	18 ± 16.3 *P* = 0.884	29 ± 19.5	43 ± 25.6 *P* = 0.010
Sp. Din. (*n* = 7)	11 ± 7.9	21 ± 6.0	15 ± 9.6 *P* = 1.000	17 ± 5.2	24 ± 28.5 *P* = 1.000	26 ± 9.9	46 ± 21.5 *P* = 0.007
Fa. Din. (*n* = 7)	7 ± 11.1	18 ± 3.5	16 ± 22.7 *P* = 1.000	20 ± 19.1	28 ± 31.3 *P* = 0.616	55 ± 29.9	67 ± 21.8 *P* = 0.011
Sp. Im. Din. (*n* = 7)	4 ± 5.3	6 ± 8.0	7 ± 4.9 *P* = 1.000	13 ± 2.7	12 ± 12.9 *P* = 1.000	35 ± 18.3	36 ± 15.1 *P* = 0.005
Fa. Im. Din. (*n* = 7)	5 ± 5.5	16 ± 2.5	13 ± 9.9 *P* = 0.430	21 ± 6.1	23 ± 26.3 *P* = 0.153	43 ± 29.1	57 ± 30.8 *P* = 0.013
Sp. 2× Im. (*n* = 6)	-	-	20 ± 20.2	15 ± 10.0	15 ± 32.1 *P* = 0.238	25 ± 10.5	35 ± 17.3 *P* = 0.316
Fa. 2× Im. (*n* = 23)	-	-	8 ± 8.4	15 ± 8.1	19 ± 16.7 *P* = 0.065	33 ± 19.4	47 ± 24.5 *P* < 0.001
Em. Ben. (*n* = 10)	-	-	15 ± 14.5	5 ± 0.0	11 ± 9.9 *P* = 1.000	16 ± 9.7	21 ± 18.8 *P* = 1.000

P-values based on Mann-Whitney U-Tests (with Bonferroni correction) comparing canopy thinning from levels at first assessment (2008 or 2010).

in mean tree diameter between subplots was small (about 10%), and an ANCOVA did not reveal DBH having a significant influence on dieback. Significant dieback for the untreated control trees occurred sooner in the N subplot than the S subplot (Tables 3 and 4). However, by the end of the experiment, the two subplots' control canopy dieback ratings reached similar levels of decline: 94 and 92% for N and S, respectively.

Like prior studies (McCullough et al. 2005, Herms 2010, Smitley et al. 2010, McCullough et al. 2011, McCullough and Mercader 2012, Herms and McCullough 2014), all insecticide treatments resulted in some degree of control, as evidenced by significantly less change in canopy dieback from 2008 (or 2010) compared to untreated control trees (Fig. 3; Fig. 6B and C). Nonetheless, fall and spring treatments of imidacloprid (at the 1× dose level), dinotefuran, and imidacloprid plus dinotefuran did not prevent significant tree decline over the 6 yr of treatment (Tables 2–4), in congruence with findings from Gandhi et al. (2007).

Values for mean reductions in canopy thinning suggested that fall-applied treatments were less effective than spring-applied treatments; however, these differences were not statistically significant for any particular insecticide treatment (Figs. 4 and 6). It is possible that this trend was an artifact of lag time between initial application of spring and fall treatments, and further studies are necessary to establish unequivocally whether application timing has a meaningful effect on long-term treatment efficacy.

Imidacloprid and dinotefuran in combination were not superior to either insecticide singly in reducing dieback (Fig. 6), and thus there was no additive effect from applying these insecticides simultaneously. According to Herms et al. (2009), dinotefuran's recommended application time is mid- to late-spring while imidacloprid's recommended application time is early- to mid-spring (Herms et al. 2009). Since the imidacloprid plus dinotefuran treatments were not applied in mid-spring, at least one active ingredient may have been applied at a nonoptimal time.

Data from 2010 and 2014 (over which time all nine insecticide treatments could be compared) indicated that emamectin benzoate-treated trees on average suffered the least increase in dieback (Fig. 6C). However, emamectin benzoate was not statistically more effective at slowing thinning than several other insecticide treatments, including 2× imidacloprid (in fall or spring) or spring dinotefuran applied with or without imidacloprid (Fig. 6C).

While ash trees are able to recover from 60% canopy dieback (Smitley et al. 2007b), practitioners generally consider only 30% canopy dieback to be an acceptable level of damage. In our study, only emamectin benzoate maintained trees below this threshold (Table 4), and thus according to our results only emamectin benzoate could potentially be considered efficacious in controlling EAB. However, trends illustrated in Figs. 3–5 imply that increasing canopy dieback was not stopped or reversed by any treatment, hence it is possible that, had the study been continued, emamectin benzoate would not have prevented mean damage levels from crossing the 30% threshold. Nonetheless, our finding that trees treated either with emamectin benzoate or imidacloprid (applied at the revised [i.e., 1.12 g/cm DBH] label rate in spring) did not have significant increases in canopy dieback by the end of the study is encouraging.

Table 5. Results of type III ANCOVA analysis on (a) canopy thinning, (b) difference in canopy thinning from 2008, and (c) difference in canopy thinning from 2010, by treatment, region, year, and season

	SS III	df	*F*-value	*P*-value
(a) Canopy thinning				
(Intercept)	325241	1	637.0	<0.001
Treatment	47583	9	10.4	<0.001
Year[a]	327209	1	640.8	<0.001
Subplot[b]	27932	1	54.7	<0.001
DBH	83	1	0.2	0.686
Residual	564232	1105		
(b) Difference in canopy thinning since 2008				
(Intercept)	311271	1	532.6	<0.001
Treatment	31522	7	7.7	<0.001
Year	312505	1	534.7	<0.001
Subplot	18306	1	31.3	<0.001
DBH	587	1	1.0	0.317
Residual	543504	930		
(c) Difference in canopy thinning since 2010				
(Intercept)	176839	1	264.8	<0.001
Treatment	45535	9	7.6	<0.001
Year	177375	1	265.6	<0.001
Subplot	17887	1	26.8	<0.001
DBH	1758	1	2.6	0.105
Residual	604970	906		

[a] Year of canopy assessment.

[b] Northern vs. southern.

References Cited

Cregg, B. M., D. Mota-Sanchez, D. G. McCullough, T. Poland, and R. Hollingworth. 2005. Distribution of 14C-imidacloprid in *Fraxinus* spp. and effects of imidacloprid on the emerald ash borer, pp. 24–25. *In* V. Mastro and R. Reardon (eds.), Proceedings of the Emerald Ash Borer Research and Technology Development Meeting, 24–26 September 2005, Pittsbugh, Pennsylvania. USDA Forest Service Forest Health Technology Enterprise Team FHTET-2004-02, Morgantown, WV.

De Mendiburu, F. 2014. Agricolae: statistical procedures for agricultural research. R package, version 1. Universidad Nacional de Ingenieria, Lima, Peru

Duan, J. J., L. S. Bauer, K. J. Abell, and R. Van Driesche. 2012. Population responses of hymenopteran parasitoids to the emerald ash borer (Coleoptera: Buprestidae) in recently invaded areas in north central United States. BioControl 57: 199–209.

Fox, J. 2011. Weisberg: r companion to applied regression. R package, version 2.0–10. Sage Publications, Thousand Oaks, California

Gandhi, K. J. K., D. A. Herms, A. Smith, and R. P. Long. 2007. Patterns of emerald ash borer-induced ash decline and mortality in the forests of southeastern Michigan, pp. 26–27. *In* V. Mastro, D. Lance, R. Reardon, and G. Parra (eds.), Proceedings of the Emerald Ash Borer/Asian Longhorned Beetle Research and Technology Development Meeting, 23–24 October 2007, Pittsburgh, PA. USDA Forest Service Forest Health Technology Enterprise Team FHTET-2007-04, Morgantown, WV.

Herms, D. A. 2010. Multiyear evaluations of systemic insecticides for control of emerald ash borer, pp. 71–75. *In* Proceedings, the Emerald Ash Rorer Research and Technology Development meeting, 20–21 October 2009, Pittsburgh, PA. USDA Forest Service Forest Health Technology Enterprise Team, Morgantown, WV.

Herms, D. A., and D. G. McCullough. 2014. Emerald ash borer invasion of North America: history, biology, ecology, impacts, and management. Annu. Rev. Entomol. 59: 13–30.

Herms, D. A., D. G. McCullough, D. R. Smitley, C. F. Sadof, R. C. Williamson, and P. L. Nixon. 2009. Insecticide options for protecting ash trees from emerald ash borer. North Central IPM Center Bulletin, p. 12. http://www.emeraldashborer.info/files/Multistate_EAB_Insecticide_Fact_Sheet.pdf.

Jennings, D. E., J. J. Duan, D. Bean, J. R. Gould, K. A. Rice, and P. M. Shrewsbury. 2016. Monitoring the establishment and abundance of introduced parasitoids of emerald ash borer larvae in Maryland, USA. Biol. Control. 101: 138–144.

Knight, K. S., J. P. Brown, and R. P. Long. 2013. Factors affecting the survival of ash (*Fraxinus* spp.) trees infested by emerald ash borer (*Agrilus planipennis*). Biol. Invasions. 15: 371–383.

McCullough, D. G., et al. 2008. Evaluation of non-invasive trunk sprays and trunk-injected emamectic benzoate, pp. 40–42. In Proceedings, Emerald ash borer research and development meeting, 23–24 October 2007, Pittsburgh, PA. US Department of Agriculture, Forest Service, Forest Health Technology Enterprise Team, Morgantown, WV.

McCullough, D. G. 2009. Putting the pieces together: can we solve the emerald ash borer management puzzle?, pp. 46–48. *In* K. A. McManus and K. W. Gottschalk (eds.), Proceedings of the19th US Department of Agriculture Interagency Research Forum on Invasive Species, USDA Forest Service General Technical Report NRS-P-36, Newtown Square, PA.

McCullough, D. G., and R. J. Mercader. 2012. Evaluation of potential strategies to SLow Ash Mortality (SLAM) caused by emerald ash borer (*Agrilus planipennis*). Int. J. Pest Manage. 58: 9–23.

McCullough, D., T. Poland, D. Cappaert, P. Lewis, and J. Molongowski. 2005. Evaluation of trunk injections for control of emerald ash borer, pp. 38–39. *In* V. Mastro, R. Reardon, and G. Parra (eds.), Proceedings of the Emerald Ash Borer Research and Technology Development Meeting, 5–6 October 2004, Romulus, MI. USDA Forest Service Forest Health Technology Enterprise Team FHTET-2004–15, Fort Collins, CO.

McCullough, D. G., T. M. Poland, A. C. Anulewicz, and D. Cappaert. 2009. Emerald ash borer (*Agrilus planipennis* Fairmaire) (Coleoptera: Buprestidae) attraction to stressed or baited ash trees. Environ. Entomol. 38: 1668–1679.

McCullough, D. G., T. M. Poland, A. C. Anulewicz, P. Lewis, and D. Cappaert. 2011. Evaluation of *Agrilus planipennis* (Coleoptera: Buprestidae) control provided by emamectin benzoate and two neonicotinoid insecticides, one and two seasons after treatment. J. Econ. Entomol. 104: 1599–1612.

Mota-Sanchez, D., B. M. Cregg, D. G. McCullough, T. M. Poland, and R. M. Hollingworth. 2009. Distribution of trunk-injected ^{14}C-imidacloprid in ash trees and effects on emerald ash borer (Coleoptera: Buprestidae) adults. Crop Prot. 28: 655–661.

Poland, T. M., and D. G. McCullough. 2006. Emerald ash borer: invasion of the urban forest and the threat to North America's ash resource. J. Forestry. 104: 118–124.

R Development Core Team. 2008. R: A language and environment for statistical computing, version 3.4.0. R Foundation for Statistical Computing, Vienna, Austria.

Sadof, C. S., G. P. Hughes, A. R. Witte, D. J. Peterson, and M. D. Ginzel. 2017. Tools for staging and managing emerald ash borer in the urban forest. Arboric. Urban For. 43: 15–26.

Siegert, N. W., D. G. McCullough, A. M. Liebhold, and F. Telewski. 2005. Spread and dispersal of emerald ash borer: a dendrochronological approach, p. 10. *In* V. Mastro, R. Reardon, and G. Parra (eds.), Proceedings of the Emerald Ash Borer Research and Technology Development Meeting, 5–6 October 2004, Romulus, MI. USDA Forest Service Forest Health Technology Enterprise Team FHTET-2005–16, Morgantown, WV.

Smitley, D., E. Rebek, and D. Herms. 2007a. Imidacloprid basal soil drench for protection of ash trees from emerald ash borer, p. 46. *In* V. Mastro, D. Lance, R. Reardon, and G. Parra (eds.), Proceedings of the Emerald Ash Borer and Longhorned Beetle Research and Technology Development Meeting, 23–24 October 2007, Pittsburgh, PA. USDA Forest Service Forest Health Technology Enterprise Team FHTET-2007-04, Morgantown, WV.

Smitley, D., T. Davis, K. Newhouse, and E. Rebek. 2007b. Evaluation of insecticide products for control of emerald ash borer, p. 47. *In* V. Mastro, D. Lance, R. Reardon, and G. Parra (eds.), Proceedings of the Emerald Ash Borer and Longhorned Beetle Research and Technology Development Meeting, 23–24 October 2007, Pittsburgh, PA. USDA Forest Service Forest Health Technology Enterprise Team FHTET-2007-04, Morgantown, WV.

Smitley, D., T. Davis, and E. Rebek. 2008. Progression of ash canopy thinning and dieback outward from the initial infestation of emerald ash borer (Coleoptera: Buprestidae) in southeastern Michigan. J. Econ. Entomol. 101: 1643–1650.

Smitley, D. R., J. J. Doccola, and D. L. Cox. 2010. Multiple-year protection of ash trees from emerald ash borer with a single trunk injection of emamectin benzoate, and single-year protection with an imidacloprid basal drench. Arboric. Urban For. 36: 206–211.

Wickham, H. 2009. ggplot2: elegant graphics for data analysis. Springer, New York, NY.