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Protection of Individual Ash Trees From Emerald Ash Borer (Coleoptera: Buprestidae) With Basal Soil Applications of Imidacloprid

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ABSTRACT We conducted field trials at five different locations over a period of 6 yr to investigate the efficacy of imidacloprid applied each spring as a basal soil drench for protection against emerald ash borer, *Agrilus planipennis* Fairmaire (Coleoptera: Buprestidae). Canopy thinning and emerald ash borer larval density were used to evaluate efficacy for 3–4 yr at each location while treatments continued. Test sites included small urban trees (5–15 cm diameter at breast height [dbh]), medium to large (15–65 cm dbh) trees at golf courses, and medium to large street trees. Annual basal drenches with imidacloprid gave complete protection of small ash trees for three years. At three sites where the size of trees ranged from 23 to 37 cm dbh, we successfully protected all ash trees beginning the test with <60% canopy thinning. Regression analysis of data from two sites reveals that tree size explains 46% of the variation in efficacy of imidacloprid drenches. The smallest trees (<30 cm dbh) remained in excellent condition for 3 yr, whereas most of the largest trees (>38 cm dbh) declined to a weakened state and undesirable appearance. The five-fold increase in trunk and branch surface area of ash trees as the tree dbh doubles may account for reduced efficacy on larger trees, and suggests a need to increase treatment rates for larger trees.

KEY WORDS *Agrilus planipennis*, borers, imidacloprid, *Fraxinus*

Emerald ash borer, *Agrilus planipennis* Fairmaire (Coleoptera: Buprestidae), is an invasive wood-boring beetle that has killed millions of native ash (*Fraxinus* spp.) trees in North America. The beetle, which is endemic to Asia, was first discovered infesting urban ash trees near Detroit, MI, in 2002 (Cappaert et al. 2005). It has now spread throughout the Lower Peninsula and into the Upper Peninsula of Michigan, into southwestern Ontario, Canada, and Ohio, Indiana, Illinois, Pennsylvania, and to an increasing number of outlying sites in Maryland, Virginia, West Virginia, Missouri, Wisconsin, Kentucky, and New York (Anonymous, 2009; http://emeraldashborer.info). In Michigan, adult beetles begin emerging in late May by chewing D-shaped emergence holes (0.3 cm) through the outer bark of host trees. Adults feed on the edges of ash leaves causing crenulation but do not cause significant damage to the canopy. Damage occurs when larvae tunnel through the cambial tissue beneath the bark, feeding on phloem and scarring xylem while creating distinctive, serpentine galleries that inhibit the flow of nutrients and water within the tree. Tree mortality usually occurs within 2–4 yr of the appearance of the first symptoms of emerald ash borer infestation and depends largely on the number of colonizing beetles and overall vigor of the host tree (Herms et al. 2004, Cappaert et al. 2005, Poland and McCullough 2006).

As emerald ash borer continues to spread outward from southeast Michigan, an increasing number of municipalities, golf courses, businesses, and homeowners face difficult decisions about the removal of ash trees or investment in insecticide treatment of selected trees. Because emerald ash borer has only recently been discovered in North America, we still know very little about the long-term prognosis for trees protected with insecticide treatments. Trunk injections of imidacloprid or emamectin benzoate, and basal soil applications of imidacloprid have all provided enough protection of ash trees against emerald ash borer in efficacy tests to look promising as treatments for individual ash trees (Cappaert et al. 2005). Although these treatments may provide 75–99% reductions in emerald ash borer larvae when compared with control trees, it is still uncertain how well ash trees protected with these insecticide treatments will survive after several years of intense pressure from emerald ash borer (McCullough et al. 2004, 2005). The relationships between initial infestation level and efficacy or between tree size and efficacy are not well understood.

To provide better information on the long-term success of annual insecticide treatments for emerald ash borer, we conducted several studies on one of the most promising and affordable treatments available to

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homeowners and tree-care professionals: basal soil application of imidacloprid. We determined efficacy of imidacloprid basal soil applications and the survival and health of treated and nontreated green and white ash trees of various sizes at five different locations over a period of three to four years at each site.

Materials and Methods

Imidacloprid Treatments. At all five research sites (see below), imidacloprid (Merit 75 WP or Bayer Advanced Tree and Shrub, Bayer Environmental Science) was applied as a basal soil drench within 0.5 m of the trunk in early May unless otherwise noted (see Rebek et al. 2008). Trees were treated at the label rate of 0.55–0.57 g (AI))/cm trunk diameter at breast height (dbh). We drenched the soil by mixing imidacloprid in a 6-liter watering-can and pouring the entire solution around the base of each tree.

Canopy Thinning Ratings. A key symptom of emerald ash borer infestation is canopy thinning (i.e., smaller or fewer leaves in the tree canopy), followed by branch dieback (the death of limbs, branches, and twigs in the tree canopy). The percentage of canopy thinning and dieback is positively related to the level of emerald ash borer infestation and the amount of internal feeding injury caused by emerald ash borer larvae (Rebek et al. 2008, Smitley et al. 2008). Symptoms of emerald ash borer infestation typically progress from a barely detectable thinning of the canopy to more pronounced canopy thinning, followed by scattered branch dieback, and eventually death of the entire above-ground stems and branches (Smitley et al. 2008). In this study, canopy thinning and dieback ratings were made as described in Smitley et al. (2008). Dieback ratings were assessed in late spring to midsummer after leaves were fully developed and before the onset of senescence. Two to three independent observers rated each tree at each site, and ratings were then averaged to derive an estimate of canopy thinning for each tree.

Estimates of Larval Gallery Density. In late fall, we harvested three 8–15-cm-diameter branches per tree (East Lansing and Adrian sites) or whole trees (Westland site) to estimate the level of emerald ash borer infestation within each treatment. Twigs were removed from all branch samples, which were bundled and labeled by site, date, and tree number. Branch and tree samples were stored at either the Michigan State University Entomology Field Research Facility located in East Lansing or the MSU Tollgate Education Center in Novi, MI. During the fall and early winter, we set each branch or small-diameter trunk sample on a modified sawhorse/clamp apparatus and carefully removed the bark with a reciprocating saw, draw knife and chisel. After bark removal, we counted and recorded the number of live larvae and larval feeding galleries that were revealed. Old galleries were recognized by their dark color, presence of an empty pupal chamber, and an adjacent, D-shaped exit hole. In contrast, new galleries had fresh tunneling from the current year and usually contained live larvae. We calculated the density of larvae and new galleries (number per square meter) per sample by dividing the numbers of larvae or galleries found by the surface area of the sample (Rebek et al. 2008).

Westland, 2003–2005. In late November 2002, 140 healthy balled and burlapped ash trees measuring 5–6 cm dbh and 3–4 m tall, were planted at a nursery in Westland, MI, located ≈25 km west of Detroit. One-half of the trees were white ash, *Fraxinus americana* L. Autumn Purple, and the rest were green ash, *Fraxinus pennsylvanica* Cimmzam Cimmaron or Patmore. We established four treatment groups by applying an annual basal soil drench of imidacloprid to 30 randomly selected trees of each species. The remaining 30 trees of each species were left untreated. Imidacloprid was applied in April or May each year from 2003 to 2005 (3 April 2003, 14 May 2004, and 27 April 2005) following established treatment methods. Trees at this site were sufficiently small (10–15 cm dbh) and enough replicates were available to allow for the removal of entire trees, which were cut and stripped of branches before labeling and storing. Each year from 2003 to 2005, we felled a minimum of five trees from each treatment in October and removed the bark from the entire trunk of each tree before counting larvae and galleries.

Because the sample size was small and transformations could not stabilize the variance in gallery counts, we used the nonparametric Kruskal-Wallis Test (PROC NPAR1WAY, SAS version 9.1, SAS Institute 1999) to analyze treatment differences separately for each tree species. Percent canopy thinning and dieback data also were tested for homogeneity of variances using Bartlett's test (Sokal and Rohlf 1995). Because variances were not different among treatments, imidacloprid drench treatment was compared with the control treatment for green ash and white ash separately, using an unpaired *t*-test. All statistical comparisons were made with a P value of ≤0.05.

Bay Pointe Country Club, 2004–2007. Bay Pointe Country Club is a golf course located in Orchard Lake, MI, a suburban community ≈32 km northwest of Detroit. The golf course was built in a marshy area between two lakes where the water table is only 1–2 m below the surface. We selected 52 green ash (*Fraxinus pennsylvanica* Marshall) trees varying in size from 15 to 65 cm dbh. In early April 2004, we measured the dbh of each tree and ranked the trees from smallest to largest. Every other tree on the ranking list was then assigned to a treatment of imidacloprid, with alternate trees left as untreated controls, thereby ensuring a random assignment of treatments with an even distribution of size classes among treated and control trees. In April or May each year from 2004 to 2006 (22 April 2004, 27 April 2005, and 31 May 2006), we treated one-half of the trees (n = 26) with imidacloprid following the treatment protocol described above.

Canopy dieback ratings were recorded in late July each year from 2004 to 2007 (29 July 2004, 21 July 2005, 31 July 2006, and 2 July 2007). We used *t*-tests (PROC TTEST, SAS version 9.1, SAS Institute 1999) to compare the mean percentage of dieback (dependent variable) in treated versus control trees. Percentage of dieback data were arcsine square root (x) transformed before analysis.

In late fall 2004, a pole-pruner was used to randomly remove three branches measuring ≈1.5 m long and 5–15 cm wide from the lower half of the tree canopy. One tree each from the treatment and control groups had >150 old galleries per m^2, densities >2 SDs of the mean for all trees (44.3 ± 48.0 old galleries per m^2). These two trees which were severely damaged by emerald ash borer before the test was initiated were removed as outliers from the data set for analyses involving larval density. The remaining 48 trees had <100 galleries per m^2 and averaged 36.7 ± 29.0 old galleries per m^2.

Barton Hills Country Club, 2004–2007. Barton Hills Country Club is located in Ann Arbor, MI, ≈56 km west of Detroit. We selected 56 green ash trees growing on the golf course to determine the efficacy of soil-applied imidacloprid, trunk- and foliar-applied cyfluthrin, and a combination of both treatments. Trees ranged from being lightly to heavily infested with emerald ash borer at the beginning of the test in 2004. Fourteen trees were assigned to each treatment and grouped into two categories of initial canopy thinning (i.e., low to medium, <60%; or high, >60%) based on initial canopy dieback ratings made in late May 2004. Ash trees at Barton Hills ranged in size from 18 to 55 cm dbh.

Ash trees in the imidacloprid-only treatment received a basal soil drench in April or May of each year from 2004 to 2006 (22 April 2004, 27 April 2005, and 31 May 2006). In a second treatment, ash trees were sprayed twice with ß-cyfluthrin, 2 wk apart, with the first application timed to the first observation of adult emerald ash borer activity. In 2004, ash trees in this treatment were sprayed in early and late June, whereas in 2005 and 2006 they were sprayed in mid June and early July. In a third treatment, ash trees were drenched with imidacloprid and sprayed once with β-cyfluthrin within a week of when the first emerald ash borer adults were observed. Trees in the control treatment were located at least 10 m away from any treated tree to minimize contamination. Following established protocol, canopy thinning ratings were obtained in late June of 2004–2007. A Fisher's protected least significant difference (LSD) test was used to compare imidacloprid treatment means to the control mean for ash trees beginning the test with a low to moderate level of canopy thinning, and a separate LSD test to compare treatment means to the control mean for trees beginning the experiment with a high level of canopy thinning. Percentage of dieback data were arcsine square root (x) transformed to meet the assumptions of normality and homogeneity of variance.

East Lansing, 2005–2008. We used green ash trees growing between the sidewalk and street in six subdivisions of East Lansing, MI for this test. These trees were between 15 and 30 yr old and ranged in size from 28 to 64 cm dbh with a mean dbh of 38 cm. Test trees were spaced a minimum of 12 m apart. Tree trunks were measured and marked with a metal tag during the first week of August 2005. Lawns in this subdivision are well maintained, but very few are equipped with an irrigation system. Each treatment was replicated 10 times with each replicate consisting of an individual tree. A basal soil drench of imidacloprid was applied as previously described as an annual fall or annual spring treatment beginning in fall of 2005 or spring of 2006. Fall treatments were made on 27 October 2005, 14 December 2006, and 28 November 2007. Spring treatments were made on 2 June 2006, 18 May 2007, and 2 June 2008. These two treatments and a control treatment were part of a larger test with other insecticide treatments and different treatment methods. The entire test area was divided into 10 blocks with one tree in each block receiving one of the treatments. If two ash trees were <12 m apart, only one of them was used in the study. Each tree was rated for canopy thinning each year in June or July (6 July 2006, 6 July 2007, and 13 June 2008). Branches from the upper one third of the tree canopy were sampled in September 2006–2008. Three branches were removed from each tree by arborists working for the City of East Lansing. Branches selected for pruning were spaced as far apart as possible to maintain canopy balance. The bark was removed from branch samples and emerald ash borer galleries and larvae were counted. Canopy thinning data were arcsine square root-converted before analysis.

Canopy thinning, larval density, and gallery density means were compared among treatments with a Fisher's protected LSD test at $P = 0.05$.

Adrian Street Tree Test, 2006–2008. We used green ash trees planted and maintained as street trees by the city of Adrian in five different neighborhoods for this test. All test trees were between 14 and 28 yr old and ranged from 15 to 66 cm dbh. Trees were spaced a minimum of 15 m apart. Each tree was marked with a metal tag and measured for circumference at breast height during the first week of September 2005. Lawns where study trees were located were well maintained, but very few were irrigated. Each treatment was replicated 10 times with each replicate consisting of an individual tree. Treatments consisted of an imidacloprid basal drench applied each spring (27 June 2006, 24 May 2007, and 3 June 2008) or fall (7 November 2006 and 5 November 2007) or an untreated control. Canopy thinning ratings were made for each tree in June or July of each year (11 July 2006, 12 July 2007, and 10 June 2008). Branches from the upper one-thirds of the canopy of each tree were sampled in late October of each year for bark removal and larval galleries were counted as previously described. Branches selected for pruning were spaced as far apart as possible to maintain canopy balance. Treatment means in the East Lansing test were compared with Fisher's protected LSD test at $P = 0.05$. Percentage of canopy thinning data were arcsine square root-converted before analysis, but real percentage of means are presented in tabular results.

Table 1. Mean ± SD emerald ash borer galleries per square meter found in October of each year after felling and removing the bark from imidacloprid-drenched and control ash trees at the Westland test site

Yr	Ash species	Treatment	n	Mean dbh (cm)	Galleries per m^2	S	Kruskal–Wallace $P > \chi^2$
2003	Green	Control	7	5.6	2.7 ± 0.9	29	0.01
	Green	Imidacloprid	8	5.6	0.1 ± 0.1		
	White	Control	7	5.2	1.1 ± 0.6	68	0.05
	White	Imidacloprid	7	5.2	0.0 ± 0.0		
2004	Green	Control	14	5.6	4.1 ± 2.0	56	0.03
	Green	Imidacloprid	9	5.6	0.0 ± 0.0		
	White	Control	12	5.2	5.8 ± 6.2	25	0.20
	White	Imidacloprid	5	5.2	0.0 ± 0.0		
2005	Green	Control	9	5.6	9.8 ± 2.7	115	0.004
	Green	Imidacloprid	6	5.6	0.5 ± 1.5		
	White	Control	8	5.2	13.6 ± 4.8	25	0.09
	White	Imidacloprid	5	5.2	0.0 ± 0.0		

Balled and burlapped nursery trees were planted in cultivated soil in November 2002.

Results

Westland. Annual imidacloprid soil drenches provided newly planted ash trees with a very high level of protection from emerald ash borer (Table 1). After three years of treatment, green ash control trees were infested with 9.8 emerald ash borer galleries/m^2 compared with 0.5 galleries per m^2 found on treated green ash trees. White ash control trees were infested with 13.6 emerald ash borer galleries per m^2 in the third year of this study, compared with 0.0 galleries per m^2 found in treated white ash trees in all 3 yr of this study. Even so, variation in gallery counts among control trees when compared with 0 galleries in all treated trees resulted in a nonsignificant comparison of means in 2004 and 2005 (Table 1). By August of 2005, all green and white ash trees receiving annual basal drenches of imidacloprid seemed healthy (<20% canopy thinning), whereas all control trees were dead.

Bay Pointe Country Club. In July 2004, two months after the first imidacloprid treatment and before emerald ash borer larvae caused any significant damage that year, the condition of test trees ranged from 33 to 90% canopy thinning in the control and imidacloprid treatments. Canopy thinning ratings at that point reflected a wide range of emerald ash borer infestation levels in summer and fall 2003, 6 mo before treatments were initiated. Because of the large variation in the condition of trees before treatments were initiated, test trees were placed into one of two categories: trees with extensive canopy thinning and dieback (>60%) and trees with low to moderate canopy thinning and dieback (<60%).

Efficacy of an annual spring basal drench of imidacloprid was then evaluated for trees starting the test in a relatively healthy condition (<60% canopy thinning), or with extensive borer damage (>60% canopy thinning). A basal soil treatment of imidacloprid was found to be much more successful when trees were not seriously compromised at the start of the test (Table 2). For trees with <60% canopy thinning at the beginning of the test, treated trees gradually improved in condition over time and were rated at 15.4 ± 12.8% (mean ± SD) canopy thinning in the last year. In contrast, control trees in the same group declined each year to a level of 78.8 ± 25.5% canopy thinning at the end of the test ($P \leq 0.01$; t-test) (Table 2).

Imidacloprid-drenched trees beginning the test with >60% canopy thinning were rated at 61.9 ± 34.1% (mean ± SD) canopy thinning at the end of the test compared with a rating of 96.2 ± 6.8% for control trees ($P \leq 0.01$; t-test) (Table 2). This reflected our observations that some of the treated ash trees died and some slowly improved in condition.

Barton Hills Country Club. Results of our test at Barton Hills were similar to results from Bay Pointe; insecticide treatments did not adequately protect ash trees that were classified as having extensive canopy thinning (>60%) at the beginning of the study in 2004 (Table 3). For trees with extensive canopy thinning at the beginning of the test, the canopy ratings increased from 83.8 to 98.3% for control trees from 2004 to 2007 but decreased from 79.8 to 62.5%, over the same period of time, for trees treated annually with a basal drench of imidacloprid (Table 3). We used Fisher's protected

Table 2. Canopy thinning ratings of ash trees at BayPointe Country Club before and after 3 yr of imidacloprid basal drench treatments

Initial tree condition in 2004	Treatment	n	Mean dbh (cm)	% canopy thinning ± SD	
				2004	2007
Extensive canopy thinning and dieback (>60%)	Control	16	36.8	77.9 ± 9.0	96.2 ± 6.8**
	Imidacloprid basal drench	17	35.8	73.3 ± 8.5	61.9 ± 34.1**
Low to moderate canopy thinning (<60%)	Control	17	33.8	51.0 ± 6.2	78.8 ± 25.5**
	Imidacloprid basal drench	10	32.3	45.9 ± 10.9	15.4 ± 12.8**

** Indicates imidacloprid drench mean is different from control mean within each tree condition group ($P \leq 0.01$; t-test).

Table 3. Canopy ratings of ash trees at Barton Hills Country Club before and after 3 yr of imidacloprid basal drench treatment

Initial condition of trees in 2004	Treatment	Mean dbh (cm)	n	% canopy thinning and dieback ± SD	
				2004	2007
Extensive canopy thinning (>60%)	Control	23.6	6	83.8 ± 7.7	98.3 ± 4.1
	Merit drench and Tempo sprays	28.2	6	77.0 ± 6.6	64.8 ± 31.1
	Merit drench	35.1	4	79.8 ± 12.9	62.5 ± 44.1
	Tempo sprays (twice)	26.7	5	81.0 ± 10.9	83.0 ± 38.0
Low to moderate canopy thinning (<60%)	Control	33.3	7	49.4 ± 7.9	97.8 ± 3.9
	Merit drench and Tempo sprays	30.5	6	35.3 ± 14.3	21.8 ± 22.7**
	Merit drench	30.2	6	35.2 ± 8.0	20.7 ± 13.12**
	Tempo sprays (twice)	29.2	6	35.8 ± 16.2	18.4 ± 14.0**

** Indicates treatment mean is significantly different from the control mean by Fisher's protected LSD test ($P \leq 0.01$).

LSD test with $P \leq 0.01$ to compare canopy thinning ratings among the four treatment means for each initial tree condition category. Although there were no significant differences among treatments with trees initially rated as having >60% canopy thinning in 2004, at least 50% of the treated trees were still alive and improving in condition in 2007, whereas all of the control trees were dead. Control trees with initial canopy ratings of <60% group declined each year, going from a canopy rating of 49.4% in 2004 to 97.8% in 2007 (Table 3). In contrast, trees receiving one of the three insecticide treatments improved in condition each year. Canopy thinning ratings for trees treated annually with a basal drench of imidacloprid and a foliar spray of cyfluthrin, a basal drench alone, or two foliar sprays of cyfluthrin, decreased during the test from 35.3 to 21.8%, 35.2 to 20.7%, or 35.8 to 18.4%, respectively. All ash trees that started the test with <60% canopy thinning, and were also treated with an annual basal soil drench of imidacloprid, survived and seemed to be in excellent condition in 2007.

East Lansing. Ash trees in this study were very healthy in July 2006 when canopy thinning and dieback ratings were first made. Mean ratings for each treatment varied from 11.8 to 16.0% canopy thinning with no differences found among treatments (Table 4). Because tree ratings in July reflect damage from the previous year, ash trees in our study were relatively healthy and harbored a very low infestation of emerald ash borer in 2005. In fall 2006, the density of emerald ash borer larvae in our test trees varied from 0.0 to 3.1 per m^2. Canopy thinning ratings in control trees increased to a mean of 28.8 in July 2007 compared with 10.8 and 9.2 for trees in both imidacloprid drench treatments. The density of emerald ash borer larvae found in branch samples collected in late September 2007 was higher in control trees (6.8 larvae per m^2) compared with trees receiving a basal drench of imidacloprid each spring (2.7 larvae per m^2). In 2008, the mean canopy thinning rating for trees receiving a spring drench (18.0%) was different from the control mean (51.3%), whereas the rating of trees receiving a fall drench (32.8%) was not different from the control mean. The same is true for the density of larvae found in branch samples in that only the spring application was significantly different from the control (Table 4).

Adrian. Imidacloprid basal drench treatments were initiated in 2006 when trees were still in good health (<10% canopy thinning) (Table 4). Canopy thinning increased in control trees to 16% in July 2007 and to 64% by August 2008. Ash trees receiving a spring basal drench with imidacloprid were successfully protected

Table 4. Protection of green ash street trees in East Lansing and Adrian, MI, with basal soil applications of imidacloprid

Location, treatment	n	2006			2007		2008	
		Mean dbh (cm)	Canopy thinning in July (%)	Larvae per m^2 in Oct.	Canopy thinning in July (%)	Larvae per m^2 in Oct.	Canopy thinning in Aug. (%)	Larvae per m^2 in Oct.
East Lansing, imidacloprid fall drench 2005, 2006, 2007, 2008	10	30.2a[a]	11.8 ± 9.3a	0.8 ± 2.5 a	10.8 ± 6.5a	2.7 ± 5.2ab	32.8 ± 15.6ab	10.8 ± 14.9b
East Lansing, imidacloprid spring drench 2006, 2007, 2008	9	26.4a	13.0 ± 9.3a	0 ± 0a	9.2 ± 15.9a	0 ± 0a	18.0 ± 12.2a	2.9 ± 6.7a
East Lansing, control	10	28.7a	16.0 ± 21.0a	3.1 ± 7.1a	28.8 ± 27.9a	6.8 ± 9.4b	51.3 ± 30.2b	28.7 ± 21.5b
Adrian, imidacloprid fall drench 2006, 2007, 2008	10	45.2a	8.0 ± 5.7a	ND	24.5 ± 15.5a	7.6 ± 17.0a	65.3 ± 25.8b	5.7 ± 5.6a
Adrian, imidacloprid spring drench 2006, 2007, 2008	10	36.1a	3.5 ± 3.6a	5.2 ± 9.5a	9.8 ± 6.4a	3.6 ± 6.8a	33.0 ± 25.8a	6.3 ± 7.8a
Adrian Control	10	40.1a	9.0 ± 7.4a	3.0 ± 2.9a	16.0 ± 11.4a	6.2 ± 6.6a	64.0 ± 29.3b	31.5 ± 43.3a

Data are means ± SD.

[a] Treatment means followed by the same letter are not significantly different from the control mean at the same location by Fisher's protected LSD test ($P \leq 0.05$).

from emerald ash borer through August 2008 when they averaged 33.0% canopy thinning. Fall drenches of imidacloprid in 2006 and 2007 did not adequately protect trees and they declined rapidly in 2008 (65.3% canopy thinning). However, conclusions about the efficacy of fall drenches compared with spring drenches are weakened by the fact that the mean dbh of trees that received a fall drench treatment is 9 cm larger than the dbh of trees that received a spring drench, because tree size is an important consideration.

Role of Tree Size in Efficacy of an Imidacloprid Basal Drench. Annual treatments of small (<15 cm dbh) ash trees with an imidacloprid basal drench are highly effective for protecting them against emerald ash borer with nearly 100% of the treated trees at the Westland site surviving and returning to a healthy condition (Table 1). Larger ash trees were also protected from emerald ash borer with annual basal drenches, but the observed rate of success was not as high (Tables 2 and 3). To investigate the influence of tree size on the efficacy of an imidacloprid basal drench we used a regression analysis for trees located at the Bay Point and Barton Hills test sites, and a separate regression analysis for trees located at the East Lansing and Adrian test sites. Trees from Bay Pointe and Barton Hills were grouped together for the first analysis because at these two locations imidacloprid drench treatments were initiated in 2004 and the trees were 1), in a similar condition (Bay Pointe: 45–78% canopy thinning, Barton Hills: 35–84% canopy thinning); 2), of a similar size (Bay Pointe: 32–37 cm, Barton Hills 24–35 cm dbh); and 3), mostly located where they received irrigation. Also, control trees at Bay Pointe and Barton Hills declined at the same rate during the 3-yr test period due to emerald ash borer (Tables 2 and 3). Trees at the East Lansing and Adrian test sites were grouped for a separate regression analysis because at these two locations spring drench treatments were initiated in 2006 when the trees were still healthy (9–15% canopy thinning), the initial infestation levels were very similar (3.1 larvae/m^2 and 3.0 larvae/m^2 for East Lansing and Adrian, respectively), and untreated trees declined at a similar rate from 2006 to 2008 (Table 4). At Bay Pointe and Barton Hills tree size had no effect on the rate of decline of control trees ($F = 0.16, r^2 = 0.01, P > 0.69$) (Fig. 1A) or trees treated each year with an imidacloprid drench ($F = 2.6, r^2 = 0.09, P > 0.12$) (Fig. 1B). Regression analysis of data from control trees in East Lansing and Adrian indicates a very weak relationship between tree size and canopy thinning ($r^2 = 0.063, F = 4.4, P = 0.04; n = 75$) (Fig. 2A). However, for trees receiving a spring basal drench of imidacloprid, canopy thinning was dependent on tree size, with tree size explaining 48% of the variation in canopy thinning ($r^2 = 0.48, F = 13.0, P < 0.002; n = 16$) (Fig. 2B). For treated trees in East Lansing and Adrian, the smallest trees (<30 cm dbh) remained in excellent condition (5–30% canopy thinning) for 3 yr, whereas most of the largest ones (>38 cm dbh) declined to a weakened state and undesirable appearance (35–80% canopy thinning) by the end of the study.

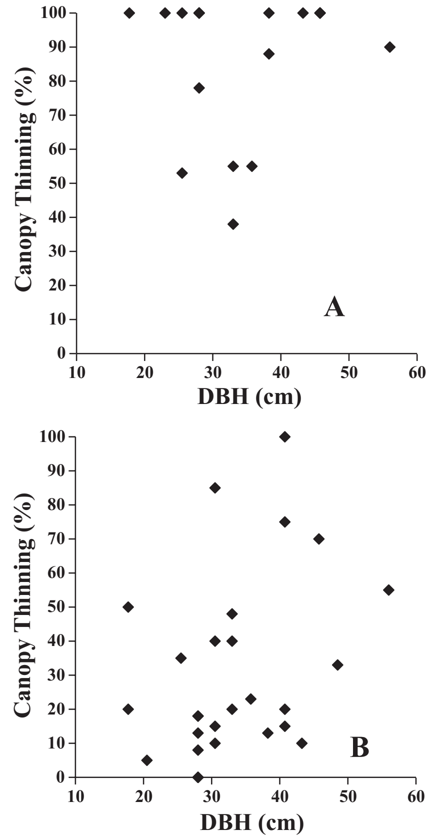

Fig. 1. Lack of a significant relationship of canopy thinning to tree dbh at Bay Pointe and Barton Hills for (A) control trees ($n = 19$) and (B) trees treated annually for 3 yr with an imidacloprid basal drench ($n = 29$).

Discussion

Imidacloprid has been used effectively against many tunneling, chewing, and sucking pests of ornamental trees (Gill et al. 1999, Lawson and Dahlsten 2003, Ahern et al. 2005, Wang et al. 2005, Poland et al. 2006, Tenczar and Krischik 2006). Because imidacloprid is absorbed by roots and moves systemically through the plant, it can be applied as a basal soil injection or as a basal soil drench. This characteristic makes imidacloprid easy to apply and several imidacloprid products are available to homeowners for purchase. Currently, no other products proven to be effective against emerald ash borer are available unless an arborist is hired to make the insecticide treatments.

Imidacloprid as a basal drench was the most successful (nearly 100% control) for protecting trees at the Westland test site where we had the smallest (5–6 cm dbh) trees, and the least successful (50% control) at the Adrian test site where we had the largest trees (36 cm dbh). Also, a regression analysis for the relatively small number of treated trees at the East Lansing

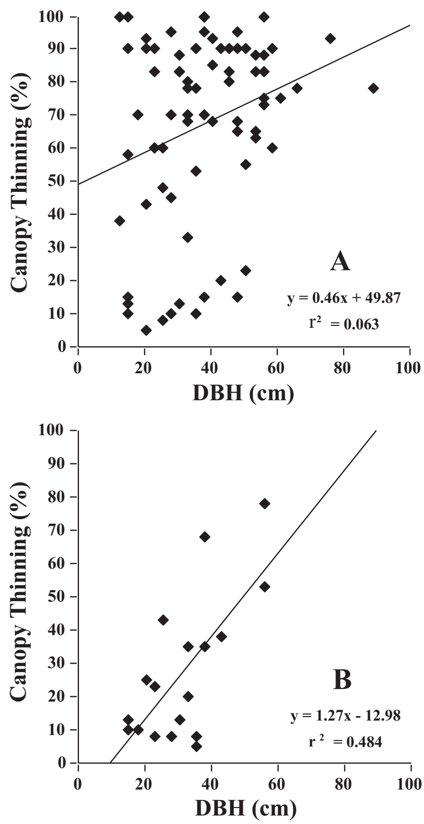

Fig. 2. Relationship of canopy thinning to tree dbh in East Lansing and Adrian for (A) control trees ($n = 76$) or (B) trees receiving annual spring treatments of imidacloprid as a basal soil drench for 3 yr ($n = 17$).

and Adrian test sites ($n = 17$) revealed that 48% of the variation in canopy thinning ratings for trees receiving an annual imidacloprid drench seemed to be due to size of the tree (Fig. 2A and B). The observed decrease in efficacy of an imidacloprid basal drench for larger trees may be due to the relationship between trunk dbh and tree surface area. Rates used in current field practices for applying imidacloprid as a basal drench or basal soil injection have been based on tree dbh in linear form, so that when the dbh doubles, the amount of imidacloprid applied doubles. However, research has shown that when ash tree dbh doubles, the tree surface area increases five-fold (LeGoff and Ottorini 1996, McCullough and Siegert 2007). The relationship between trunk dbh (x) and trunk and branch surface area (y) for ash trees has been reported as a second order polynomial ($y = 0.024x^2 - 0.307x + 2.63$; McCullough and Siegert 2007). This suggests a need to increase treatment rates for larger trees so that the amount of imidacloprid applied reflects the tree surface area and phloem biomass.

We may not have seen the same relationship between tree size and efficacy at the Bay Pointe and Barton Hills sites because the trees did not vary as much in size (15–55 cm dbh) as the trees at the East Lansing and Adrian sites (15–90 cm dbh). Also, the trees at Bay Pointe and Barton Hills may not have been as stressed, particularly during periods of dry weather, because most of the trees were growing in irrigated and fertilized turfgrass without any root-growth restrictions, whereas the street trees in East Lansing and Adrian were not growing in irrigated sites and root growth was restricted by a sidewalk on one side and a paved street on the other side. Until the impact of drought stress on efficacy of imidacloprid basal drenches is better understood it is prudent to water treated trees during prolonged periods of dry weather.

In addition to tree size, the level of success achieved in controlling emerald ash borer depends on the initial condition of ash trees when insecticide treatments are initiated. At Bay Pointe and Barton Hills where ash trees were of a moderate size (23–37 cm dbh), 19 of 22 trees (86%) treated with an annual basal drench of imidacloprid survived and seemed to be healthy at the end of the test, as long as the trees were not seriously compromised before treatments began (<60% canopy thinning). However, the survival rate for treated trees that started the test with >60% canopy thinning was only five of 16 trees (31%). Clearly, severely compromised trees (>60% canopy thinning) are not good candidates for receiving a basal soil treatment with imidacloprid.

Emerald ash borer larval feeding damage is concentrated from late summer through autumn. This late season feeding damage may cause a decline in tree health that is not observed until the following spring. Heavily infested trees may progress from a 30% canopy thinning rating in August to a 60% rating in June of the following year. Therefore, treatment decisions being made in early spring before the new canopy is established may be based on an inaccurate assessment of tree health. More accurate assessments can be made after the trees are fully flushed.

Although other highly effective treatment options are available to tree care professionals, very few treatments are available that homeowners can make themselves. Imidacloprid products that are available in local garden centers are relatively safe, affordable, and can be easily applied as a basal drench. This gives homeowners a reasonable alternative to tree removal, which is the certain outcome for any ash trees in an emerald ash borer-infested area that are not treated with insecticide. Imidacloprid drenches are also an option for tree care professionals and city foresters, particularly when they are looking for treatments that can be applied quickly and cost less than trunk injections.

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