Efficacy of Soil-Applied Neonicotinoid Insecticides for Long-term Protection Against Emerald Ash Borer (Coleoptera: Buprestidae)

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ABSTRACT Protection of green ash trees (*Fraxinus pennsylvanica* Marshall) from the emerald ash borer (EAB), *Agrilus planipennis* Fairmaire, by soil applications of neonicotinoids (imidacloprid, clothianidin, and dinotefuran) was tested at five locations between 2005 and 2013. Application rate and spring versus fall application dates were evaluated in tests with neighborhood street trees and in one plantation of 65 ash trees. Insecticide treatments of ash trees at all five sites were initiated as the leading edge of the EAB invasion began to kill the first ash trees at each location. Trees were treated and evaluated at each site for 4 to 7 yr. Spring applications of imidacloprid were more efficacious than fall applications. Application rates of 0.8 g a.i./cm dbh or greater per year gave a higher level of protection and were more consistent than rates of 0.56 g a.i./cm dbh per year or less. The number of years between the first observation of canopy loss due to EAB and death of most of the control trees varied from three to seven years among test sites, depending on how many non-treated ash trees were nearby.

KEY WORDS emerald ash borer, *Agrilus planipennis*, *Fraxinus pennsylvanica*, green ash, imidacloprid

Emerald ash borer (EAB), *Agrilus planipennis* Fairmaire (Coleoptera: Buprestidae), was first identified in North America from beetles collected in June of 2002 from dying ash trees near Detroit, Michigan (Haack et al. 2002, Cappaert et al. 2005, Herms and McCullough 2014). At the time of this writing, it has spread to at least 24 states and two provinces, killing the aboveground growth of nearly every unprotected ash (*Fraxinus* spp.) in a steadily expanding area radiating outward from southeast Michigan (Smitley et al. 2008, USDA 2014). Because *Fraxinus* is the second-most abundant type of planted tree found in cities in the eastern United States, usually accounting for 5 to 20% of all street trees, municipalities and property owners must bear the cost of either insecticide treatments to preserve trees or tree removal (Raupp et al. 2006, Sadof et al. 2011). Although initial efforts to protect trees from EAB between 2002 and 2006 were largely unsuccessful, extensive research has yielded several reliable insecticide treatment options (Cappaert et al. 2005; Smitley et al. 2008, 2010a,b; McCullough et al. 2011; Herms et al. 2014). In the previously cited papers, trunk injections of emamectin benzoate made every second or third year, consistently gave the highest level of protection against EAB. Although many professional arborists are using trunk-injected insecticides now, another treatment option is a basal soil drench with a neonicotinoid insecticide applied in late spring of each year. Homeowners can purchase and apply a basal soil drench of imidacloprid, but they cannot make trunk injections because of the need for expensive injection equipment and because injections must be made by a certified pesticide applicator. In addition, cities, industrial properties, or golf courses with many small ash trees (<20 cm dbh) may prefer a basal soil drench to a trunk injection because basal drenches may cost less and take much less time to apply. Efficacy of neonicotinoid drenches for protection against EAB is usually very good, but it has not always been consistent, particularly for larger ash trees (>30 cm dbh) (Smitley et al. 2010b).

Soil drenches or soil injections of neonicotinoid insecticides made around the base of trees or shrubs have also been used successfully against other important insect pests (Gill et al. 1999, Lawson and Dahlsten 2003, Webb et al. 2003, Ahern et al. 2005, Wang et al. 2005, Poland et al. 2006, Frank et al. 2007, Szczepaniec and Raupp 2007). Although the potential detrimental effects of imidacloprid and other neonicotinoid insecticides to honey bees must be considered in any crop or landscape setting, basal soil applications are more desirable than previous treatment methods for borer control, which consisted of spraying the trunk and foliage of a tree one to four times per year.

Because basal soil drenches of neonicotinoids are the most readily available products to homeowners to protect trees from EAB, the purpose of this research was to determine if these products can provide a

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consistently high level of protection against EAB. In particular, we evaluated fall versus spring applications, and a range of application rates that can be used with these products. Also, we compared efficacy of a basal soil drench of imidacloprid with efficacy of basal soil drenches of dinotefuran and clothianidin at similar application rates. Long-term (4 to 7 yr) experiments were conducted with ash street trees in four cities in southern Michigan and northwestern Ohio, and at one plantation of 65 ash trees in East Lansing, Michigan, between 2005 and 2013. All experiments were initiated when the first signs of canopy loss and branch dieback in the subdivision or planting were confirmed to be caused by EAB.

Materials and Methods

Imidacloprid, clothianidin, and dinotefuran were tested as a basal application of product diluted in 1.5 l of water, or as undiluted liquid or granular product, applied in fall or spring at rates varying from 0.31 to 1.12 g a.i./cm dbh. Experiments with 3 to 15 different treatments per site, including an untreated control, were evaluated at five different sites in southern Michigan or northwestern Ohio. Product names and active ingredients tested at each site for protecting ash trees against EAB are given in Table 1. Active ingredients, application dates and rates for each treatment, and a site description are given under the subheading for each of the five sites that follow.

MSU HTRC: Basal drenches applied every 1–3 yr. At the Hancock Turfgrass Research Center (HTRC), Michigan State University, East Lansing campus (42°42′28.47″ N 84°28′32.57″ W), 80 green ash trees (*Fraxinus pennsylvanica* 'Marshall Seedless') were planted in 1996 in a plantation setting on 3.0-m centers in two adjacent rectangular grids for the purpose of growing turfgrass under shady conditions. The shade study ended in 2002, and the entire plot area was maintained with a standard low-maintenance turf fertility program and no irrigation for the next three years. This study began in spring of 2005 using the ash trees from the shade study. At that time, the green ash trunks varied from 5.0 to 15.0 cm in diameter at breast height (dbh), and all of the trees had a full canopy. A few trees had one or two branches with raised and split bark, indicating that EAB was detectable within the planting, but scarce. A woodlot located 250 m from the planting contained about 20% ash, and most of the trees in the woodlot were showing signs of EAB infestation and decline. The two adjacent stands of ash trees are located on nearly level ground on the south border of the research center property.

Five imidacloprid basal drench treatments were evaluated in this study. Treatments 1, 2, and 3 were made by taking the highest labeled rate that could be applied in a single application (0.56 g a.i./cm dbh), dissolving the product in 4 l of water, and drenching it over a 30-cm-wide band around the base of each tree. A total of five treatments were applied: 1) imidacloprid applied annually, 2) imidacloprid applied every other year, 3) imidacloprid applied every third year, 4) imidacloprid applied at the label rate for white grub control in turfgrass (0.4 gram a.i. imidacloprid mixed in 1520 ml H_2O) by spraying the solution evenly over a 9.0-m^2 area, centered at the base of the trunk, and 5) an untreated control. Application dates for all treatments were 17 May 2005, 9 June 2006, 31 May 2007, 18 June 2008, 15 May 2009, and 9 June 2010.

The decline of test trees due to EAB infestation was evaluated by observing the canopy of each tree and making ratings in July of each year, as described by Smitley et al. (2008). Extensive tunneling initially causes trees to produce smaller leaves, followed by branch dieback and eventual death of the entire aboveground portion of the tree. The overall impact of leaf thinning and branch dieback can be visually observed and recorded as percent canopy loss. A set of photographs of ash trees with 0 to 100% canopy loss in 10%

Table 1. Active ingredients and application method for products tested at each research site

Product name	Active ingredient			Consistency	App. method	Site and treatment numbers				
	Imidacloprid	Clothianidin	Dinotefuran			HTRC MSU Table 2	Adrian Table 3	Kentwood North Table 4	Kentwood South Table 5	Toledo Table 6
Arena 50WDG		50%		Soluble granule	Drench				11, 12	
Bayer Advanced protect and feed II[a]	0.74%	0.37%		Liquid	Undiluted drench			4, 5, 8	4, 5, 8	
Bayer Advanced granules II[b]	0.55%	0.28%		Granular	Undiluted			3, 7	3, 7, 15	
Merit 2F	25%			Liquid	Drench					2, 3
Xytect 75WSP	75%			Soluble powder	Drench					4, 5, 6
Merit 75	75%			Powder	Drench	1, 2, 3, 4	1, 2	1, 2, 6	1, 2, 6	
Safari 20SG			20%	Soluble granule	Drench				10, 12, 14	
Safari 2G			2%	Granule	Undiluted				13	

Treatment numbers as they appear in each table are given for the nine products tested. More than one treatment per product at a test site indicates that time or year or application rate was also tested.

[a] Bayer Advanced 12 Month Tree & Shrub Protect and Feed II.

[b] Bayer Advanced 12 Month Tree & Shrub Protect Granules II.

increments was used to train observers, along with a field training session where estimates were shared among observers. This set of photographs is in the article by Smitley et al. (2008). Canopy loss estimates were always made by the same observers for all trees in any given experiment. At MSU HTRC, all canopy loss estimates were made by the same, single observer, each year. Canopy loss and dieback estimates were made on 13 June 2005, 27 July 2006, 2 July 2007, 18 June 2008, 7 July 2009, 11 August 2010, and 22 August 2011, as described by Smitley et al. (2008).

Data analysis for MSU HTRC test. Percent canopy loss ratings were converted to arcsine square root of the percent before analysis, although results are reported in actual percentages. This was done for percentage data at all sites. At HTRC, an ANOVA with treatment, block, and a treatment–block interaction was first used to determine whether or not a treatment–block interaction existed. This was conducted for each year of data. For all years, with the exception of 2006, when all canopy loss ratings were zero, the interaction was statistically insignificant ($P = 0.09$ for 2005, $P = 0.56$ for 2007, $P = 0.13$ for 2008, $P = 0.59$ for 2009, $P = 0.45$ for 2010, and $P = 0.35$ for 2011). Because the interaction was found to be insignificant, ANOVAs for each year were re-run without the treatment–block interaction (but with main effects for both treatment and block). If treatment was deemed to be significant, a Dunnett's test was conducted to determine which treatment outcomes differed from the control outcome. Type II sum of squares was used instead of Type III sum of squares because this test is more powerful while still robust for unbalanced data (Langsrud 2003).

Adrian, Michigan Street Trees: Comparison of Fall Versus Spring Application. Green ash street trees in six neighborhoods in Adrian, MI, were used for this test (Lenawee Co, MI T6S R3E, T7S R3E). These trees were between 14 and 28 yr old and ranged in size from 15.3 to 66.0 cm dbh. The mean dbh was 43.2 cm. The trees were planted and maintained by the city of Adrian and were located between the street and the sidewalk in six different neighborhoods. Trees were spaced a minimum of 16 m apart. Tree trunks were measured and marked with a metal tag during the first week of September 2005. Lawns where study trees were located at this sited tended to be low-maintenance. Very few lawns were irrigated. Each treatment was replicated 10 times with each replicate consisting of an individual tree. The three treatments in this test were: 1) imidacloprid (Merit 75WP) applied at a rate of 0.56 g a.i./cm dbh as a basal drench in the spring (late April to June) of each year, 2) imidacloprid applied at the same rate as a basal drench in fall (November) of each year, and 3) an untreated control. The appropriate amount of Merit 75 WP was mixed in 6.0 l of water and poured around the base of the tree within 0.67 m of the trunk on 27 June 2006, 24 April 2007, and 3 June 2008 for the spring treatment, or on 7 November 2006, 5 November 2007, and 20 November 2008 for the fall treatment. Percent canopy loss ratings were made as previously described, on 11 July 2006, 12 July 2007, 10 June 2008, and 18 July 2009, by having two evaluators independently rate each tree. The mean value was used for analysis. Branches from the upper one-third of the tree canopy were sampled between 1 October and 20 December of 2006, 2007, and 2008. Three branches were removed from each tree by the arborists of the City of Adrian. Branches selected for removal were spaced as far apart as possible to maintain aesthetic canopy balance. EAB larvae were counted after removing bark with a drawknife and chisel. The bark was removed indoors at Michigan State University's Entomology Field Research Station. The length of the area of the branch sampled and diameters of each end of the sampled branch section were used to calculate the surface area sampled.

Adrian Street Tree Data Analysis. Means and standard errors were calculated for each treatment within each year using all remaining trees. Within each year, a one-way ANOVA was used to determine if there was any difference among treatments. Type II sum of squares was used instead of Type III sum of squares for reasons previously explained (Langsrud 2003). If the *P*-value for a treatment in a given year's was significant (ANOVA, $P < 0.05$), a Dunnett's test was conducted to determine which treatments were different from the control. A *P* value of 0.05 was considered to be significant for the Dunnett's test. The same approach was used to separate means for larvae found under the bark of branch samples. Within each year, a second one-way ANOVA was used on a subset of that year's data with all control observations excluded to determine if spring and fall treatments were significantly different. If the *P* value for treatment in a given year's ANOVA was significant ($P < 0.05$), a significant difference was determined to exist between the spring and fall treatment outcomes.

Kentwood North, Michigan Street Trees: Comparison of Application Rates. Fifty green ash street trees in a suburban neighborhood located 10 km southeast of Grand Rapids (42°56′21.67″ N 85°33′16.23″ W) were marked with numbered aluminum tags in early November 2008. Very few ash trees were present in the neighborhood other than the street trees in our test. These trees varied in size from 23 to 52 cm dbh with a mean diameter of 40 cm. Each treatment was replicated three to five times, with 6 of the 10 treatments having five replications. Four of the 10 treatments had three or four replications because a few trees were felled or had to be removed from the test owing to an insecticide treatment made by the homeowner. A replication consisted of an individual tree. Insecticide treatments were applied once per year in late May or early June beginning in 2009, with the exception of one treatment that started in fall of 2008. Basal granular applications were made by spreading the granular insecticide evenly over a circular area extending from the trunk out to a distance of 31 cm using a small leaf rake. Application rates for neonicotinoids applied as a basal drench were based on the dbh of each tree as indicated on the product label. For all liquid insecticide treatments with the exception of Treatments 4 and 8, the correct amount of product for each tree was measured into a bucket and water added to bring the volume of the solution to a total of 5.0 liters. The measured amount of insecticide product for each tree receiving Treatments 4 and 8 was poured around the base of each tree as undiluted product. A letter was mailed to homeowners in the neighborhood each year to ask if they had treated their ash trees at any time in the past, and to request that they do not make any insecticide treatments during the test. In addition, we checked each tree for trunk injection plugs. Insecticide treatments at this site were: 1) Merit 75 (imidacloprid) applied as a drench each spring and fall at a rate of 0.56 g a.i./cm dbh per application or 1.12 g a.i./cm dbh per year (26 May 2009, 26 August 2009, 27 May 2010, 23 August 2010, 25 May 2011, 22 August 2011, 16 May 2012, and 23 August 2012); 2) Merit 75 (imidacloprid) applied as a drench twice each spring, 2 to 3 weeks apart, at a rate of 0.56 g a.i./cm dbh per application or 1.12 g a.i./cm dbh per year (26 May 2009, 12 June 2009, 27 May 2010, 17 June 2010, 25 May 2011, 28 June 2011, 16 May 2012, and 20 June 2012); 3) Bayer Advanced granular (imidacloprid 0.55% and clothianidin 0.275%) applied twice each spring, 2–3 weeks apart, at a rate of 0.305 g a.i. imidacloprid and 0.155 g a.i. clothianidin/cm dbh per application or a total of 0.61 and 0.31 g a.i./cm dbh per year (26 May 2009, 12 June 2009, 27 May 2010, 17 June 2010, 27 May 2011, 28 June 2011, 16 May 2012, and 20 June 2012); 4) Bayer Advanced liquid (imidacloprid 0.74% and clothianidin 0.37%) applied undiluted each spring at a rate of 0.54 g a.i. imidacloprid and 0.26 g a.i. clothianidin/cm dbh per year (26 May 2009, 27 May 2010, 25 May 2011, and 16 May 2012); 5) Bayer Advanced liquid (imidacloprid 0.74% and clothianidin 0.37%) applied undiluted twice each spring at a rate of 0.27 g a.i. imidacloprid and 0.13 g a.i. clothianidin/cm dbh per application or 0.54 g a.i. and 0.26 g a.i. per year (26 May 2009, 12 June 2009, 27 May 2010, 17 June 2010, 27 May 2011, 28 June 2011, 16 May 2012, and 20 June 2012); 6) Merit 75 (imidacloprid) applied as a drench in spring of each year at a rate of 0.56 g a.i./cm dbh per year (26 May 2009, 27 May 2010, 25 May 2011, and 16 May 2012); 7) Bayer Advanced granular (0.55% imidacloprid and 0.275% clothianidin applied once each spring at a rate of 0.31 g a.i. imidacloprid and 0.15 g a.i. clothianidin/cm dbh per application and per year (26 May 2009, 27 May 2010, 25 May 2011, and 16 May 2012); 8) Bayer Advanced liquid (0.74% imidacloprid and 0.37% clothianidin) applied undiluted once each spring at a rate of 0.54 g a.i. imidacloprid and 0.26 g a.i. clothianidin/cm dbh per application and per year (26 May 2009, 27 May 2010, 27 May 2011, and 16 May 2012); and 9) untreated control (Table 4). Percent canopy loss ratings were made as previously described, once per year, on 10 July 2009, 12 July 2010, 22 July 2011, 10 July 2012, and 12 July 2013. Visual ratings were made by two to four different individuals, and averaged. Ratings were made according to the canopy loss scale described by Smitley et al. (2008).

Kentwood South, Michigan Street Trees: Comparison of Application Rates and Active Ingredients. This neighborhood is located about 1.0 km south of the Kentwood North neighborhood (42°55′54.12″ N 85°33′11.19″ W). Very few ash trees were found in the area that were not in our test. The 175 trees in this test were 15-18-years-old with trunk diameters ranging from 13 to 35 cm dbh, with a mean dbh of 25 cm. The number of replications per treatment varied from 6 to 10. Neonicotinoid basal drenches or basal granular applications were made as described for Kentwood North. All of the treatments (1–9) listed above for Kentwood North were also applied at Kentwood South, plus the following additional seven treatments (10–15): (10) Safari 20SG (dinotefuran) applied once each spring as a drench at a rate of 0.94 g a.i./cm dbh (3 June 2009, 27 May 2010, 27 May 2011, and 16 May 2012); (11) Arena 50WDG (clothianidin) applied as a drench once each spring at a rate of 0.94 g a.i./cm dbh (3 June 2009, 27 May 2010, 27 May 2011, and 16 May 2012); (12) Arena 50WDG (clothianidin) and Safari 20SG (dinotefuran) applied once each spring as a drench at a rate of 0.47 g a.i. and 0.47 gr a.i./cm dbh, respectively (3 June 2009, 4 June 2010, 27 May 2011, and 16 May 2012); (13) Safari 2G (dinotefuran granular) applied once each spring at a rate of 0.94 g a.i./cm dbh (3 June 2009, 27 May 2010, and 27 May 2011); (14) Safari 20SG (dinotefuran) applied as a drench once each summer at a rate of 0.94 g a.i./cm dbh (10 July 2009, 17 June 2010, 28 June 2011, and 20 June 2012); (15) Bayer Advanced granular (0.55% imidacloprid and 0.275% clothianidin) applied in fall of 2008 (instead of in spring of 2009) and in the spring of 2010, 2011, and 2012 at a rate of 0.61 g a.i. imidacloprid and 0.31 g a.i. clothianidin /cm dbh per application and per year (26 November 2008, 27 May 2010, 25 May 2011, and 16 May 2012). Percent canopy loss ratings were made as previously described once each year in July and on the same days as described for Kentwood North.

Data Analysis for Kentwood North and South. For each year of data, a one-way ANOVA was used to determine if the mean canopy loss ratings differed among treatments. Type II sum of squares was used instead of Type III sum of squares because of unbalanced data as previously explained (Langsrud 2003). If the P-value on treatment in the ANOVA analysis was less than or equal to 0.05, a significant difference in outcome across treatments was indicated, and a Dunnett's post hoc test was used to compare the outcomes of all treatments versus the control for that year. A Dunnett's test P-value of 0.05 or lower was considered to indicate that a given treatment's outcome was significantly different from that of the control.

Toledo, Ohio Street Trees: Comparison of Application Rates and Fall Versus Spring Timing of Basal Drenches. Green ash street trees growing on a single street in a subdivision in Toledo, Ohio, with a dbh of 35.6–45.8 cm, were randomly assigned to one of six treatments in spring of 2006. None of the trees showed any external signs or symptoms of EAB infestation, although some trees within 400 m of the study site were declining or dead. Treatments included: 1) untreated control ($n = 5$); 2) imidacloprid (2F formulation) basal drench applied at the rate of 0.56 g a.i. /cm dbh in spring of each year ($n = 5$); 3) imidacloprid (2F

Table 2. Protection of ash trees at the MSU-HTRC from emerald ash borer with basal soil drenches of imidacloprid applied in late May of each year, every second year, every third year, or annually at the rate labeled for grub control in turfgrass

Imidacloprid treatment	n	Canopy loss ratings ± SE (%)						
		2005	2006	2007	2008	2009	2010	2011
Basal drench once per year (0.56 g a.i./cm dbh)	15	0	0	1.0 ± 0.4	18.0 ± 2.8	1.7 ± 1.1	12.3 ± 3.8*	8.0 ± 3.0**
Basal drench once every 2 years (0.56 g a.i./cm dbh)	15	0	0	0.5 ± 0.3	14.8 ± 2.5	2.0 ± 1.2	15.7 ± 3.8*	23.7 ± 7.3**
Basal drench once every 3 years (0.56 g a.i./cm dbh)	15	0.2 ± 0.2	0	1.3 ± 0.3	24.2 ± 5.7	10.7 ± 6.3	32.7 ± 4.6	51.0 ± 9.3
Turf spray within drip-line at grub rate each year (0.4 g a.i. per tree)	15	0	0	1.0 ± 0.4	22.3 ± 6.0	7.7 ± 6.4	29.0 ± 8.1	46.3 ± 9.8
Control	15	6.2 ± 4.3	0	2.2 ± 0.7	24.3 ± 2.7	5.0 ± 2.6	40.1 ± 3.6	60.9 ± 8.2

Data are means ± SE canopy loss ratings (%).
Treatment means ± SE followed by an * are different from the control mean by Dunnett's test at $P = 0.05$. Means ± SE followed by ** are different from the control mean at $P = 0.01$.

formulation) basal drench applied at the rate of 0.56 g a.i./cm dbh in fall of each year ($n = 5$); 4) imidacloprid (75 WSP formulation) basal drench applied at the rate of 0.56 g a.i./cm dbh in fall of each year ($n = 4$); 5) imidacloprid (75 WSP formulation) basal drench applied at the rate of 1.12 g a.i./cm dbh in fall of each year ($n = 4$); and 6) imidacloprid (75 WSP formulation) basal drench applied at the rate of 1.12 g a.i./cm dbh in spring of each year ($n = 3$). Imidacloprid drenches were made by filling a bucket with 3.79 liters of water, adding the correct amount of imidacloprid product, stirring, and pouring the solution as evenly as possible around the base of the trunk. All trees received soil drench treatments on the same day in the fall or spring of each year. The dates that drenches were made are 18 May 2006, 4 November 2006, 13 June 2007, 5 November 2007, 23 May 2008, 21 October 2008, 10 May 2009, 19 October 2009, 24 May 2010, 22 October 2010, 3 May 2011, 2 November 2011, and 28 April 2012. All trees were done flowering in the spring when treatments were applied. Trees were visually rated for canopy loss as previously described on 15 August 2007, 26 August 2008, 11 June 2009, 10 August 2010, 8 September 2011, and 16 June 2012.

Data Analysis for Toledo Site. Percent canopy loss data were analyzed separately for each year using SAS PROC GLM with Type 3 sums of squares to account for the uneven number of replicates (SAS Institute 1999). Percent data were square root and log transformed before analysis. If the F value for the general model was significant ($P < 0.05$) in any given year, then means were compared using LS means with an LSD of $P = 0.05$.

Results

MSU HTRC: Basal Drenches Applied Every 1–3 yr. The EAB infestation developed slowly in this stand of 78 ash trees when compared with ash trees in a nearby woodlot. In the nearby woodlot, ash trees died 2 to 3 yr earlier than the control trees in our research plots, probably because of a group effect where treated trees were suppressing the overall EAB population within the stand. All ash trees in this test looked very good from 2005 through 2007, with very little (<5%) canopy loss in any tree (Table 2). In 2008, a spring and early summer drought caused some canopy loss (5 to 35%), but the trees recovered in 2009 and canopy ratings improved. In 2010 and 2011, ash trees in all treatments, with the exception of the annual imidacloprid basal drench treatment and the every second year imidacloprid basal drench treatment, began to decline rapidly with control trees averaging 40.1 and 60.9% canopy loss in 2010 and 2011, respectively (Table 2). In the absence of pressure from EAB, no treatments effects were observed from 2005 through 2009. In 2010, mean canopy ratings for trees receiving an annual imidacloprid drench or an imidacloprid drench every second year drench were different from the mean canopy rating for control trees (Dunnett's test, $P = 0.05$). Ratings for the same two treatments were different from the control treatment again in 2011, but at a higher level of significance (Dunnett's test, $P = 0.01$). Mean canopy ratings for ash trees receiving an annual basal drench were highest in 2010 (12.3%) and improved slightly in 2011 (8.0%), indicating that long-term protection was realized.

For 2005, 2007, and 2009, there was no difference in the canopy ratings among the two adjacent planting blocks. However, in 2008, before the EAB infestation began to impact tree health, and following a lengthy drought in early summer of that year, canopy ratings for trees in one of the two identical and adjacent planting blocks were significantly greater than canopy ratings in the other block ($P < 0.01$). This was also true for 2010 after EAB caused significant damage to control trees, but not for 2011 (Table 2).

Adrian, Michigan Street Trees: Comparison of Fall Versus Spring Application. Ash street trees receiving a basal soil drench of imidacloprid in late May or early June of 2006, 2007, and 2008 maintained an acceptable visual appearance and scored better (30.3%, compared with 62.0%, canopy loss) on canopy ratings made in July of 2008 and 2009 than did control trees (Dunnett's test, $P = 0.01$, Table 3). Ash trees treated with a basal drench at the same rate each fall instead of each spring were not acceptable at the end of the test in 2009, with a mean canopy loss rating of 62.0%, although this was still different from mean control rating of 86.8% (Dunnett's test, $P = 0.05$). In 2006, canopy ratings for spring and fall treatments did not differ ($P = 0.052$). In 2007, 2008, and 2009, spring and fall treatments were found to have significantly different outcomes, as determined by a second ANOVA with

Table 3. Adrian, Michigan: efficacy of spring compared with fall applications of imidacloprid for protection against emerald ash borer

Treatment	*n*	Canopy loss rating ± SE (%), July 2006	*n*	Canopy loss rating ± SE (%), July 2007	*n*	Canopy loss rating ± SE (%), July 2008	*n*	Canopy loss rating ± SE (%), July 2009
Imidacloprid basal drench applied once each spring (0.56 g a.i./cm dbh per year)	10	3.5 ± 1.1	9	9.8 ± 2.0	9	33.0 ± 8.2**	8	30.3 ± 7.8**
Imidacloprid basal drench applied once each fall (0.56 g a.i./cm dbh per year)	9	8.3 ± 2.0	9	25.8 ± 5.3	9	65.0 ± 9.1	5	62.0 ± 5.1*
Control	20	10.5 ± 2.6	20	17.2 ± 4.2	20	61.1 ± 6.1	11	86.8 ± 3.7

Treatment	*n*	Larvae per m^2 ± SE in branch samples 2006	*n*	Larvae per m^2 ± SE in branch samples 2007	*n*	Larvae per m^2 ± SE in branch samples 2008
Control	10	3.0 ± 0.9	18	4.4 ± 1.6	15	25.5 ± 8.7
Imidacloprid basal drench applied each fall	0	NA (NA)	9	2.3 ± 0.8	4	5.7 ± 2.8
Imidacloprid basal drench applied each spring	9	5.2 ± 3.2	10	3.6 ± 2.1	8	5.8 ± 2.7

Trees with more than 50% dieback in July were usually removed by the city within a year.

Treatment means ± SE followed by an * are different from the control mean by Dunnett's test at $P = 0.05$. Means ± SE followed by ** are different from the control mean at $P = 0.01$.

Table 4. Kentwood North: comparison of application rates. Insecticides were applied basally to ash street trees from 2008 through 2012, and final canopy loss ratings were made in July, 2013

Treatments made 2008–2012	Rate per application (g a.i./cm dbh)	Rate per year (g a.i./cm dbh)	*N*	Canopy loss rating in 2013 (%)
1. Imidacloprid drench, once each spring and fall	0.56	1.12	3	15.0 ± 2.5
2. Imidacloprid drench, twice each spring, 2–3 wk apart	0.56	1.12	4	17.2 ± 5.9
3. Imidacloprid + clothianidin granular, twice each, spring 2–3 wk apart	0.31 + 0.16	0.61 + 0.31	3	18.3 ± 11.5
4. Imidacloprid + clothianidin, undiluted drench, once each spring	0.54 + 0.26	0.54 + 0.26	4	25.6 ± 5.3
5. Imidacloprid + clothianidin, undiluted, twice each spring, 2–3 wk apart	0.27 + 0.13	0.54 + 0.26	5	27.0 ± 5.9
6. Imidacloprid drench, once each spring	0.56	0.56	5	29.5 ± 8.1
7. Imidacloprid + clothianidin granular, once each spring	0.31 + 0.16	0.31 + 0.15	4	34.1 ± 7.1
8. Imidacloprid + clothianidin, undiluted drench, once each spring	0.54 + 0.26	0.54 + 0.26	5	34.4 ± 8.3
9. Untreated control	–	–	5	51.2 ± 6.8

Treatment numbers refer to the list of treatments as presented in the Materials and Methods with complete details.

the control treatment removed ($P = 0.01$, 0.01, and 0.02, respectively). The number of live larvae counted after scraping the bark from branch samples collected in October of 2006, 2007, and 2008 was similar for trees receiving spring or fall imidacloprid drenches, but neither treatment differed from the control, even in 2008 when a mean of 25.5 larvae per m^2 was found in branch samples from control trees compared with 5.7 or 5.8 larvae per m^2 in branch samples from trees in the two basal drench treatments.

Kentwood North, Michigan Street Trees: Comparison of Application Rates. The EAB infestation developed slowly between 2008 and 2012. In 2013, trees in the control treatment were compromised from borer infestation, with the mean canopy rating being 51.2%, compared with ratings of 15 to 18% in the best insecticide treatments (Table 4). Data analysis with ANOVA determined there was no significant treatment effect in any year, probably owing to a limited number of replicates per treatment, and variation in tree health and infestation pressure.

Kentwood South, Michigan Street Trees: Comparison Application Rates and Active Ingredients. In 2009, the first year of this test, some symptoms of EAB infestation, including epicormic growth, bark splits on branches with a diameter of 8–20 cm, and woodpecker excavations were found on a few trees on each street. The only two ash street trees in the test area with more than 40% canopy loss and EAB emergence holes were excluded from the test. The EAB infestation developed slowly in this neighborhood, apparently due to the large proportion of ash trees receiving an effective insecticide treatment. By 2011, the third year of this study, the mean canopy loss rating for ash trees in any treatment, including the control, was still below 11%. Tree crews from the City of Kentwood offered to remove trees for homeowners when they reached 50% canopy decline. The final number of replicate trees in each treatment varied from 8 to 12 because of this and because some homeowners chose to have a relatively healthy tree removed. The city had to honor these requests because they had given homeowners in other parts of Kentwood the same option. Canopy loss ratings were not significantly different among treatments in any year prior to 2013. By July of 2013, the mean canopy loss rating for untreated ash trees in the control averaged 29.6% (Table 5). Mean canopy loss ratings at the end of the test in 2013 for trees in all treatments receiving an annual basal soil drench of imidacloprid, clothianidin, or dinotefuran, at a total combined rate of greater than 0.9 g a.i./cm dbh per year, were significantly lower

Table 5. Kentwood South: comparison of application rates and active ingredients. Insecticides were applied basally to ash street trees from 2008 through 2012, and final canopy loss ratings were made in July, 2013

Treatments 2008–2012	Rate per application (g a.i./cm dbh)	Rate per year (g a.i./cm dbh)	N	Canopy loss rating in 2013 (%)[1]
10. Dinotefuran drench applied once each spring	0.94	0.94	9	3.5 ± 1.0*
11. Clothianidin drench once each spring	0.94	0.94	9	6.1 ± 1.8*
3. Imidacloprid + clothianidin granular, twice each spring, 2–3 wk apart	0.31 + 0.16	0.61 + 0.31	8	6.7 ± 1.4*
12. Clothianidin + dinotefuran drench, once each spring	0.47 + 0.47	0.94	10	7.4 ± 2.3*
1. Imidacloprid drench once each spring and fall	0.56	1.12	8	8.9 ± 2.4*
13. Dinotefuran granular once each spring	0.94	0.94	10	9.2 ± 3.7*
14. Dinotefuran drench once each summer	0.94	0.94	10	11.8 ± 2.2*
7. Imidacloprid + clothianidin granular once each spring	0.31 + 0.16	0.31 + 0.15	7	11.8 ± 3.0*
2. Imidacloprid drench twice each spring, 2–3 wk apart	0.56	1.12	8	12.8 ± 4.7
8. Imidacloprid + clothianidin, undiluted drench, once each spring	0.54 + 0.26	0.54 + 0.26	7	13.9 ± 5.5
6. Imidacloprid drench once each spring	0.56	0.56	7	14.3 ± 4.1
8. Imidacloprid + clothianidin, undiluted drench, once each spring	0.54 + 0.26	0.54 + 0.26	7	20.3 ± 4.9
5. Imidacloprid + clothianidin, undiluted, twice each spring, 2–3 wk apart	0.27 + 0.13	0.54 + 0.26	6	20.6 ± 5.6
9. Untreated control	–	–	6	29.6 ± 10.8
15. Imidacloprid + clothianidin granular once in fall of 2008, once in spring 2010, 2011 and 2012	0.61 + 0.31	0.61 + 0.31	6	33.8 ± 10.5

Treatment numbers refer to the list of treatments as presented in the Materials and Methods with complete details.
* An asterisk following treatment mean ± SE indicates that it is significantly different from the control mean by Dunnett's Test ($P = 0.05$).

Table 6. Toledo, Ohio: efficacy of spring compared with fall applications of imidacloprid as a basal drench to ash street trees at two different rates for protecting ash trees against emerald ash borer

Treatment[a]	Canopy loss ratings (%)					
	2007	2008	2009	2010	2011	2012
Control	2 ± 2a	42 ± 13a[a]	93 ± 3a	97 ± 2a	NA[b]	NA
Imidacloprid 2F drench at 0.56 g a.i /cm dbh, each Fall	10 ± 10a	26 ± 10ab	44 ± 10b	52 ± 13b	45 ± 21ab	NA
Imidacloprid 2F drench at 0.56 g a.i /cm dbh, each Spring	4 ± 4a	16 ± 7ab	22 ± 15b	28 ± 13bc	26 ± 19b	0 ± 0a
Imidacloprid 75 WSP drench at 0.56 g a.i./cm dbh, each Fall	7 ± 7a	17 ± 16ab	43 ± 14b	53 ± 9b	77 ± 21a	NA
Imidacloprid 75 WSP drench at 1.12 g a.i./cm dbh, each Fall	8 ± 8a	0 ± 0b	8 ± 5c	28 ± 13bc	10 ± 16b	0 ± 0
Imidacloprid 75 WSP drench at 1.12 g a.i./cm dbh, each Spring	10 ± 10a	3 ± 3b	10 ± 6c	17 ± 3c	7 ± 6bc	0 ± 0a

[a] Means within a column (for each year) followed by the same letter are not significantly different ($P = 0.05$).
[b] Data not available because dead trees were removed before ratings were made.

(3.5 to 11.8%) than mean canopy ratings for control trees (29.6%) by Dunnett's test ($P = 0.05$, Table 5). Canopy ratings for trees in Treatment 15 were similar to ratings for control trees at the end of the test, despite being treated with imidacloprid at a rate of 0.92 g a.i./cm dbh per year, probably because no treatment was made in 2009. Instead, the trees in Treatment 15 received a basal drench in fall of 2008 and in spring of 2010, 2011, and 2012. One of the treatments (Treatment 7) where less than a combined total of 0.75 g a.i./cm was applied per year was also significantly different from the control treatment, but the remaining five treatments where less than 0.75 g a.i./cm dbh per year was applied were not different from the control.

Toledo, Ohio Street Trees: Comparison of Fall Versus Spring Applications. In this subdivision in Toledo, the EAB infestation progressed much more rapidly than in Kentwood, with the canopy loss ratings of untreated control trees going from a mean of 2% in 2007 to 93% in 2009 (Table 6). In 2009, canopy loss ratings of ash trees in treatments receiving an annual basal soil drench of imidacloprid varied from 8 to 93%, depending on the timing of soil drench applications (spring or fall) and the application rate (0.56 or 1.12 g a.i./cm dbh). By 2010, only ash trees treated with imidacloprid in the spring of each year with either the low or high rate, or trees treated in the fall with the high rate, were still healthy, with mean canopy loss ratings of 28, 17, and 28%, respectively. From 2009 to 2011, trees receiving the low rate in spring had much better canopy ratings than trees receiving the low rate in fall, which continued to decline over time. Trees were removed by the city when canopy loss exceeded 50%, and by 2012, all untreated trees had been removed, as had all trees treated with the low rate in fall. However, all trees treated in the spring (high and low rate) remained healthy, as did trees treated in the fall with the high rate. The surviving trees, in all three, of these two treatments improved in condition each of the last two years, to complete the test with near-perfect canopy ratings (Table 6).

Discussion

At the Adrian and Toledo test sites, the EAB infestation developed rapidly and trees progressed from healthy (0 to 15% canopy loss) to mostly dead (>75% canopy loss) in 3 years, while at MSU Hancock HTRC site and the Kentwood North and South sites, the infestation took longer to develop, taking 5 or 6 years for trees to progress from <15% canopy loss to >50%

canopy loss. Also the final ratings for control trees at MSU HTRC and Kentwood were 60 and 39%, compared with 90 and 97% for Adrian and Toledo, respectively. One key difference between the two sites where emerald ash developed rapidly and the three sites where it developed slowly was the density of ash trees in the immediate area that did not receive any insecticide treatment. At the Adrian and Toledo sites, many ash non-treated ash trees were present in the immediate vicinity of the experimental street trees. At the MSU-HTRC site, 80% of all the ash trees in the experimental planting received an imidacloprid drench treatment, varying in frequency from once per year to once every third year, and at the Kentwood site, 80% of all the ash street trees in the subdivision received a treatment effective against EAB. Because EAB adults feed on ash leaves and are strong flyers, it is likely that many adult females died after feeding on the leaves of treated trees, which are toxic to the beetles because imidacloprid is systemically moved through xylem to the leaves after it is absorbed by the roots (Taylor et al. 2007, Mota-Sanchez et al. 2009, McCullough et al. 2011).

Similar results at the Toledo and Adrian test sites confirm that imidacloprid applied as a basal soil drench each year between late April and early June gave a higher level and more consistent level of protection against EAB than imidacloprid applied as a basal soil drench at the same rate each year in late October or early November. Fall treatments were effective at the Toledo site when applied at the high rate but were not effective at the low rate. However, both the low and high rates were effective when imidacloprid was applied in spring. This indicates that, all things being equal, spring applications were more effective than those made in fall. Alternatively, applications made in fall required a higher rate to achieve equal efficacy. Arborists were hopeful that fall treatments would be as effective as spring treatments because they are often very busy in late May and early June, and have more time to apply treatments in the fall. However, our results demonstrate a clear advantage to making spring applications instead of fall applications. In fact, fall applications were not consistent enough to be recommended for EAB control.

When results are compared among all five efficacy test sites, the level of protection against EAB infestation provided by a basal soil drench of imidacloprid or of imidacloprid plus clothianidin applied at a rate of 0.80 g a.i./cm dbh per year or higher, and in the spring, was excellent (<17% canopy loss for all treatments), while protection given by spring basal soil drenches applied at less than 0.80 g a.i./cm dbh per year or less was not as reliable. These results are consistent with previous tests on basal soil drenches of imidacloprid, and help to explain why many arborists, landscapers, and homeowners reported that basal drenches failed to provide adequate protection against EAB (Smitley et al. 2010b). Results from this research indicates that an annual spring basal drench of 0.80 g a.i./cm dbh, beginning before trees are compromised from borer attack, will provide reliable control. However, because rates on product labels are not in metric units, and because of restrictions on the label, it may be confusing to determine how to apply products at 0.80 g a.i./cm dbh per year.

At the Kentwood South test site where other neonicotinoids were tested, clothianidin and dinotefuran also gave a very high level of protection against EAB when applied as spring basal drench at rates greater than 0.8 g a.i./cm dbh per year. When imidacloprid basal treatments were made each spring at the same rate, we did not see any differences in the level of protection against EAB given by granular products compared with liquid products. However, the liquid homeowner products were much easier to apply than the granular products because when the label rate of the granular products was applied, it completely covered the turfgrass for the first 20 cm around the base of the trunk and had to be raked to expose the turf blades. Overall, our results indicate that homeowners can successfully protect their ash trees with imidacloprid, dinotefuran, or clothianidin products purchased from local garden centers, if they are applied as basal drench each spring at a rate of 0.8 g a.i./cm dbh. To assist readers in comparing the label rates of products tested in this research with our research results, we have constructed a table with product rates as they appear on the label and converted to metric units (Table 7). Application restrictions which may prevent the use of higher rates are also given. Other products may be available containing the same active ingredients. Dinotefuran was tested as a basal soil application in this research, but the primary use of dinotefuran for EAB control is as a direct trunk spray, not as a basal drench.

When neonicotinoid insecticides are applied basally for systemic protection against EAB or other pests, the potential movement of the insecticide into nectar and pollen should be considered because recent research indicates that even a short exposure period of 14 d at field-relevant rates (<10 ppb) can reduce winter survival of bumble bee colonies (Whitehorn et al. 2012). Many other papers report similar results, and there is growing consensus for the need to exercise caution when neonicotinoids are used on plants visited by pollinators (Goulson et al. 2015). In this case, the neonicotinoid drench should be applied for EAB in late May or early June, which is after ash trees are done blooming. Although ash street trees are not considered an important source of pollen, bees do visit ash trees and for one or two weeks during peak bloom in early spring ash pollen can account for 10% of the pollen collected by *Osmia lignaria*, a solitary bee (Kraemer and Favi 2005, Fortunato et al. 2006). Research is needed to collect pollen from ash trees treated the previous spring to determine how much insecticide is in the pollen.

At MSU-HTRC, the location of ash trees in either Block A or Block B had a significant effect on canopy loss following a drought in June and July of 2008. Because a drainage ditch ran along the edge of one block and not the other, soil moisture levels may have been higher for the first two or three rows of trees in that block, but without soil moisture data, we have no way to separate soil moisture from other site variables

Table 7. Application rates for tested products that are currently labeled for use against emerald ash borer

Product name	Active ingredients	Application rate as it appears on product label[a]	Application rate in metric units[a] (g ai/cm dbh)	Application restrictions on product label
Merit 75	Imidacloprid	1–2 oz per 30" of dbh	0.28–0.57	Do not apply more than 8.6 oz per acre per year
Merit 75 WSP	Imidacloprid	1.6 oz/12–48" of dbh	0.28–1.12	You may apply the higher rate only to control the listed borers.[b] Do not exceed 8.53 oz/acre per year.
Xytect 75 WSP	Imidacloprid	1.6 oz/12–48" of dbh	0.28–1.12	You may apply the higher rate only for trees greater 15" dbh to control the listed borers[b]. Do not exceed 8.53 oz/acre per year.
Bayer Advanced 12-month Tree & Shrub Protect & Feed Concentrate II	Imidacloprid, clothianidin	1.0 oz per inch of circumference	0.40	Do not make more than one application per year
Bayer Advanced 12-month Tree & Shrub Protect & Feed RTU Granules II	Imidacloprid, clothianidin	1.0 oz per inch of circumference	0.40	Do not make more than one application per year

Rates are given as they appear on the label and after metric conversion for comparison with research results. Restrictions on application rate or frequency are also given for each product.
[a] Application rate is given as the total amount of active ingredient for all insecticides in the product.
[b] The borers listed are: emerald ash borer, bronze birch borer, Asian long-horned beetle, eucalyptus borer, and alder borer.

such as soil type. However, we can say that there was a significant site effect following a very dry summer, and it is still recommended that arborists and landscapers minimize stress and water trees during dry periods to achieve the best possible results when treating trees for EAB. Also, when conducting EAB studies where canopy loss ratings are used, it is important to understand that these ratings can vary from year-to-year by as much as 20% due to drought stress. At the MSU-HTRC site, canopy loss ratings of ash trees in the control treatment jumped from 2% in 2007 to 24% in 2008, and then returned to 5% in 2009, mostly due to a drought in June and July of 2008, with more normal precipitation amounts the year before and after.

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