

Evaluation of a Single Application of Neonicotinoid and Multi-Application Contact Insecticides for Flatheaded Borer Management in Field Grown Red Maple Cultivars¹

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Abstract

Two trials evaluated insecticides for flatheaded borer control and effect on red maple (*Acer rubrum* L.) cultivar growth over 4 years. *Chrysobothris femorata* (Olivier) was the only species reared from borer damaged maples during the study. Soil-applied systemic insecticides (acephate, imidacloprid, clothianidin, dinotefuran, and thiamethoxam) and trunk-applied contact insecticides (chlorpyrifos and bifenthrin) were tested. In the 2005 trial, a one-time drench of Allectus (imidacloprid + bifenthrin) or Discus (imidacloprid + cyfluthrin) provided 2 to 4 years of protection with 'Autumn Flame' and 'Franksred' from *C. femorata*. Soil-applied experimental imidacloprid tablets prevented borer damage in the third and fourth post-treatment years, but were not as effective as imidacloprid drenches in the first two years. Soil applied acephate tablets, chlorpyrifos (Dursban 4E) trunk sprays, or untreated control plants had borer damage each year, which totaled up to 41.7% damage by year 4 in 'Autumn Flame'. Trunk diameter growth and tree canopy size was greater with Discus drench or imidacloprid tablet treatments than other treatments. In the 2006 trial, drenches of Allectus, Discus, or Safari 20SG (dinotefuran) applied in May and Discus or Arena 50WDG (clothianidin) drenches applied in March provided complete protection from *C. femorata* the first year in 'Fairview Flame', 'Franksred', and 'October Glory'. Discus (March) drench provided four years of complete protection among the three cultivars, while other neonicotinoid drenches had 3.7–6.3% (Arena March), 3.7–12.5% (Arena May), 0–6.3% (Discus May), 0–10.3% (Safari), and 12.5–20.5% (Flagship) total damage. Ineffective treatments included an experimental imidacloprid gel (7.4–18.8% damage), acephate tablets (18.5–75.0%), Onyx Pro Insecticide (5.1–18.8%), Dursban 2E (11.1–31.3%), one imidacloprid tablet (15.4–43.8%), or untreated plants (32.1–41.0%). This study demonstrates a single application of some neonicotinoid treatments can provide multi-year *C. femorata* prevention, increased maple trunk growth, and provide borer protection superior to trunk sprays.

Index words: flatheaded appletree borer (*Chrysobothris femorata*), Coleoptera: Buprestidae, Neonicotinoid, *Acer rubrum*, insecticide, tree growth.

Insecticides used in this study: experimental imidacloprid tablet formulation (Merit FXT; currently marketed as CoreTect); experimental imidacloprid gel formulation; experimental acephate tablet (Borer-Stop EcoTab); bifenthrin (Onyx Pro Insecticide); chlorpyrifos (Dursban 2E or 4E); clothianidin (Arena 50WDG); dinotefuran (Safari 20SG); imidacloprid + bifenthrin (Allectus SC); imidacloprid + cyfluthrin (Discus); thiamethoxam (Flagship 25WG); potassium polyacrylamide acrylate copolymer (Terra-Sorb Fine Hydrogel).

Species used in this study: red maple (*Acer rubrum* L.) cultivars 'Autumn Flame', 'Fairview Flame', 'Franksred', and 'October Glory'.

Significance to the Nursery Industry

Flatheaded borers can significantly impact nursery production for up to four years after transplanting, causing mortality or rendering trees unmarketable from trunk scarring. In this study, non-insecticide-treated red maple cultivars sustained high levels of flatheaded borer damage in 2005 (2.3–39.6%)

and 2006 (32.1–41.0%) trials, indicating almost half of the crop was lost without insecticide protection. The only flatheaded borer species reared from red maples was the flatheaded appletree borer [*Chrysobothris femorata* (Olivier)] (FAB), indicating the potential importance of FAB in middle Tennessee production nurseries. Untreated plants and plants receiving ineffective treatments continued to sustain FAB

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damage every year, contradicting a common belief that borer attacks only occur during the first year after transplanting. Current recommendations to prevent FAB damage are trunk sprays of chlorpyrifos (e.g., Dursban) during mid May and mid-to-late June; however these applications did not provide acceptable *C. femorata* control even at twice the labeled rate in this study. Imidacloprid-based drench formulations like Discus or Allectus provided excellent control and were more effective than other imidacloprid formulations like an experimental gel or tablets during the first and second post-treatment year. Imidacloprid tablets provided complete FAB control in years 3 and 4, suggesting the tablet formulation eventually released enough imidacloprid to protect trees. Discus or Arena 50WDG (clothianidin) drenches applied in March were more effective than May applications, suggesting early season application provides a FAB control advantage. For some cultivars, trunk diameter growth was greater with Discus or Safari 20SG (dinotefuran) applications than the non-treated control and other treatments, which indicates these neonicotinoids can increase tree value since pricing is usually based on trunk caliper size.

Introduction

The metallic wood-boring beetles (Coleoptera: Buprestidae) can be significant pests of woody plants. There are approximately 750 species of buprestids in North America (16). Buprestid larvae are commonly called flatheaded borers because the first segment of the thorax is enlarged behind the reduced head, which gives the appearance of a 'flattened' head (Fig. 1). Buprestid species attack living or dead host materials, as well as small to large trees, branches, main trunks, roots, or mine leaves; and a few species are problematic on dry seasoned timber (5). In nursery and landscape settings, the flatheaded appletree borer [*Chrysobothris femo-*



Fig 1. Buprestid larvae are commonly called flatheaded borers because the first thorax segment (prothorax) is enlarged behind the reduced head, which gives the appearance of a 'flattened' head. Photo courtesy, Josh Basham.



Fig 2. Damage from FAB larval tunneling beneath the bark typically begins as a sunken dark area on the trunk and may eventually split to reveal 'caked' frass beneath the bark.

rata (Olivier)], the Pacific flatheaded borer (*Chrysobothris mali* Horn), the two-lined chestnut borer [*Agrilus bilineatus* (Weber)], the bronze birch borer (*Agrilus anxius* Gory), and the emerald ash borer (*Agrilus planipennis* Fairmaire) are problem species that attack living trees.

The flatheaded appletree borer (FAB) is one of the most important buprestid borers of deciduous shade trees. It occurs throughout the United States (2, 3) and has been problematic in nursery-grown and landscape trees in Oklahoma, Georgia, Kentucky, Tennessee, and numerous western states (3, 8, 9, 14, 22). Larval FAB damage results from tunneling beneath the bark and is generally first recognized by a sunken dark area on the trunk, which may eventually split to reveal 'caked' frass (3) (Fig. 2). The FAB can attack over 30 different tree species (3), but in the Tennessee and Kentucky regions, maples have been particularly susceptible (14, 22). Red maples (*Acer rubrum* L.) are popular ornamental trees widely grown by the U.S. nursery industry. Numerous cultivars

have been developed for superior growth, fall color, insect resistance, and other plant qualities (1, 7, 18). Maple crops in the middle Tennessee nurseries commonly have flatheaded borer losses in the range of 25 to 40% by the third to fourth production year (Oliver and Fare, unpublished data).

One challenge with FAB management is the cryptic nature of damage. Problems are usually not apparent until the larva becomes large enough to produce visible injury on the trunk surface or branch dieback occurs (21). By the time larval damage is obvious, the tree is often unmarketable due to trunk scarring, even if the tree subsequently survives the FAB attack. Adult FAB flight periods and egg deposition can vary between years and regions (2, 3, 8, 14), making it difficult to predict the optimal timing of insecticide applications. Some FAB larvae may require 2 years to complete development, which can also result in variable adult emergence (2, 3). The key to producing quality nursery crops in areas with high FAB activity is to prevent injury from reaching a point where unsightly trunk damage occurs and vascular tissues are not compromised.

Nursery growers and landscapers often make prophylactic calendar sprays as airblast, backpack or handgun applications to prevent borer damage due to the difficulty in monitoring and predicting buprestid attacks. Contact insecticides such as bifenthrin, chlorpyrifos, or permethrin are commonly used to manage flatheaded borers. In recent years, new neonicotinoid insecticides have entered the market, providing alternative opportunities to manage borers that attack trees internally. The systemic properties of neonicotinoids allow root uptake and translocation in the vascular tissues of trees (11). In addition, neonicotinoids are characterized by photostability, as well as acute and residual activity against many pest groups including beetles, which may allow them to provide long-term protection of trees against flatheaded borers (11). Past research with imidacloprid and thiamethoxam indicate activity against FAB and potential for FAB management (6).

The objectives of the research described here were to 1) evaluate soil-applied systemic insecticides (acephate, clothianidin, dinotefuran, imidacloprid, thiamethoxam) and two trunk-applied contact insecticides (bifenthrin and chlorpyrifos) for management of flatheaded borers in field grown red maples, 2) to determine the species of flatheaded borers responsible for attacks on red maples, and 3) to determine the effect of insecticide applications on maple growth.

Materials and Methods

Description of test sites. Two field trials were established at a commercial field nursery near Tullahoma, TN. Tree liners were purchased from a West Coast nursery and transplanted in late winters of 2005 and 2006 in field blocks with row spacing of 3.0 m (10 ft) apart with 1.5 m (5 ft) in row spacing.

2005 Trial. In May 2005, eight insecticide treatments and an untreated control were assigned to two fields of red maple (*Acer rubrum* L.) cultivars, 'Autumn Flame' and 'Franksred' that had been planted in March 2005 (Table 1). Within each cultivar planting, treatments were randomly assigned to consecutive trees within a row, which constituted an experimental block. Each experimental block was replicated 44 and 47 times for 'Franksred' and 'Autumn Flame', respectively. A randomized complete block design was chosen due to the large field size and to ensure that all treatments were present in each area of the field. The soil type in the field planted

with 'Franksred' was a silt loam, and the 'Autumn Flame' field was a clay loam soil.

To determine insecticide rates, trunk diameters on a subsample of nine replications were measured with a digital caliper (Mitutoyo Corp., Kanagawa, Japan) at 15 cm (6 in) above the soil line on May 5, 2005. Trunks averaged 22.8 and 20.1 mm (0.9 and 0.8 in) for 'Franksred' and 'Autumn Flame', respectively. Drench rates were based on the Discus insecticide label, which recommends 22 to 44 ml·25 mm⁻¹ (0.75 to 1.5 fl oz·in⁻¹) of trunk diameter at breast height (DBH) [137 cm above the soil surface (4.5 ft)]. The DBH measurement is normally used for mature landscape trees and not smaller nursery trees. In this study, insecticide rates were based on the trunk diameter at the height nursery trees are typically measured [15 cm (6 in) above the soil line].

Three treatments applied as drenches were Allectus SC (Allectus) (imidacloprid + bifenthrin) [5.6 ml (0.2 fl oz) product·tree⁻¹] and Discus (imidacloprid + cyfluthrin) [22 or 44 ml (0.7 or 1.5 fl oz) product·tree⁻¹]. A 250 ml (8.5 fl oz) solution was poured into a 3.8-liter (1-gal) sprinkle can that was used to drench the lower trunk and the soil at the base of the tree [15 cm circle at tree base (5.9 in)]. Small divots were made at the base of trees when necessary to keep the solution from flowing away from the root zone. In addition to drench treatments, two experimental tablet formulations were included: imidacloprid [Merit FXT (currently marketed as CoreTect), Bayer Environmental Science, Research Triangle Park, NC] (imidacloprid tablet) [0.5 g (0.02 oz) ai·tablet⁻¹] and acephate (Borer-Stop EcoTab, AgSci Tech, Logan, UT) (acephate tablet) [75%, 1.0 g (0.04 oz) ai·tablet⁻¹]. Two imidacloprid or two acephate tablets were inserted on opposite sides of the tree 7.6 cm (3 in) below the soil surface and 7.6 cm (3 in) from the trunk. A soil probe was used to create a hole, which was closed by hand following placement of the tablets. Three Dursban 4E (chlorpyrifos) [5 ml·liter⁻¹ (0.64 fl oz·gal⁻¹), 2× labeled rate] treatments were applied on the trunk from the soil line up to about 1.2 m (3.9 ft). One was a standard trunk spray (Dursban Full) applied with a CO₂ backpack sprayer equipped with an 8002VS flat fan spray tip. The entire bark surface of the trunk was sprayed to runoff. A second Dursban 4E spray treatment (Dursban SW) was applied on the southwest side of the trunk with a single up-and-down pass applied to runoff using equipment and mix rates previously described. To protect adjacent trees from chlorpyrifos spray treatments, a plastic barrier was held on the opposite side of the tree during each spray to prevent drift. A third Dursban 4E treatment (Dursban Roll) was mixed at the rate previously described and then rolled on all sides of the tree trunk using a 7.6-cm (3-in) wide paint roller. All imidacloprid and chlorpyrifos treatments were applied on May 24, 2005, and the acephate tablets were applied on June 8, 2005.

Trunk diameter (measured as described above) and height were measured on all replicates on August 23, 2005, December 21, 2005, November 3, 2006, October 19, 2007, and October 23, 2008. The growth increase for 2005, 2006, 2007 and 2008 was considered the difference between December 2005 and August 2005, November 2006 and December 2005, October 2007 and November 2006, and October 2008 and October 2007, respectively (height data for 2005 and 2008 and trunk data for 2008 not shown) (Table 2). Cumulative trunk diameter growth was the difference between the October 2008 and August 2005 measurements. A canopy size

Table 1. Percentage of yearly flatheaded borer attacks on *Acer rubrum* 'Autumn Flame' and 'Franksred' treated once in May or June 2005 with acephate-, chlorpyrifos-, or imidacloprid-based insecticides^a.

Treatment ^b	Active ingredient(s)	Treatment method ^c	Product /tree	Active ingredient /tree	Cumulative percent of total trees damaged by FAB				Number of trees damaged by FAB				
					2005	2006	2007	2008	2005	2006	2007	2008	Total
‘Autumn Flame’ (n = 48)													
Acephate tablet	Acephate	Soil insertion	2 tablets	2.0 g	12.5	16.7	27.1	35.4	6a ^w	2ab	5ab	4a	17
Dursban 4E	Chlorpyrifos	Full trunk spray	2× spray	—	8.3	20.8	29.2	33.3	4ab	6a	4abc	2a	16
Dursban 4E	Chlorpyrifos	SW trunk spray	2× spray	—	10.4	18.8	27.1	35.4	5a	4ab	4abc	4a	17
Dursban 4E	Chlorpyrifos	Trunk roll	2× roll	—	12.5	25	37.5	41.7	6a	6a	6a	2a	20
Allectus SC	Imidacloprid + bifenthrin	Drench	5.6 ml	0.30 g	0	0	4.2	8.3	0b	0b	2bc	2a	4
Discus	Imidacloprid + cyfluthrin	Drench	22 ml	0.69 g	0	0	2.1	6.4	0b	0b	1bc	2a	3
Discus	Imidacloprid + cyfluthrin	Drench	44 ml	1.38 g	0	0	0	0	0b	0b	0c	0a	0
Imidacloprid tablet	Imidacloprid	Soil insertion	2 tablets	1.00 g	4.2	6.3	6.3	6.3	2ab	1b	0c	0a	3
Untreated	None	—	—	—	12.5	25	37.5	39.6	6a	6a	6a	1a	19
Fisher Exact Test (p ≤ 0.05)									0.0019	0.0001	0.0012	0.0890	
‘Franksred’ (n = 44)													
Acephate tablet	Acephate	Soil insertion	2 tablets	2.0 g	6.8	6.8	9.1	9.1	3a	0	1a	0a	4
Dursban 4E	Chlorpyrifos	Full trunk spray	2× spray	—	0	0	0	0	0a	0	0a	0a	0
Dursban 4E	Chlorpyrifos	SW trunk spray	2× spray	—	2.3	2.3	2.3	4.5	1a	0	0a	1a	2
Dursban 4E	Chlorpyrifos	Trunk roll	2× roll	—	0	0	0	0	0a	0	0a	0a	0
Allectus SC	Imidacloprid + bifenthrin	Drench	5.6 ml	0.30 g	0	0	0	0	0a	0	0a	0a	0
Discus	Imidacloprid + cyfluthrin	Drench	22 ml	0.69 g	0	0	0	4.5	0a	0	0a	2a	2
Discus	Imidacloprid + cyfluthrin	Drench	44 ml	1.38 g	0	0	0	0	0a	0	0a	0a	0
Imidacloprid tablet	Imidacloprid	Soil insertion	2 tablets	1.00 g	0	0	0	0	0a	0	0a	0a	0
Untreated	None	—	—	—	2.3	2.3	2.3	2.3	1a	0	0a	0a	1
Fisher Exact Test (p ≤ 0.05)									0.0986	—	0.1049	0.1762	

^aFAB ratings were conducted on August 23, 2005, October 19, 2005, March 9, 2006, October 18, 2006, April 3, 2007, October 18, 2007, April 9, 2008, October 22, 2008, March 4, 2009, and September 21, 2009.

^bThe imidacloprid and acephate tablets were experimental, but are now marketed as CoreTect and Borer-Stop EcoFab, respectively. Dursban, Allectus, Discus, and imidacloprid tablets were applied on May 24, 2005, and acephate tablets were applied on June 8, 2005. No additional treatments were made in subsequent years.

^cDursban full trunk spray was applied to the entire lower tree trunk until runoff, while Dursban SW was applied only to the southwest side of the trunk to runoff.

^wMeans within a column and tree variety followed by different letters are significantly different (α = 0.05).

Table 2. Trunk diameter and height growth with *Acer rubrum* ‘Autumn Flame’ and ‘Franksred’ treated in May or June 2005 with acephate-, chlorpyrifos-, or imidacloprid-based insecticides.

Treatment ^z	Treatment method	Product /tree	Active ingredient /tree	Trunk diameter, mm ^{yx}			Cumulative trunk diameter increase, 2008, mm ^w	Height, cm ^y		Canopy size index ^y
				2005	2006	2007		2006	2007	
‘Autumn Flame’										
Acephate tablet	Soil insertion	2 tablets	2.0 g	0.8a ^u	9.1cd	2.7ef	25.0cd	31.2d	19.0b	252.2ab
Dursban 4E	Full trunk spray	2× spray	—	0.3c	8.3de	2.5f	23.6de	28.3d	16.4b	241.3cd
Dursban 4E	SW trunk spray	2× spray	—	0.3bc	7.6e	3.1def	23.0de	29.1d	17.1b	243.6bcd
Dursban 4E	Trunk roll	2× roll	—	0.3c	7.7e	2.9def	22.5e	32.8bcd	16.5b	240.0cd
Allectus SC	Drench	5.6 ml	0.30 g	0.5bc	10.2bc	3.4cde	26.4bc	33.1bcd	20.9ab	250.5b
Discus	Drench	22 ml	0.69 g	0.5bc	11.1ab	4.0abc	28.5ab	37.6bc	17.9b	260.2ab
Discus	Drench	44 ml	1.38 g	0.5b	11.6a	4.5a	29.8a	43.6a	24.5a	263.3a
Imidacloprid tablet	Soil insertion	2 tablets	1.00 g	0.3c	10.2b	4.3ab	27.3b	38.5ab	21.4ab	261.5a
Untreated	—	—	—	0.3c	7.8e	3.5bcd	24.5cde	32.3cd	19.5ab	248.1bc
LSD				0.2	1.2	0.8	2.1	6.0	5.3	7.6
‘Franksred’										
Acephate tablet	Soil insertion	2 tablets	2.0 g	1.6ab	10.2cd	4.5bc	25.0c	41.9cd	24.2ab	304.9cd
Dursban 4E	Full trunk spray	2× spray	—	1.5b	10.4cd	4.4bc	24.7c	49.9b	20.9b	304.6cd
Dursban 4E	SW trunk spray	2× spray	—	1.5b	10.6cd	4.6abc	25.1c	50.4b	28.8a	304.1cd
Dursban 4E	Trunk roll	2× roll	—	1.4b	10.7cd	4.5bc	24.7c	46.9bc	23.5ab	299.9d
Allectus SC	Drench	5.6 ml	0.30 g	1.8ab	10.8c	4.2c	24.9c	35.2d	25.0ab	305.4cd
Discus	Drench	22 ml	0.69 g	1.7ab	12.2b	4.9ab	27.2b	39.2d	23.6ab	310.4bc
Discus	Drench	44 ml	1.38 g	2.0a	13.1a	4.9ab	29.1a	57.7a	23.3ab	317.8a
Imidacloprid tablet	Soil insertion	2 tablets	1.00 g	1.7ab	12.1b	5.2a	28.5a	60.5a	25.6ab	315.9ab
Untreated	—	—	—	1.7ab	10.1d	4.3bc	24.8c	48.0bc	23.1ab	300.7d
LSD				0.4	0.7	0.6	1.2	7.0	6.1	6.5

^zAllectus and Discus are combination products with imidacloprid as the systemic active ingredient. The imidacloprid and acephate tablets were experimental, but are now marketed as CoreTect and Borer-Stop EcoTab, respectively. Dursban, Allectus, Discus, and imidacloprid tablets were applied on May 24, 2005, and acephate tablets were applied on June 8, 2005. No additional treatments were made in subsequent years.

^yHeight and trunk diameter were measured on August 23, 2005, December 21, 2005, November 3, 2006, October 19, 2007, and October 23, 2008. The yearly growth increase for 2005, 2006, 2007, and 2008 was the difference between December 2005 and August 2005, November 2006 and December 2005, October 2007 and November 2006, and October 2008 and October 2007, respectively. Initial sample size was 48 and 44 trees for ‘Autumn Flame’ and ‘Franksred’, respectively. In subsequent years, trees were not measured if damaged by borers, so sample size decreased.

^xTrunk diameter measured at 15 cm (6 in) above soil line.

^wCumulative trunk diameter growth was the difference between the October 2008 and August 2005 measurements.

^yCanopy size index = [Canopy width at widest point + width perpendicular to widest point + canopy height] / 3. Canopy height = tree height – trunk height to lowest branch.

^uMeans within a column and tree variety followed by different letters are significantly different ($\alpha = 0.05$).

index was calculated using the formula: (canopy width at the widest point + width perpendicular to widest point + canopy height) / 3. Canopy height = tree height – trunk height to lowest branch. The change in plant growth each year was only analyzed for plants that had not received a confirmed FAB attack the previous year. Therefore, each cumulative year, there were fewer trees included in the analysis of growth effects for some treatments due to borer attacks. For each cultivar, growth differences were compared among treatments by analysis of variance (ANOVA) and means separated using a least significant difference test ($P \leq 0.05$).

2006 Trial. In 2006, 14 insecticide treatments using different application methods and timings and an untreated control were assigned in a randomized complete block design to

three fields of red maple cultivars planted in February 2006 at the same nursery as the 2005 trial (Table 3). Replications in each red maple field were based on available tree numbers and included ‘Franksred’ (n = 39), ‘Fairview Flame’ (n = 16), and ‘October Glory’ (n = 27). The soil type was a silt loam in the nursery blocks.

Neonicotinoid drench rates were determined from label or manufacturer recommendations and were based on initial trunk diameter as previously described. Trunk diameters averaged 25.9, 24.0, and 23.8 mm (1 in) for ‘Fairview Flame’, ‘Franksred’ and ‘October Glory’, respectively. Drench treatments were applied as previously described and included Allectus (same rate as 2005 trial), Arena 50WDG (clothianidin) (Arena) [0.92 g (0.03 oz) product-tree⁻¹], Discus [22 ml (0.7 fl oz) product-tree⁻¹], Flagship 25WG (thiamethoxam)

Table 3. Cumulative percentage and number of trees attacked by flatheaded borer on *Acer rubrum* 'Fairview Flame', 'Franksred' and 'October Glory' treated once in March, April, or May 2006 with systemic insecticides or multiple times with chlorpyrifos or bifenthrin trunk sprays^a.

Treatment ^b	Active ingredient(s)	Treatment method	Treatment timing 2006	Product /tree	Active ingredient /tree	Cumulative percent of total trees damaged by EAB						Total		
						2006	2007	2008	2009	2006	2007		2008	2009
*Fairview Flame' (n = 16)														
Accephate tablet	Accephate	Soil insertion	Apr 10	6 tablets	6.00 g	37.5	50	75	75	6a*	2a	4a	0	12
Allectus SC	Imidacloprid + bifenthrin	Drench	May 15	5.6 ml	0.30 g	0	0	0	0	0c	0a	0b	0	0
Discus	Imidacloprid + cyfluthrin	Drench	Mar 23	22 ml	0.69 g	0	0	0	0	0c	0a	0b	0	0
Discus	Imidacloprid + cyfluthrin	Drench	May 15	22 ml	0.69 g	0	6.3	6.3	6.3	0c	1a	0b	0	1
Discus + Terrasorb	Imidacloprid + cyfluthrin	Root dip	Mar 13	~26 ml	~0.82 g	0	0	0	0	0c	0a	0b	0	0
Imidacloprid gel	Imidacloprid	Soil insertion	Mar 23	10 g	0.50 g	6.3	18.8	18.8	18.8	1b	2a	0b	0	3
Imidacloprid tablet 1	Imidacloprid	Soil insertion	Mar 17	1 tablet	0.50 g	31.3	43.8	43.8	43.8	5a	2a	0b	0	7
Imidacloprid tablet 2	Imidacloprid	Soil insertion	Mar 17	2 tablets	1.00 g	12.5	18.8	18.8	18.8	2b	1a	0b	0	3
Arena 50WDG	Clothianidin	Drench	Mar 17	0.92 g	0.46 g	0	6.3	6.3	6.3	0c	1a	0b	0	1
Arena 50WDG	Clothianidin	Drench	May 15	0.92 g	0.46 g	6.3	12.5	12.5	12.5	1b	1a	0b	0	2
Flagship 25WG	Thiamethoxam	Drench	May 15	0.33 g	0.0812 g	0	0	12.5	12.5	0c	0a	2ab	0	2
Safari 20SG	Dinotefuran	Drench	May 15	6 g	1.20 g	0	0	0	0	0c	0a	0b	0	0
Onyx Pro Insecticide	Bifenthrin	Full trunk spray	May 18 ^w	2.5 ^x spray	—	12.5	18.8	18.8	18.8	2b	1a	0b	0	3
Dursban 2E	Chlorpyrifos	Full trunk spray	May 18 & Jun 20 ^w	2 ^x spray	—	12.5	25	31.3	31.3	2b	2a	1b	0	5
Untreated	None	—	—	—	—	12.5	31.3	37.5	37.5	2b	3a	1b	0	6
Fisher exact test (p ≤ 0.05)						0.0004	0.1699	0.0001	—					
*Franksred' (n = 39)														
Accephate tablet	Accephate	Soil insertion	Apr 10	6 tablets	6.00 g	0	20.5	25.6	28.2	0c	8b	2a	1a	11
Allectus SC	Imidacloprid + bifenthrin	Drench	May 15	5.6 ml	0.30 g	0	2.6	5.1	7.7	0c	1d	1a	1a	3
Discus	Imidacloprid + cyfluthrin	Drench	Mar 23	22 ml	0.69 g	0	0	0	0	0c	0d	0a	0a	0
Discus	Imidacloprid + cyfluthrin	Drench	May 15	22 ml	0.69 g	0	0	0	5.1	0c	0d	0a	2a	2
Discus + Terrasorb	Imidacloprid + cyfluthrin	Root dip	Mar 13	~26 ml	~0.82 g	0	2.6	2.6	2.6	0c	1d	0a	0a	1
Imidacloprid gel	Imidacloprid	Soil insertion	Mar 23	10 g	0.50 g	5.1	7.7	10.3	12.8	2b	1d	1a	1a	5
Imidacloprid tablet 1	Imidacloprid	Soil insertion	Mar 17	1 tablet	0.50 g	2.6	10.3	15.4	15.4	1b	3cd	2a	0a	6
Imidacloprid tablet 2	Imidacloprid	Soil insertion	Mar 17	2 tablets	1.00 g	5.1	5.1	5.1	5.1	2b	0d	0a	0a	2
Arena 50WDG	Clothianidin	Drench	Mar 17	0.92 g	0.46 g	0	2.6	5.1	5.1	0c	1d	1a	0a	2
Arena 50WDG	Clothianidin	Drench	May 15	0.92 g	0.46 g	0	2.6	5.1	7.7	0c	1d	1a	1a	3
Flagship 25WG	Thiamethoxam	Drench	May 15	0.33 g	0.0812 g	2.6	15.4	17.9	20.5	1b	5bc	1a	1a	8
Safari 20SG	Dinotefuran	Drench	May 15	6 g	1.20 g	0	7.7	7.7	10.3	0c	3cd	0a	1a	4

Table 3 continued ...

Table 3. Continued ...

Treatment*	Active ingredient(s)	Treatment method	Treatment timing 2006	Product /tree	Active ingredient /tree	Cumulative percent of total trees damaged by FAB					Number of trees damaged by FAB				
						2006	2007	2008	2009	2006	2007	2008	2009	Total	
*Franksred' (n = 39) (continued)															
Onyx Pro Insecticide	Bifenthrin	Full trunk spray	May 18 ^w	2.5× spray	—	0	0	0	5.1	0c	0d	0a	2a	2	
Dursban 2E	Chlorpyrifos	Full trunk spray	May 18 & Jun 20 ^w	2× spray	—	0	7.7	7.7	17.9	0c	3cd	0a	4a	7	
Untreated	None	—	—	—	—	10.3	41	41	41	4a	12a	0a	0a	16	
Fisher exact test (p ≤ 0.05)											0.0117	0.0001	0.4094	0.2883	
*October Glory' (n = 27)															
Accephate tablet	Accephate	Soil insertion	Apr 10	6 tablets	6.00 g	3.7	18.5	18.5	18.5	1a	4a	0b	0a	5	
Allectus SC	Imidacloprid + bifenthrin	Drench	May 15	5.6 ml	0.30 g	0	0	0	3.6	0a	0c	0b	1a	1	
Discus	Imidacloprid + cyfluthrin	Drench	Mar 23	22 ml	0.69 g	0	0	0	0	0a	0c	0b	0a	0	
Discus	Imidacloprid + cyfluthrin	Drench	May 15	22 ml	0.69 g	0	0	0	0	0a	0c	0b	0a	0	
Discus + Terrasorb	Imidacloprid + cyfluthrin	Root dip	Mar 13	~26 ml	~0.82 g	0	0	0	0	0a	0c	0b	0a	0	
Imidacloprid gel	Imidacloprid	Soil insertion	Mar 23	10 g	0.50 g	3.7	3.7	3.7	7.4	1a	0c	0b	1a	2	
Imidacloprid tablet 1	Imidacloprid	Soil insertion	Mar 17	1 tablet	0.50 g	0	19.2	19.2	19.2	0a	5a	0b	0a	5	
Imidacloprid tablet 2	Imidacloprid	Soil insertion	Mar 17	2 tablets	1.00 g	0	3.7	3.7	3.7	0a	1b	0b	0a	1	
Arena 50WDG	Clothianidin	Drench	Mar 17	0.92 g	0.46 g	0	3.7	3.7	3.7	0a	1b	0b	0a	1	
Arena 50WDG	Clothianidin	Drench	May 15	0.92 g	0.46 g	0	0	3.7	3.7	0a	0c	1b	0a	1	
Flagship 25WG	Thiamethoxam	Drench	May 15	0.33 g	0.0812 g	0	7.4	11.1	14.8	0a	2ab	1b	1a	4	
Safari 20SG	Dinotefuran	Drench	May 15	6 g	1.20 g	0	3.7	3.7	7.4	0a	1b	0b	1a	2	
Onyx Pro Insecticide	Bifenthrin	Full trunk spray	May 18 ^w	2.5× spray	—	0	7.7	7.7	7.7	0a	2ab	0b	0a	2	
Dursban 2E	Chlorpyrifos	Full trunk spray	May 18 & Jun 20 ^w	2× spray	—	0	7.4	11.1	11.1	0a	2ab	1b	0a	3	
Untreated	None	—	—	—	—	3.6	21.4	32.1	32.1	1a	5a	3a	0a	9	
Fisher exact test (p ≤ 0.05)											0.8291	0.0020	0.0181	0.8472	

^wFAB ratings were conducted on October 18, 2006, April 3, 2007, October 18, 2007, April 9, 2008, October 22, 2008, March 4, 2009, September 15, 2009, and September 21, 2009.

^yThe imidacloprid and acephate tablets were experimental, but are now marketed as CoreTect and Borer-Stop EcoFab, respectively. Root dips were prepared by mixing 45 g (1.6 oz) Terrasorb in 11.4 liters (3 gal) of water and then adding 3.8 liters (1 gal) of Discus. Tree roots were then dipped in the Discus + Terrasorb mixture with each tree removing about 105 g (3.7 oz) of material (based on post-dip weight change). Imidacloprid gel was an experimental formulation applied into the soil with a caulk gun. Dursban 2E and Onyx Pro Insecticide were applied to all tree trunk sides until runoff.

^xMeans within a column and tree variety followed by different letters are significantly different (α = 0.05).

^wOnyx and Dursban were reapplied on May 10, 2007. Dursban was also reapplied on June 21, 2007.

Table 4. Mean increase in trunk diameter growth with *Acer rubrum* ‘Fairview Flame’ and ‘Franksred’ from spring 2006 to fall 2008 for plants treated once in March, April, or May 2006 with systemic insecticides or multiple times with chlorpyrifos or bifenthrin trunk sprays.

Treatment ^a	Treatment method ^b	Treatment timing 2006	Product /tree	Active ingredient /tree	Trunk diameter ^c (mm)			Trunk diameter ^c (mm)		
					2006	2007	Total growth ^d	2006	2007	Total growth ^d
					‘Fairview Flame’			‘Franksred’		
Acephate tablet	Soil insertion	Apr 10	6 tablets	6.00 g	2.8c ^e	6.8def	24.4c	1.1e	3.8de	16.3ef
Allectus SC	Drench	May 15	5.6 ml	0.30 g	5.4ab	7.9a–d	27.6ab	2.1a–d	5.2a	19.4ab
Discus	Drench	Mar 23	22 ml	0.69 g	5.1ab	8.8ab	29.5a	1.6de	4.7a–d	18.0a–e
Discus	Drench	May 15	22 ml	0.69 g	5.4ab	8.9a	29.6a	2.1a–d	4.7a–d	18.2a–d
Discus + Terrasorb	Root dip	Mar 13	~ 26 ml	~ 0.82 g	4.1bc	7.7a–e	27.5abc	1.1e	3.8e	15.9f
Imidacloprid gel	Soil insertion	Mar 23	10 g	0.50 g	5.6a	7.1c–f	29.2a	2.1a–d	5.1ab	19.3abc
Imidacloprid tablet 1	Soil insertion	Mar 17	1 tablet	0.50 g	5.7a	6.6ef	28.1ab	2.1a–d	5.0abc	18.6a–d
Imidacloprid tablet 2	Soil insertion	Mar 17	2 tablets	1.00 g	5.8a	7.9a–d	28.2ab	2.7a	4.9abc	19.7a
Arena 50WDG	Drench	Mar 17	0.92 g	0.46 g	5.1ab	8.3abc	27.7ab	1.8cd	4.3b–e	17.6c–f
Arena 50WDG	Drench	May 15	0.92 g	0.46 g	5.7a	8.2abc	28.6ab	2.4ab	4.7a–d	19.1abc
Flagship 25 WG	Drench	May 15	0.33 g	0.0812 g	6.1a	7.2c–f	28.6ab	2.0bcd	5.0abc	17.9b–e
Safari 20SG	Drench	May 15	6 g	1.20 g	5.4ab	8.1abc	29.1a	2.6ab	5.2a	19.8a
Onyx Pro Insecticide	Full trunk spray	May 18 ^u	2.5× spray	—	5.2ab	7.8a–d	28.5ab	2.1a–d	4.2cde	17.2def
Dursban 2E	Full trunk spray	May 18 & Jun 20 ^u	2× spray	—	6.3a	7.6b–e	28.3ab	2.2a–d	4.5a–d	18.2a–d
Untreated	—	—	—	—	5.2ab	6.3f	25.7bc	2.3abc	4.1cde	19.4ab
LSD					1.4	1.2	3.1	0.6	0.9	1.8

^aAllectus and Discus are combination products with imidacloprid as the systemic active ingredient. The imidacloprid and acephate tablets were experimental, but are now marketed as CoreTect and Borer-Stop EcoTab, respectively.

^bRoot dips were prepared by mixing 45 g (1.6 oz) Terrasorb in 11.4 liters (3 gal) of water and then adding 3.8 liters (1 gal) of Discus. Tree roots were then dipped in the Discus + Terrasorb mixture with each tree removing about 105 g (3.7 oz) of material (based on post-dip weight change).

^cTrunk diameter measured at 15 cm (6 in) above soil line.

^dTotal trunk diameter growth was the difference between the October 23, 2008, and March 23, 2006, measurements. Initial sample size was 16 and 39 trees for ‘Fairview Flame’ and ‘Franksred’, respectively. In subsequent years, trees were not measured if damaged by borers, so sample size decreased.

^eMeans within a column followed by different letters are significantly different ($\alpha = 0.05$).

^uOnyx and Dursban were reapplied on May 10, 2007. Dursban was also reapplied on June 21, 2007.

(Flagship) [0.33 g (0.01 oz) product·tree⁻¹], and Safari 20SG (dinotefuran) (Safari) [6 g (0.21 oz) product·tree⁻¹]. Drenches were applied May 15, 2006, with the exception of March-only Arena or Discus treatments (March 17 or 23, 2006, respectively). Imidacloprid (1 or 2 tablets·tree⁻¹) and acephate (6 tablets·tree⁻¹) tablet treatments (same formulations as 2005 trial) were inserted into the soil as previously described by making separate holes around the tree base for each tablet on March 17, 2006, and April 10, 2006, respectively. An experimental imidacloprid gel formulation was applied on March 23, 2006, in a hole in the soil 7.6 cm (3 in) from the trunk [1.3 cm (0.5 in) wide and 7.6 cm (3 in) deep] using a caulk gun calibrated to deliver a 10 g (0.35 oz) bead·tree⁻¹ [0.5 g (0.02 oz) ai·tree⁻¹]. Discus was also applied as a root dip on March 13, 2006. To prepare the root dip treatment, 45 g (1.6 oz) of Terra-Sorb, an absorbent potassium polyacrylamide acrylate copolymer hydrogel (Plant Health Care, Pittsburgh, PA) was thoroughly mixed into 11.4 liters (3 gal) of water. Discus [3.8 liters (1 gal)] was added to the Terra-Sorb solution and thoroughly mixed. Maple liners receiving the Terra-Sorb + Discus root dip had already been planted, but were still dormant. These trees were lifted from the soil with a shovel and soil was removed from the roots by gently dipping in water.

Roots and the lower trunk were then dipped into the Terra-Sorb + Discus solution. Pre- and post-weighing of dipped trees indicated a weight change of ~ 105 g (3.7 oz), which was estimated to be ~ 0.82 g (0.03 oz) imidacloprid·tree⁻¹. Trees were immediately replanted. In addition to systemic treatments, Onyx Pro Insecticide (bifenthrin) [2.5 ml·liter⁻¹ (0.32 fl oz·gal⁻¹), 2.5× labeled rate] was applied as a trunk spray on May 18, 2006, and May 10, 2007. Dursban 2E [10 ml·liter⁻¹ (1.28 fl oz·gal⁻¹), 2× labeled rate] was applied as a trunk spray on the same dates as Onyx, as well as June 20, 2006, and June 21, 2007. Trunk sprays were applied to the entire bark surface as previously described in the 2005 trial.

Trunk diameters were measured initially on March 23, 2006, and at the end of each growing year (October 18, 2006, October 19, 2007, and October 23, 2008). The growth increase for 2006, 2007, and 2008 was considered the difference between October 2006 and March 2006, October 2007 and October 2006, and October 2008 and October 2007, respectively (trunk diameter data for ‘October Glory’ not shown) (Table 4). Total trunk diameter growth was the difference between the October 2008 and March 2006 measurements. Growth differences were analyzed as previously described in the 2005 trial.

Flatheaded borer incidence and data analysis. Flatheaded borer damage in the 2005 trial was rated on August 23, 2005, October 19, 2005, March 9, 2006, October 18, 2006, April 3, 2007, October 18, 2007, April 9, 2008, October 22, 2008, March 4, 2009, and September 15, 2009. Flatheaded borer damage in the 2006 trial was rated on the same dates as the 2005 trial beginning October 18, 2006 and thereafter. All borer-damaged trees were tagged and geo-referenced with a LandMark Systems© RT-INW-I sub-meter WAAS DGPS running SoloField™ CE3.2 or a LandMark Systems© CSI sub-meter series with a Tripod Data Systems™ Recon running SoloField™ CE (LandMark Systems, Tallahassee, FL). Global positioning data were used to create maps of borer attack patterns in the maple fields (data only shown for 'Autumn Flame') (Fig. 3). Trees that were severely damaged by borers beyond marketable value were cut down each spring and taken to the laboratory to rear adult flatheaded borers for identification of species responsible for tree attacks. New flatheaded borer attacks are initiated in the late spring/early summer and are generally not visible on the trunk until fall or the next spring. Therefore, for data analysis purposes, new borer hits that were detected in the fall or early spring of the next year were considered attacks that occurred during the same growing season. For each red maple cultivar, treatments were compared for differences in flatheaded borer frequency using Fisher's Exact Test ($P \leq 0.05$) and means separated using a least significant difference test ($P \leq 0.05$).

Nursery practices provided by grower. Plants were maintained by the nursery using standard cultural practices, which included fertilizer, herbicide and insecticide applications during the study period. As a result, some of our experimental plots received additional insecticide treatments with a tractor-applied airblast sprayer. In the 2005 trial, the nursery grower airblast-applied Dursban 4E [260.2 ml/100 liters⁻¹ (33.3 fl oz/100 gal⁻¹)] and a non-ionic surfactant oil [104.2 ml/100 liters⁻¹ (13.3 fl oz/100 gal⁻¹)] to the entire 'Franksred' selection on July 8, 2005, June 23, 2006, July 4, 2007, and June 24, 2008. No additional insecticides were applied to 'Autumn Flame' in the 2005 trial. In the 2006 trial, airblast-applied Dursban 4E and non-ionic surfactant oil were again sprayed at the same rate as the 2005 trial on June 22, 2006, July 3, 2007, and June 19, 2008, to 'Franksred'; on June 22, 2006, to 'Fairview Flame'; and on June 26, 2006, July 2, 2007, and June 19, 2008 to 'October Glory'. No supplemental irrigation was applied to any of the nursery fields in this study.

Results and Discussion

Flatheaded borer rearing. A total of 11, 17, 18, and 24 FAB adults were reared from 'Fairview Flame', 'October Glory', 'Franksred', or 'Autumn Flame' red maples between 2006 and 2009, respectively. No other buprestid species were reared from experimental maple trees during the study, indicating the importance of FAB in attacks of middle Tennessee nursery stock. It is assumed that all of the tree attacks reported in this study were probably caused by FAB based on the absence of other species emerging from the rearing studies.

Flatheaded borer control. 2005 Trial. The number of FAB attacks varied significantly among insecticide treatments (Table 1). Though no statistical analysis was conducted to compare cultivar differences, numerically 'Autumn Flame'

had more FAB attacks each evaluation year of the test than 'Franksred' maples. In the first year (i.e., 2005), no statistical differences were found in borer attacks for 'Autumn Flame' treated with acephate tablets, Dursban treatments, imidacloprid tablets (4.2 to 12.5% damage) and the untreated control (12.5%). There was no FAB damage with the other imidacloprid-based insecticides. In 2006, 2007, and 2008, FAB attacks continued in the 'Autumn Flame' selection with the acephate tablet and all Dursban treatments, as well as the untreated control. It should be noted that other than Dursban treatments applied by the grower, experimental Dursban sprays were not applied after 2005. Therefore, the Dursban treatments were essentially non-treated treatments in years following 2005. All imidacloprid treatments provided borer protection for over 700 days post-treatment, with the exception of the imidacloprid tablets. However, the imidacloprid tablets had no FAB damage beginning in year 2007 and continuing into year 2008.

A late spring freeze followed by a summer drought in 2007 probably stressed plants more than in a typical growing season. The 'Autumn Flame' planting was located on a southern exposed hillside with gravelly soil, which probably contributed to more borer attacks than observed in the 'Franksred' planting. The percentage of trees being attacked by FAB remained relative constant for acephate, Dursban, and the non-treated control across all test years in the 'Autumn Flame' selection. By the end of the test, a substantial amount of FAB crop loss had occurred for plants treated with Dursban trunk roll (41.7%) or the untreated control (39.6%) (Table 1). All Dursban trunk treatments had unacceptable levels of borer injury in the 'Autumn Flame' selection during the first year when experimental Dursban treatments were applied, and the Dursban treatments provided no advantage over the untreated control treatment. The Dursban rate was 2× the labeled rate, yet FAB management was still ineffective in the first year. Since only a late May Dursban application and not a June application was made in the first year and no Dursban applications in subsequent years, treatments were not made according to current Extension recommendations. The only treatment in the 'Autumn Flame' selection with no damage at the end of the test was the Discus 44 ml treatment. The yearly percentage of borer attacks declined overall between the final years (2007 and 2008), but all Dursban treatments still had significantly more FAB attacks ($P \leq 0.05$) than the untreated plants in the 'Autumn Flame' planting. Though not statistically analyzed, there may be a rate effect in the 'Autumn Flame' selection for the three imidacloprid drench treatments because FAB incidence decreased with increasing imidacloprid rate (Table 1).

Flatheaded borer attacks were very low in the 'Franksred' selection with several treatments having no damage at the end of the test (Table 1). In 2006, there were no FAB attacks with 'Franksred' and in 2007 only the acephate treatment had one plant with an FAB attack. At the end of the fourth year (2008), plants treated with Discus (22 ml) and the Dursban (SW) each had 2 and 1 FAB attacks, respectively. The number of FAB attacks in the 'Franksred' selection were too low to detect statistical differences between treatments. The 'Franksred' trees were initially larger and faster growing than the 'Autumn Flame' trees (Table 2), which may have been a factor in the lower FAB attack rates. Unlike 'Autumn Flame', 'Franksred' trees were growing on a bottomland soil and were probably less stressed during transplant establish-

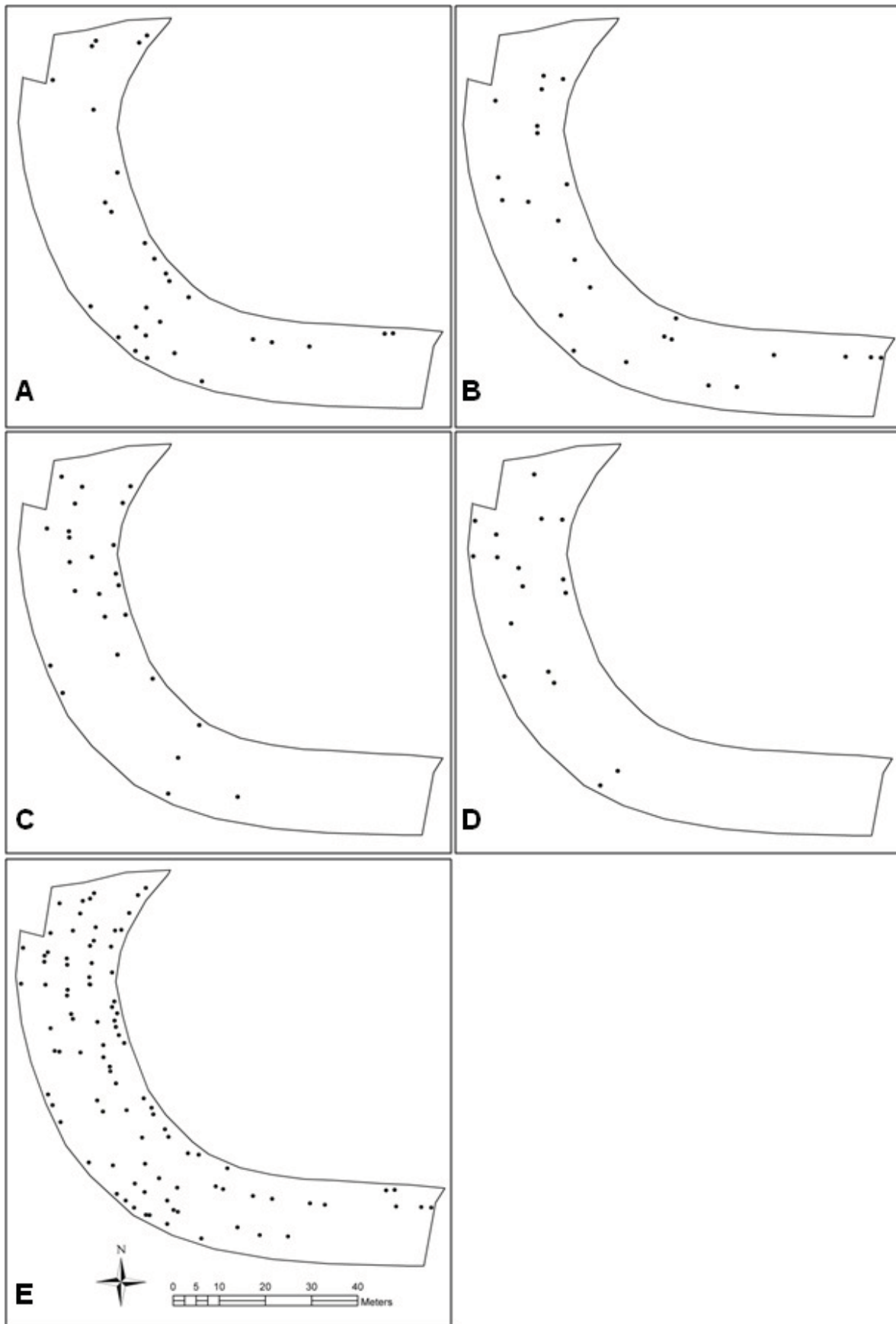


Fig. 3. Flatheaded borer attacks on red maple cultivar 'Autumn Flame' during A) 2005, B) 2006, C) 2007, D) 2008, and E) all years combined. Points depict new flatheaded borer attacks and the surrounding line represents an imaginary perimeter ~ 0.25 m (0.8 ft) from trees on the edge of the nursery block. The block had a total of 432 trees.

ment. However, total cumulative trunk diameter growth was similar for both cultivars by the end of the study. The grower also made one Dursban treatment each year during June or July to the entire 'Franksred' planting, which may have been a factor in the overall lower incidence of FAB damage in 'Franksred' compared to 'Autumn Flame'. However, the extra Dursban applications in the 'Franksred' plants did not prevent FAB damage from occurring in the acephate tablet, Dursban (SW), or untreated control treatments.

Interestingly, new FAB damage in the 'Autumn Flame' block during 2006 and 2007 was about equivalent to FAB damage that occurred during 2005. Therefore, FAB can be significant pests for several years after transplanting, despite anecdotal reports in the growing community that borer damage is only an issue during the first growing season. The global positioning system (GPS) bearings of FAB attacks in the 'Autumn Flame' selection during 2005 to 2008 indicate a somewhat random attack pattern with no discernable edge effect (Fig. 3a–e). The GPS results confirm that FAB is capable of attacking anywhere within a crop field, as suggested by Fenton (8) who commented that the strong 'migratory' (i.e., dispersal) habits of FAB made spraying small treatment areas impractical. There undoubtedly would have been more attacks in the 'Autumn Flame' field had some of the trees not been protected from attack by effective insecticides like Allectus, Discus, or imidacloprid tablets.

Past FAB damage surveys in nurseries (Oliver and Fare, unpublished data) have indicated a high percentage of flat-headed borer damage occurs on the southwest side of the tree trunk. A higher frequency of FAB damage on the southwest side of the tree was also documented in this test (data not shown). However, treating the southwest side of the trunk with Dursban did not prevent FAB attacks; nor did treating the entire trunk with Dursban. It is possible a more effective insecticide than Dursban might have protected the trees with a southwest spray. Brooks (2) reported that FAB prefers to oviposit on the sunny side of the tree and Franklin and Lund (9) indicated larval injury starts and stops where the bark is exposed to sunlight, so it is logical that treating the southwestern side of the tree thoroughly with an effective insecticide could improve FAB management.

Flatheaded borer control. 2006 Trial. The number of FAB attacks varied significantly among insecticide treatments and treatment dates (Table 3). By the end of the fourth year (2009), the three maple cultivars in the 2006 trial had similar percentages of FAB damage in the untreated control (32.1–41%) with damage approaching one third of the trees (a substantial level of crop damage).

'Fairview Flame' treated with one imidacloprid tablet or 6 acephate tablets had 31.3 and 37.5% of the trees attacked by FAB during the first year (2006), respectively, which was about 2.5 times more damage than the untreated plants (12.5%) in the same year (Table 3). Arena (May) and imidacloprid gel treatments each had one tree attacked in the first year (2006). All of the imidacloprid drench or root dip treatments had no damage during any of the four test years with the exception of one tree attacked in the Discus (May) drench during the second year (2007). In general, most of the trunk spray treatments (Dursban and Onyx Pro Insecticide) had 1 to 2 FAB attacks each year. Safari had no damage in any of the years and Flagship had no damage in the first and second years. Arena fluctuated between 0 and 1 FAB attack

each year and was the least effective of the neonicotinoid drenches tested. The active ingredient rate of Arena was one-third lower than the Discus active ingredient rate. It appears Arena may need a higher rate to be more effective. The imidacloprid tablets, as in the 2005 trial, were more effective in the third and fourth years (2008 and 2009), as evidenced by the absence of FAB damage, suggesting these tablets are effective once the imidacloprid is released or accumulates in the tree over time. Acephate tablets were the least effective treatment in the study with a final total damage of 75% of the trees. The six-tablet rate of acephate caused severe leaf phytotoxicity during the first year, which may have contributed to increased tree stress and more vulnerability to FAB.

'Franksred' maple had the highest percentage of FAB attacks on the non-treated control (41%) and the acephate tablet (28.2%) treatments, both an unacceptable level of damage (Table 3). All of the FAB attacks on the non-treated control occurred during years one (2006) and two (2007), whereas the acephate tablet treatment had the most damage in year two (2007). The Discus drench (March) treatment was the only treatment in this test with no FAB attacks at the end of 4 years, whereas the Discus root dip, Discus drench (May), or Allectus drench treatments each had 1, 2, or 3 total FAB attacks at the end of four years, respectively. The two-tablet imidacloprid treatment was completely effective after the first year, but the single-tablet imidacloprid treatment had FAB attacks during the first three years. Safari or Arena treatments were effective the first year, but had FAB attacks in subsequent years, whereas Flagship had attacks in all years evaluated. Unlike the 'Fairview Flame' selection, Onyx or Dursban trunk treatments had no attacks in the first year, but Dursban had three attacks in the second year. In the 2005 and 2006 trials, Dursban was applied at a 2× labeled rate; however in the 2006 trial, Dursban was applied according to Extension recommended timings (i.e., mid-May and late June applications) (10) during both the first and second years. Dursban did not provide FAB protection in the second year. Onyx Pro provided superior FAB control in the 'Franksred' maples to that of Dursban with only one mid-May application. It is likely FAB control would have been less if the Dursban had been applied at the labeled rate.

The 'October Glory' selection had relatively few FAB attacks until the second year (2007) (Table 3). The non-treated control, acephate tablets, and single imidacloprid tablet treatments had the most FAB damage compared to the imidacloprid drench treatments. All of the imidacloprid drench or dip treatments provided complete FAB protection with the exception of one attack in the Allectus drench in year four (2009). Arena, Flagship, Safari, two imidacloprid tablets, Dursban, or Onyx treatments also had no FAB attacks in the first year, but had 1 to 2 attacks in years two and three. Most of the FAB attacks occurred in the second year (2007). A late spring freeze that damaged all the leaves in the tree crown followed by a summer drought during 2007 added plant stress that may have increased vulnerability to FAB.

Among the three maple selections in the 2006 trial, the untreated control or acephate tablet treatments generally had the highest level of FAB damage (~30 to 40%) compared to the other treatments (~0 to 20%) (Table 3). Acephate tablets were unsuccessful in preventing FAB attacks, and acephate-treated trees were attacked more than the untreated plants. The only treatment that provided complete FAB control in all four years among the three maple cultivars was the

Discus drench (March). The Discus root dip treatment was the next best treatment with only one tree lost among the three cultivars in 4 years. Discus drench (May) or Allectus (May) were both comparable with each treatment losing three to four total trees among the three cultivars. Because a March-applied Discus drench provided 100% control, an early season application may provide more time for neonicotinoids to reach the trunk before FAB larval entry, thereby increasing the likelihood of eliminating the FAB larva when it was small and probably more vulnerable to insecticide effects. Allectus was applied at the lowest imidacloprid active ingredient amount (0.30 g-tree^{-1}), which was about half the rate of the Discus drenches, yet it still provided complete FAB control in two of the cultivars. The imidacloprid gel or tablet treatments generally provided greater FAB control in the third and fourth years, but the overall control in these treatments was lower than the drench or dip imidacloprid treatments due to tree losses in the first and second years. The release rate of the imidacloprid from the tablet was apparently slower than the drench treatments, and it is possible more time is required to accumulate protective imidacloprid levels in a plant with the tablets. In the 2006 test, the tablets were inserted shortly after the trees were planted in mid-March; however, the FAB prevention was still not acceptable during the first year. Imidacloprid tablets can be easily applied at planting, thus improving production efficiency, while the tablet formulation reduces worker exposure risk.

The other neonicotinoid drench treatments were less consistent than the imidacloprid drench treatments and had the greatest FAB control during the first year (i.e., 0 or 1 attack total among the three maple cultivars). Flagship was generally effective at preventing FAB attacks on all the maple selections during the first year of application, but the FAB attack rate increased during subsequent years. Flagship and Arena were the most inconsistent neonicotinoids evaluated, and both may require a higher rate or yearly applications to provide effective FAB control. Since drench treatments of Arena (March), Safari (May), Discus (May and March), and Allectus (May) had no FAB attacks during the first year, it appears a May application may not be too late in the year for these products to control FAB (Table 3). Safari has the shortest reported soil-half life among the neonicotinoids tested (19), is very water-soluble, can rapidly enter plant roots, and translocates in the vascular tissues after soil application (11). Thus, Safari may be well suited for late spring application such as mid-May, as supported by the first year results in the red maple selections. Mota-Sanchez et al. (12) reported that trunk tissues could potentially function as a sink for imidacloprid residues, so it is possible that Safari and other neonicotinoids may be retained in the trunk tissues, thereby providing FAB protection after the insecticide is no longer available in the soil. Arena, Discus, Flagship, and Safari reduced leafhopper damage compared to the non-treated control in years 1 and 2, which indicates these insecticides continue to function in the plant after the first year and are either retained in plant tissues at some level or are still available to the plant from continuous uptake of residues in the soil (13).

The trunk spray treatments were less consistent than the neonicotinoid treatments with Onyx having less FAB damage than Dursban. 'Fairview Flame' treated with Dursban were attacked every year these treatments were applied (i.e.,

2006 and 2007), and 'Franksred' and 'October Glory' were attacked during the second year (2007) of the test despite the higher $2\times$ rate. In addition, all trunk sprays were applied with a backpack sprayer to the point of runoff, which is probably a more thorough bark wetting than occurs with typical airblast applications performed by commercial operations. Adult FAB are active as early as mid-April in middle Tennessee (Oliver and Fare, unpublished data), females begin oviposition in 4 to 8 days if provided with food, and eggs require another 6 to 8 days to hatch (at an unspecified temperature) (8). Therefore, it is possible a mid-May trunk application of Dursban or Onyx may be too late to effectively manage FAB adults that emerged in mid-April because larvae may have had sufficient time to enter the tree. If that is the case, Dursban or Onyx may have been more effective if applied sometime before mid-May.

Neonicotinoid movement in trees and other properties that may affect FAB control. Most of the studies describing neonicotinoid movement in trees involve imidacloprid. Imidacloprid translocates primarily in the xylem towards the foliage (acropetally) and very poorly towards the phloem (basipetally) (12, 17). Imidacloprid that reaches leaf tissue is generally trapped (i.e., sink) and very little if any moves back into the non-foliar parts of the plant (12, 17). Imidacloprid concentrations in ash trees following injection of the trunk were 30 times greater in the leaf tissues than the outer bark, phloem, or root tissues (12). The FAB is reported to feed in the outer wood to inner bark (3) to almost exclusively in the phloem (15). Since most of the neonicotinoids evaluated prevented FAB damage, active ingredients are reaching areas where FAB feeds in dosages sufficient to kill larvae. It is likely any FAB feeding in the xylem would lead to even greater larval poisoning.

In our study, some soil-applied imidacloprid treatments completely prevented FAB trunk attacks over a four-year period. In another study, imidacloprid drench or trunk injections of hemlock resulted in detectable imidacloprid residues in plant tissues from 1 month up to 3 years post-treatment, suggesting very long periods of residual activity are possible in some tree species (4). Interestingly, soil applied drench treatments provided more consistent hemlock woolly adelgid control than imidacloprid trunk injections, even though imidacloprid residue levels in the plant tissues were similar between application methods (4). Mortality bioassays of adult emerald ash borers, *Agrilus planipennis* Fairmaire, (i.e., another flatheaded borer species) feeding on leaf tissue from ash trees injected with imidacloprid indicate insufficient active ingredient in the leaves during the second year to provide effective control (12). This finding suggests when imidacloprid is injected into the trunk, most of the active ingredient translocates to the leaves during the first year and imidacloprid residues may be unavailable subsequently in the second year due to leaf drop. There are two possibilities that could explain why imidacloprid or other neonicotinoids that predominantly translocate to leaf tissue can kill trunk-attacking FAB larvae over multiple years. First, it is possible root uptake from the soil-applied imidacloprid continues to supply the trunk with a dosage sufficient to kill FAB larvae over time. This might explain why Safari, which has a shorter soil-half life, was generally less effective against FAB over time than imidacloprid (longer soil-half life) (19, 20). Other factors that can influence neonicotinoid

root uptake and transport in xylem (and potentially movement between xylem and phloem) could also account for differences in FAB control observed among neonicotinoids, including hydrophilic and lipophilic nature, molecular shape, isosteric segments, polarity, open-chained compounds and functional groups (11). Lipophilic neonicotinoids (e.g., clothianidin) have higher root uptake rates, but do not transport as readily in the xylem as hydrophilic neonicotinoids (e.g., thiamethoxam, dinotefuran) (11). Second, it is possible the small quantity of imidacloprid that does move basipetally into the phloem remains trapped at that location (i.e., phloem serves as a trunk reservoir). In ash-tree-trunk-injection studies with radio-labeled imidacloprid, an imidacloprid 'reservoir hypothesis' for some trunk tissues was proposed after the authors found high levels of imidacloprid remaining in the trunk tissues near the injection site (12). The authors also reported that most of the imidacloprid was found in the inner wood rings, which are less hydro-active in ring porous trees like ash. Unlike ash trees, maples have a diffuse porous vascular system, which may allow imidacloprid and other neonicotinoids to move differently within the trunk tissues. Another study found evidence that imidacloprid residues are very stable over time once inside tree tissue (4), which might explain the long residual activity against FAB that occurred in our study. One advantage of early applications like mid-March, which were more effective for Arena and Discus drenches than late applications like mid-May, could be more time to accumulate a reservoir of active ingredient in the plant tissues where FAB larvae feed.

Regardless of whether neonicotinoids are continuously supplied from root uptake or are maintained in the inner wood and phloem region in a reservoir, apparently small dosages are sufficient to eliminate FAB. The root uptake following a soil application of imidacloprid is about 5% of the total dose applied (17), which would equate to uptake rates for drench treatments of 0.015, 0.035, and 0.07 g (0.0005, 0.001, and 0.002 oz) for Allectus, Discus 22 ml, and Discus 44 ml, respectively. If only 5% of the total active ingredient translocates into the plant from the soil, undoubtedly even smaller quantities are moving from the xylem to areas like phloem where FAB larvae are presumed to predominantly feed.

Plant growth. 2005 Trial. Red maple trunk growth was affected by insecticide treatments (Table 2). During the first year (2005), 'Autumn Flame' plant growth was minimal, probably due to transplant establishment coupled with the field location, which had a sloping southwestern exposure. 'Franksred' maples, which were located in bottomland soil, had more than twice the trunk growth increase of 'Autumn Flame'. For 'Franksred' maples, a significant increase in trunk growth occurred with plants treated with the high rate of Discus (44 ml) compared to all plants treated with Dursban. Other treatments had similar trunk diameter growth.

At the end of the second year (2006), both maple cultivars treated with a Discus drench (22 or 44 ml) and imidacloprid tablets had greater trunk diameter growth than plants treated with acephate, chlorpyrifos or untreated plants (Table 2). 'Autumn Flame' plants treated with Allectus had growth equivalent to plants treated with acephate, but less growth than plants treated with Discus (44 ml). Although Allectus had the least amount of imidacloprid active ingredient among imidacloprid-based treatments, it still resulted in greater growth with 'Autumn Flame' maples than all the Dursban

treatments. 'Franksred' treated with Allectus had greater trunk increase than untreated plants, but was less than imidacloprid tablets.

During the third year (2007), trunk diameter increase for all treatments was about half of the previous year's growth, and the lower growth was likely the result of a severe spring freeze (April 2007) and summer drought (Table 2). However, despite the lower overall growth, trunk growth of 'Autumn Flame' was still greater with plants treated with Discus (44 ml) drench compared to Dursban treated and untreated plants. 'Autumn Flame' plants treated with Discus (22 ml) or imidacloprid tablets were larger than Dursban treated plants, but no significant differences were found with untreated plants. 'Franksred' treated with imidacloprid tablets had the greatest trunk diameter increase (5.2 mm), but was not statistically different from Discus treatments (22 or 44 ml). The imidacloprid tablet treatment had significantly greater trunk growth with 'Franksred' than untreated plants or plants treated with acephate tablets, Allectus, or most Dursban treatments.

By the fall of 2008 (end of test), the majority of imidacloprid treatments improved tree growth compared to other treatments. 'Autumn Flame' treated with Discus (44 ml) had the largest increase in cumulative trunk diameter compared to other treatments with the exception of plants treated with Discus (22 ml) (Table 2). Imidacloprid-tablet-treated plants of 'Autumn Flame' had similar growth to Discus (22 ml) or Allectus. 'Franksred' treated with Discus (44 ml) or imidacloprid tablets had larger cumulative trunk diameter increases than all other treatments. Cumulative trunk growth with the Allectus treatment was not statistically greater than acephate tablet, Dursban, or untreated treatments. Allectus was applied at 0.30 g (0.01 oz) ai-tree⁻¹, which was the lowest imidacloprid rate among the imidacloprid treatments, did not have as much growth increase as the higher rates in the Discus or imidacloprid tablet treatments, possibly indicating a rate relationship with growth. Most growers' price nursery stock based on trunk diameter, and therefore, any increase in trunk caliper could translate into more profit. In this test, a one-time application of insecticide enhanced growth for at least 3 years with 'Autumn Flame' and 4 years with 'Franksred'.

Height growth in the 2005 trial was affected by insecticide treatments (Table 2). Negligible height growth occurred during 2005 with both 'Autumn Flame' and 'Franksred' (data not shown). In the second year (2006), 'Autumn Flame' and 'Franksred' treated with Discus (44 ml) or imidacloprid tablets had significantly greater increases in height compared to the acephate, Dursban (full trunk and SW trunk spray), or untreated plants. 'Autumn Flame' maples treated with Allectus or Discus (22 ml) had height growth similar to the untreated plants, and these treatments applied to 'Franksred' resulted in less height growth than untreated plants. In year 3 (2007), height increase in 'Autumn Flame' treated with Discus (44 ml) was greater than acephate or Dursban treatments, but similar to the control. Growth increase was similar with most treatments on 'Franksred' with the exception of the Dursban SW trunk spray, which grew 27% more than the Dursban trunk roll. In general, height data results were more variable among the treatments than trunk growth data.

By the fall of 2008, 'Autumn Flame' treated with Discus (44 ml) had the largest canopy size index and was significantly larger than Allectus, Dursban, or untreated treatments

(Table 2). Discus (44 ml) also had the largest canopy size index in 'Franksred' and was significantly larger than the other treatments, except the imidacloprid tablet treatment. Plants treated with Dursban or the untreated plants had the smallest canopy size index, but in most cases were not statistically different from acephate or Allectus treatments. With both 'Autumn Flame' and 'Franksred' maples, canopy size index increased in the imidacloprid drench treatments as imidacloprid rate increased.

Plant growth. 2006 Trial. In the 2006 trial, red maple trunk growth was influenced by the insecticide treatments and method of application (Table 4). At the end of year 1 (2006), 'Fairview Flame' and 'Franksred' plants treated with acephate tablets had less trunk diameter increase than the untreated plants. 'Franksred' treated with Discus + Terrasorb and drenches of Discus (March) and Arena (March) had less growth increase than untreated plants. Other treatments had similar growth gains during 2006.

Total trunk growth (years 1 through 4) with 'Fairview Flame' was greater with Discus 22 ml (May or March), imidacloprid gel, or Safari than plants treated with acephate tablets or untreated plants, but was not statistically different from other insecticide treatments (Table 4). Total trunk growth on 'Franksred' treated with Safari or imidacloprid tablets (2 tablets) increased more than plants treated with acephate tablets, Arena drench (March), Discus + Terrasorb, Flagship, or Onyx, but did not differ statistically from plants treated with the other imidacloprid treatments, Dursban, or the untreated plants. Although total cumulative trunk growth was greater for some treatments, the actual insecticide-associated increase in trunk growth primarily occurred during the first two growing seasons; then yearly growth increase became similar in the third and fourth years regardless of treatment.

In conjunction with FAB monitoring, trees in this study were also rated for leafhopper herbivory during August of each post-treatment year (13). Oliver et al. (13) hypothesized that the increase in maple growth observed for some systemic insecticides may have been indirectly related to a reduction in potato leafhopper herbivory, or conversely, the insecticides may have directly increased growth by altering the trees' physiology. However, without controlled experiments to exclude leafhopper herbivory, it was not possible to determine the cause of insecticide-associated growth enhancement in this study.

'Fairview Flame' maple, a more vigorous growing selection than 'Franksred', had more than double the trunk diameter increase in the first and second years (2006 and 2007) and about 35% total growth at the end of the third year (Table 4). One study evaluating imidacloprid concentrations in white and green ash trunk cores proposed that lower concentrations found in the white ash were due to larger tree size (12), indicating a possible imidacloprid dilution-effect with trunk size. The authors also speculated that imidacloprid movement is affected by tree size, citing another study by some of the co-authors that found imidacloprid movement decreased as tree size increased. If larger tree size increases the dilution of systemic insecticides, then fast growing trees like 'Fairview Flame' might be more vulnerable to FAB due to a lower concentration of insecticide active ingredient. However, total FAB attacks on 'Fairview Flame' declined each year (i.e., 21, 16, 8, and 0 from 2006 to 2009, respectively). It is possible

that plants with rapid trunk growth rates, like 'Fairview Flame', may reduce FAB colonization success.

In conclusion, neonicotinoids were very effective at managing FAB and offer many advantages for borer management programs owing to the diverse methods by which they can be effectively soil-applied; including pellets, seed dressing, root dips, implantation, injection, or painting (11). Although systemic neonicotinoid treatments are more expensive than trunk sprays like Dursban and Onyx, borer damage in trunk spray treatments was generally higher than the neonicotinoid insecticides. Another disadvantage for trunk sprays is they must be applied at least two times each year, whereas neonicotinoids utilized in this study were applied only one time at the beginning of the four-year test. Imidacloprid drenches at rates from 0.3 to 0.69 g (0.011 to 0.024 oz) ai-in⁻¹ trunk diameter provided complete FAB prevention for two to three years and at rates of 1.38 g (0.049 oz) ai-in⁻¹ provided complete prevention for four years. Since any FAB damage generally ruins the marketability of a nursery tree, the economic threshold for damage is essentially none. Therefore, treatments that provide 100% FAB protection and reduce the number of pesticide applications needed to control FAB can save growers money over the typical 3-year crop production cycle, even if initial application costs are higher. A growth increase in trunk diameters occurred with a Safari drench and most imidacloprid treatments. Growers price their nursery trees based on caliper size, and therefore, any increase in growth can potentially increase profit. Overall, this study found that neonicotinoid insecticides applied one-time were the most effective treatments for preventing FAB damage, and these insecticides have the potential to be an important FAB management tool with the added benefit of providing enhanced plant growth.

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