The Range and Response of Neonicotinoids on Hemlock Woolly Adelgid, *Adelges tsugae* (Hemiptera: Adelgidae)[1]

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Abstract

Hemlock woolly adelgid (HWA), *Adelges tsugae* Annand is a serious pest of eastern and Carolina hemlock in the eastern United States. A series of experiments compared commercially available and experimental insecticides, rates, application methods and timing for HWA control in Georgia and North Carolina. Safari 20 SG (dinotefuran) provided an average of 79 to 87% suppression of adelgid populations within one month after spring application. Arena 50 W (clothianidin) and Merit 75 WP (imidacloprid) were slower acting but provided longer-term adelgid suppression than dinotefuran. However, 26 months after application in spring 2006 HWA re-colonized trees treated with dinotefuran while imidacloprid treatments were still effective. High volume treatments like soil drenches of dinotefuran did not improve adelgid control over low volume applications such as soil injection. Evaluation in July 2008 of a fall 2007 application of Tristar 30 SG (acetamiprid) using arborjet trunk injectors showed no reduction of nymphal populations. Treatment timing and rates did not affect HWA relative to untreated check. The Xytect 75 WSP (imidacloprid) soil injection treatments applied during May, August, or November 2007 and Xytect root-flare micro injection system treatment in November 2007 provided 99 to 100% control in all treatments.

Index words: hemlock woolly adelgid, insecticide, dinotefuran, imidacloprid, clothianidin, acetamiprid, suppression.

Species used in this study: eastern hemlock, *Tsuga canadensis* L. Carrière.

Chemicals used in this study: Safari 20 SG (dinotefuran), N-methyl-N'-nitro-N''-[(tetrahydro-3-furanyl)methyl]guanidine; Safari 2 G (dinotefuran); Merit 75 WP (imidacloprid), (*E*)-1-(6-chloro-3-pyridylmethyl)-*N*-nitroimidazolidin-2-ylideneamine; Arena 50 W (clothianidin), (E)-1-(2-chloro-1,3-thiazol-5-ylmethyl)-3-methyl-2-nitroguanidine; Arena 50 WDG (clothianidin); Tristar 30SG (acetamiprid), (E)-N^1-[(6-chloro-3-pyridyl)methyl]-N^2-cyano-N^1-methyl acetamidine; Xytect 75 WSP (imidacloprid); Xytect infusible (imidacloprid).

Significance to the Nursery Industry

Hemlock woolly adelgid (HWA), *Adelges tsugae* Annand (Hemiptera: Adelgidae) is an invasive pest of eastern hemlock, *Tsuga canadensis* L. Carrière, and Carolina hemlock, *Tsuga caroliniana* Engelmann, in the eastern United States. The adelgid injects toxins causing needle drop, reduced shoot growth and branch dieback. Hemlock tree mortality can occur between 4 and 10 years after first infestation depending on the initial tree health (16). Eastern and Carolina hemlock fill a unique ecological niche in native forests and are valued landscape ornamentals. Hemlock trees are integral components of public sites, farms and private properties. Sustainable management of HWA may be realized through host plant resistance and biological control (2). However, for management of high value hemlock trees, chemical control is an important tool. This study evaluated the efficacy of neonicotinoid insecticides to suppress HWA populations on eastern hemlocks.

Introduction

Hemlocks are long-living shade-tolerant trees that form dense, evergreen, multi-layered canopies that support diverse species of wildlife (12, 29). Hemlock stands have both aesthetic and ecological value; thus, it is important to preserve the gene pool (8). Since its introduction in 1951, near Richmond, VA, HWA has become established from southwestern Maine to northeastern Georgia. Adelgids attack newly growing shoots, settle at the needle base, and feed on the cortical parenchyma ray cells of xylem tissues (16).

Adelges tsugae has a polymorphic life cycle consisting of two wingless generations, a winter generation (the sistens) and a summer generation (the progrediens), and a winged generation per year (1, 13, 15, 16). The adelgid is a small aphid-like (0.4–1.4 mm) sucking-insect that secretes a white, woolly wax which covers its body and egg masses (10, 14). They only reproduce parthenogenetically in the United States (14, 16). Overwintering adults lay eggs in egg masses beginning mid-February (15, 16). The active first-instar crawlers hatch from these eggs and subsequently settle at an unoccupied needle base. Depending on tree health, they develop into wingless or winged (sexuparae) summer adults and immediately initiate egg laying in early spring. The offsprings of winged adults perish because they need a spruce host that does not occur in North America (14, 16). Crawlers are actively dispersed by mammals, wind or birds (17). The settled first-instars of the winter generation remain inactive throughout the summer until October or November, depending on location, when they molt into older-instars that actively feed on hemlock (13, 15, 16).

Management tactics including biological control or increasing host plant resistance (5) can reduce populations of *A. tsugae* on hemlock (2, 3). Meanwhile, chemical control is an important strategy in protecting or rescuing certain high

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value hemlock trees in forests and landscapes. Various insecticides have already been applied using different delivery mechanisms such as foliar sprays, soil drenches, and trunk or soil injections to suppress HWA populations (3, 6, 11, 18, 25). Foliar sprays of horticultural oil and insecticidal soap caused greater than 90% mortality of HWA (18) but did not provide uniform insecticide coverage. Chemical applications may be challenging in a forest as it is difficult to reach remote locations; however, landscape trees are relatively accessible. Neonicotinoids, especially imidacloprid, are widely accepted by the nursery and landscaping industries as they are effective against a variety of pests such as aphids (21, 22) and HWA (3, 20, 24, 30). Their high oral toxicity to targets and systemic activity make them especially useful for treating trees. More neonicotinoids have become commercially available recently, but information about their efficacy against HWA is not known. The objectives of this project were to: (1) evaluate speed of control and length of residual of eight insecticides to suppress HWA on eastern hemlock; and (2) compare timing, rate and method of application.

Materials and Methods

Hemlock trees were selected at various sites in Macon Co., NC, and at the University of Georgia Mountain Research Station (Union Co.) in Blairsville, GA. The selection of trees was based on suitable size, accessibility and adequate separation between trees. Tree-sizes were representative of the hemlock stand and had accessible branches for sampling. Density-dependent adelgid suppression has been reported on heavily infested trees due to decreasing nutritional suitability and reduced new growth (19). Selected trees at various sites were inspected for moderate populations of adelgid prior to initiation of studies. All the trees were appropriately tagged and recorded by global positioning system (GPS) to facilitate relocation.

Sampling procedure and data analysis. Samples consisted of four branch terminals (15 cm long) collected (two/height) at 1.5 and 6.1 m (5 and 20 ft) above the ground using a hand or pole pruner. Branches were sealed in plastic bags, immediately stored in a cooler and returned to the laboratory. In the laboratory, samples were maintained at 27C (81F), 80% relative humidity and 14:10 (L:D) photoperiod in a growth chamber (Percival Environmental Chambers, Percival scientific Inc., Perry, IA) for approximately 24 hours. All life stages of HWA and new growth were counted for each sampling date under 10× magnifications. HWA counts also included number of egg sacs and each egg sac had an adult female in it. The variable 'total immatures' is the sum of eggs, crawlers, and settled first- and older-instars wherever applicable. The adelgid count data were transformed as the square root of adelgid counts and analyzed using the general linear models (GLM) procedure of SAS (23). Means were separated using the LSD ($\alpha = 0.05$) method. Since the square root transformation restructures the original data by reducing positively skewed data points to attain a normal distribution, the treatment means generated by the LSD method may not be the same as the direct square root of the untransformed treatment means.

Experiment 1. The main objective of this experiment was to compare efficacy, time to control and persistence of Safari® 20 SG (dinotefuran), Merit® 75 WP (imidacloprid) and Arena® 50 W (clothianidin). The trees selected in spring and fall were 24.3 ± 2.3 cm (9.6 ± 0.89 in) (mean ± S. E.), and 20.3 ± 2.2 cm (8.0 ± 0.85 in) diameter at breast height (dbh), respectively. Two separate sets of hemlock trees were treated with neonicotinoid products in the spring (May 4, 2006) and fall (November 3, 2006). Six treatments were tested on each date: an untreated control; three rates of Safari 20 SG [3, 6 or 12 g (AI)·2.5 cm^{-1} (1 in^{-1} dbh)], one rate of Merit 75 WP (2 g AI·2.5 cm^{-1} dbh), and one rate of Arena 50 W (2 g AI·2.5 cm^{-1} dbh). Treatments were replicated five times and blocked by diameter class. The absorbing fine-roots of hemlock trees are primarily located near the soil surface and within the dripline area of a tree (3). Insecticides were applied to the soil layer (6 cm deep) using Kioritz soil injectors (Kioritz Corp. Tokyo, Japan). Numbers of injections per tree were determined based on the insecticide rate and dbh of each tree. Nine sets of branch samples (see description below) were collected to evaluate the efficacy of the spring application for HWA control [April 25 (precount), May 25, June 27, July 25, September 26 and November 3, 2006; May 29 and November 14, 2007; and July 17, 2008], and 5 sets of samples were collected to evaluate the fall application [November 3 (precount) and December 3, 2006; May 29 and November 14, 2007; and July 17, 2008].

Experiment 2. This experiment evaluated dinotefuran applied in the spring as a soil drench, as a low volume injection or as a granule, and compared these applications to imidacloprid applied by soil injection. Selected trees had a mean ± SE dbh of 18.6 ± 0.9 cm (7.33 ± 0.36 in). The six treatments included an untreated control, Safari 20 SG (6 g·2.5 cm^{-1} dbh) applied by Kioritz soil injection or soil drench, Safari 2 G (60 g·2.5 cm^{-1} dbh) applied by hand broadcast, and Merit 75 WP (2 g·2.5 cm^{-1} dbh) applied by Kioritz soil injection or soil drench on May 4, 2007. The application volume for Kioritz soil injection and soil drench were 30 mL (1 fl oz)·2.5 cm^{-1} dbh and 1 liter (1 qt)·2.5 cm^{-1} dbh, respectively. Treatments were blocked by diameter class with each treatment applied to a single tree in each block. Insecticide applications were administered to treatment trees once. The Kioritz soil injection procedure was the same as previously described. For soil drench treatments the insecticide was mixed with water and poured within 1 meter of the tree trunk. The granular insecticide was directly applied to the soil after raking back the mulch and needles at the base of trees. Branch samples were collected May 29, June 12, July 12 and November 14, 2007, and July 16, 2008, to evaluate efficacy and duration of control.

Experiment 3. Seven treatments were evaluated on hemlock trees at the Georgia Mountain Station on September 7, 2007, and replicated five times. The first three treatments were an untreated control and Safari 20 SG at a rate of 6 g·2.5 cm^{-1} dbh applied by either Kioritz soil injection or soil drench. The other four treatments were: Safari 20 SG (3 g·2.5 cm^{-1} dbh) plus Arena 50 WDG (clothianidin; 2 g·2.5 cm^{-1} dbh) applied by either Kioritz soil injection or soil drench, and Arena 50 WDG (2 g·2.5 cm^{-1} dbh) alone applied by soil drench, and Merit 75 WP (2 g·2.5 cm^{-1} dbh) alone applied by soil drench. Three sets of branch samples were collected on November 14, 2007, and February 7 and July 9, 2008.

Experiment 4. This experiment evaluated the speed and length of activity of Tristar® 30 SG (acetamiprid) applied by Arborjet trunk injection (Arborjet, Woburn, MA) for suppression of adelgid. In addition, it evaluated time of application, application rate, and single or double applications of acetamiprid for control of HWA. Two rates of Tristar 30 SG (6 or 12 mL AI·2.5 cm^{-1} dbh) were applied November 3, 2006. A second set of trees received Tristar 30 SG at 6 or 12 mL (AI)·2.5 cm^{-1} dbh on April 4, 2007. A third set of trees received Tristar 30 SG at low or high rates applied once in spring 2007 and again on November 14, 2007. The completely randomized design had seven treatments (3 timings by 2 rates plus an untreated control) with four single tree replicates. The Arborjet truck injection system was used to deliver the diluted insecticide at the rate of 4 ml (0.14 oz)·2.5 cm^{-1} dbh. At each injection point a 0.74 cm diameter hole was drilled approximately 1.5 cm deep and capped with a plastic plug containing a septum. A needle was inserted through the septum and insecticide solution was delivered under pressure into the sapwood. The site of drilling was within 90 cm of the soil. Branch samples were collected and evaluated for HWA on November 3 (precount) and December 7, 2006; March 14, May 29, and November 14, 2007; and July 17, 2008.

Experiment 5. Xytect 75 WSP (imidacloprid) was applied with a HTI 2000 soil-injection probe (Rainbow Treecare Scientific Advancements, Minnetonka, MN) or by root-flare injection with an M3 injection system (Rainbow Treecare Scientific Advancements). The HTI 2000 soil-injection probe accurately delivers insecticide solution to the root-zone area of trees. This experiment compared the efficacy of spring and fall applications using these application methods. Xytect 75 WSP treatment rates were proportional to the dbh of the trees. Rates were 0.75 g (AI)·2.5 cm^{-1} dbh for 10 to 40 cm (4 to 16 in) dbh trees, 1 g (AI)·2.5 cm^{-1} dbh for 42.5 to 50 cm (17 to 20 in) dbh trees, and 1.5 g (AI)·2.5 cm^{-1} dbh for 52.5 to 65 cm (21 to 26 in) dbh trees and were applied on May 3, 2007. Additional summer and fall soil injection treatments were applied to separate trees on August 22 and November 1, 2007. A Xytect infusible treatment at the rate 0.75 g (AI)·2.5 cm^{-1} dbh was applied as a root-flare injection with the M3 injection system also in November. There were five single-tree replications per treatment in this design. Trees were sampled May 29, August 22 and November 1, 2007; July 16, 2008; and November 12, 2009, to assess efficacy.

Results and Discussion

Experiment 1. Medium (6 g [AI]·2.5 cm^{-1} dbh) and high (12 g [AI]·2.5 cm^{-1} dbh) rates of Safari reduced HWA populations one month after a spring application (Table 1). This result was most evident for settled first-instars but was also true for total immatures. Numbers of egg sacs were not reduced by treatments. By June 27, 2006, trees treated with Safari averaged 79 to 87% adelgid suppression for the medium and high rates, respectively (Table 1). All stages of adelgid on trees treated at those rates of Safari were lower than on the untreated controls. Conversely, Merit and Arena resulted in low or no HWA suppression throughout 2006 (Table 1).

By May 2007 medium and high rates of Safari provided 99 to 100% suppression. No egg sacs, eggs, crawlers, or settled first- and older-instars were observed in the high Safari treatment, but a few settled first-instars were observed on medium rate of Safari-treated trees. However, the low rate resulted in only 57% control. Merit and Arena also reduced adelgid populations by an average of 86 and 78%, respectively, relative to the untreated control trees at that time. Growth of new shoots, an indication of tree health, was significantly higher on Safari treated trees (Table 1). By November 2007 both medium and high rates of Safari, Merit and Arena resulted in 100% adelgid suppression. The efficacy of Safari declined two years post-application as adelgid populations on Safari treated trees were comparable to untreated trees by July 2008 (Table 1). In contrast, Merit and Arena were still providing nearly 100% control.

Fall applications of Arena and Merit resulted in 85–87% reductions in total HWA immatures relative to controls 18 months after treatment (Fig. 1). None of the fall applications of Safari reduced HWA populations significantly despite being made nearly 7 months after the spring treatment.

Safari was the most rapid acting of the neonicotinoid insecticides tested, but also the least persistent following a spring treatment. In contrast, Merit was slower acting but more persistent. Meanwhile, fall treatment with Merit provided significant suppression of HWA while Safari was less effective (Fig. 1).

Experiment 2. On May 29, 2007, about one month after spring treatments (May 4, 2007) adelgid egg densities were noticeably reduced by an average of 99 to 100% in Safari-treated trees as compared to the untreated control regardless of the application method used (Table 2). This result was consistent with the rapid rate of mortality caused by Safari in Experiment 1. On the same date, Merit-treated trees had significantly more eggs, settled first-, and older-instars relative to the Safari treatments. Merit-treated trees also had fewer new branches compared to the other treatments including the controls. In June, all Safari treatments significantly reduced total immature-adelgids by an average of 90 to 95% compared to untreated trees. New growth was still lower on Merit soil-injected trees than on other treated trees but not soil drenched trees. These trends continued through July with 100% settled first-instar mortality on trees receiving soil injected Safari as well as 98 and 94% reduction when granular and drench applications of Safari were used. By November 2007, and still evident in July 2008, all the insecticide products regardless of application method resulted in nearly 100% mortality relative to the untreated trees. In Experiment 1 spring applications (May 4, 2006) of Merit did not result in adelgid suppression until one year later. However, in this experiment Merit was effective earlier (by November, 2007). A year after treatment both insecticides, regardless of application method, were effectively suppressing HWA populations.

Experiment 3. By February 2008, Safari and Arena soil injections resulted in an average of 100% adelgid egg mortality compared to untreated trees after a fall application in September of the previous year (Table 3). July 2008 samples from both soil-injected and soil-drenched Safari trees and Arena soil-injected trees had significantly fewer settled first-instar adelgids than untreated trees. However, the combined treatment of Safari and Arena applied as a drench did not reduce populations significantly compared to the untreated control.

Experiment 4. Fall 2006 trunk injections of Tristar using the Arborjet system did not result in significant reductions of adelgids until March, 2007 and then only settled first-instars

Table 1. Number (Mean ± S.E.) of hemlock woolly adelgids and new growth after application of products on May 4, 2006.

Sampling date^z	HWA life-stages	Untreated control	Safari 20 SG (L^y)	Safari 20 SG (M)	Safari 20 SG (H)	Merit 75 WP	Arena 50 W	df	F^x
May 06	Egg sacs	14.6 ± 3.8a	9.8 ± 1.8a	22.6 ± 6.1a	13.0 ± 8.0a	14.8 ± 4.3a	4.4 ± 1.3a	5	2.6^{NS}
	Eggs	169.4 ± 93.5a	37.8 ± 7.2a	22.0 ± 9.6a	66.0 ± 53.1a	146.2 ± 76.4a	33.6 ± 10.8a	5	1.6^{NS}
	Crawlers	21.6 ± 8.9a	16.8 ± 7.8a	11.0 ± 3.9a	14.0 ± 9.6a	24.4 ± 9.6a	7.2 ± 3.6a	5	1.1^{NS}
	Settled first-instars	69.4 ± 18.0a	25.2 ± 15.2ab	5.4 ± 3.9b	10.4 ± 8.7b	116.0 ± 63.2a	73.8 ± 41.7ab	5	3.1^{*}
	Total immatures	260.4 ± 113.6a	79.8 ± 25.8ab	38.4 ± 14.5b	90.4 ± 60.9b	286.6 ± 101.9a	114.6 ± 50.3ab	5	3.1^{*}
	New growths	3.6 ± 2.1a	6.4 ± 3.5a	3.2 ± 1.3a	4.4 ± 1.7a	7.0 ± 4.6a	3.8 ± 3.1a	5	0.5^{NS}
June 06	Egg sacs	10.4 ± 2.1a	3.0 ± 1.8bc	0.2 ± 0.2c	0.0c	5.4 ± 1.5ab	6.0 ± 3.6b	5	6.7^{***}
	Eggs	66.8 ± 27.1a	21.2 ± 15.7bc	0.0c	0.0c	22.0 ± 3.0ab	24.0 ± 12.9b	5	5.8^{**}
	Crawlers	41.0 ± 10.9a	4.8 ± 2.4b	1.0 ± 0.8b	0.8 ± 0.8b	54.4 ± 24.5a	32.4 ± 11.8a	5	7.9^{***}
	Settled first-instars	61.6 ± 20.3a	50.4 ± 22.4a	7.4 ± 3.2bc	1.8 ± 1.4c	56.8 ± 19.3a	41.0 ± 13.3ab	5	4.1^{*}
	Older-instars	4.0 ± 2.1ab	0.8 ± 0.6bcd	0.4 ± 0.4cd	0.0d	4.0 ± 1.3a	2.6 ± 1.7abc	5	3.9^{*}
	Total immatures	173.4 ± 45.4a	77.2 ± 32.5b	8.8 ± 4.2c	2.6 ± 2.1c	137.2 ± 31.3ab	100.0 ± 35.6ab	5	9.9^{***}
	New growths	1.6 ± 0.7a	2.8 ± 0.8a	1.8 ± 0.6a	2.0 ± 0.9a	2.6 ± 0.4a	2.8 ± 0.5a	5	0.7^{NS}
July 06	Egg sacs	3.8 ± 1.5a	0.2 ± 0.2b	0.0b	0.4 ± 0.4ab	5.2 ± 2.8a	1.2 ± 1.2ab	5	2.8^{*}
	Eggs	13.4 ± 6.4a	0.0b	0.0b	0.0b	16.6 ± 8.8a	6.6 ± 6.4ab	5	3.3^{*}
	Crawlers	15.2 ± 5.8a	2.0 ± 2.0a	0.8 ± 0.8a	0.1 ± 0.8a	7.4 ± 4.3a	3.0 ± 2.3a	5	2.2^{NS}
	Settled first-instars	337.6 ± 119.4bc	147.6 ± 55.9cd	74.6 ± 32.1d	44.2 ± 14.2d	637.4 ± 105.1a	517.0 ± 130.8ab	5	11.3^{***}
	Older-instars	4.0 ± 1.5a	0.0b	0.4 ± 0.4b	0.6 ± 0.4ab	4.8 ± 2.3a	0.6 ± 0.6b	5	3.1^{*}
	Total immatures	370.2 ± 130.9bc	149.6 ± 56.0cd	75.8 ± 32.9d	45.8 ± 15.2d	666.2 ± 117.2a	527.2 ± 137.1ab	5	10.9^{***}
	New growths	1.6 ± 0.8a	1.0 ± 0.8a	0.0a	0.2 ± 0.20a	2.2 ± 0.7a	1.4 ± 0.9a	5	2.5^{NS}
Sept. 06	Settled first-instars	183.4 ± 52.7a	24.6 ± 20.7bc	4.6 ± 2.5c	2.8 ± 1.2c	114.2 ± 41.9a	38.0 ± 12.1b	5	14.6^{***}
	Older-instars	15.0 ± 6.9a	1.6 ± 1.6b	0.0b	0.0b	8.6 ± 3.5a	0.2 ± 0.2b	5	5.9^{**}
	Total immatures	198.4 ± 54.8a	26.2 ± 22.3bc	4.6 ± 2.5c	2.8 ± 1.2c	122.8 ± 39.7a	38.2 ± 12.0b	5	15.2^{***}
	New growths	2.0 ± 1.0a	11.6 ± 5.8a	2.8 ± 0.6a	6.2 ± 2.6a	3.4 ± 0.8a	3.0 ± 1.1a	5	1.0^{NS}
Nov. 06	Settled first-instars	41.8 ± 13.6ab	7.8 ± 3.5bc	1.0 ± 1.0c	1.4 ± 1.4c	114.0 ± 73.9a	12.8 ± 6.3bc	5	3.4^{*}
	Older-instars	93.6 ± 58.7a	60.2 ± 60.2a	0.0a	5.4 ± 5.4a	68.8 ± 28.3a	24.6 ± 15.5a	5	0.2^{NS}
	Total immatures	135.4 ± 69.7a	68.0 ± 62.8ab	1.0 ± 1.0b	6.8 ± 6.8b	182.8 ± 82.5a	37.4 ± 21.6ab	5	2.9^{*}
	New growths	1.6 ± 0.8a	1.8 ± 0.7a	0.8 ± 0.4a	2.0 ± 0.7a	2.2 ± 0.7a	2.0 ± 0.5a	5	0.7^{NS}
May 07	Egg sacs	12.8 ± 5.2a	5.8 ± 3.6ab	0.0b	0.0b	3.0 ± 1.8b	2.0 ± 2.0b	5	4.2^{**}
	Eggs	7.4 ± 4.9a	8.0 ± 8.0a	0.0a	0.0a	0.8 ± 0.8a	3.8 ± 3.8a	5	1.0^{NS}
	Crawlers	10.8 ± 10.1a	7.0 ± 7.0a	0.0a	0.0a	0.0a	1.6 ± 1.6a	5	1.1^{NS}
	Settled first-instars	35.8 ± 14.2a	9.8 ± 9.3b	0.4 ± 0.4b	0.0b	7.2 ± 3.7b	1.4 ± 0.9b	5	6.1^{**}
	Older-instars	5.4 ± 1.9a	0.8 ± 0.6a	0.0a	0.0a	0.2 ± 0.2a	6.2 ± 6.2a	5	2.2^{NS}
	Total immatures	59.4 ± 27.9a	25.6 ± 24.9b	0.4 ± 0.4b	0.0b	8.2 ± 3.6b	13.0 ± 11.8b	5	3.7^{*}
	New growth	1.2 ± 0.6b	10.8 ± 4.3ab	11.4 ± 2.9ab	28.4 ± 6.8a	16.6 ± 9.5ab	10.2 ± 4.7b	5	2.9^{*}
Nov. 07	Older-instars	126.6 ± 51.3a	21.6 ± 13.5b	0.0b	0.0b	0.0b	0.0b	5	8.5^{**}
July 08	Settled first-instars	439.4 ± 111.1ab	613.2 ± 101.7a	313.4 ± 141.2b	221.2 ± 87.0b	0.0c	23.4 ± 18.4c	5	11.8^{***}

^{z}Samples were collected on May 25, June 27 July 25, September 26 and November 3 in 2006, May 29 and November 14 in 2007, and July 17, 2008.

^{y}Rates of Safari L = low; M = Medium; H = High, 3 or 6 or 12 (AI) g·2.5 cm^{-1} dbh, respectively.

^{x}Significantly different: * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; NS, not significant.

were affected (Table 4). By May 2007 egg densities were 88 and 60% lower than untreated controls in fall applied low- and high-dose Tristar treated trees, respectively. Total nymphs were also reduced an average of 85 and 60% with low and high doses of Tristar. No significant differences in adelgid populations between fall and spring applications were noted during this sample period. In November 2007 samples, adelgid survival repeated the same pattern as observed on the previous date. However, the highest reduction was 99% for older-instars when the high rate of Tristar was applied in spring and fall, but this was not significantly better than the other insecticide treatments. Evaluation of trunk injection treatments in July 2008 showed surviving settled first-instar populations were the same among all treatments of Tristar.

Experiment 5. Trees treated with Xytect in May 2007 had similar numbers of settled first-instars in August 2007 (F = 0.4; df = 2; P = 0.670) as untreated trees (Fig. 2). However, by November 2007, applications of Xytect made in May and August both resulted in significant reductions of older-instars (F = 6.4; df = 4; P = 0.003). All treatment methods and application times result in significant reductions in the number of nymphs in July 2008 samples (F = 9.9; df = 4; P < 0.001) compared with controls, and Xytect applied using the M3 injection system to root flares in spring 2007 had fewer adelgids than the other insecticide treatments. By November 2009, all treatments significantly reduced adelgid populations (F = 34.5; df = 4; P < 0.001) resulting in nearly 100% control.

These experiments indicate that Safari can play a valuable role when rapid control of HWA is needed to rescue trees. Suppression of adelgids by Safari was consistent in all soil applied experiments except for fall treatments as described in Experiment 1. Many factors such as drought, low tem-

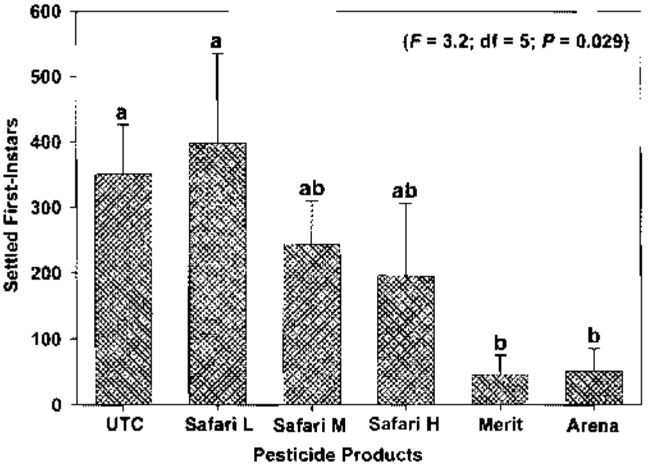

Fig. 1. Number (Mean ± S.E.) of adelgids in July 2008 branch samples from trees treated fall (November) 2006 in Highlands, NC. The rates of Safari represent: UTC = untreated control; L = low (3 g·2.5 dbh⁻¹); M = Medium (6 g·2.5 dbh⁻¹); H = High (12 g·2.5 dbh⁻¹).

perature or low soil organic matter, might affect insecticide efficacy immediately after application. These factors could delay their mobility and proper root interception in the soil. Low temperature, 5 to 15C (50 to 60F), especially during winter, and lack of soil moisture resulting in reduced evapotranspiration from hemlock needles and less xylem sap flow, could result in inefficient translocation of insecticides (7, 28). We found that treatment with Safari during spring was equally efficacious in controlling adelgid. Because the active ingredient in Safari has excellent water solubility of 39,800 ppm, Cowles et al. (3) predicted it would be effective against HWA since they found it more effective for armored scales compared with the widely used Merit insecticide. Similarly, an unregistered neonicotinoid, thiamethoxam (active ingredient) was tested for its efficacy against adelgids and yielded immediate suppression as compared with Merit (9).

Low volume applications of Safari delivered via soil injection provided rapid and significant suppression in different sites. Moreover, high volume application such as soil drenching with Safari did not yield additional control of adelgid populations. This means that under suitable soil conditions, recommended rates of Safari can be adequately distributed throughout hemlock trees as early as one month after soil injection. Diminishing densities of HWA remarkably improved overall tree health through increased shoot growth. The shallow placement of insecticide and adequate soil organic matter will minimize the risk of leaching and runoff during heavy rainfall. It is important that plant care professionals carefully consider the most efficacious insecticide and best application techniques that pose negligible risk to non-target organisms and the environment.

Merit in our trials in the southeastern United States provided persistent but delayed residual activity on HWA requiring up to one year after application to reach effective levels in the trees. It has been shown that soil applied Merit could take as little as 2 to 3 months (27) or from one year (3) to 2.2 years (30) to become effective. Merit might have restricted mobility in the soil by forming a strong bond to soil organic matter before coming in contact with the active roots of hemlock trees (4). Interestingly, Xytect having the same active ingredient as Merit (imidacloprid), when applied using the HTI 2000 soil injection system provided adelgid reduction within 6 months after spring treatment in our study. Furthermore, spring treated trees after 13 months had the same adelgid populations as fall treated trees after

Table 2. Number (Mean ± S.E.) of hemlock woolly adelgids and branches with new growth after soil injection, granular application or drenching on May 4, 2007.

Sampling date[z]	HWA life-stages	Untreated control	Safari 20 SG Kioritz soil injection	Safari 20 SG soil drench	Safari 2 G hand broadcast	Merit 75 WP Kioritz soil injection	Merit 75 WP soil drench	df	F[y]
May 07	Egg sacs	20.0 ± 6.7a	32.8 ± 7.8a	12.2 ± 7.8a	17.8 ± 5.9a	22.8 ± 12.0a	—	4	1.0^{NS}
	Eggs	18.8 ± 11.2b	0.4 ± 0.4c	0.0c	0.0c	49.4 ± 16.7a	—	4	13.0^{***}
	Crawlers	14.4 ± 10.1ab	1.8 ± 1.1b	0.2 ± 0.2b	5.8 ± 5.8b	20.8 ± 4.8a	—	4	4.4^{*}
	Settled first-instars	32.4 ± 21.3a	30.0 ± 12.0a	31.0 ± 5.4a	15.0 ± 2.7a	84.2 ± 24.4a	—	4	2.8^{NS}
	Older-instars	2.4 ± 1.6bc	0.2 ± 0.2c	4.4 ± 2.1b	2.2 ± 0.6bc	11.0 ± 0.8a	—	4	6.9^{**}
	Total immatures	68.0 ± 34.4b	32.4 ± 10.8b	35.6 ± 6.8b	23.0 ± 6.9b	165.4 ± 22.6a	—	4	8.0^{**}
	New growth	10.6 ± 5.5a	9.8 ± 4.2a	11.0 ± 2.4a	10.2 ± 3.2a	0.2 ± 0.2b	—	4	3.0^{*}
June 07	Egg sacs	44.6 ± 11.8ab	29.8 ± 14.9b	20.0 ± 9.1b	85.6 ± 18.3a	115.2 ± 38.9a	60.0 ± 17.3ab	5	2.9^{*}
	Eggs	750.0 ± 309.9a	0.0b	29.0 ± 29.0b	43.6 ± 43.1b	383.8 ± 84.9a	525.6 ± 144.4a	5	11.2^{***}
	Crawlers	54.6 ± 21.9a	0.4 ± 0.2b	2.2 ± 1.9b	0.8 ± 0.6b	38.2 ± 10.1a	42.2 ± 12.1a	5	10.1^{***}
	Settled first-instars	236.2 ± 77.9a	48.0 ± 18.5c	65.6 ± 37.4c	27.0 ± 7.9c	86.2 ± 16.9bc	189.4 ± 24.7ab	5	6.6^{***}
	Older-instars	32.4 ± 8.6a	0.4 ± 0.4b	2.6 ± 2.6b	2.0 ± 2.0b	23.2 ± 4.5a	32.0 ± 6.6a	5	15.3^{***}
	Total immatures	1073.2 ± 411.1a	48.8 ± 18.8b	99.4 ± 55.2b	73.4 ± 43.9b	531.4 ± 97.3a	789.2 ± 174.5a	5	9.5^{***}
	New growth	10.4 ± 3.4a	12.4 ± 2.3a	11.8 ± 1.6a	13.8 ± 3.5a	3.4 ± 1.4b	6.8 ± 2.7ab	5	3.6^{*}
July 07	Settled first-instars	193.2 ± 32.2a	0.0c	10.0 ± 9.5c	2.6 ± 2.6c	44.4 ± 15.0b	47.0 ± 12.4b	5	21.7^{***}
	New growth	7.6 ± 1.5a	11.0 ± 2.9a	11.8 ± 2.6a	8.6 ± 2.6a	1.8 ± 0.6b	5.0 ± 1.3ab	5	3.2^{*}
Nov. 07	Older-instars	32.6 ± 12.1a	0.0b	0.0b	1.0 ± 1.0b	0.0b	0.0b	5	31.1^{***}
July 08	Settled first-instars	595.0 ± 79.8a	0.0b	0.0b	2.6 ± 2.6b	1.6 ± 1.6b	0.0b	5	170.2^{***}

[z] Samples were collected on May 29, June 12, July 12 and November 14 in 2007, and July 16 in 2008 to evaluate efficacy and duration of control.

[y] Significantly different: * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; NS, not significant.

Table 3. Number (Mean ± S.E.) of hemlock woolly adelgids after treatment by soil injection or drench on September 7, 2007.

Sampling dates[z]	HWA Life-Stages	Untreated control	Safari 20 SG Kioritz soil injection	Safari 20 SG soil drench	Safari 20 SG + Arena 50 WDG Kioritz soil injection	Safari 20 SG + Arena 50 WDG soil drench	Arena 50 WDG Kioritz soil injection	Arena 50 WDG soil drench	df	F^y
Nov. 07	Older-instars	112.0 ± 36.5a	14.4 ± 10.3a	20.4 ± 14.0a	88.4 ± 41.9a	65.6 ± 39.7a	73.4 ± 26.9a	67.6 ± 30.2a	6	1.6^{NS}
Feb. 08	Eggs	208.1 ± 94.4a	0.0c	9.4 ± 9.4bc	103.2 ± 40.2a	186.6 ± 56.8a	0.0c	70.2 ± 36.3ab	6	5.7^{**}
	Older-instars	77.5 ± 30.9a	3.2 ± 1.5b	21.0 ± 19.6b	47.4 ± 16.9ab	79.6 ± 20.3a	3.4 ± 1.5b	37.6 ± 18.5ab	6	3.2^{*}
	Total immatures	285.7 ± 124.2a	3.2 ± 1.5c	30.4 ± 29.2abc	150.6 ± 56.4ab	266.2 ± 75.7a	3.4 ± 1.5c	107.8 ± 54.6abc	6	4.5^{**}
July 08	Crawlers	2.2 ± 1.2a	0.0b	0.0b	0.0b	0.0b	0.0b	0.0b	6	6.5^{***}
	Settled first-instars	256.5 ± 35.5a	10.8 ± 4.7c	22.0 ± 11.1c	36.4 ± 13.6bc	167.7 ± 33.9a	74.4 ± 19.4b	22.8 ± 3.9c	6	19.5^{***}

[z]Samples were collected on November 14, 2007, and February 7 and July 9, 2008.

[y]Significantly different: * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; NS, not significant.

Table 4. Number (Mean ± S.E.) of hemlock woolly adelgids after treatment using the Arborjet trunk injection system on November 3, 2006, April 4, 2007, and November 14, 2007.

Sampling dates[z]	HWA life-stages	Untreated control	Tristar low fall treatment 2006	Tristar high fall treatment 2006	Tristar low spring treatment 2007	Tristar low spring and fall treatment 2007	Tristar high spring treatment 2007	Tristar high spring and fall treatment 2007	df	F^y
Nov. 06	Settled first-instars	118.5 ± 108.6a	36.0 ± 23.0a	66.3 ± 62.6a	—	—	—	—	2	0.1^{NS}
	Older-instars	115.3 ± 87.2a	108.0 ± 44.5a	156.3 ± 110.9a	—	—	—	—	2	0.0^{NS}
	Total immatures	233.8 ± 195.8a	144.0 ± 66.2a	222.5 ± 173.1a	—	—	—	—	2	0.1^{NS}
	New growth	2.8 ± 0.5a	2.3 ± 0.5a	3.3 ± 0.5a	—	—	—	—	2	3.7^{NS}
Dec. 06	Settled first-instars	10.0 ± 7.1a	5.8 ± 2.2a	23.0 ± 17.7a	—	—	—	—	2	0.5^{NS}
	Older-instars	81.3 ± 43.3a	70.5 ± 19.8a	62.5 ± 20.9a	—	—	—	—	2	0.0^{NS}
	Total immatures	91.3 ± 50.3a	76.3 ± 20.6a	85.5 ± 21.4a	—	—	—	—	2	0.0^{NS}
	New growth	3.3 ± 0.5a	2.5 ± 0.6a	3.3 ± 0.5a	—	—	—	—	2	1.1^{NS}
Mar. 07	Egg sacs	19.5 ± 5.3a	21.3 ± 10.8a	33.3 ± 16.4a	—	—	—	—	2	0.2^{NS}
	Eggs	106.2 ± 47.5a	68.3 ± 24.9a	39.3 ± 23.4a	—	—	—		2	0.9^{NS}
	Settled first-instars	69.3 ± 34.8a	36.5 ± 23.4b	6.5 ± 3.8b	—	—	—	—	2	13.3^{**}
	Total immatures	175.5 ± 34.5a	104.8 ± 38.9a	46.3 ± 25.3a	—	—	—	—	2	4.2^{NS}
May 07	Egg sacs	99.8 ± 63.0a	18.3 ± 3.9a	21.7 ± 11.2a	42.5 ± 19.4a	30.0 ± 17.0a	46.0 ± 43.4a	7.8 ± 7.4a	6	1.2^{NS}
	Eggs	300.5 ± 76.4a	35.0 ± 30.8b	119.7 ± 110.2b	8.5 ± 5.3b	18.5 ± 12.2b	26.3 ± 26.3b	1.5 ± 1.1b	6	4.9^{**}
	Crawlers	100.0 ± 44.5a	2.5 ± 2.5b	41.8 ± 41.1b	0.0b	1.3 ± 0.6b	5.3 ± 4.0b	0.0b	6	5.1^{**}
	Settled first-instars	213.8 ± 84.3a	50.0 ± 32.7a	86.1 ± 43.8a	86.5 ± 37.0a	45.3 ± 19.5a	19.5 ± 6.4a	19.5 ± 4.8a	6	2.5^{NS}
	Older-instars	62.3 ± 26.7a	8.3 ± 2.5b	18.0 ± 14.4b	1.3 ± 0.9b	2.8 ± 0.9b	3.3 ± 2.3b	0.8 ± 0.5b	6	6.7^{***}
	Total immatures	676.5 ± 147.7a	95.8 ± 51.7b	265.8 ± 198.6b	96.3 ± 32.3b	67.8 ± 24.9b	54.3 ± 36.8b	21.8 ± 5.3b	6	5.0^{**}
	New growth	16.8 ± 4.3ab	10.5 ± 4.5abc	21.3 ± 6.9a	7.5 ± 6.2bc	9.8 ± 4.2abc	1.3 ± 1.8c	1.0 ± 0.7c	6	3.4^{*}
Nov. 07	Older-instars	195.0 ± 56.2a	12.0 ± 8.7b	97.0 ± 89.2b	5.3 ± 3.1b	15.8 ± 13.8b	14.0 ± 14.0b	0.8 ± 0.8b	6	4.1^{**}
July 08	Settled first-instars	161.5 ± 18.9a	2.8 ± 2.8a	86.5 ± 78.4a	50.5 ± 27.3a	14.8 ± 14.4a	80.5 ± 51.3a	37.5 ± 37.5a	6	2.1^{NS}

[z]Samples were collected on November 3 and December 7 in 2006, March 14, May 29, and November 14 in 2007, and July 17 in 2008.

[y]Significantly different: * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; NS, not significant.

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