Reducing Insecticide Volume and Nontarget Effects of Ambrosia Beetle Management in Nurseries

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ABSTRACT Ambrosia beetles (Coleoptera: Curculionidae: Scolytinae) are increasingly important pests of nursery-grown trees because of the arrival of several invasive species. Ambrosia beetles bore into young trees and inoculate them with ambrosia fungus, which interferes with vascular transport resulting in limb or tree death. In spring, when beetles are active, growers make frequent applications of pyrethroid insecticides to susceptible tree species to deter beetles from boring into trees. Applications often are made with airblast sprayers that forcefully release insecticide mist that billows through nursery beds. Our objective was to compare the environmental, nontarget, and economic effects of airblast sprayer applications to applications made with a new dual-nozzle spray wand that makes targeted applications only to tree trunks where beetles attack. Through replicated experiments at commercial nurseries, we found that 5 times more insecticide was released by airblast sprayers than the manual spray wand. The extra insecticide from airblast applications landed on tree canopies, between rows, and left the nursery beds as drift. As a consequence of not spraying tree canopies, 50% more natural enemies and 50% fewer spider mites were captured in nursery beds treated with the manual spray wand than beds treated with the airblast sprayer. Manual applications require 12 times more labor than airblast applications. However, increased need for expensive miticide applications may make manual applications an economically feasible strategy for integrated pest management (IPM) of ambrosia beetles in nurseries.

KEY WORDS economic analysis, insecticide coverage, *Oligonycus aceris*, *Xylosandrus crassiusculus*, secondary pest outbreak

Ambrosia beetles (Coleoptera: Curculionidae: Scolytinae) are important pests of ornamental trees grown in nurseries (Mizell et al. 1994, Adkins et al. 2010). Two of the most abundant and economically important are the exotic species *Xylosandrus crassiusculus* Motschulsky and *X. germanus* Blandford (Oliver and Mannion 2001, Adkins et al. 2010). *Xylosandrus crassiusculus* first was reported in South Carolina in 1974 (Anderson 1974). *Xylosandrus germanus* also was introduced from Asia and first was reported from New York vineyards in 1932 (Felt 1932). In the decades since their introduction, both species have spread to parts of the southern, northeastern, and Midwestern U.S. (Schneider and Farrier 1969, Ree and Hunter 1995, Rabaglia et al. 2006, Miller and Rabaglia 2009). These and other ambrosia beetle species are among the most important pests of nursery-grown trees (Hudson and Mizell 1999, Adkins et al. 2010).

Xylosandrus crassiusculus and *X. germanus* attack over 200 tree species. Their host range includes some of the most popular and valuable trees grown in nurseries such as maple (*Acer* spp.), dogwood (*Cornus* spp.), redbud (*Cercis canadensis* L.), *Styrax* spp., crape myrtle (*Lagerstroemia* spp.), ornamental cherry (*Prunus* spp.), elm (*Ulmus* spp.), and *Magnolia* spp. (Schneider and Farrier 1969, Weber and McPherson 1983, Ree and Hunter 1995). Female beetles become active in early spring (Oliver and Mannion 2001) and locate host trees via volatile emissions (Klimetzek et al. 1986, Ranger et al. 2010). They bore into host tree trunks and excavate galleries in the heartwood where eggs are deposited and larvae develop (Hoffmann 1941, Weber and McPherson 1983). In addition to boring damage, ambrosia beetles inoculate trees with ambrosia fungus on which the larvae feed (Baker and Norris 1968). Infested plants die or become unmarketable from boring damage, ambrosia fungus, or infection by secondary pathogens (Buchanan 1941).

Ambrosia beetles are difficult to manage because, once inside a tree, they are protected from insecticides. Therefore, the current management recommendation is to spray the trunk of susceptible trees with a pyrethroid insecticide when beetles become active in early spring and to repeat these applications every 2 wk until beetle activity subsides 12–16 wk later (Mizell et al. 1998, Hudson and Mizell 1999). Despite this intensive insecticide regimen, growers still lose substantial numbers of trees to ambrosia beetle damage each year (Adkins et al. 2010; S.D.F., unpublished

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Fig. 1. Manual (left) and airblast (right) sprayers used to make permethrin applications throughout experiments. Photos: S. D. Frank. (Online figure in color)

data). This may be a consequence of incomplete insecticide coverage of tree trunks or insecticides losing efficacy between applications.

In large nurseries, growers make pyrethroid applications with a tractor-drawn airblast sprayer (S. D. Frank, unpublished data). Airblast sprayers have insecticide nozzles positioned at the opening of an 8- to 10-in (20- to 25-cm) -diameter tube. A large fan forces air out of the tube as the nozzles release insecticide. This produces a forceful insecticide mist directed at the trees. Airblast sprayers allow growers to treat a large number of trees in a short amount of time. However, we suspect that only a small portion of the insecticide contacts tree trunks where it is needed to prevent ambrosia beetle damage. The rest penetrates the canopy or settles elsewhere in the environment. Thus, airblast sprayers are likely to release more insecticide into the environment than is required to protect trees from damage.

Repeated cover sprays of broad spectrum insecticide increase the risk of worker exposure and environmental contamination. In addition, routine, broad spectrum insecticide applications can result in secondary pest outbreaks (McClure 1977, Penman and Chapman 1988, Raupp et al. 2001, Hardman et al. 2007). Spider mites are a major pest of nursery crops (Adkins et al. 2010) and are particularly prone to outbreaks after insecticide applications (Penman and Chapman 1988, Gerson and Cohen 1989, Trichilo and Wilson 1993, Hardman et al. 2007, Szczepaniec et al. 2011). Current ambrosia beetle management exposes mites and natural enemies to several pyrethroid applications early in the growing season. If these applications positively affect spider mite survival by reducing natural enemies or increasing fecundity, outbreaks could occur later in the season.

The goal of this research was to reduce the volume of insecticide applied for ambrosia beetle management in nurseries and the potential for environmental contamination, nontarget effects, and secondary mite outbreaks associated with different application methods. To achieve this, our first objective was to determine the effect of application frequency and to evaluate the use of a sticker product on permethrin efficacy for reducing ambrosia beetle attacks. In a second experiment, we compare manual insecticide applications made directly to tree trunks to conventional airblast applications, which broadcast insecticide throughout nursery beds. The objectives of this study were to determine how manual and airblast permethrin applications affect 1) efficacy by measuring insecticide coverage and ambrosia beetle damage, 2) environmental impact by measuring active ingredient released and insecticide residue on unintended surfaces, and 3) natural enemy abundance and secondary mite outbreaks. Our hypothesis is that manual applications will take more time than airblast applications but also will have significant benefits, including less insecticide volume applied per tree, greater natural enemy abundance, and less spider mite damage.

Methods

Study System. We conducted experiments at two container nurseries in 2009 and 2010. Panther Creek Nursery, located in Willow Spring, NC, produces trees and shrubs using a pot-in-pot container system. Adcock's Nursery, located in Fuquay-Varina, NC, produces trees and shrubs in above-ground containers on weed cloth. Both nurseries grow many ambrosia beetle hosts and incur yearly ambrosia beetle damage to trees. Experimental trees were red maple (*Acer rubrum* L.) 'October Glory'. Maples frequently are damaged by ambrosia beetles and represent one of the most common tree genera produced in nurseries (USDA 1998).

All experiments employed a dual-nozzle spray wand developed by Richard Currin, owner of Currin's Nursery, in Willow Spring, NC. The spray wand has two opposing full-cone nozzles 8 in apart to spray all sides of a trunk with a single pass (Fig. 1). The dual-nozzle wand applies insecticide directly to tree trunks where ambrosia beetls attack rather than covering the canopy. Applications were made using a CO_2 powered backpack sprayer with full-cone nozzles at 30 psi.

Duration of Permethrin Efficacy. We evaluated application frequency and the use of a sticker product on permethrin efficacy in 2010. Six treatments were established by spraying tree trunks with permethrin (Covert, Loveland Products, Inc., Greeley, CO) at the middle labeled rate (25.75 ml/liter) every week, every 2 wk, or every 3 wk with or without sticker added (Nu Film, Miller Chemical and Fertilizer Corp., Hanover, PA; 29.26 ml/l). A seventh treatment contained untreated trees. Insecticide was applied with the dual-nozzle spray wand. Trees were sprayed from the first scaffold branches down to the base in a single pass down the trunk lasting ≈3 s. Each treatment was replicated ten times in a randomized complete block design. One block of five replicates was at Adcock's nursery using trees in 94.6-liter containers (3.5–3.7 m tall; 5- to 6.4 cm in diameter at breast height (dbh)). The second block of five replicates was at Panther Creek Nursery using trees in 56.8-liter containers (2.4–3.0 m tall; 3.2–3.8 cm dbh).

All treatments were applied 18 March 2010, after which trees were re-sprayed based on assigned treatment intervals for 12 wk. Trees were injected with 75 ml of 90% ethanol on 18 March and 6 April 2010 using an Arbor Jet Tree I.V. (Arbor Jet, Inc., Woburn, MA) injection system to make them attractive to ambrosia beetle attack (Buchanan 1941, Ranger et al. 2010). After 12 wk (22 June) trees were cut at the base and below the second branches and returned to the laboratory to inspect for ambrosia beetle galleries. Data were not normally distributed and were analyzed with Kruskal–Wallis Test in the NPAR1WAY procedure of SAS 9.1 (SAS Institute 2002). Because trees with even one attack would be considered unsalable by growers, we also analyzed the number of trees in each treatment that incurred at least one attack by using χ^2 tests.

Manual Versus Airblast Permethrin Applications. This experiment was conducted in 2009 and 2010 at Panther Creek Nursery. The experiment had two treatments: permethrin applied using the dual-nozzle wand (hereafter 'manual application') or airblast sprayer. Manual applications were as described above and replicated seven times: three in 2009 and four in 2010. In 2009, manual plots were 23 m wide and 11, 25, or 15 m long and contained 89, 174, and 96 trees. In 2010, manual plots were 23 m wide and 15, 11, 18, or 11 m long and contained 89, 72, 137, and 46 trees. Airblast applications were replicated four times in each year. Applications were made using a 2007 Tifone Aircannon (Tifone s.r.l. Cassana, Italy) airblast sprayer attached to a tractor. Airblast applications were made to two parallel sides of each plot. In 2009 four nursery beds assigned to the airblast application treatment were 23 m wide and 20, 25, 25, 23 m long containing 177, 201, 200, and 171 trees. In 2010, four nursery beds were assigned to the airblast application treatment that were 23 m wide and 16, 18, 11, 11 m long containing 125, 127, 65, and 52 trees. In all plots trees were 'October Glory' red maples in 15-gallon pot-in-pot containers spaced 1.8 m within rows and 1.7 m between rows. All plots were at least 10 m apart to prevent contamination of manual plots by the airblast sprayer.

Insecticide applications were made on 19 March, 16 April, and 30 April in 2009 and 16 March, 30 March, and 20 April in 2010. Application dates in each year correspond to different stages of beetle and tree phenology. The first (early) application of each year was made when beetles were first captured in traps and trees had no leaves. The second (mid) and third (late) applications were made when leaves were ≈50% and fully expanded respectively.

Insecticide Coverage and Ambrosia Beetle Damage. TeeJet water sensitive spray cards (Spraying Systems Co. Wheaton, IL) were used to measure insecticide coverage. Spray cards turn from yellow to blue when contacted with liquid to provide a measure of area covered with insecticide. Cards were hung at the base (0.1 m high), middle (1 m high), and in the canopy (2.0–2.5 m high) of three randomly selected trees per plot using twist ties. After application, we collected the cards and scanned them using a flatbed scanner. We used Image J (http://rsbweb.nih.gov/ij/index.html) to measure the percent of each image that was blue (i.e., covered with insecticide). The average percent coverage at each height position was determined for each plot. Early-, mid-, and late-season applications were analyzed separately because leaf expansion could affect coverage. Data for each date were analyzed within a factorial design with two application treatments (manual, airblast) and three card positions (low, middle, canopy) with year as a blocking factor (Proc Mixed, SAS 9.1; SAS Institute 2002).

In both years, trees were monitored for beetle damage throughout the experiment by nursery staff. In 2010, sentinel trees were used to estimate damage to trees that received airblast, manual, or no insecticide applications in a completely randomized design. Sentinel trees were injected with 75 ml of 90% ethanol to make them more attractive to ambrosia beetles (Buchanan 1941, Ranger et al. 2010). Control trees (n = 13) received no insecticide to confirm ambrosia beetle activity and damage in the absence of permethrin applications. Tree in airblast and manual application treatments received applications on the same dates as nursery plots and were replicated eight times. We inspected all trees on 22 June to count ambrosia beetle attacks.

Permethrin Released and Insecticide Coverage of Unintended Surfaces. To compare the volume of insecticide applied with each application method, the applicator measured insecticide volume in the backpack or airblast tank before and after spraying each plot. At two randomly selected places in each plot string was tied between two trees within a row and two trees between rows. A spray card was hung (1 m high) on each string to measure insecticide coverage where no tree was planted. A stake was placed 2 m outside of each plot on a side perpendicular to airblast applications to measure insecticide coverage of surfaces outside the target area. Spray cards were collected, scanned as above, and analyzed by analysis of variance (ANOVA) within a 2 by 2 factorial design (Proc Mixed, SAS 9.1; SAS Institute 2002).

Natural Enemy Abundance and Secondary Mite Outbreaks. One hour after each permethrin application we hung a yellow sticky card (7.6 by 12.7 cm) in the canopy of three randomly selected trees per plot to measure the effect of each application method on natural enemy abundance. We collected sticky cards after 7 d and identified natural enemies to family.

In 2010 we evaluated the effect of each application method on maple spider mite, *Oligonychus aceris* (Shimer), abundance and damage. On 5 May, 18 June, and 25 June we collected six randomly selected leaves from each of four trees in each plot. To remove mites we brushed the leaves onto 14-cm petri plates coated in cooking spray by using a mite brushing machine (Leedom Engineering, Twain Harte, CA). Plates were examined under a dissecting scope to count the number of maple spider mites and predatory mites present. Two people visually estimated the percent of each leaf with mite damage, then scores were averaged.

Natural enemies per card were summed across dates. Data for season totals of natural enemies, predators, and parasitoids were analyzed using ANOVA with year as a blocking factor. Very few mites were collected the first date indicating they had just become active. Therefore, only the second and third date were used to analyze mite abundance per 6-leaf sample using repeated measures ANOVA (Proc Mixed, SAS 9.1; SAS Institute 2002).

Economic Cost of Each Method. On each application date, we recorded the time required to make manual and airblast applications in each plot during early-, mid-, and late-season applications in 2009 and 2010. We divided application time by the number of trees present in each plot on each application date. We conducted a phone survey of five area growers to determine the time required to prepare for an application (measuring, mixing, setting up manual or airblast equipment) and time required to clean up after an application. To estimate labor costs, we multiplied total time investment (preparation and cleanup time plus application time [average of all dates]) by $15/h.

To determine insecticide costs, we averaged the cost of 3.79-liter containers of Astro (FMC, Philadelphia, PA) from Southern Agricultural Insecticides (Boone, NC) and Carlin Horticultural Supplies (Milwaukee, WI). Using the maximum label rate (236.6 ml/379 liters) we calculated the cost of insecticide solution applied per tree by averaging the early-, mid-, and late-application volume per tree in airblast and manual plots. Permethrin cost per acre was determined by multiplying the per-tree cost by 1,144, which is the average number of trees per acre of pot-in-pot production (UKY 2009). For a more realistic cost of airblast applications, we also determined the cost per acre assuming growers applied 757 liters/acre, the standard volume used to cover the high densities of trees grown in containerized production. Total costs of applying insecticides to protect trees from ambrosia beetles were estimated by multiplying the per acre cost by eight to cover a 16-wk flight period (Mizell et al. 1998, Hudson and Mizell 1999).

Because mite outbreaks are a potential consequence of airblast applications we calculated the cost per acre of miticide applications. We surveyed four companies (Southern Agricultural Insecticides, Carlin Horticultural Supplies, B and T Grower Supply [Forest Hill, LA], and J R Johnson Supply [Roseville, MN]) online and by phone to determine the average cost to spray one acre of trees with four common miticides (Judo [OHP], Floramite SC [OHP], Sanmite [Gowan], and Tetrasan five WDG [Valent]) based on labeled rates.

Results

Duration of Permethrin Efficacy. The number of trees that received at least one attack (three out of 30) and the number of ambrosia beetle attacks (0.12 ± 0.1) was identical between trees in the 'sticker' and 'no sticker' treatments when data were pooled across permethrin treatments. The frequency of permethrin application had a significant effect on ambrosia beetle attacks ($X^2 = 14.08$; df = 3; $P = 0.003$). Untreated trees received an average of 2.70 ± 1.5 attacks (range, 0–16) whereas trees sprayed every 1, 2, or 3 wk received 0.20 ± 0.2 (range, 0–3), 0.05 ± 0.1 (range, 0–1), and 0.55 ± 0.4 (range, 0–7) attacks, respectively. The number of trees attacked significantly was affected by application of permethrin ($X^2 = 15.79$; df = 3; $P = 0.001$) such that 60% of unsprayed trees were attacked ($n = 10$) whereas 10, 5, and 15% of trees sprayed every 1, 2, or 3 wk, respectively incurred at least one attack ($n = 20$ in each treatment).

Manual Versus Airblast Permethrin Applications. *Insecticide Coverage and Ambrosia Beetle Damage.* There was a significant interaction of spray coverage and card location on each application date (Table 1). This reflects equal coverage of cards at the base of trees and on the trunks below the first branches by manual and airblast applications, but significantly greater coverage of canopy cards by airblast applications (Fig. 2).

No ambrosia beetle damage occurred to trees within plots of either treatment, indicating both application methods provide similar plant protection. Thirty-one percent of untreated sentinel trees incurred at least one ambrosia beetle attack with an average of 0.62 ± 0.3 (range, 0–3; $n = 13$). Trees in manual and airblast application treatments received no attacks.

Permethrin Released and Insecticide Coverage of Unintended Surfaces. The volume of insecticide released by the airblast sprayer was five times greater than insecticide released by the manual wand in early-, mid-, and late-season applications (Fig. 3; $F = 18.05$; df = 1,13; $P < 0.001$; $F = 39.93$; df = 1,13; $P < 0.001$; $F = 27.23$; df = 1,13; $P < 0.001$). As much as 80 times more insecticide landed on unintended surfaces

Table 1. Results of ANOVA for the percent coverage of water-sensitive cards hung at the base of trees, on the trunk below first branches, or in the canopy of trees during early, mid, and late season manual and airblast permethrin applications

Effect	Early season		Midseason		Late season	
	F	*P*	*F*	*P*	*F*	*P*
Application method[a]	2.41	0.129	0.32	0.575	4.17	0.048
Card position[b]	24.76	<0.001	53.53	<0.001	80.50	<0.001
Method × position[b]	5.86	0.006	5.41	0.009	10.26	<0.001

[a] numerator, denominator degrees of freedom 1, 38.
[b] numerator, denominator degrees of freedom 2, 38.

or left application plots during airblast applications than manual applications (Fig. 4; Table 2).

Natural Enemy Abundance and Secondary Mite Outbreaks. Fifty percent more natural enemies (predators and parasitoids combined) were captured on sticky cards in manual plots than in airblast plots (F = 9.66; df = 1,12; P = 0.009; Fig. 5). Likewise, 50% more predators were captured in manual than airblast plots (F = 6.87; df = 1,12; P = 0.022; Fig. 5). Predatory beetles from the families Coccinellidae, Carabidae, Cantharidae, and Staphylinidae also were significantly more abundant in manual than airblast plots (mean ± SEM per card in manual and airblast plots respectively; 0.31 ± 0.05, 0.16 ± 0.04; F = 5.06; df = 1,12; P = 0.044). It is interesting to note that several groups of predators were up to twice as abundant in manual than airblast plots, although data were insufficient to analyze separately. These include predatory bugs (Hemiptera) such as *Orius* spp. (Anthocoridae), *Geocoris* spp. (Lygaeidae), and stinkbugs (Pentatomidae) (0.10 ± 0.05, 0.05 ± 0.02); hoverflies (Diptera: Syrphidae) 0.11 ± 0.03, 0.06 ± 0.03; and predatory thrips (Phaelothripidae) 2.2 ± 0.7, 1.4 ± 0.6. There were 37% fewer parasitoid wasps in airblast than manual plots (F = 26.09; df = 1,12; P < 0.001; Fig. 5).

Overall, maple spider mites were twice as abundant (per 6-leaf sample) in plots receiving airblast compared with manual applications (F = 6.17; df = 1,12; P = 0.028; Fig. 6). Maple mite abundance did not differ by date (F = 2.36; df = 1,12; P = 0.151) and date did not interact with application type (F = 0.12; df = 1,12; P = 0.730). Predatory mite abundance (per 6-leaf sample) (Phytoseiidae) in airblast (0.69 ± 0.2) and manual (0.31 ± 0.2) plots was not affected by application method (F = 3.29; df = 1,12; P = 0.095); date (F = 3.72; df = 1,12; P = 0.078); or their interaction (F = 1.06; df = 1,12; P = 0.323). Likewise, percent leaf damage by maple spider mite in airblast (17.6 ± 3.6) and manual (21.9 ± 5.3) plots was not affected by application method (F = 0.32; df = 1,12; P = 0.582); date (F = 0.15; df = 1,12; P = 0.706); or their interaction (F = 2.50; df = 1,12; P = 0.140). However, maple spider mite abundance was positively, significantly correlated with leaf damage (r_{64} = 0.38; P = 0.008).

Economic Cost of Each Method. Approximately 12 times more time was required to make early-, mid-, and late-season manual applications than airblast applications (Fig. 6; F = 2034.09; df = 1,13; P < 0.001; F = 2180.08; df = 1,13; P < 0.001; F = 1527.10; df = 1,13; P < 0.001). The average of early-, mid-, and late-season application times used in the cost calculation was 0.52 s and 6.19 s per tree in airblast and manual plots, respectively (Table 3). In our survey of five area growers, the average amount of time required to setup and cleanup airblast and manual sprayer equipment was 67.6 ± 3.1 and 60 ± 0 min, respectively.

Total insecticide costs were 4.5 times higher using airblast applications calculated on a per tree basis and ten times higher using a more realistic estimate of applying 200 gallons of permethrin solution per acre

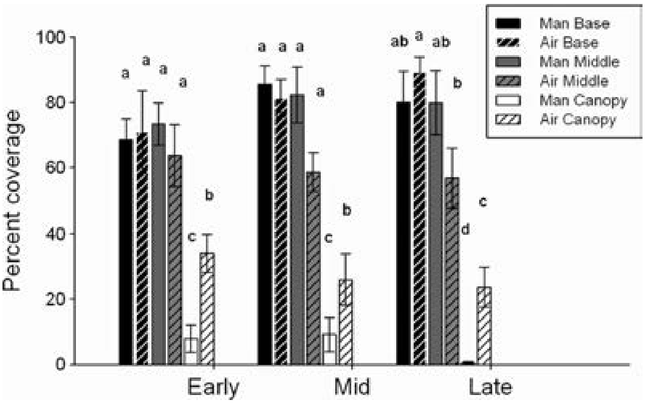

Fig. 2. Insecticide coverage of water-sensitive cards attached to containerized maple tree trunks 0.1 m (Base), 1.0m (Middle) and 2.5 m (Canopy) above the ground after manual (Man) or airblast (Air) applications of permethrin during early, mid, and late ambrosia beetle activity. Means below different letters, within each date, are significantly different (P < 0.05).

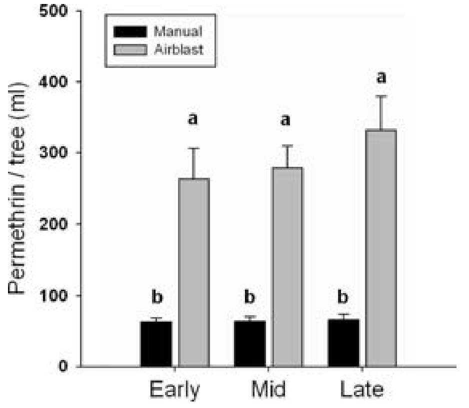

Fig. 3. Volume of permethrin solution per maple tree used to make manual and airblast applications of permethrin to containerized nursery beds during early, mid, and late ambrosia beetle activity. Means below different letters, within each date, are significantly different ($P < 0.05$).

(Table 3). In contrast, labor costs were 3.5 times more when making manual applications (Table 3). Thus, calculated on a per tree basis, reduced insecticide cost does not compensate for the increased labor cost of manual applications, which cost more than airblast applications per acre. Similarly, these costs remain higher even when estimating costs for applying 200 gallons of product on an acre of trees. One miticide application would cost an average of \$325.64 ± \$43.38 per acre including \$20.25 labor costs (Table 3), considerably more than the \$131 to \$168 difference between seasonal cost of manual insecticide application.

Discussion

Targeted insecticide applications are a cornerstone of IPM programs. This can include timing applications with pest activity, spot treating areas of pest activity, and treating only susceptible plants or plant parts rather than making broadcast applications (Raupp et al. 2001, Stewart et al. 2002). As such, timing pyrethroid applications for ambrosia beetles to trap catches helps ensure applications are not made too early, which wastes insecticide, or too late, which risks plant damage (Hudson and Mizell 1999, Oliver and Mannion 2001). Targeting permethrin applications only to tree trunks, where nursery-infesting ambrosia beetles mainly attack (Oliver and Mannion 2001, Reding et al. 2010), provided equal plant protection as airblast cover sprays. An important benefit of targeted applications by using the dual-nozzle wand was a fivefold reduction in the amount of insecticide released into the environment, which reduced nontarget effects on natural enemies and maple spider mite abundance.

Manual application indicated that ≈0.063 liters of permethrin solution was need to protect the trunk of each tree. The airblast sprayer applied up to 0.3 liters of permethrin solution per tree; this is five times more than is needed to coat each tree trunk. A large portion of permethrin solution released by the airblast sprayer ended up on nontarget surfaces. Tree trunks in the

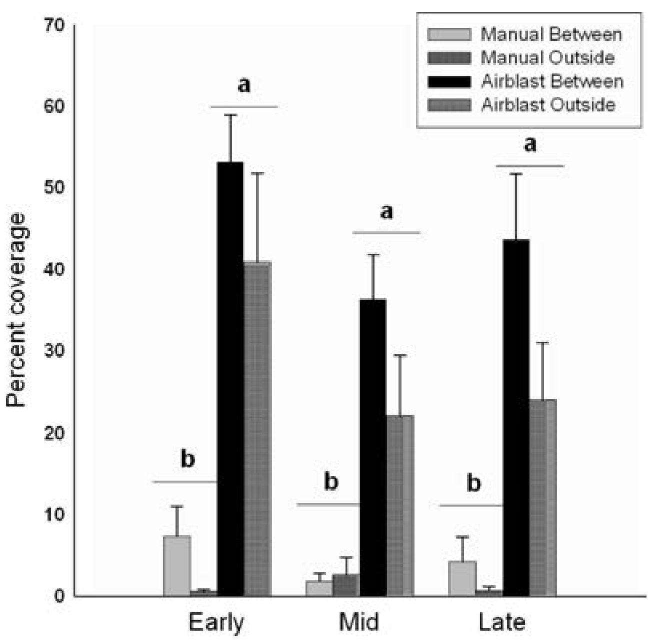

Fig. 4. Insecticide coverage of water-sensitive cards between tree rows and outside of containerized nursery beds after manual of airblast application of permethrin during early, mid, and late ambrosia beetle activity. Significant main effect of application method is indicated by means below horizontal bars with different letters within each date. Main effect of position also was significant wherein cards between rows received more coverage than cards outside of plots (Table 1).

Table 2. Results of ANOVA for the percent coverage of water-sensitive cards hung between trees or outside of nursery beds during early, mid, and late season manual and airblast permethrin applications

Effect[a]	Early season		Midseason		Late season	
	F	*P*	*F*	*P*	*F*	*P*
Application method	90.11	<0.001	61.14	<0.001	39.21	<0.001
Card position	7.20	0.013	3.92	0.058	5.15	0.032
Method × position	0.16	0.692	3.23	0.084	0.88	0.357

[a] numerator, denominator degrees of freedom 1, 13.

study nursery were 1.5 m apart and ≈3.5 cm in diameter. Thus, for every 3 m (two rows) of nursery bed, only 0.07 m or 2.3% is tree trunk that requires pesticide coverage. The remaining 2.93 m is empty space between trees. Spray cards in this space were up to 53% covered with insecticide that settled on weed cloth or left the plot as drift. Spray cards placed 2 m outside of each plot were 21–41% covered by airblast applications, whereas almost no insecticide solution left plots treated with the manual applicator.

As predicted, insecticide coverage in tree canopies was much greater after airblast than manual applications. Spray cards tied to the tree trunk within the canopy were up to 34% covered, which underestimates the amount of insecticide covering the outer leaves. Application of permethrin to tree canopies had strong effects on the abundance of natural enemies captured. Nearly 37% fewer parasitoid wasps were captured in the canopy of trees in airblast plots. Parasitoid mortality because of insecticides can result in outbreaks of many different tree pests but particularly scale (McClure 1977, Raupp et al. 2001). For example, Raupp and colleagues (2001) demonstrated cover sprays of ornamental landscape plants resulted in greater scale infestations, which was considered to be a consequence of insecticides killing natural enemies more effectively than pests. Likewise, mosquito fogging programs in California reduced parasitoid attack of pine needle scale, *Chionaspis pinifolia* (Fitch), resulting in scale outbreaks and damage in subsequent years (Roberts et al. 1973; Luck and Dahlsten 1975). European fruit lecanium [*Parthenolecanium corni* (Bouchė)] reached outbreak levels on street trees after weekly applications of dimethoate, which reduced parasitoid and other natural enemy activity (Merritt et al. 1983). Scales are a leading mortality factor of landscape and street trees and a major pest of nursery stock (Adkins et al. 2010). Broadcast insecticide applications targeting ambrosia beetles or other pests could result in plant damage and costly follow-up applications targeting secondary pests.

Maple spider mite abundance was greater in the canopy of trees that received airblast than manual permethrin applications. Although the exact mechanism behind this was not investigated it is likely due, in part, to mortality of predators when tree canopies were sprayed. Predators captured in our samples such as *Orius* spp., predatory thrips, lacewing larvae, and phytoseiid mites feed on spider mites but are very sensitive to pyrethroid insecticides (S. D. Frank, unpublished data). Other spider mite species, such as twospotted spider mites and European red mites, frequently outbreak after pyrethroid applications in orchards because of negative effects on predators (Gerson and Cohen 1989, Hardman et al. 2007).

Although we did not find greater mite damage in airblast plots sampled in June, trees had twice as many maple spider mites and mite abundance was corre-

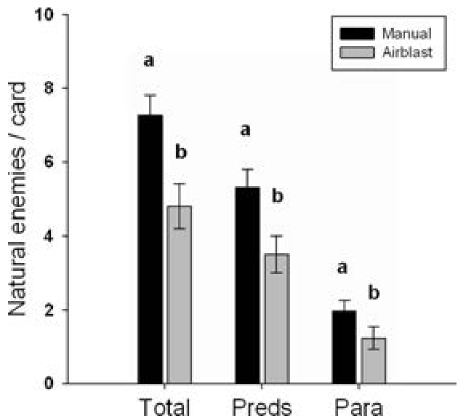

Fig. 5. Total natural enemies, predators, and parasitoids captured per sticky for 1 wk after manual of airblast application of permethrin in containerized nursery beds during early, mid, and late ambrosia beetle activity (all dates combined). Means below different letters, within each guild, are significantly different ($P < 0.05$).

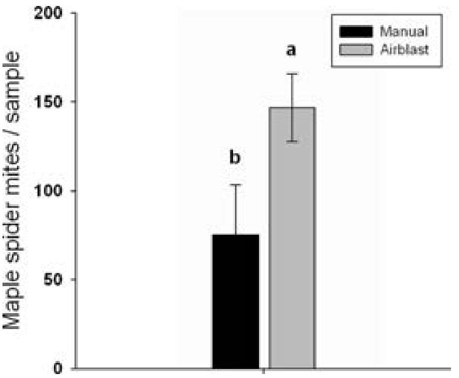

Fig. 6. Maple spider mites brushed from each 6-leaf sample per plot on 15 June and 23 June (combined) after manual of airblast applications of permethrin during early, mid, and late ambrosia beetle activity. Means below different letters are significantly different ($P < 0.05$).

Table 3. Economic cost of manual and airblast permethrin applications based on product and labor costs determined during experiments

	Insecticide costs				
	Cost ($)/ml	Volume/tree (ml)	Cost ($)/tree	Cost ($)/acre (per tree basis)	Cost ($)/acre (200 gal /acre)
Manual	0.000012	64.3	0.0014	0.81	–
Airblast	0.000012	290.8	0.0032	3.65	8.30
Labor costs					
	Time (s)/tree	Application time (h)/acre	Prep and clean-up (h)	Labor cost[a]/acre	
Manual	6.19	1.97	0.97	$44.10	
Airblast	0.52	0.17	1.18	$20.25	
Total costs					
				Total cost ($)/acre (per tree basis)	Total cost ($)/acre (200 gal /acre)
Manual				$44.91	–
Airblast				$23.90	$28.55
Difference from manual				$21.01	$16.36
Seasonal difference[b]				$168.08	$130.88

[a] based on $15.00 per hour.
[b] based on 8 sprays per season.

lated with leaf damage. Thus, increased mite abundance might be expected to result in more severe damage later in the season (S. D. Frank, unpublished data). Spider mites reproduce quickly and cause extensive damage that can reduce plant photosynthesis and growth, but also the trees' esthetic and monetary value (Sadof and Raupp 1997). To reduce damage caused by permethrin-induced spider mite outbreaks, growers would need to make additional miticide applications. Each miticide application would cost from 10 to 20 times the difference in labor cost ($23.85) per acre between manual and airblast applications.

The innovation of the dual-nozzle spray wand by a grower proved valuable in reducing insecticide volume, nontarget effects, and the potential for environmental contamination. Growers could save money by using five times less permethrin making manual applications, but labor costs are higher. Integrated Pest Management programs often cost more in the short term because of labor required to scout, implement cultural or mechanical pest management tactics, or make targeted insecticide applications (Stewart et al. 2002). However, there are potential long-term costs associated with not using IPM that are more difficult to quantify, such as plant damage and applications that result from secondary pest outbreaks. In maple production, maple spider mite is a severe and perennial pest that growers must manage. Because airblast sprayers exacerbate maple spider mite abundance, which is positively related to leaf damage, sustainable manual applications are an economically and environmentally sound way to manage ambrosia beetles in nurseries.

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