Evaluating the Use of an Air-blast Sprayer with Variable-Rate Technology for High Coverage Trunk Applications in Multi-row Blocks of Field and Pot-in-Pot Nursery Production[1]

Karl McKim[2], Lauren Fessler Mathews[2], Wesley C. Wright[3], Xiaocun Sun[4], Heping Zhu[5], and Amy Fulcher[2]*

Abstract

Trunk-boring insects, including flatheaded borers, can weaken and even kill a range of nursery crops. Controlling flatheaded borers is particularly challenging because the larvae hatch and chew directly into the wood, which limits their exposure to contact insecticides. An air-blast sprayer equipped with laser-guided, variable-rate spray technology was investigated for its spray application to trunks in field and pot-in-pot production systems. Spray characteristics were compared to those from a conventional, constant-rate application. Water and water-sensitive paper were used to quantify spray applications to trunks. Airborne and ground off-target movements were also assessed within and outside of the production block. In the field system, trunk coverage was high on all directional faces, 75.7% to 96.5% for variable-rate and 90.2% to 99.7% for constant-rate, but did not achieve 100% despite discharging a high volume in both sprayer modes, 124.7±0.3 L (33±0.08 gal) and 78.6±0.7 L (21±0.2 gal) for constant-rate and variable-rate, respectively. In the pot-in-pot system, coverage on directional faces ranged from 29.8% to 96.2% and 35.7% to 95.4% in variable-rate and constant-rate, respectively, in spite of a high-volume application. The row number and related crop density of this pot-in-pot system did not allow 100% coverage regardless of sprayer mode. Future research should include surfactants, nozzle types, and better defining the coverage needed for flatheaded borers.

Species used in this study: Northern red oak (*Quercus rubra* L.), Nuttall oaks (*Quercus texana Buckley*).

Index words: borer, flatheaded borer, integrated pest management, Intelligent spray, pest control, pesticide application.

Significance to the Horticulture Industry

In order to protect tree crops from trunk-boring insects such as flatheaded borers (Chrysobothris spp.), most nursery producers rely on either systemic insecticides applied to the root system or contact insecticides directly applied to trunks with an air-blast sprayer. Due to increasing concern about non-target effects of systemic insecticides, in particular to pollinators, we investigated the potential to use the laser-guided, variable-rate spray technology to thoroughly coat trunks in field and pot-in-pot nursery systems in a labor-efficient manner while also reducing waste, as has been possible when using variable-rate technology for foliar applications. We found that even when applying high volumes, 100% coverage could not be achieved with both new, variable-rate and conventional, constant-rate applications. More research is needed to substantiate the presumption that 100% coverage is necessary to achieve control of flatheaded borers and evaluate other sprayer types for the ability to provide thorough trunk coverage in a pesticide and labor-efficient manner.

Introduction

Nurseries and garden centers in the United States (US) are a $48.7 billion industry, with nursery and floriculture production accounting for $18.5 billion in revenue in 2022 (Perdomo 2023, Rose 2023). The appearance and health of trees and shrubs is of primary importance to growers, as both affect market value (Bethke and Cloyd 2009). Foliar pests like Japanese beetles (*Popillia japonica* Newman, 1841) damage the canopies of trees by chewing foliage, and species of aphids (*Aphididae*) and thrips (*Thrips*) can damage crops by feeding on foliage while also serving as vectors for disease (Bethke and Cloyd 2009). Trunk-boring insects such as ambrosia beetle (*Xylosandrus* spp.) and those in the flatheaded borer (FHB) complex (*Chrysobothris* spp.) chew through bark and excavate galleries, causing significant damage to the vascular system of trees. A single FHB can kill a tree or damage it beyond the point of sale in just one season (Potter et al. 1988, Seagraves et al. 2013). Thus, infestations by trunk-boring insects are a major concern for nursery owners.

Protecting plants from trunk-boring and other insects as well as diseases is critical to the production process, and many nursery owners utilize Integrated Pest Management (IPM) programs to accomplish this goal (Ehler 2006,

Received for publication January 6, 2025; in revised form May 30, 2025.

[1]The authors gratefully acknowledge Brianna Alred, Amber Gunter, Jakob Johnson, Carolyn Krauss, Grace Pietsch, Lily Slade, Hannah Sutt, and Laura Whaley for their technical assistance, Hale and Hines Nursery, Terry, James, and John Hines, Princess Gribble, and Reuben and Adrian Suarez, and USDA NIFA Specialty Crop Research Initiative grant # 2020-51181-32199.

[2]Extension Assistant, Research Specialist, and Professor, respectively, Department of Plant Sciences, University of Tennessee, 301 Agriculture and Natural Resources Building, 2431 Joe Johnson Drive, Knoxville, TN 37996.

[3]Senior Research Associate, Department of Biosystems Engineering and Soil Science, University of Tennessee, 2506 E.J. Chapman Drive, Knoxville, TN 37996.

[4]IT Specialist III, Office of Information Technology, University of Tennessee, 2309 Kingston Pike, Suite 132, Knoxville, TN 37996.

[5]Agricultural Engineer and Lead Scientist, USDA-ARS, 1680 Madison Ave., Wooster, OH 44691.

*Corresponding author email: afulcher@utk.edu.

LeBude et al. 2012). IPM employs multiple strategies to manage pests in an ecologically and economically sound manner. One of the components to IPM is the responsible application of pesticides to prevent and control pests. In fact, Popp et al. (2012) estimates that the application of pesticides saves growers in the U.S. up to $60 billion from dead or unmarketable crops annually.

Air-assisted (air-blast) sprayers are most commonly used to apply pesticides to foliage in nurseries (Zhu et al. 2008). Air-blast sprayers deliver air-carried droplets of pesticide as a cloud into and across multiple rows of plants and provide an alternative to manual applications made with backpack sprayers, which can achieve high application efficiency when making trunk applications but can require 12 times the amount of labor (Frank and Sadof 2011). Pesticide application using air-blast sprayers is not targeted, however, and studies have shown that over 70% of the total spray volume from an air-blast sprayer can land in off-target locations, with over a third of that volume landing on the ground (Salcedo et al. 2021, Zhu et al. 2006, 2008). Airborne particles can also be carried large distances by the wind, resulting in non-target contact as far as 88 m (96 yd) away from the intended application site (Grella et al. 2017, Kasner et al. 2018, Salcedo et al. 2021). This off-target drift can have negative environmental impacts. It can lead to reduced biodiversity and increased pest resistance and can easily seep into and contaminate soil and groundwater (Pimentel 2005).

Due to the popularity and inefficiencies of air-blast sprayers, a laser-guided, variable-rate spray system was developed that aims to increase application efficiency and reduce both spray volume and off-target drift (Chen et al. 2012). This system uses a light detection and ranging (LiDAR) laser sensor to determine plant characteristics in real-time, including plant presence, dimensions, and density. An integrated computer uses this information in conjunction with data obtained from an on-board ground speed sensor to calculate the appropriate spray timing and output, which is controlled by a pulse-width modulated (PWM) solenoid upstream of each nozzle (Chen at al. 2012). When actuated, solenoids individually open to deliver the calculated spray volume to their designated area of the plant, then close as the LiDAR senses gaps within tree canopies and between trees. This differs from a conventional sprayer, which emits a constant spray from each nozzle. Following successful tests with a prototype system, the "intelligent" spray system was developed to be retrofitted to existing sprayers (Shen et al. 2017).

Studies have shown that the intelligent spray system can reduce overall spray volume anywhere from 30-80% depending on sprayer and crop type (Boatwright et al. 2020, Chen et al. 2019, 2020, 2021, Fessler et al. 2020, Nackley et al. 2021, Salcedo et al. 2020, Zhu et al. 2017a, 2017b), providing economic savings for growers. These economic savings extend beyond a reduction in chemical costs, however. The intelligent spray system also reduces the amount of water and fuel used when spraying crops (Manandhar et al. 2020). This translates into additional savings in labor, as operators do not need to refill tanks with water as often or refuel tractors as frequently, thus reducing the time spent spraying. These savings on labor are important to note, as automation for pesticide application is a primary desire for growers (Fulcher et al. 2023) who must continue to provide high-quality products despite facing an industry-wide labor shortage (Rihn et al. 2022). In addition to reducing economic costs, growers using this system could also reduce their environmental impact. Intelligent sprayers provide a more targeted application than conventional air-blast sprayers, and numerous studies have shown these sprayers to reduce both airborne drift (Boatwright et al. 2020, Chen et al. 2013, Fessler et al. 2023b, Salcedo et al. 2021) and off-target ground loss (Chen et al. 2013, Fessler et al. 2020, 2023b, Nackley et al. 2021, Salcedo et al. 2021) in woody crops.

Despite outputting a reduced volume, intelligent sprayers have been shown to control foliar pests and diseases at levels similar to conventional air-blast sprayers. Fessler et al. (2023a) found intelligent sprayers reduced spray volume by 50% in a field nursery and by 24% in a pot-in-pot (PNP) production nursery compared to conventional sprayers. Intelligent sprayers provided similar control for tar spot (*Rhytisma* spp.) and anthracnose (*Gloeosporium* spp., *Gnomonia* spp., and *Apiognomonia* spp.) in field-grown red maple trees (*Acer rubrum* L.; Fessler et al. 2023a). In the PNP production system, these sprayers also provided similar levels of control for cylindrosporium leaf spot (*Cylindrosporium* spp.) and tar spot on red maple trees and for Japanese beetles on zelkova (*Zelkova serrata* (Thunb.) Makino; Fessler et al. 2023). Chen et al. (2021) found that using an intelligent sprayer for a three-year period reduced the amount of pesticide sprayed between 30% and 65% on average at a fruit farm and two ornamental nurseries in Ohio, US while still controlling five species of insects and six diseases on seven different orchard and nursery tree crops at levels similar to or more effective than a conventional air-blast sprayer. Similar results for the control of foliar pests and diseases with substantially less pesticide volume occurred in multi-year studies at several nurseries (Chen et al. 2019).

While there have been numerous studies examining the effectiveness of intelligent sprayers for foliar applications, little published research has been conducted to examine the usefulness of using these systems for applying pesticide to the trunks of trees in multi-row production systems. Initial investigations into the efficacy of intelligent sprayer systems at achieving full-trunk coverage in field-grown trees were conducted by Fessler et al. (2023b, 2023c). This article builds on those initial findings. Boring insects such as FHB are of concern to nursery owners due to their broad geographic range, wide variety of host plants, and highly destructive nature (Dawadi et al. 2019, Frank et al. 2013). Seagraves et al. (2013) examined the distribution of FHB attacks on the trunks of several red maple cultivars. They found that 64% of FHB attacks occurred between the southeast and southwest faces of tree trunks between the soil and a height of 40 cm (16 in). Utilizing intelligent spray technology to apply pesticides to tree trunks could result in reduced pesticide application volume, as has been seen when using it for foliar applications and would provide economic savings while reducing environmental impact.

The objective of these experiments was to compare trunk coverage between constant-rate (CR) and variable-rate (VR) modes in a two-block (12 row) PNP production system and a single block (2 row) field production system when spraying water using the lower nozzles of a retrofitted intelligent, variable-rate, air-blast sprayer. Our goal was to determine if it would be possible to achieve 100% coverage on the trunks of trees in both CR and VR modes using the specified sprayer settings in these two production systems.

Materials and Methods

Retrofit intelligent sprayer. The experiments were conducted using an air-assisted trailer sprayer (Storm 2000, Tifone, Porotto, Italy) that had been retrofitted with a laser-guided, variable-rate control system. The retrofitting process included the addition of an embedded touchscreen computer, a switch box to control operating mode, a non-contact Doppler-radar ground travel speed sensor (RVSIII radar velocity sensor, Dickey John Corp., Auburn, IL, USA), a high-speed laser scanning sensor (UTM-30LX, Hokuyo Automatic Co., Ltd., Japan), an automatic flow control box, and PWM solenoids (115880-1-12, TeeJet, Glendale Heights, IL, USA). These components were added to the original sprayer which consisted of a 2,000 L (528 gal) spray tank, 20 radial nozzles (10 on each side), a fan with an 80 cm (31 in.) propeller, and a pressure regulator. Variable-rate applications are achieved by manipulating the spray output of each spray nozzle using PWM solenoid valves. Spray output was based on tree characteristics (presence, height, width, density), tractor speed, and spray rate (designated spray volume per crop volume). This rate is set by the operator using the touchscreen computer. The intelligent sprayer system is described in detail in Shen et al. (2017).

Preliminary experiments were conducted in 2022 and 2023 to inform spray parameters, discs and cores, nozzle positions eligible to spray, nozzle angle, and travel speed in the present study. When operating in constant-rate mode, the sprayer simulated a sprayer without the retrofit technology and applied the maximum spray rates mentioned below. All nozzles were on in constant-rate mode and eligible to be activated if the target (tree) was detected in variable-rate mode for the experiment with field grown trees. The four uppermost nozzles (positions 1 to 4) were inactivated regardless of spray mode for sprays to the PNP plot. While operating in variable-rate mode, the spray rate was set to 0.20 $L \cdot m^{-3}$ (0.20 $oz \cdot ft^{-3}$), and the spray output ranged from 0 to 87.3 $L \cdot min^{-1}$ (0 to 23.0 $gal \cdot min^{-1}$) in the PNP plot and 0 to 98.0 $L \cdot min^{-1}$ (26.3 $gal \cdot min^{-1}$) in the field plot. The nozzles in positions 1 through 4 had a maximum flow rate of 2.6 $L \cdot min^{-1}$ (0.7 $gal \cdot min^{-1}$) (disc D6, core DC25), nozzle 5 had a maximum flow rate of 6.6 $L \cdot min^{-1}$ (1.74 $gal \cdot min^{-1}$) (disc D6, core DC56), while nozzles in positions 6 through 10 had a maximum flow rate of 16.2 $L \cdot min^{-1}$ (4.36 $gal \cdot min^{-1}$) (disc D10, core DC56) (TeeJet Technologies, Glendale Heights, IL). Nozzles on the right side of the sprayer, the side not facing the experimental block, were ineligible to spray. The sprayer was set to spray width (left) = 15.2 m (50 ft), vertical maximum = 15 m (49.2 ft), vertical minimum = 0.1 m (0.3 ft), horizontal maximum = 30 m (98.4 ft), and horizontal minimum = 0.1 m (0.3 ft).

Field experiment. The field experiment was conducted in a 325 m (1,066.3 ft) long production block of field-grown red maple trees (*Acer rubrum* Red Sunset®) at Hale and Hines Nursery, Inc. (lat. 35.719757°N, long. -85.748158°W, McMinnville, TN, USA; Fig. 1). Trees were planted in an offset pattern, in two side-by-side rows with 2 m (6.6 ft) between rows and 1.8 m (5.9 ft) between trees within a row. Trees were pruned in the summer, leaving 1.2 m (4 ft) below the lowest branch. The average height was 362 cm (143 in) and the average canopy width was 150 cm (59 in). This block was bordered on the north and south by 6 m (19.7 ft) wide driveways from which the block was sprayed. During sprays, the tractor was driven at an average speed of 3.2 $km \cdot hr^{-1}$ (2 mph) with the power-take-off (PTO) at 540 rotations per minute (RPM) and the nozzles pressurized to 689 kPa (100 psi). The block was sprayed first while driving west to east along the southern driveway, and then again while driving east to west along the northern driveway. The sprayer was actuated 5 trees, approximately 9 m (29.5 ft) before the first target tree and remained so until 9 m after the final target tree, running for a total of 41.7 m (136.8 ft). A total number of 42 trees were sprayed.

PNP experiment. The PNP experiment was conducted at Hale and Hines Nursery, Inc. (McMinnville, TN, USA) in the WH field (lat. 35.726508°N, long. -85.744959°W; Fig. 2) which has 10 production blocks of trees grown in 57-L (15-gal) containers in a PNP production system. Two adjacent blocks of trees with lengths of 230.3 and 229.8 m were selected as the experimental block. The southern block contained 6 rows of Northern red oak trees (*Quercus rubra*) while the northern block contained Nuttall oaks (*Quercus texana*). Trees were pruned on June 23, 2023, just prior to commencing the experiments, leaving 1.2 m (4 ft) before the lowest branch. The average height was 249 cm (98 in) and the average canopy width was 175 cm (69 in). The blocks were divided east to west down the middle by a narrow driveway [2.4 m (7.9 ft)] and were bordered on the north and south by wide driveways [3.4 m (11.2 ft)] from which sprays were conducted. Trees within rows had 1.2 m (3.9 ft) between them, and rows were spaced 1.2 m (3.9 ft) apart. Sprays were conducted by first driving the sprayer west to east down the wide driveway on the southern edge of the block. The sprayer was then driven east to west down the wide driveway on the northern edge of the block, spraying across the block from the opposite direction. The tractor pulling the sprayer was driven at an average speed of 1.6 $km \cdot hr^{-1}$ (1 mph) with the PTO at 540 RPM and the nozzles pressurized to 689 kPa (100 psi). The sprayer was actuated when the tractor was 5 trees, approximately 6 m (19.68 ft) from the first target tree and remained actuated 6 m past the final target, running for a total of 54.7 m (179.5 ft). Approximately 497 trees were sprayed, which accounts for 10% of the socket pots being empty (visual determination).

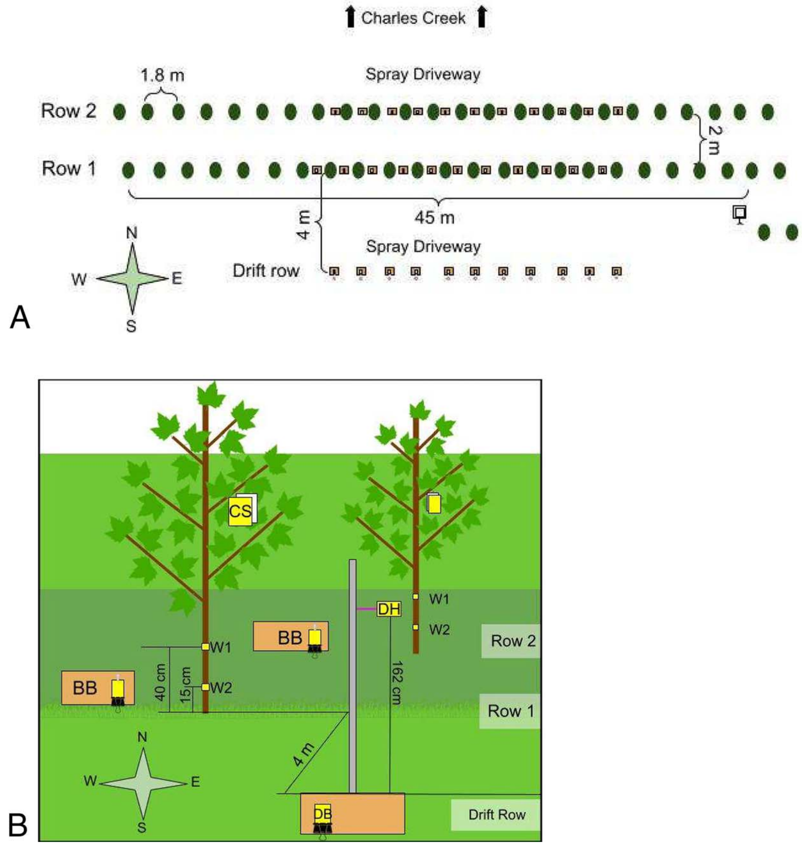

Fig. 1. WSP locations used to assess spray characteristics in the field plot. A) aerial perspective, B) perspective from the ground. Eleven consecutive trees were selected from each row and were sprayed with each treatment. Eleven drift structures were installed 4 m south of the block to assess aerial and ground drift. DH = Drift high, DB = Drift board, CS = canopy south, CN = canopy north, BB = within block board, W1 = upper wrap (40 cm), W2 = lower wrap (15 cm).

Water sensitive paper. Spray characteristics were assessed by placing 5.2 × 7.6-cm (2 × 3 in) water sensitive paper (WSP) cards (Water sensitive paper, Syngenta Crop Protection AG, Basel, Switzerland) in target tree canopies and strips of WSP around the trunks of target trees. When WSP is contacted by droplets of liquid, it changes color from yellow to dark blue. WSP can then be analyzed to quantify spray characteristics. To assess in-block spray characteristics, trees with lateral branches on their east side were selected as target trees. The lateral branches were marked with flagging tape, and a single electrical clip was secured 5.1 to 15.2 cm (2 to 6 in) from the branch tip, at a height between 1.4 and 1.8 m (4.6 and 5.9 ft). This clip was used to hold a pair of back-to-back WSP cards perpendicular to the direction of the spray cloud being discharged from the sprayer. To quantify trunk deposition, a 2.54 × 10.8 cm (1 × 4.25 in) strip of WSP was wrapped clockwise around the trunk circumference of target trees at two heights (15 cm and 40 cm) and secured with adhesive vinyl (McKim et al. 2025). To measure non-target spray reaching the ground applications within the block, one WSP card was secured to a board which was placed on the ground in the block. Boards were placed equidistant between the pots of target trees.

After each spray run was completed, WSP cards were collected in labelled envelopes and stored with desiccant packs. Trunk wraps were removed, attached to labels, and stored in the same manner as WSP cards. Blocks were sprayed in both the conventional, constant-rate and intelligent, variable-rate mode. New WSP was placed and collected for each spray, and sprayer volume-output, temperature, and relative humidity were recorded for each spray.

In the field plot, a solar-powered weather station composed of an anemometer (034A-L Wind Set; Met One, Grants Pass, OR, USA) and an air temperature and relative humidity sensor (HMP60-10-PT, Vaisala Corp., Helsinki, Finland) connected to a data logger (CR1000; Campbell Scientific, Logan, UT, USA) was used to obtain weather data. In the PNP plot, maximum and average windspeeds were collected using a handheld anemometer (Kestrel 3000, Nielsen-Kellerman Company, Boothwyn, PA, USA) due to the sprayer's close proximity to the weather station which artificially inflated the windspeed measurements when spraying one end of the plot. Parallel light measurements were taken using a line quantum sensor (LQS706; Apogee Instruments, Logan, UT, USA) connected to a quantum meter (QMSS, Apogee Instruments, Logan, UT, USA). A full sun measurement was taken as a baseline, and a second measurement, which was centered in the shadow cast by the canopy of each target tree, was taken to determine the percent full sun which penetrated the canopies.

WSP was scanned in the lab at 600 dpi (dots per inch) with a multi-function computer printer (HP Photosmart Plus All-in-One Printer-B209, Hewlett-Packard, Palo Alto, CA, USA) and saved as jpg files. These files were then

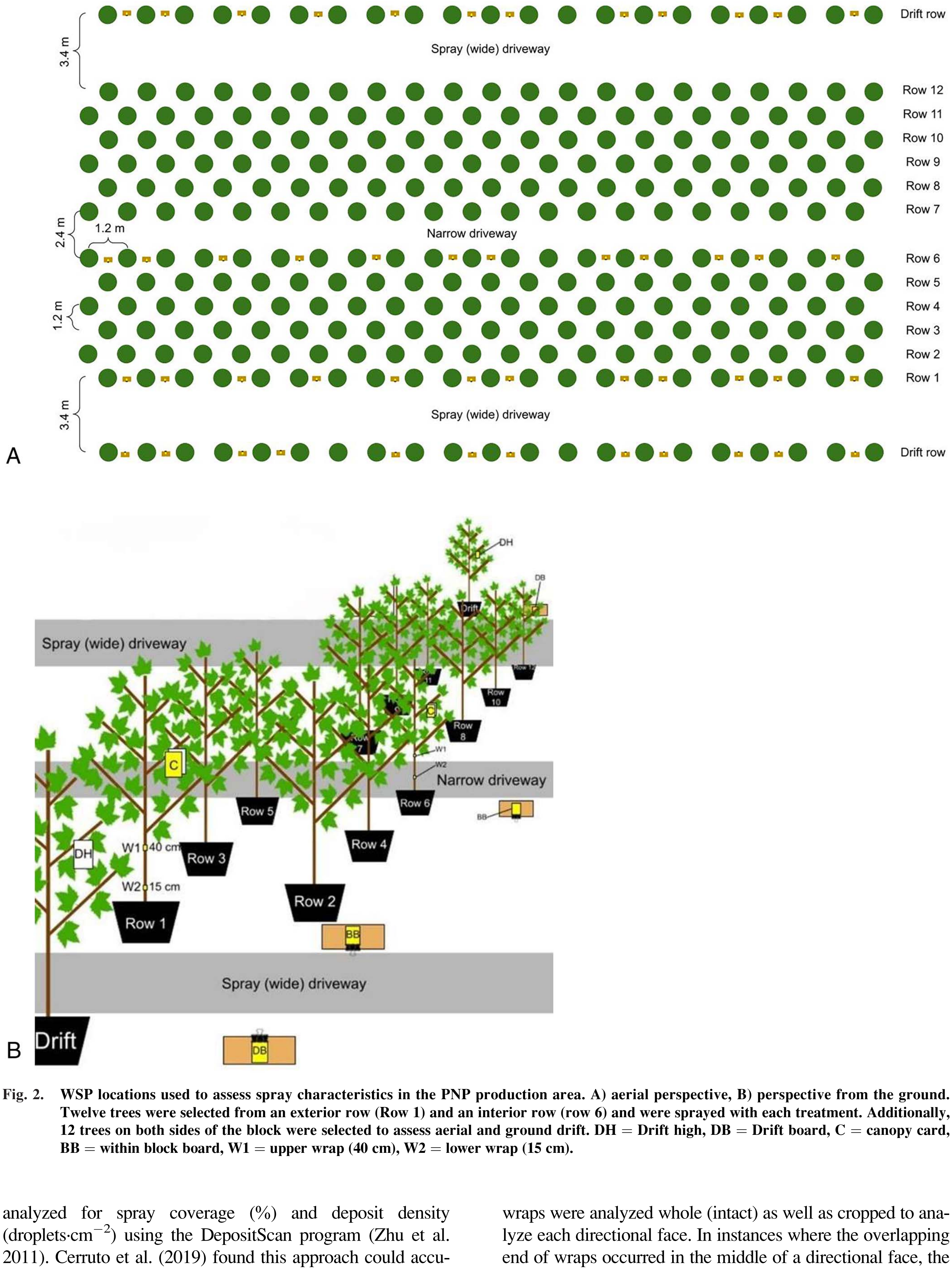

Fig. 2. WSP locations used to assess spray characteristics in the PNP production area. A) aerial perspective, B) perspective from the ground. Twelve trees were selected from an exterior row (Row 1) and an interior row (row 6) and were sprayed with each treatment. Additionally, 12 trees on both sides of the block were selected to assess aerial and ground drift. DH = Drift high, DB = Drift board, C = canopy card, BB = within block board, W1 = upper wrap (40 cm), W2 = lower wrap (15 cm).

analyzed for spray coverage (%) and deposit density (droplets·cm^{-2}) using the DepositScan program (Zhu et al. 2011). Cerruto et al. (2019) found this approach could accurately measure unit deposit and characterize droplet spectra, even when WSP has a high percentage of coverage. WSP wraps were analyzed whole (intact) as well as cropped to analyze each directional face. In instances where the overlapping end of wraps occurred in the middle of a directional face, the more representative portion of that directional face was selected for the directional analysis. This can lead to small discrepancies in averages generated from analysis of the directional face and a difference in significance within interactions between total wrap data and directional face data.

Field experiment plot design. For this experiment, 11 trees in the southern row (row 1) of the experimental block and the 11 adjacent trees in the northern row (row 2) were used as target trees. A pair of back-to-back WSP cards was placed in the electrical "Alligator" clip on the lateral branch, and a single card was placed on each board between target trees within the block.

To assess spray drift, a row of 11 drift structures was installed 4 m (13.1 ft) south of the trunks of target trees in row 1. Each structure had one electrical clip extending east attached at a height of 162 cm. This clip held a single WSP card perpendicular to the direction of the spray cloud. A board holding one WSP card was placed on the ground against the base of each drift structure to measure off-target ground deposition.

PNP plot design. Twelve trees in an external row (row 1) and internal row (row 6) of the experimental block were selected as target trees for this experiment. Each target tree held WSP cards in the same positions on lateral branches as the field plot, and boards with WSP cards were placed in the same positions between target trees within rows.

Twelve trees in the external rows of adjacent blocks were used to characterize spray drift. Drift row trees were located directly across the wide driveways from target trees, and canopy clips were secured on eastern-growing lateral branches in the same manner as on target trees. These clips held a single card that faced perpendicular to the direction of the spray cloud, and a board holding one WSP card was placed to the west of drift row trees in the same position as those contained within the block.

Statistical analysis. Both the field and PNP experiments were arranged in a completely randomized design. There were 11 and 12 single tree (target) and off-target replications for the field and PNP experiments, respectively. The difference between spray treatments on volume was analyzed using one-way ANOVA. The effects of spray treatment, wrap direction, wrap height, row orientation, card location and their interactions on spray coverage and deposit density were respectively analyzed using mixed model analysis for a split-plot design with treatment and row orientation as the whole-plot effects while other factors as the split-plot factors. Rank data transformation was applied when diagnostic analysis on residuals exhibited violation of normality and equal variance assumptions using Shapiro–Wilk test and Levene's test respectively. Post hoc multiple comparisons were performed with Tukey's adjustment. Statistical significances were identified at $P < 0.05$. Data were presented as means and standard errors. All analyses were conducted in SAS 9.4 TS1M8 (SAS Institute Inc., Cary, NC).

Results and Discussion

Field experiment

Application volume. Spray treatment influenced total volume sprayed ($P = 0.0099$) in the field experiment

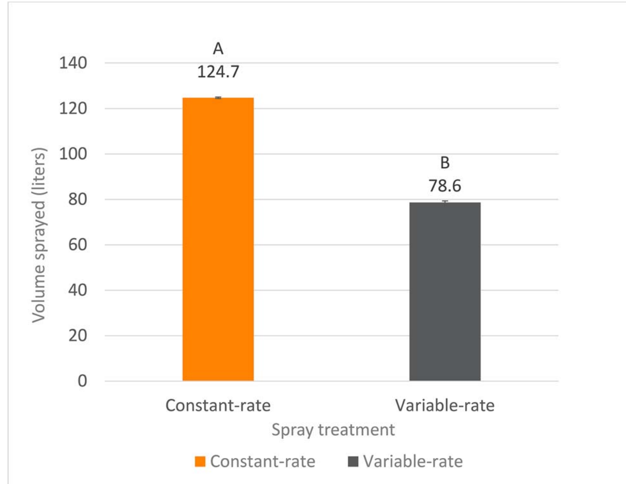

Fig. 3. Volume applied by constant-rate and variable-rate spray treatments in the field production block ($P = 0.0099$). Means with different letters are significantly different, alpha = 0.05. Error bars signify standard error.

(Fig. 3). The constant-rate treatment emitted 124.7±0.3 liters (33±0.08 gal) per spray, nearly 60% more volume than the variable-rate mode, which averaged 78.6±0.7 liters (21±0.2 gal). This volume reduction aligns with prior research in which variable-rate technology had a 30-80% reduction in spray volume versus constant-rate technology (Boatwright et al. 2020; Chen et al. 2019, 2020, 2021, Fessler et al. 2020, 2023d, Nackley et al. 2021, Salcedo et al. 2020, Zhu et al. 2017a, 2017b). However, the nearly 5,416 $L{\cdot}ha^{-1}$ (580 $gal{\cdot}A^{-1}$) emitted in the constant-rate mode far exceeded the standard application rate of 1060 $L{\cdot}ha^{-1}$ (113 $gal{\cdot}A^{-1}$) in field nurseries (Zhu et al. 2006), 1871 $L{\cdot}ha^{-1}$ (200 $gal{\cdot}A^{-1}$) in PNP nurseries (Frank and Sadof 2011), and the minimum recommended rate of 1402-1869 $L{\cdot}ha^{-1}$ (150-200 $gal{\cdot}A^{-1}$) for orchards (Walgenbach et al. 2024).

Wraps: whole (intact). WSP in the field experiment had an interaction between treatment and wrap height on total coverage ($P = 0.0002$; Fig. 4). Within each spray treatment there was greater coverage on wraps in the lower position than on wraps in the upper position ($P < 0.0001$). Air-blast sprayers produce fan-shaped spray clouds, much of which travels at an angle towards the ground (Zhu et al. 2008). Lower wraps benefit from this spray angle as well as from gravity, which pulls droplets towards the ground over distance. Constant-rate lower wrap coverage, 98.1%±0.2%, was higher than any other wrap location ($P < 0.0001$), followed by constant-rate upper wrap coverage, 94.7%±0.4% ($P = 0.0016$). Variable-rate lower wrap coverage, 89.9%±0.8%, was greater than variable-rate upper wrap coverage, 85.9%±1.1% ($P \leq 0.0001$), which had less coverage than all other wraps ($P < 0.0001$). The difference in coverage between treatments is likely accounted for by the greater volume sprayed in constant-rate mode, with wraps at both heights in the constant-rate treatment having greater coverage than those in the variable-rate treatments. Despite emitting nearly 60% more spray, wraps in the constant-rate treatment did not receive 100% coverage and had <10% greater coverage

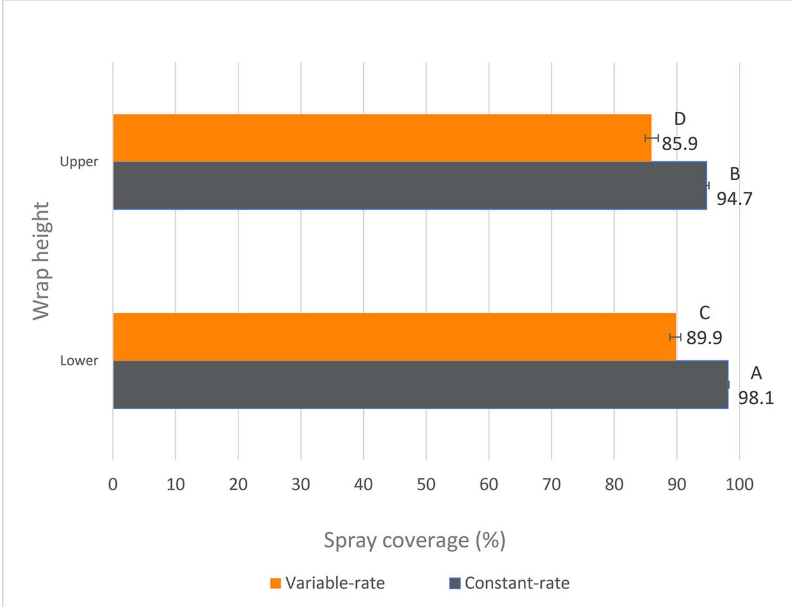

Fig. 4. Spray coverage on WSP wraps by height in the field experiment [spray treatment × wrap height (*P* 0.0002)] following constant-rate and variable-rate spray treatments. Means with different letters are significantly different, alpha = 0.05. Error bars signify standard error.

than their variable-rate counterparts at the same height. This is consistent with results from a series of 15 trunk application trials with a different air-blast sprayer in which increasing liters per hectare beyond a particular rate, in this case 366 $L{\cdot}ha^{-1}$ (146 $gal{\cdot}A^{-1}$), did not yield greater coverage (McKim et al. 2024). We hypothesized that 100% coverage with contact insecticides is required to control FHBs, which are levels that were not achieved by either treatment. However, further research is required to determine if levels of coverage below 100%, such as the 98.1% on constant-rate lower wraps, 89.9% on variable-rate lower wraps, or lower rates, would provide acceptable control of FHBs and effectively balance the cost of damage with the economic, societal, and ecological costs of pesticide applications.

The phenology of these insects presents management challenges. It is thought that females oviposit from mid-May to June with larvae entering trees about 15-20 days later (Oliver et al. 2019). Applications of contact insecticides must be timed so that larvae ingest a lethal dose as they begin to bore through tree bark (Potter et al. 1988). Upon hatching, larvae do not traverse the trunk surface prior to boring in (Frank et al. 2013), thus contact insecticide residue is essential. Further research on the timing of these events could help growers schedule sprays to align with vulnerable life stages and optimize protection. Furthermore, little is known about the reproductive habits of FHBs. For example, it is uncertain how many adult females are present when a field is infested, the number of trees upon which a female oviposits per season, or whether infestations are a result of local populations in infested fields or catalyzed by events that attract external females (Oliver et al. 2019). FHBs show a preference for the southern side of tree trunks at a height below 40 cm (Seagraves et al. 2013), in particular, where the stub or "cut back" is located (LeBude and Adkins 2014) and may be deterred by weeds or cover crops growing around trunks at this height (Addesso et al. 2020, Dawadi et al. 2019); however, the mechanisms behind these behaviors are unknown. Ongoing research suggests that container-grown trees placed in a field of weeds that has been treated with glyphosate may induce FHB attacks (Gonzalez et al. 2023). It is possible that using a bait tree in this manner could alleviate the need to achieve high coverage throughout entire production blocks, although it is still unknown how far adults travel in search of mates or suitable oviposition sites. Moreover, Oliver et al. (2010) suggests that attacks occur randomly throughout blocks. Finally, there is not currently a research-based threshold, be it for economic damage or population density, above which spraying crops for FHBs is recommended. Research into these life history traits and behaviors could help establish these thresholds and shape effective IPM programs.

Wraps: directional faces. There was a significant three-way interaction among treatment, wrap height, and wrap direction on percent coverage ($P = 0.0315$). The constant-rate treatment had greater coverage than the variable-rate treatment on wraps at any given wrap height and wrap direction combination ($P < 0.0001$, Figs. 5A and B). The differences in coverage between treatments ranged from 3.2% to 16.3%. In the upper wrap position, wraps in the constant-rate mode had more than 98.1% coverage on north and south faces, whereas east and west were lower, 90.2%±0.9%, and 91.8%±0.9 coverage, respectively. Constant-rate upper east wrap faces were not significantly different from constant-rate upper west faces ($P \geq 0.9795$) which were not different from variable-rate upper wraps facing north or south ($P \geq 0.1725$). Within the variable-rate treatment, upper east-facing wraps, 76.6%±1.5%, did not differ from upper west-facing wraps, 75.7%±2.5% ($P \geq 0.9999$) or lower east-facing wraps, 80.4%±1.3% ($P \geq 0.9997$). These wraps had the least coverage of any wraps in the field experiment ($P \leq 0.0190$). Coverage on upper wraps was not different for north- and south-facing wrap

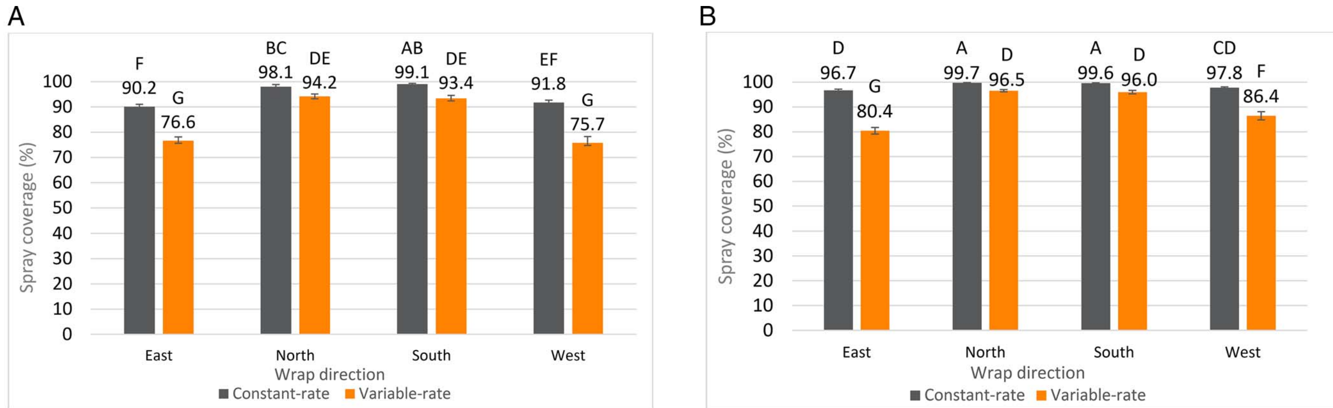

Fig. 5. Coverage on WSP wraps by directional face at the (A) upper wrap height and (B) lower wrap height in the field production block [treatment × wrap height × wrap direction ($P = 0.0325$)] following constant-rate and variable-rate spray treatments. Means with different letters are significantly different, alpha = 0.05. Error bars signify standard error.

positions within the constant-rate treatment ($P = 0.9611$), nor for the variable-rate treatment ($P = 1.0000$). Having the same orientation towards the spray cloud likely contributed to the similarity in coverage seen between north- and south-facing wraps, as well as the similarity between east- and west-facing wraps. Upper wraps on the north and south faces had greater coverage than east and west faces because north- and south-facing wraps were directly perpendicular to the direction of the spray cloud as the sprayer travelled down adjacent driveways.

As with upper wraps, the north and south positions on lower wrap faces had the highest coverage within each treatment. For constant-rate lower wraps, coverage did not differ between east- and west-facing wrap faces ($P = 0.9926$), nor did it differ between north- and south-facing wraps ($P = 1.0000$). Coverage also did not differ between lower north- and south-facing wraps in the variable-rate treatment ($P \geq 0.0590$).

Coverage for north- and south-facing upper wraps spanned 3.9 and 5.7 percentage points between treatments for wraps located at the same height. For upper wraps in the east- and west-facing positions, coverage differences due to spray treatment ranged from 13.6 to 16.1 percentages points. Some of these differences in coverage likely resulted from the larger volume emitted in the constant-rate treatment while some might be attributed to the difference in spray delivery between treatments. The larger volume emitted in the constant-rate mode produced a greater number of droplets available to penetrate rows of trees and contact WSP. When spraying in variable-rate mode, the spray needed to travel from the sprayer to the target each time spray nozzles were actuated in order to contact targets. In constant-rate mode, the spray was emitted in a steady stream meaning that droplets were already present at the distance of the target as the sprayer approached and needed only to be intercepted by wraps on the east and west side of trunks as the spray cloud moved across them.

In addition to spray coverage, WSP samples were also analyzed for deposit density (droplets·cm^{-2}). When measuring deposit density using DepositScan, the results may be artificially low when the percent coverage is high, due to the tendency of spots to coalesce (Nackley et al. 2021). Only the significant interactions and averages are reported for deposit density.

In the field experiment, there was a significant interaction between treatment and wrap height ($P = 0.0052$) with constant-rate lower wraps having 28±5.7 droplets·cm^{-2} and constant-rate upper wraps having 77±5.6 droplets·cm^{-2}. Variable-rate lower wraps averaged 114±5.6 droplets·cm^{-2} while variable-rate upper wraps averaged 126±5.6 droplets·cm^{-2}. These results are similar to what were observed with WSP cards placed in the canopy or in non-target locations, i.e., higher coverage in the lower wrap position lowers the deposit density compared to the upper wraps position due to increasing incidence of spots coalescing with greater coverage. All wraps except for constant-rate lower wraps exceeded the WSP manufacturer's recommended deposit density for foliar insecticide sprays (20-30 droplets·cm^{-2}). However, the actual deposit density is much greater due to coalescing spots, thus the true deposit density of the lower wraps in constant-rate mode met or exceeded the recommendations. The total wrap coverage obtained in this experiment was >85% on all wraps; however, it is uncertain whether these levels of coverage would be sufficient to control FHB, or if it exceeds necessary coverage. FHB larvae chew through their egg cases and directly into tree trunks (Frank et al. 2013), thus avoiding contact with pesticides applied on the leaf surface of trees. However, adults are mobile, consuming foliage and chewing on woody tissue in a variety of locations including branch crotches, the base of leaf petioles and around bud scars. If both newly hatched larvae and adult FHBs or, alternatively, solely adults are the target of preventative sprays, less than 100% coverage on trunks may be effective in their control, as adults may contact insecticide residue as they move across trunks and throughout production blocks.

Off-target WSP locations. Treatment did not affect coverage on WSP cards ($P = 0.3551$), likely because of the high application rate compared with a typical canopy application in which variable-rate often yields lower off-target coverage (Chen et al. 2013, Fessler et al. 2023b, Nackley et al. 2021). However, card location did affect coverage ($P < 0.0001$; Fig. 6). Cards in the BB position, i.e., boards between rows within the production block,

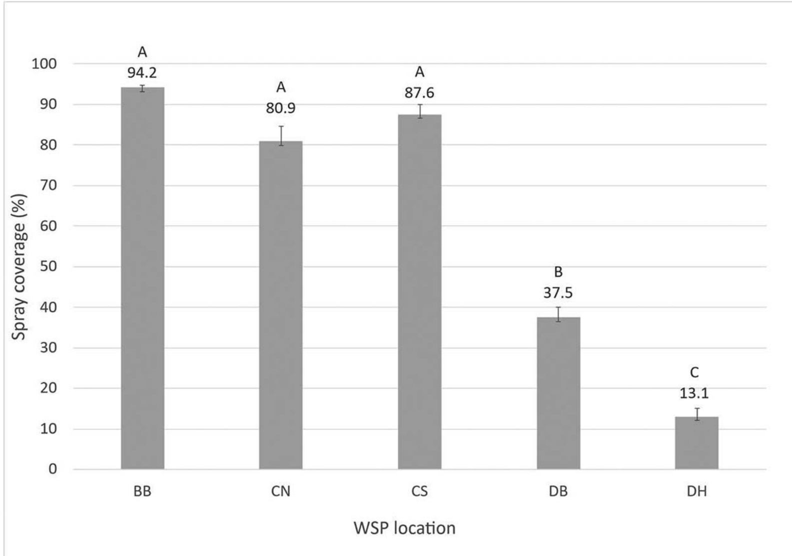

Fig. 6. Spray coverage on off-target water sensitive paper (WSP) locations ($P < 0.0001$) in the field production block following constant-rate and variable-rate spray treatments. Means with different letters are significantly different, alpha = 0.05. Error bars signify standard error. DH = Drift high, DB = Drift board, CN = canopy north, CS = canopy south, BB = within block board.

were not different from cards in the canopy south (CS) or canopy north (CN) positions ($P \geq 0.1273$), suggesting that off-target movement is somewhat evenly distributed between ground and this aerial location. Additionally, coverage levels on WSP cards were comparable to those in target (trunks) locations. The sprayer was operated with the top four nozzles closed to obtain maximum coverage on the trunks of trees, not tree canopies, yet cards in the canopy positions, generally on the lowest branch, averaged coverage of 80.9%±3.7% to 87.6%±2.5%. It is possible that both spray volume and non-target canopy coverage could be further reduced by closing more of the upper nozzles on the sprayer, however, doing so may reduce trunk coverage, especially on upper wrap faces that are not perpendicular to the spray cloud.

For these trunk sprays, individual nozzles were selected, and the angle of these nozzles was adjusted to aim lower than for foliar applications. Consequently, much of the spray was delivered at a height that was too low to be intercepted by the full height of tree canopies and at a volume too great to be entirely blocked by tree trunks. Off-target cards in the drift board (DB) position averaged 37.5%±2.4% coverage, less than BB, CN, and CS cards ($P < 0.0001$), but greater than aerial drift (Drift high; DH) cards 13.1%±2.0% ($P = 0.0140$). Coverage on non-target locations BB, CN, CS, and DB cards exceeded the overspray threshold (>30% coverage; Chen et al. 2013) for coverage on intended targets, indicating substantial off-target movement, yet no single wrap face from either treatment had 100% coverage despite the high liters per hectare sprayed in the constant-rate mode. The off-target coverage on DB cards is of particular concern as the similar coverage between treatments suggests that this coverage is not due to the difference in volume between treatments, but rather by the height and angle at which the bulk of the spray was delivered. Narrow tree trunks could not block enough of the spray at the rates used in this experiment to prevent it from travelling an additional 13 feet and contacting DB cards.

PNP experiment

Application volume. In the PNP experiment, treatment had a significant effect on total volume sprayed ($P = 0.0016$; Fig. 7). The constant-rate treatment emitted 383.5±4.1 liters (101.3±1.1 gal) per spray, 16% more than the variable-rate mode, which averaged 330.1±15.9 liters (87.2±4.2 gal) per spray. The constant-rate mode emitted a rate of almost 3650 L·ha^{-1} (391 gal·A^{-1}), nearly four times the recommended rate for nurseries (Zhu et al. 2006).

Prior research conducted using variable-rate technology found reductions of 30% to 80% compared to conventional spray technology for foliar applications (Chen et al. 2019, Fessler et al. 2021, Nackley et al. 2021, Zhu et al. 2017b). In a prior experiment in this same block albeit on a different crop of trees and targeting the canopy, there was a 43% reduction between variable-rate and constant-rate treatments (Fessler et al. 2023a). The 16% reduction found in this experiment falls outside of that range and may be due to a combination of factors including high density of plants that caused the sprayer to continuously discharge near the maximum when in variable-rate mode. Additional factors include discs and cores with a much higher maximum flow rate that caused the system to operate near the maximum pump capacity, greater fluid ounces per cubic foot of crop (base spray rate in the intelligent system), and a denser target. Previous studies found that when using variable-rate technology, the reduction in spray volume decreased as the growing season progressed due to tree canopies becoming larger and denser and consequently, the system detecting the need for and applying a greater spray volume (Boatwright et al. 2020, Chen et al. 2013, Nackley et al. 2021). While the sprayer was set to detect and spray tree trunks, the PNP production system contained twelve offset rows

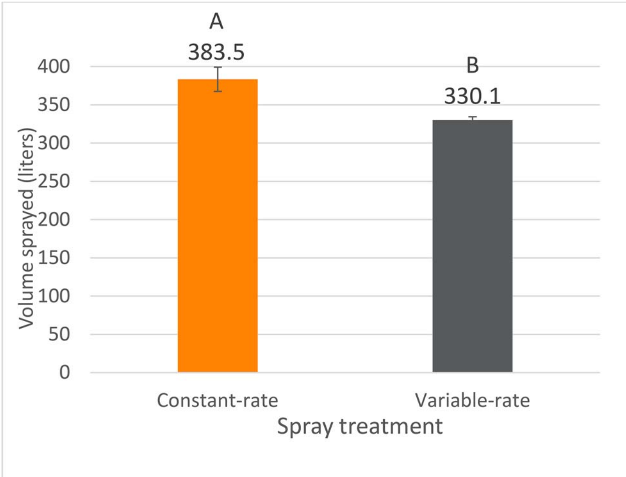

Fig. 7. Total volume applied in the constant-rate and variable-rate treatments in the pot-in-pot (PNP) production block (P = 0.0016). Means with different letters are significantly different, alpha = 0.05. Error bars signify standard error.

of trees grown closely together. In this high-density production system and with the selected sprayer settings, when in variable-rate mode, the sprayer would have detected not only the presence of many targets but also predominantly detected high density trunks. This, in combination with the greater maximum flow rate and spray rate, increased the volume sprayed, thus reducing the difference in volume between treatments.

Wraps: whole (intact). There was an interaction between treatment, wrap height, and row orientation on total coverage ($P = 0.0173$; Fig. 8). At the lower wrap height, coverage was not affected by treatment or row orientation ($P \geq 0.8631$). At the upper wrap height, constant-rate coverage, 68.7%±5.5%, and variable-rate coverage, 60.0%±5.4% on external rows were not different from one another ($P = 0.3099$), but both had greater coverage than wraps in the internal row treated with the variable-rate technology, 53.0%±4.2% ($P = 0.0066$).

Deposit density in the PNP experiment was affected by wrap height ($P = 0.0008$) and row orientation ($P < 0.0001$), there was no interaction between the two ($P = 0.4551$), nor was there a difference between treatments ($P = 0.3718$). Lower wraps had 81±4.9 droplets·cm^{-2} while upper wraps had 101±4.8 droplets·cm^{-2}. Internal wraps had 123±5.2 droplets·cm^{-2}, and external wraps averaged 59±5.2 droplets·cm^{-2}.

Less coverage on upper wrap positions and in interior rows was not unexpected as gravity pulled spray droplets down while the spray cloud moved across the block and some of the spray was intercepted by trees in rows closer to the sprayer before reaching internal rows. Wraps in the internal upper position were the most difficult for sprays to reach, as they were the most obstructed and the spray needed to travel a greater distance to contact them. By comparison, lower internal wraps benefitted not only from the effects of gravity, which pulled droplets towards the ground over distance, but also from the settings of the sprayer which had the two top nozzles closed. Operating with these nozzles closed reduced the volume of spray delivered at heights above the upper wraps and reduced the opportunity for interior upper wraps to benefit from gravity to the same degree as interior lower wraps.

Wraps: directional faces. There was an interaction between treatment, wrap direction, and row orientation ($P < 0.0001$) on wrap coverage (Figs. 9A and B). There was no difference in coverage between treatments at a given direction within a given row orientation ($P \geq 0.4302$) and east-, north-, and south-facing wraps were also not different across row orientations ($P = 0.2111$).

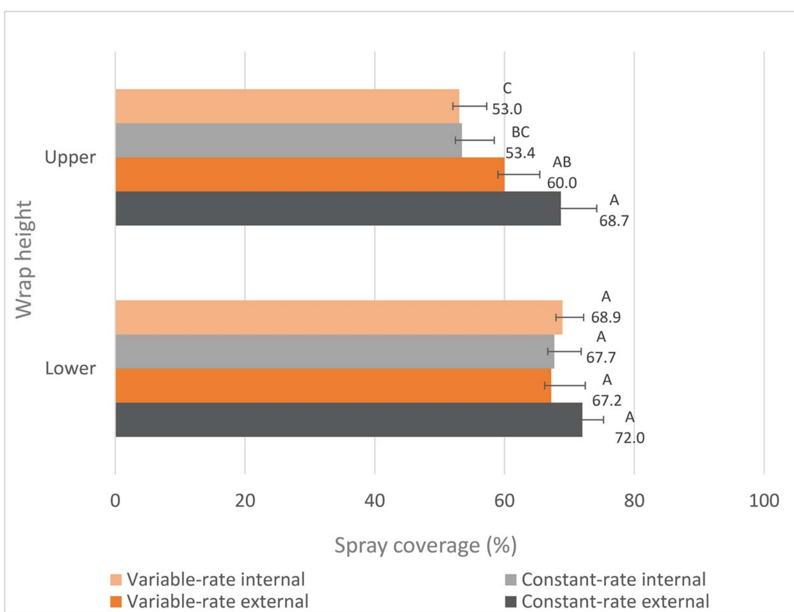

Fig. 8. Spray coverage by spray treatment and row at the lower and upper wrap heights in the PNP production block following constant-rate and variable-rate spray treatments [spray treatment × wrap height × row orientation (P = 0.0002)]. Means with different letters are significantly different, alpha = 0.05. Error bars signify standard error.

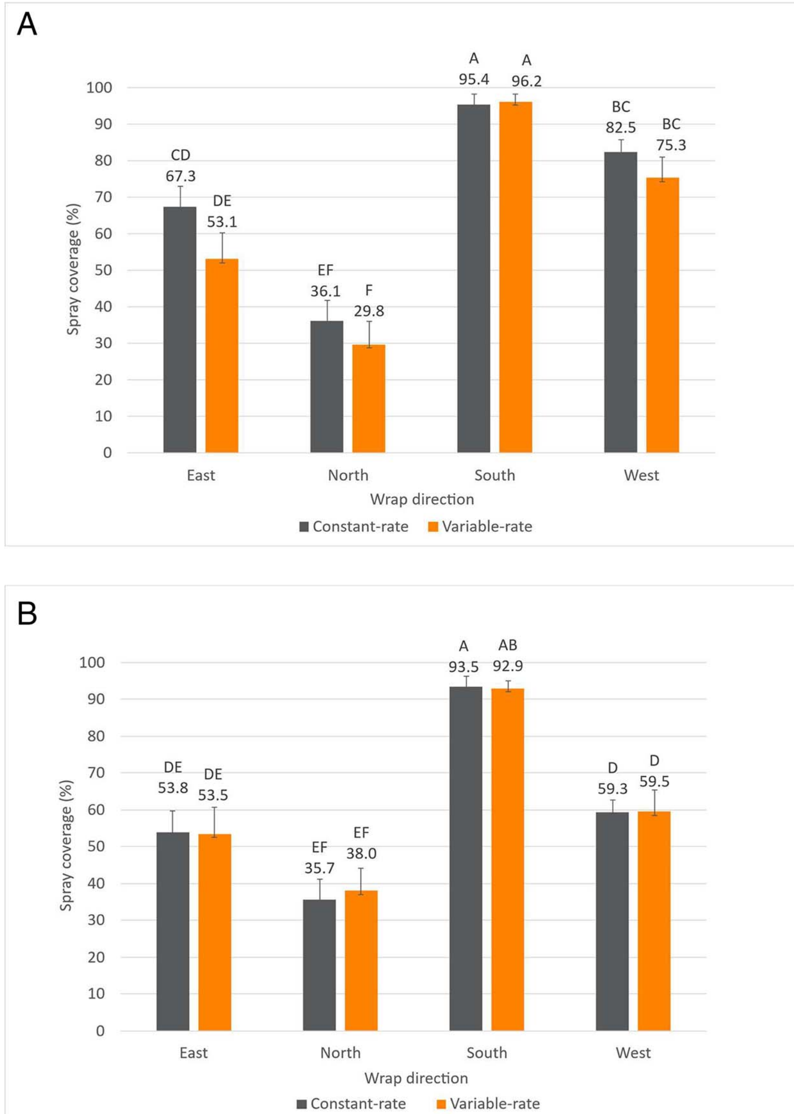

Fig. 9. WSP wrap coverage by spray treatment and directional face in (A) external and (B) internal rows in the PNP production block following constant-rate and variable-rate spray treatment [spray treatment × wrap direction × row orientation ($P < 0.0001$)]. Means with different letters are significantly different, alpha = 0.05. Error bars signify standard error.

Coverage on south-facing wraps did not vary with the treatment within a row orientation ($P = 0.9970$) or across row orientation ($P > 0.1414$). Treatments did not affect coverage for west faces of wraps within a given row orientation ($P = 1.0000$). However, west-facing wraps in the external row had greater coverage than west-facing wraps in the internal row ($P \leq 0.0099$) but were the same as internal south-facing variable-rate wraps ($P = 0.4550$). West is the only wrap direction for which coverage differed across row orientation. West-facing wraps had more coverage than north-facing wraps ($P = 0.0109$), regardless of row orientation or treatment. This pattern of coverage on the south- and west-facing sides was not unexpected. Compared to wraps on the same directional face in internal rows, south-facing wraps in the external row benefited from their proximity to the sprayer as did external west-facing wraps. The sprayer traveled from west to east down the southern driveway which was directly adjacent to trees in the external row. To contact the south and west faces of external wraps, the spray cloud had a short, relatively direct route. Coverage was generally lower on external trees on the north and east sides as well as on the north, east, and west sides of internal rows.

Coverage for north-facing wraps in the external row was not different from north-facing wraps in the internal row ($P \geq 0.9982$). North-facing wraps received the least coverage as these wraps faced away from the sprayer while it sprayed from the south and were obstructed by other trees in production when spraying from the north. To reach north-facing wraps, the spray needed to travel unimpeded and penetrate 6 to 12 rows of trees. However, the spray only needed to travel a short, unimpeded distance, to reach exterior southern wrap faces and across or through five rows of trees to reach interior southern wrap faces. East-facing and west-facing wraps had two opportunities to be sprayed, as they were parallel to the sprayer as it travelled down each driveway, whereas north-facing wraps were located on the distal side of trunks, facing away from the

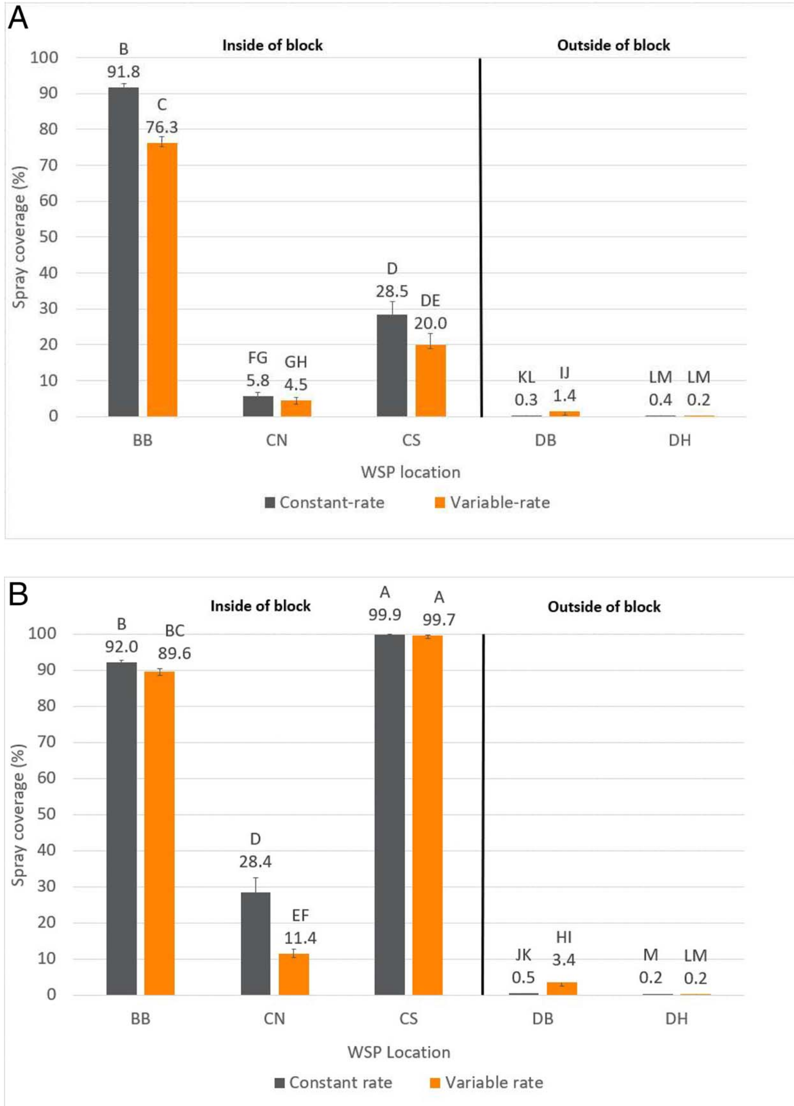

Fig. 10. Coverage on off-target water sensitive paper (WSP) locations within and outside the production block and associated with (A) external and (B) internal rows of the PNP production blocks following constant-rate and variable-rate spray treatment [spray treatment × row orientation ($P < 0.0001$)]. Means with different letters are significantly different, alpha = 0.05. Error bars signify standard error. DH = Drift high, DB = Drift board, CN = canopy north, CS = canopy south, BB = within block board.

sprayer as it travelled down the southern driveway. Additionally, the northern half of the block contained Nuttall oaks which might have intercepted more of the spray from the northern driveway than the Northern red oaks in the southern block as they were larger and had denser canopies.

Off-target WSP locations. There was a significant interaction between treatment and row orientation on WSP card coverage (P-value <0.0001; Fig. 10). There were four card locations for which treatment affected coverage. Within the external rows, variable-rate BB cards had less coverage, 76.3%±1.8% ($P = 0.0025$) than constant-rate BB cards, 91.8%±1.0%. Variable-rate external BB cards had less coverage than constant-rate BB cards in the internal row, 92.05%±0.78% ($P = 0.0060$). This could be due in part to the reduced volume emitted by the variable-rate mode and partially due to the sprayer turning on and off between trees when operating in variable-rate mode, especially along the southern driveway when the sprayer was close to external BB cards. This reduction in coverage on BB cards when operating in variable-rate mode aligns with results from Nackley et al. (2021), which found a similar reduction coverage when spraying WSP cards in both modes in both a vineyard and an apple orchard.

Constant-rate CN cards in the internal row had greater coverage than all other CN cards ($P \leq 0.0032$). The increased volume from the constant-rate mode likely contributed to this difference. Constant-rate and variable-rate CS cards in the internal row had greater coverage than all other internal and external card locations ($P < 0.0001$), including more than 70 percentage points greater coverage than internal CN cards. The difference between rows was due to the internal row minimizing distance to the sprayer from both driveways, while the difference between CN and CS cards is likely due to the size and density of the tree canopies in the northern block. Spray delivered from the northern driveway needed to penetrate six rows of dense canopy compared to spray delivered to internal CS cards, which needed to travel through five rows of less dense foliage. Additionally, internal CS cards as well as internal BB cards from both treatments had >89% coverage, and south wraps from both treatments in both rows had $\geq$92% coverage. This supports that spray was present between the ground and canopy cards at a height appropriate to contact trunk wraps. Likewise, within external rows, the presence of spray on BB and CN cards supports that the angle of the spray was appropriate for the target (trunk). However, the spray appears to have been largely below the CN card given the low percent coverage, i.e., <6.0%.

Within each treatment, coverage on DB cards was not affected by row orientation ($P \geq 0.2498$). Variable-rate external DB cards were also not different from constant-rate internal DB cards ($P = 1.0000$). Coverage on WSP cards in DH locations was not affected by row orientation or treatment ($P = 1.0000$). Coverage was generally lower than that reported on drift cards (0.9-3.9%) located in a comparable position in a study by Fessler et al (2023a). That study examined foliar applications, however, and the spray nozzles were aimed higher than in the present study.

Within the production block, variable-rate treatment reduced off-target movement. Outside of the production block, variable-rate treatment increased off-target coverage to the ground. However, all airborne and ground drift cards outside of the block had very low coverage, i.e., 0.2-3.4%. Variable-rate sprays were subjected to modestly higher average windspeeds [2.68 $m \cdot s^{-1}$ (1.2 mph) and 3.8 $m \cdot s^{-1}$ (1.7 mph)] than the constant-rate runs [0.56 $m \cdot s^{-1}$ (0.25 mph) and 3.8 $m \cdot s^{-1}$ (1.7 mph)], which could have contributed to the differences in coverage on ground cards in the drift row (DB). Zhu et al. (2006) found that wind had more influence on ground spray deposits than spray method when examining the spray patterns of air-blast sprayers using air-induction nozzles, hollow cone nozzles, and hollow cone nozzles with a drift retardant.

In conclusion, for the field experiment, the constant-rate treatment emitted a 59% greater volume of spray and achieved greater coverage on trunk wraps than the variable-rate treatment by 3.2 to 16.3 percentage points depending on directional face. Coverage was generally similar between spray treatments for both wraps and cards in the PNP experiment despite the variable-rate mode emitting 16% less spray. However, neither experiment achieved the intended 100% coverage on trunks. Further, the results suggest it is improbable that 100% trunk coverage can be achieved with the crop size, block layout and sprayer used in the PNP experiment, even when spraying high volumes, i.e., 3,657 $L \cdot ha^{-1}$ (391 $gal \cdot A^{-1}$) regardless of sprayer mode. Research is needed to explore trunk applications using other sprayer types and in different production block spacings to establish the potential to achieve high coverage trunk sprays from means other than manual applications with backpack sprayers. Additionally, the requirement for, and the specific percent threshold of, high coverage applications needs to be better defined. For example, the coverage required to control flatheaded borers is assumed to be 100% because of larval behavior upon egg hatch and the significant damage from as little as one larva per tree, but that has not been established empirically. Future research should determine the role that pesticide distribution, possibly utilizing deposit density, plays in control of flatheaded and other borers when applying contact insecticides as well the potential for control of gravid females prior to oviposition. Finally, in this study, water alone was applied to WSP artificial targets. While this practice was according to WSP manufacturer guidelines, it may contribute to underestimating trunk coverage. Surfactants increase the spread of liquids and are commonly used in spray applications to increase coverage. Moreover, adding a surfactant to the spray tank could increase both trunk and WSP coverage, potentially enabling 100% coverage to be achieved depending on crop size and production block configuration.

Literature Cited

Addesso, K.M., J.B. Oliver, N.N. Youssef, and D.C. Fare. 2020. Evaluation of systemic imidacloprid and herbicide treatments on flatheaded borer (Coleoptera: Buprestidae) management in field nursery production. J. Econ. Entomol. 113(2):2808–2819. https://doi.org/10.1093/jee/toaa228.

Bethke, J.A. and R.A. Cloyd. 2009. Pesticide use in ornamental production: What are the benefits? Pest Manage. Sci. 65(4):345–350. https://doi.org/10.1002/ps.1695.

Boatwright, H., H. Zhu, A. Clark, and G. Schnabel. 2020. Evaluation of the intelligent sprayer system in peach production. Plant Dis. 104(12):3207–3212. https://doi.org/10.1094/Pdis-04-20-0696-Re.

Cerruto, E., G. Manetto, D. Longo, and S. Failla. 2019. A model to estimate the spray deposit by simulated water sensitive papers. Crop Prot. 124:104861. https://doi.org/10.1016/j.cropro.2019.104861.

Chen, L.M., M. Wallhead, M. Reding, L. Horst, and H. Zhu. 2020. Control of insect pests and diseases in an Ohio fruit farm with a laser-guided intelligent sprayer. HortTechnology. 30(2):168–175. https://doi.org/10.21273/Horttech04497-19.

Chen, L.M., M. Wallhead, H. Zhu, and A. Fulcher. 2019. Control of insects and diseases with intelligent variable-rate sprayers in ornamental nurseries. J. Environ. Hort. 37(3):90–100. https://doi.org/10.24266/0738-2898-37.3.90.

Chen, L.M., H. Zhu, L. Horst, M. Wallhead, M. Reding, and A. Fulcher. 2021. Management of pest insects and plant diseases in fruit and nursery production with laser-guided variable-rate sprayers. HortScience 56(1):94–100. https://doi.org/10.21273/Hortsci15491-20.

Chen, Y., H. Zhu, and H.E. Ozkan. 2012. Development of a variable-rate sprayer with laser scanning sensor to synchronize spray outputs to tree structures. Trans. ASABE. 55(3):773–781. https://doi.org/10.13031/2013.41509.

Chen, Y., H. Zhu, H.E. Ozkan, R.C. Derksen, and C.R. Krause. 2013. Spray drift and off-target loss reductions with a precision air-assisted sprayer. Trans. ASABE. 56(6):1273–1281. https://doi.org/10.13031/trans.56.10173.

Dawadi, S., J.B. Oliver, P. O'Neal, and K.M. Addesso. 2019. Management of flatheaded appletree borer (Chrysobothris femorata Olivier) in woody ornamental nursery production with a winter cover crop. Pest. Manage. Sci. 75(7):1971–1978. https://doi.org/10.1002/ps.5310.

Ehler, L.E. 2006. Integrated pest management (IPM): Definition, historical development and implementation, and the other IPM. Pest Manage. Sci. 62(9):787–789. https://doi.org/10.1002/ps.1247.

Fessler, L., A. Fulcher, D. Lockwood, W. Wright, and H. Zhu. 2020. Advancing sustainability in tree crop pest management: Refining spray application rate with a laser-guided variable-rate sprayer in apple orchards. HortScience 55(9):1522–1530. https://doi.org/10.21273/Hortsci15056-20.

Fessler, L., A. Fulcher, L. Schneider, W.C. Wright, and H. Zhu. 2021. Reducing the nursery pesticide footprint with laser-guided, variable-rate spray application technology. HortScience 141(2):1572–1584. https://doi.org/10.21273/HORTSCI16157-21.

Fessler, L., D. Lockwood, W. Wright, G. Pietsch, X. Sun, W. Yeary, H. Zhu, T. Bordeau, L. Russo, and A. Fulcher. 2023a. Intelligent spray technology to control pests in nursery and orchard systems with reduced pesticide application rates. Acta Hortic. 1360:151–176. https://doi.org/10.17660/ActaHortic.2023.1360.20.

Fessler, L., G. Pietsch, W. Wright, H. Zhu, S. Xiaocun, and A. Fulcher. 2023b. Characterizing spray deposits from variable- and constant-rate spray technologies: Implications for future optimization to target trunk and foliar pests. Acta Hortic. 1360:267–290. https://doi.org/10.17660/ActaHortic.2023.1360.34.

Fessler, L., W. Wright, G. Pietsch, L. Schneider, H. Zhu, C. Fust, and A. Fulcher. 2023c. Characterizing spray deposits for control of trunk pests from an experimental air-blast sprayer with 5-port nozzle bodies. Acta Hortic. 1378:203–218. https://doi.org/10.17660/ActaHortic.2023.1378.28.

Fessler, L., X. Sun, W.C. Wright, H. Zhu, and A. Fulcher. 2023d. Intelligent, variable-rate spray technology reduces total pesticide output while controlling foliar disease of Shumard oak. J. Environ. Hort. 41(3):109–120. https://doi.org/10.24266/0738-2898-41.3.109.

Frank, S.D., W.E. Klingeman, S.A. White, and A. Fulcher. 2013. Biology, injury, and management of maple tree pests in nurseries and urban landscapes. J. Integr. Pest Manage. 4(1):B1–B14. https://doi.org/10.1603/IPM12007.

Frank, S.D. and C.S. Sadof. 2011. Reducing insecticide volume and nontarget effects of ambrosia beetle management in nurseries. Econ. Entomol. 104(6):1960–1968. https://doi.org/10.1603/EC11124.

Fulcher, A., A.L. Rihn, L.A. Warner, A. LeBude, S. Schexnayder, J.E. Altland, N. Bumgarner, S.C. Marble, L. Nackley, M. Palma, M. Velandia, H. Zhu, H. Gan, and J.S. Owen. 2023. Overcoming the nursery industry labor shortage: A survey of strategies to adapt to a reduced workforce and automation and mechanization technology adoption levels. HortScience 58(12):1513–1525. https://doi.org/10.21273/HORTSCI17230-23.

Gonzalez, A., J.B. Oliver, C.L. Perkovich, K.M. Addesso, and J. Lee. 2023. Evaluation of winter cover crop methods for management of flatheaded appletree borer (Coleoptera: Buprestidae). J. Econ. Entomol. 116(4):1268–1275. https://doi.org/10.1093/jee/toad090.

Grella, M., P. Marucco, M. Manzone, M. Gallart, and P. Balsari 2017. Effect of sprayer settings on spray drift during pesticide application in poplar plantations (*Populus* spp.). Sci. Total Environ. 578:427–439. https://doi.org/10.1016/j.scitotenv.2016.10.205.

Kasner, E.J., R.A. Fenske, G.A. Hoheisel, K. Galvin, M.N. Blanco, E.Y.W. Seto, and M.G. Yost. 2018. Spray drift from a conventional axial fan airblast sprayer in a modern orchard work environment. Ann. Work Expos. Heal. 62(9):1134–1146. https://doi.org/10.1093/annweh/wxy082.

LeBude, A. and C. Adkins. 2014. Incidence and severity of buprestid infestation in field-grown *Acer platanoides* related to cardinal orientation of understock bud union. J. Environ. Hort. 32(4):215–218. https://doi.org/10.24266/0738-2898.32.4.215.

LeBude, A., S.A. White, A. Fulcher, S. Frank, W.E. Klingeman, J.-H. Chong, M. Chappell, A. Windham, K. Braman, F. Hale, W. Dunwell, J. Williams-Woodward, K. Ivors, C. Adkins, and J. Neal. 2012. Assessing the integrated pest management practices of Southeastern U.S. apple ornamental nursery operations. Pest Manage. Sci. 68:1278–1288. https://doi.org/10.1002/ps.3295.

Manandhar, A., H. Zhu, E. Ozkan, and A. Shah. 2020. Techno-economic impacts of using a laser-guided variable-rate spraying system to retrofit conventional constant-rate sprayers. Precision Agric. 21(5):1156–1171. https://doi.org/10.1007/s11119-020-09712-8.

McKim, K., L. Whaley, L. Slade, D. Lockwood, C. Fust, H. Zhu, and A. Fulcher. 2024. Factors affecting spray coverage on red maple trunks from an air-assisted sprayer. HortScience 59(9S):S352. https://doi.org/10.21273/HORTSCI.59.9S.S1.

McKim, K., L.F. Mathews, H. Zhu, W.C. Wright, G. Pietsch, and A. Fulcher. 2025. Using water sensitive paper to assess and refine pesticide applications: A guide for producers, Extension professionals, and researchers. University of Tennessee Extension Publication (in press).

Nackley, L.L., B. Warneke, L. Fessler, J.W. Pscheidt, D. Lockwood, W.C. Wright, X. Sun, and A. Fulcher. 2021. Variable-rate spray technology optimizes pesticide application by adjusting for seasonal shifts in deciduous perennial crops. HortTechnology 31(4):479–489. https://doi.org/10.21273/Horttech04794-21.

Oliver, J.B., K.M. Addesso, D.C. Fare, F. Baysal-Gurel, A. Witcher, N.N. Youssef, J. Basham, B. Moore, and P. O'Neal. 2019. Flatheaded appletree borer ecology and knowledge gaps. Proc. Flatheaded Borer Workshop. 1:12–24.

Oliver, J.B., D.C. Fare, N.N. Youssef, M.E. Reding, C.M. Ranger, J.J. Moyseenko, and M.A. Halcomb. 2010. Evaluation of a single application of neonicotinoid and multi-application contact insecticides for flatheaded borer management in field grown red maple cultivars. J. Environ. Hort. 28(3):135–149. https://doi.org/10.24266/0738-2898-28.3.135.

Perdomo, C. 2023. Nursery and garden stores in the US. https://my.ibisworld.com/us/en/industry/44422/at-a-glance. Accessed 19 September 2023.

Pimentel, D. 2005. Environmental and economic costs of the application of pesticides primarily in the United States. Environ. Dev. Sustain. 7:229–252. https://doi.org/10.1007/s10668-005-7314-2.

Popp, J., K. Pető, and J. Nagy. 2012. Pesticide productivity and food security. A review. Agron. Sustain. Dev. 33(1):243–255. https://doi.org/10.1007/s13593-012-0105-x.

Potter, D., M. Timmons, and F. Gordon. 1988. Flatheaded apple tree borer (Coleoptera: Buprestidae) in nursery-grown red maples: Phenology of emergence, treatment timing, and response to stressed trees. J. Environ. Hort. 6(1):18–22. https://doi.org/10.24266/0738-2898-6.1.18.

Rihn, A.L., M. Velandia, L.A. Warner, A. Fulcher, S. Schexnayder, and A. LeBude. 2022. Factors correlated with the propensity to use automation and mechanization by the US nursery industry. Agribusiness 39(1):110–130. https://doi.org/10.1002/agr.21763.

Rose, A. 2023. Plant and flower growing in the US. https://my.ibisworld.com/us/en/industry/11142/at-a-glance. [accessed 19 September 2023].

Salcedo, R., H. Zhu, E. Ozkan, D. Falchieri, Z.H. Zhang, and Z.M. Wei. 2021. Reducing ground and airborne drift losses in young apple orchards with PWM-controlled spray systems. Comput. Electron. Agric. 189. https://doi.org/10.1016/j.compag.2021.106389.

Salcedo, R., H. Zhu, Z.H. Zhang, Z.M. Wei, L.M. Chen, E. Ozkan, and D. Falchieri. 2020. Foliar deposition and coverage on young apple trees with PWM-controlled spray systems. Comput. Electron. Agric. 178. https://doi.org/10.1016/j.compag.2020.105794.

Seagraves, B.L., C.T. Redmond, and D.A. Potter. 2013. Relative resistance or susceptibility of maple (*Acer*) species, hybrids and cultivars to six arthropod pests of production nurseries. Pest Manage. Sci. 69(1):112–119. https://doi.org/10.1002/ps.3375.

Shen, Y., H. Zhu, H. Liu, Y. Chen, and E. Ozkan. 2017. Development of a laser-guided, embedded-computer-controlled, air-assisted precision sprayer. Trans. ASABE. 60(6):1827–1838. https://doi.org/10.13031/trans.12455.

Walgenbach, J., M. Parker, T. Kon, S. Villani, W. Mitchem, and D. Lockwood, editors. 2024. Integrated orchard management guide for commercial apples in the Southeast. North Carolina Cooperative Extension Service AG-472. 106 p.

Zhu, H., R.C. Derksen, H. Guler, C.R. Krause, and H.E. Ozkan. 2006. Foliar deposition and off-target loss with different spray techniques in nursery applications. Trans. ASABE. 49(2):325–334. https://doi.org/10.13031/2013.20400.

Zhu, H., H. Liu, Y. Shen, H. Liu, and R.H. Zondag. 2017a. Spray deposition inside multiple-row nursery trees with a laser-guided sprayer. J. Environ. Hort. 35(1):13–23. https://doi.org/10.24266/0738-2898-35.1.13.

Zhu, H., R. Rosetta, M.E. Reding, R.H. Zondag, C.M. Ranger, L. Canas, A. Fulcher, R.C. Derksen, H.E. Ozkan, and C.R. Krause. 2017b. Validation of a laser-guided variable-rate sprayer for managing insects in ornamental nurseries. Trans. ASABE. 60(2):337–345. https://doi.org/10.13031/trans.12020.

Zhu, H., M. Salyani, and R.D. Fox. 2011. A portable scanning system for evaluation of spray deposit distribution. Comput. Electron. Agr. 76(1):38–43. https://doi.org/10.1016/j.compag.2011.01.003.

Zhu, H., R.H. Zondag, R.C. Derksen, M. Reding, and C.R. Krause. 2008. Influence of spray volume on spray deposition and coverage within nursery trees. J. Environ. Hort. 26(1):51–57. https://doi.org/10.24266/0738-2898-26.1.51.