Spray deposition inside multiple-row nursery trees with a laser-guided sprayer

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Abstract

Multiple-row container-grown trees require specially designed sprayers to achieve efficient spray delivery. A five-port air-assisted sprayer with both automatic and manual control modes was developed to discharge adequate spray deposition inside multiple-row trees. The sprayer resulted from integration of a high-speed laser-scanning sensor with a sophisticated nozzle flow control system, an embedded computer with a touch screen, a Doppler speed sensor, a specially-designed algorithm and an air-assisted sprayer base. It was able to detect target tree presence and measure target tree size, shape and leaf density. The sprayer then controlled the spray output of each nozzle to match tree structures. The sprayer was tested for its sprayer deposition quality inside canopies in a four-row willowy silver linden (Tilia tomentosa ‘Sterling Silver’ Moench) field and another six-row northern red oak (Quercus rubra L.) field. Tests were conducted with the sprayer in variable-rate application (VRA) and constant-rate application (CRA) modes. The average spray deposition on foliage of trees was 1.37±0.47 µL cm⁻² from VRA and 1.29±0.42 µL cm⁻² from CRA in linden, and was 2.15±0.57 µL cm⁻² from VRA and 2.72±0.94 µL cm⁻² from CRA in red oak, respectively. In comparison, spray coverage on foliage of trees was 19.8±3.0% from VRA and 20.9±4.3% from CRA in the linden trial, and was 27.9±3.7% from VRA and 30.5±5.4% from CRA, respectively, in the red oak trial. The newly developed air-assisted sprayer in both VRA and CRA modes would be able to discharge adequate spray deposition inside multiple-row tree plants while conserving pesticide.

Significance to the Horticulture Industry

There is much more variability in tree architectures in ornamental nurseries than in tree fruit production. However, sprayers used in nurseries are adopted from other crops. Hence, the spray efficiency is very low. Specially designed sprayers are needed to improve pesticide application efficiency and reduce excess pesticide waste, thus improving the environment. In this research, the five-port automatic sprayer designed and evaluated for multiple-row container nursery crops demonstrated significant reduction in spray volume while providing adequate spray deposition and coverage inside canopies, thereby offering an environmentally responsible spray technology for the nursery industry to protect crops against damage from insects and diseases.

Introduction

The nursery industry generates significant revenue in crop production. Sale of nursery stock reached over five billion dollars in the United States in 2012 (USDA 2014). One factor influencing revenue for individual growers is how many plants can be grown per unit of area. A denser planting is desirable due to the potential to increase revenue. For production of woody ornamentals, there is a balance between planting density and accessibility for cultivation. It must be possible for equipment such as farm tractors to access trees and shrubs in the field for pesticide application, digging, and other cultural practices. Leaving room for a tractor to drive between each planted row maximizes access to plants but does not efficiently use land.

Current recommendations suggest alternating between two planting rows and a single drive row (LeBude et al., 2007; Bilderback et al. 2013). This multiple-row planting has the advantage of maximizing the number of plants that can be grown in a given area (Mantinger 2000). Bilderback et al. (2013) suggested growers who want even more plants per unit of area can plant as many as four to six rows between drive rows, although this has the disadvantage of further limiting access for digging and pesticide application.

Application of pesticides is essential to the production of woody ornamentals that meet customers’ quality expectations. An important problem in nurseries is managing the wide variety of insect and disease pests (Gambrell 1938, Schuh and Mote 1948). Plant species relatively resistant to pest problems in maturity fall victim to pests in their early years. Seagraves et al. (2012) found maple (Acer) species, although relatively pest free in maturity, are susceptible to various arthropod pests in nursery settings. Plants free of pest damage are more marketable than those that have damage from insect feeding or otherwise stressed. As a result, the United States greenhouse and nursery industries use a combined 2.8 million pounds of active ingredient (Hudson et al. 1996). Any reduction in this pesticide use should have a positive effect on the environment.
Radial air-assisted sprayers are commonly used to deliver chemicals to multiple-row plants for pest control in ornamental nurseries but spray deposition uniformity inside canopies varies greatly across tree heights (Derkseken et al. 2004, 2006; Krause et al. 2004, Zhu et al. 2006b 2008). To ensure adequate spray deposition at all locations inside canopies, air-blast sprayers must consume excessive amounts of spray, resulting in pesticide waste. In addition, sufficient penetration of dense canopies using conventional sprayers, especially in the case of multi-row plantings is difficult to achieve (Derkseken et al. 2006, Sutton and Unrath, 1988 Travis et al., 1987, Zhu et al. 2011).

There are much more variabilities in tree structures in ornamental nurseries than in tree fruit production. However, sprayers used in nurseries are adopted from other crops. Hence, the spray efficiency is very low. Specially designed sprayers are needed to deliver uniform spray coverage in multiple-row nursery plants to improve pesticide application efficiency and reduce pesticide waste to the environment (Zhu et al. 2006a).

A laser-guarded air-assisted sprayer was developed for tree crop applications (Chen et al. 2012). This sprayer consists of four five-port manifolds at each side of the sprayer. The four manifolds are arranged equidistant in the vertical direction. Each manifold consists of five nozzles coupled with pulse width modulated (PWM) solenoid valves that produce fan-shaped spray patterns. A high-speed laser-scanning sensor enables the sprayer to adjust application rate based on plant structure, canopy volume, and foliage density. The sprayer is capable of spraying where and when chemicals are needed. This sprayer has produced more uniform spray deposits inside canopies and used 27 to 53 percent of the spray mixture compared with conventional constant-rate air-blast sprayers (Chen et al. 2013). The sprayer was later modified with an improved laser sensor, algorithm and control system (Zhu 2014).

Chen et al. (2013) evaluated spray performance for the laser-guarded air-assisted sprayer for single row crops. The objective of this research was to evaluate spray deposition distribution for the newly modified laser-guided air-assisted sprayer in a nursery setting with multiple-row container-grown plants. Both automatic and manual control functions were evaluated. The desired outcome is a new spray system for multiple-row ornamental nurseries capable of efficient and adequate pesticide application.

Materials and Methods

Sprayer for tests. The experimental laser-guided, air-assisted, variable-rate sprayer was designed and built in the USDA-ARS Application Technology Research Unit, OARDC at Wooster, Ohio. The sprayer was modified from our previous experimental sprayer (Chen et al. 2012). Modifications included use of a high-speed, 270° radial and 30-m range laser scanning sensor (UTM-30LX, Hokuyo Automatic CO., LTD, Japan) in conjunction with a non-contact Doppler radar travel speed sensor (Radar III, Dickey-John Co., Springfield, IL, USA), a sophisticated automatic nozzle flow rate controller (Liu et al. 2014), an embedded computer, a touch screen, and 40 variable-rate nozzles coupled with PWM solenoid valves on a multi-port air-assisted delivery system (Fig. 1). The base of the laser-guided sprayer mainly consisted of an axial turbine fan, a 400 L spray tank, and a diaphragm pump.

The laser-scanning sensor, which was mounted between the tractor and sprayer, detected the return distance signals of the bilateral tree structure. An algorithm, written in C++ language and stored in the embedded computer, translated these distance signals along with the sprayer travel speed into 3-dimensional tree surface structures, estimated canopy volume, and calculated the amount of spray for each nozzle. All 40 nozzles (20 nozzles on each side of the sprayer) were controlled independently to discharge variable flow rates to their designated canopy sections. Nozzles were modified from XR 8004 flat-fan tips (Zhu et al. 2006a) and operated at pressures in a range of 240 to 310 kPa (35 to 45 PSI) when the 40 nozzles were performing variable rates. The volume median diameter of droplets discharged from the nozzles was 223 μm. The flow rate of each nozzle was automatically determined in compliance with its designated sectional canopy volume and a pre-determined spray solution rate. The sprayer had a function to choose the pre-determined spray rate, which was the amount of spray solution required to cover a cubic meter of canopy volume (Chen et al. 2012). For this application, the pre-determined rate was 0.06 L m⁻³ (0.06 fl oz ft⁻²) because 0.06 to 0.10 L m⁻³ could cover canopies to the point of runoff (Pergher 1995).

With this design, the sprayer was able to characterize the presence, size, shape, and foliage density of target trees and accommodate the sprayer travel speed to automatically apply appropriate, variable amounts of pesticides based on tree canopy volume in real time. Another precaution included a flat jet mounted on the top of the laser sensor that provided an air stream from the sprayer fan to prevent dust and droplet contaminations landing on the laser scanning sensor surface. The sprayer also had a manual control mode that enabled the sprayer to become a conventional air-assisted sprayer to discharge at constant application rates. Detailed descriptions of the sprayer were reported by Zhu (2014).

To evaluate spray deposition inside canopies with variable-rate application (VRA) and constant-rate applications (CRA), the same sprayer was tested with and without the automatic control functions. Thus, two sprayer treatments were included in the tests: VRA for the sprayer with an active automatic control function, and CRA for the same sprayer with the automatic control functions disabled. During the tests with CRA, all 20 nozzles at one side were activated with a total output of 24.0 L min⁻¹ (6.3 gal min⁻¹) discharged from the sprayer which was operated at 240 kPa pressure (35 PSI), and travelled at 5.6 km h⁻¹ speed (3.5 MPH).

Field tests. There were two separate plots selected for the tests. Each plot was 72 m (236 ft) long and 7.8 m (26 ft) wide (Fig. 2). The first plot (Plot #1) consisted of four rows of sterlimg silver linden trees grown in 95.2 L (25 gal) containers, and the second plot (Plot #2) consisted of six rows of 3-year old northern red oak trees grown in 26 L (7 gal) containers. All trees were placed in a pot-in-pot production system. Space between the two rows was 1.52
m (5 ft) in Plot #1 and 1.28 m (4 ft) in Plot #2. Also, space between two trees in the same row in Plot #1 and #2 was 1.52 m (5 ft) and 0.91 m (3 ft), respectively. Tests were conducted when trees were at the full-foliage growth stage. The average tree height, lowest branch height, maximum tree width, caliper at 0.20 m (0.6 ft) above the ground, and leaf area index were 3.4±0.5 m, 1.1±0.1 m, 1.2±0.4 m, 6.1±7 mm, and 3.00±0.96 in Plot #1, and 2.3±0.2 m, 1.0±0.1 m, 0.7±0.1 m, 2.3±3 mm, and 1.21±0.45 in Plot #2, respectively. The leaf area indexes were measured with a plant canopy analyzer (Model # LAI-2000, LI-COR Biosciences, Lincoln, NE) with two optical sensors (Gu et al. 2014).

Each plot was evenly divided into three 24-m (79 ft) long blocks for both VRA and CRA treatments (Fig. 2). The first 5 m (16 ft) section of each test block was used for sprayer acceleration, the middle 14 m (46 ft) section for spray deposition samples, and the last 5 m (16 ft) section for sprayer deceleration. The sprayer started to discharge droplets at the beginning and stopped at the end of each block. Each plot was sprayed from both sides for each spray run, and three spray runs were conducted to present three replications for each VRA or CRA treatment.

The tree in the middle of the 14 m (46 ft) section in each block was chosen as a target tree for placement of sampling targets to measure the amount of spray deposits and coverage. For each test run, two different sampling targets were mounted at each sample position (Fig. 3). The targets consisted of a 5.1 by 5.1-cm (2 by 2 inch) monofilament nylon screen (Filter Fabrics Inc., Goshen, IN) to simulate leaves for collection of foliar spray deposits discharged from sprayers on both sides, and two water-sensitive papers (WSP) (Syngenta Crop Protection AG, Basel, Switzerland) to collect the spray deposits for measuring spray coverage. The two WSPs were 5.1 by 7.6 cm (2 by 3 inch) and 2.5 by 7.6 cm (1 by 3 inch) and were set back to back to intercept spray deposits discharged from sprayers on both sides of each test block. At each sample position, both nylon screen and two WSPs were held by an electric clip on tree limbs. The screen had a nominal porosity of approximately 56% or fiber frontal area percentage of 44%. The frontal area of the 5.1 by 7.6-cm (2 by 3 inch) WSPs faced the spray nozzles.

In Plot #1, sampling targets were mounted on 12 trees (Fig. 2, left side) at four different heights in the middle of each tree. Three target positions were selected on foliage.
within the canopy (Fig. 3a) and one target position was on
the trunk (Fig. 3b). The mean heights of the four target
positions across the four rows in the three test blocks were
2.5 ± 0.2, 1.9 ± 0.1, 1.4 ± 0.1 and 0.7 ± 0.1 m above the
ground. Similarly, in Plot #2, a total of 18 trees were
selected for the tests (Fig. 2, right side), and targets were
mounted at three different heights in the middle of each
tree canopy (two were within the foliage and one was on
the trunk). The mean heights of the targets across the six
rows in the three test blocks were 2.0 ± 0.1, 1.3 ± 0.1, and
0.6 ± 0.1 m above the ground for the three target positions,
respectively. These trees and target locations in all three
blocks were repeatedly used for both VRA and CRA
treatments.

The spray mixture was water with 3 g L⁻¹ of a
fluorescent tracer, Brilliant Sulfaflavine (MP Biomedicals,
Inc., Aurora, OH). All sampling targets were collected 15
minutes after each spray run. The nylon screens were
placed in 125-mL plastic bags stored in 120 mL jars. WSPs
were stored in paper bags.

Screens were brought to the laboratory and washed free
of the fluorescence tracer with purified water. The amount
of spray deposition on targets was based on the fluorescent
intensity of each wash solution which was then converted
to the volume of spray per unit area in microliters per
square centimeter (µL cm⁻²). Fluorescent intensity of each
wash solution was determined with a Trilogy® laboratory
fluorometer (Turner Designs, Sunnyvale, CA) at an
excitation wavelength of 460 nm.

The spray coverage on each WSP was analyzed with a
computer imaging system which included a handheld
ScanShell 800N business card scanner (CSSN, Inc., Los
Angeles, CA), a laptop computer, and a custom-designed
software “DepositScan” (Zhu et al., 2011). The resolution
for the image analysis was 600 dots/inch. The spray
coverage was determined from calculation of the percent-
age of the total area of a WSP covered by spray deposits.

During the tests, the ambient temperature was between
25 and 30 °C, relative humidity was between 34% and 52%,
and wind speed was below 3.2 m s⁻¹ (10 ft s⁻¹). To
compare differences in spray deposit and coverage distributions among different sample locations and among different rows, samples at each height on three trees in the same row in each block with three replications were grouped to calculate means and standard deviations.

Results and Discussion

Spray deposits at different heights of trees. An average spray rate of three replications recorded for the VRA was 386 L ha\(^{-1}\) (41 gal A\(^{-1}\)) in Plot #1, and was 315 L ha\(^{-1}\) (34 gal A\(^{-1}\)) in Plot #2. This was because trees in Plot #1 were wider, taller and denser than trees in Plot #2, resulting in greater total tree canopy volume in Plot #1. The average spray rate of three replications for the CRA was 467 L ha\(^{-1}\) (50 gal A\(^{-1}\)) in both Plot #1 and Plot #2. These VRA and CRA application rates were significantly lower than the 934 L ha\(^{-1}\) (100 gal A\(^{-1}\)) application rate commonly used in ornamental nursery production (Zhu et al. 2013).

There were variations in spray deposits at different heights on the same trees in each row and each block for both VRA and CRA treatments (Table 1 and Table 2). However, there was no trend showing the amount of deposits at one height was greater than that at another height. In general, spray deposits on trunks in both plots were higher and more consistent than those within the foliage because there were no leaves to interfere with spray droplets reaching the trunk.

Among the four rows in three blocks in Plot #1, the maximum and minimum spray deposits discharged from VRA were 4.49 ± 0.79 and 0.22 ± 0.12 μL cm\(^{-2}\) on foliage samples, and were 3.03 ± 0.68 and 0.77 ± 0.30 μL cm\(^{-2}\) on trunk samples, respectively (Table 1). Similarly, these deposits discharged from CRA were 4.85 ± 1.49 and 0.24 ± 0.12 μL cm\(^{-2}\) on foliage samples, and were 3.71 ± 0.74 and 1.20 ± 0.23 μL cm\(^{-2}\) on trunk samples, respectively. These spray deposits could be converted to the amount of active ingredients deposited on targets when the tank mixture concentration was known.

In Plot #2, targets at the 1.3 and 2.0 m heights were within the foliage and targets at the 0.6 m height were exposed on the trunks. The average spray deposit across three blocks in Row #1 for VRA were 2.71 ± 0.46 μL cm\(^{-2}\) at 2.0 m high, 2.82 ± 0.61 μL cm\(^{-2}\) at 1.3 m high and

Table 1. Average spray deposits of three replications discharged with variable-rate application (VRA) and constant-rate application (CRA) at four different heights on trees in four rows and three blocks in Plot 1.

| Row No. | Height (m) | VRA Deposit (μL cm\(^{-2}\)) | CRA Deposit (μL cm\(^{-2}\)) |
|---------|-----------|-------------------------------|-------------------------------|
|         |           | Block 1                       | Block 2                       | Block 3                       |
| 1       | 2.5       | 2.50 ± 0.72                   | 2.98 ± 0.23                   | 1.21 ± 0.13                   | 0.97 ± 0.20                   | 0.77 ± 0.17                   | 1.48 ± 1.01                   |
| 1       | 1.9       | 3.36 ± 0.34                   | 2.23 ± 0.50                   | 2.25 ± 0.22                   | 1.84 ± 0.58                   | 0.70 ± 0.24                   | 0.67 ± 0.23                   |
| 1       | 1.4       | 1.51 ± 0.30                   | 1.06 ± 0.29                   | 0.72 ± 0.07                   | 0.68 ± 0.26                   | 2.32 ± 0.65                   | 0.74 ± 0.27                   |
| 1       | 0.7\(^{[1]}\) | 2.53 ± 0.11                   | 2.59 ± 1.71                   | 2.27 ± 0.08                   | 3.71 ± 0.74                   | 3.03 ± 0.68                   | 3.59 ± 1.10                   |
| 2       | 2.5       | 0.59 ± 0.16                   | 0.49 ± 0.13                   | 0.65 ± 0.11                   | 0.72 ± 0.66                   | 0.60 ± 0.15                   | 0.55 ± 0.18                   |
| 2       | 1.9       | 0.22 ± 0.16                   | 0.31 ± 0.19                   | 0.30 ± 0.03                   | 0.53 ± 0.15                   | 0.51 ± 0.04                   | 0.80 ± 0.35                   |
| 2       | 1.4       | 0.35 ± 0.15                   | 0.28 ± 0.12                   | 0.30 ± 0.03                   | 0.53 ± 0.15                   | 0.75 ± 0.17                   | 0.65 ± 0.15                   |
| 2       | 0.7\(^{[1]}\) | 0.77 ± 0.30                   | 1.20 ± 0.23                   | 1.09 ± 0.28                   | 1.35 ± 0.48                   | 1.98 ± 0.55                   | 2.89 ± 0.49                   |
| 3       | 2.5       | 1.17 ± 0.64                   | 1.67 ± 0.71                   | 0.85 ± 0.35                   | 1.07 ± 1.02                   | 2.62 ± 0.97                   | 1.17 ± 0.13                   |
| 3       | 1.9       | 0.44 ± 0.10                   | 0.75 ± 0.40                   | 0.31 ± 0.44                   | 0.24 ± 0.12                   | 1.27 ± 0.97                   | 0.75 ± 0.17                   |
| 3       | 1.4       | 0.33 ± 0.09                   | 0.38 ± 0.14                   | 0.40 ± 0.12                   | 0.31 ± 0.31                   | 0.69 ± 0.13                   | 0.67 ± 0.14                   |
| 3       | 0.7\(^{[1]}\) | 1.40 ± 0.45                   | 2.92 ± 0.34                   | 2.06 ± 0.68                   | 2.67 ± 0.95                   | 1.65 ± 0.52                   | 2.70 ± 1.87                   |
| 4       | 2.5       | 4.01 ± 1.64                   | 4.22 ± 1.10                   | 4.49 ± 0.79                   | 4.85 ± 1.49                   | 3.85 ± 1.11                   | 2.81 ± 1.54                   |
| 4       | 1.9       | 1.15 ± 0.37                   | 1.22 ± 0.41                   | 0.61 ± 0.41                   | 0.82 ± 0.36                   | 2.62 ± 1.84                   | 3.74 ± 0.67                   |
| 4       | 1.4       | 2.24 ± 0.97                   | 2.07 ± 0.37                   | 0.78 ± 0.19                   | 0.62 ± 0.20                   | 1.42 ± 1.06                   | 1.47 ± 0.12                   |
| 4       | 0.7\(^{[1]}\) | 1.43 ± 0.21                   | 3.56 ± 1.33                   | 2.71 ± 0.50                   | 3.55 ± 2.20                   | 1.86 ± 0.55                   | 3.22 ± 0.83                   |

\(^{[1]}\) sample collect on the trunk

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Table 2. Average spray deposits of three replications discharged with variable-rate application (VRA) and constant-rate application (CRA) at different heights on trees in six rows and three blocks in Plot 2.

| Row No. | Height (m) | VRA | CRA | VRA | CRA | VRA | CRA |
|---------|-----------|-----|-----|-----|-----|-----|-----|
| 1       | 2.0       | 3.81±0.59 | 3.13±0.39 | 2.07±0.25 | 3.20±0.13 | 2.24±0.53 | 2.84±0.45 |
| 1       | 1.3       | 2.22±0.14 | 2.12±0.21 | 3.15±0.36 | 4.32±0.81 | 3.99±0.72 | 3.22±0.13 |
| 1       | 0.6[^1]   | 1.20±0.37 | 2.85±0.65 | 2.55±0.33 | 4.40±1.75 | 1.98±0.58 | 5.23±2.94 |
| 2       | 2.0       | 2.89±0.49 | 5.45±1.17 | 1.19±0.50 | 1.71±0.38 | 1.48±0.62 | 1.54±0.70 |
| 2       | 1.3       | 1.65±0.50 | 2.89±1.05 | 2.74±0.62 | 5.73±2.08 | 2.68±1.04 | 2.84±0.89 |
| 5       | 2.0       | 2.01±0.88 | 3.36±1.72 | 4.52±0.82 | 2.77±1.97 | 1.16±0.43 | 1.54±0.70 |
| 2       | 1.3       | 1.14±0.70 | 2.19±1.13 | 2.39±0.88 | 1.62±0.59 | 1.28±0.43 | 1.68±0.60 |
| 3       | 2.0       | 3.77±0.17 | 3.18±1.62 | 2.27±0.67 | 3.18±1.07 | 3.08±0.65 | 4.14±1.16 |
| 3       | 1.3       | 2.24±1.30 | 3.11±0.60 | 1.86±1.01 | 2.06±2.14 | 1.81±0.62 | 1.84±0.99 |
| 3       | 0.6[^1]   | 1.58±0.76 | 2.03±0.97 | 1.18±0.48 | 1.49±0.77 | 1.31±0.29 | 1.05±0.79 |
| 4       | 0.6[^1]   | 2.25±1.10 | 4.38±0.47 | 2.57±0.14 | 4.06±1.39 | 1.92±1.06 | 3.33±1.13 |
| 5       | 2.0       | 1.51±0.48 | 2.83±1.13 | 2.61±0.33 | 4.83±0.85 | 3.67±1.33 | 4.29±2.03 |
| 5       | 1.3       | 1.11±0.12 | 1.38±0.33 | 1.56±0.47 | 2.15±0.70 | 1.29±0.46 | 1.44±0.99 |
| 5       | 0.6[^1]   | 3.71±1.09 | 4.12±0.76 | 2.99±1.51 | 5.78±4.17 | 2.38±1.14 | 4.01±0.76 |
| 6       | 2.0       | 1.86±0.19 | 3.29±1.20 | 2.35±0.44 | 4.40±1.07 | 2.70±0.79 | 1.36±0.58 |
| 6       | 1.3       | 3.01±0.20 | 3.53±0.54 | 1.79±0.23 | 2.29±0.67 | 1.95±0.40 | 2.81±0.40 |
| 6       | 0.6[^1]   | 4.59±1.42 | 3.36±1.23 | 1.75±0.53 | 2.15±0.72 | 3.43±0.73 | 3.96±1.07 |

[^1]0.6 – sample collect on the trunk

1.74±0.44 µL cm⁻² at 0.6 m high. These deposits in Row #2 were 2.51±0.70, 1.33±0.48 and 3.31±0.65 µL cm⁻² at 2.0, 1.3 and 0.6 m heights, respectively (Table 2). In comparison, the average spray deposit across three blocks in Row #1 for CRA were 3.06±0.32 µL cm⁻² at 2.0 m high, 2.94±0.45 µL cm⁻² at 1.3 m high and 3.59±1.52 µL cm⁻² at 0.6 m high. These deposits in Row #2 were 4.51±1.67, 2.05±0.71 and 5.37±2.59 µL cm⁻² at the 2.0, 1.3 and 0.6 m heights, respectively (Table 2). The average deposits across six rows and three blocks were 2.77±0.75 µL cm⁻² on trunks and 2.15±0.57 µL cm⁻² within foliage for CRA, and were 4.03±1.55 µL cm⁻² on trunks and 2.72±0.94 µL cm⁻² within foliage for CRA, respectively.

Spray deposits varied from 0.20±0.07 to 1.24±0.47 µL cm⁻² inside 2.5-m (8.2 ft) tall Malus ‘Spring Snow’ crabapple canopies from a conventional air-blast sprayer at the 440 L ha⁻¹ (47 GPA) application rate (Zhu et al. 2008) and from 1.72 to 7.52 µL cm⁻² on 4-m (13.1 ft) tall red maple canopies (‘Red Sunset’, Acer rubrum L.) from an air curtain sprayer conventional tower sprayer at 750 L ha⁻¹ (80 GPA) application rate (Derksen et al. 2004) while the pest control efficacy was satisfactory with these amounts of deposits (Zhu et al. 2013).

Spray deposits in different rows. As expected, variations in spray deposits within foliage and on trunks occurred from row to row for both VRA and CRA treatments. Because the capability of air discharged from the sprayer to carry droplets varied with the droplet travel distance and trees closer to the sprayer could intercept more droplets, the spray deposits on trees decreased as the distances between tree rows and the sprayer increased (Fig. 4a).

In Plot #1, spray deposits on trees in Row #1 and #4 were significantly higher than those in Row #2 and #3 (Fig. 4a). This was because trees in Row #1 and #4 were closer to the sprayer than trees in Row #2 and #3. The average spray deposits on three foliage samples across three blocks in Row #1, #2, #3, and #4 were 1.70±0.32, 0.51±0.13, 0.90±0.52, and 2.35±0.93 µL cm⁻² for VRA, and were 1.41±0.40, 0.53±0.25, 0.78±0.35, and 2.42±0.70 µL cm⁻² for CRA, respectively. In comparison, the mean deposits on trunks across the three blocks in Row #1, #2, #3, and #4 were 2.61±0.29, 1.28±0.38, 1.70±0.55, and 2.00±0.42 µL cm⁻² for VRA, and were 3.30±1.18, 1.81±0.40, 2.76±1.05, and 3.44±1.45 µL cm⁻² for CRA, respectively. The average spray deposits on foliage samples among four rows and three blocks were 1.37±0.48 µL cm⁻² for VRA and 1.29±0.42 µL cm⁻² for CRA. Thus, spray deposits within foliage for VRA and CRA were comparable. However, the average spray deposit on trunks from CRA was 1.49 times the deposit from VRA (or 2.83±1.02 µL cm⁻² vs 1.90±0.41 µL cm⁻²). The lower nozzles of the sprayer continuously discharged sprays to trunks with the CRA mode while intermittent sprays were discharged only to trunks from the lower nozzles with the VRA mode.

In Plot #2, the average spray deposits on foliage across three blocks for VRA were 2.76±0.53 µL cm⁻² in Row #1, 1.92±0.59 µL cm⁻² in Row #2, 2.33±0.67 µL cm⁻² in Row #3, 1.66±0.74 µL cm⁻² in Row #4, 1.96±0.53 µL cm⁻² in Row #5, and 2.28±0.38 µL cm⁻² in Row #6 (Fig. 4b). Similarly, the average spray deposits on foliage across three blocks for CRA were 3.99±0.39 µL cm⁻² in Row #1, 3.28±1.19 µL cm⁻² in Row #2, 3.25±1.26 µL cm⁻² in Row #3, 1.93±1.04 µL cm⁻² in Row #4, 2.82±1.01 µL cm⁻² in Row #5, and 2.95±0.74 µL cm⁻² in Row #6 (Fig. 4b). Based on ANOVA, no significant difference in spray deposits on trees between Row #1 and Row #6 was found because trees in the two rows were closest to the sprayer among the six rows. VRA and CRA had similar spray...
deposits on trees in each of the six rows while VRA used 45% of the spray volume that CRA applied.

Spray deposits in different blocks. In Plot #1, the average spray deposits within foliage on the tree in Block #1, #2 and #3 for VRA were 2.46 ± 0.45, 1.39 ± 0.14 and 1.26 ± 0.35 μL cm⁻² for Row #1, and were 0.39 ± 0.16, 0.52 ± 0.12 and 0.62 ± 0.12 μL cm⁻² in Row #2, respectively. Similarly, these average spray deposits for CRA were 2.09 ± 0.34, 1.16 ± 0.35, and 0.96 ± 0.50 μL cm⁻² in Row #1, and were 0.36 ± 0.15, 0.57 ± 0.37 and 0.67 ± 0.23 μL cm⁻² in Row #2, respectively. Although spray deposits varied with blocks for both VRA (Table 1) and CRA (Table 2), there were no significant differences in spray deposits in each block between VRA and CRA. The average spray deposits within foliage across four rows discharged from VRA and CRA were 1.49 ± 0.47 and 1.47 ± 0.38 μL cm⁻² in Block #1, 1.10 ± 0.26 and 1.09 ± 0.47 μL cm⁻² in Block #2, and 1.51 ± 0.70 and 1.29 ± 0.41 μL cm⁻² in Block #3, respectively.

In Plot #2, the average deposits on the foliage from VRA in Row #1 at Block #1, #2 and #3 were 3.01 ± 0.36, 4.11 ± 0.61, 2.67 ± 0.63 μL cm⁻², respectively. Under the same conditions for the CRA, these deposits were 2.67 ± 0.30, 3.76 ± 0.47, 2.56 ± 0.39 μL cm⁻².

Spray coverage. Figure 5 shows examples of spray deposits collected on WSPs at three heights on trees in Row #1 and Row #2 in Plot #1. Figure 6 shows examples of spray deposits collected on WSPs at three heights on trees in Row #1, #2 and #3 in Plot #2. These spray deposits were discharged from VRA. Because the plots were sprayed at both sides, spray deposits on trees in Row #4 and 3 in Plot #1 were similar to those in Row #1 and #2 respectively, and spray deposition on trees in Row #6, #5 and #4 in Plot #2 were similar to those in Row #1, #2 and #3, respectively.

Similar to spray deposits discussed above, the percent areas covered with spray droplets (spray coverage) in foliage and trunks produced with VRA and CRA also varied with sample locations in Plot #1 (Table 3) and Plot #2 (Table 4). Overall, spray coverage on foliage of trees (not including spray coverage on trunks) was 19.8 ± 3.0% from VRA and 20.9 ± 4.3% from CRA in Plot #1, and was 27.9 ± 3.7% from VRA and 30.5 ± 5.4% from CRA, respectively.

Fig. 4. Spray deposits collected with nylon screens on foliage and trunks discharged from variable-rate application (VRA) and constant-rate application (CRA): (a) in Plot #1 and (b) in Plot #2.

Fig. 5. Spray deposits discharged from variable-rate application (VRA) on water-sensitive papers (WSP) located at three different heights in Block #2 of Plot #1. Two WSPs were set back to back at each height to intercept spray deposits, and the back side WSP faced toward the centerline of the block.
In Plot #1, spray coverage on tree foliage in Row #1 and #4 was much greater than those in Row #2 and #3 (Fig. 7a). For example, the average spray coverage on tree foliage in rows #1 and #4 across the three blocks was 3.0 times of those in Rows #2 and #4 for VRA and 2.7 times of those for CRA. Visual observation of spray deposition on WSPs also indicated that trees in Row #1 apparently received more spray coverage than trees in Row #2 (Fig. 7a). Even though these variations, the minimum percent spray coverage was still 5.6 ± 0.8 for VRA and 4.6 ± 1.0 for CRA, both occurred at the 1.4 m high position in Row #1 of Block #1. VRA and CRA applied similar spray coverage on foliage in each particular row (Fig. 7a), but on trunks the spray coverage from CRA was greater than that from VRA because of the continuous spray clouds from CRA. The average percent spray coverage on foliage across three blocks from VRA was 25.1 ± 3.5, 10.5 ± 2.4, 9.1 ± 2.6, and 34.4 ± 3.5 in Row #1, #2, #3, and #4, respectively. Similarly, the average percent spray coverage on foliage across three blocks from CRA was 25.3 ± 5.5, 12.0 ± 4.1, 10.5 ± 2.6, and 35.6 ± 4.8 in Rows #1, #2, #3, and #4.

Similarly, CRA provided a slightly greater overall spray coverage than VRA in Plot #2. The reason was the CRA produced great amounts of airborne drift above trees and between gaps of trees. Some of these airborne droplets drifted on the targets. The average coverage at the two foliage locations (1.3 and 2.0 m heights) in six rows from VRA and CRA was 25.7 ± 3.0% and 29.4 ± 4.4% in Block #1, 30.4 ± 3.7% and 33.6 ± 5.8% in Block #2, and 27.7 ± 4.3% and 28.6 ± 6.1% in Block #3, respectively (Fig. 7b). The overall average spray coverage on trunks at

| Height (m) | Row #1 Forward | Row #1 Backward | Row #2 Forward | Row #2 Backward | Row #3 Forward | Row #3 Backward |
|-----------|----------------|-----------------|----------------|-----------------|----------------|----------------|
| 2.0       | ![image]       | ![image]        | ![image]       | ![image]        | ![image]       | ![image]        |
| 1.3       | ![image]       | ![image]        | ![image]       | ![image]        | ![image]       | ![image]        |
| 0.6 (on trunk) | ![image] | ![image] | ![image] | ![image] | ![image] | ![image] |

Fig. 6. Spray deposits discharged from variable-rate application (VRA) on water sensitive papers (WSP) located at three different heights in Block #2 of Plot #2. Two WSPs were set back to back at each height to intercept spray deposits, and the back side WSP faced toward the centerline of the block.
on the same target locations, spray coverage tended to differ between VRA and CRA were comparable. The average spray coverage of three replications discharged with variable-rate application (VRA) and constant-rate application (CRA) at four different heights on trees in six rows and three blocks in Plot 1.

Table 3. Average spray coverage of three replications discharged with variable-rate application (VRA) and constant-rate application (CRA) at four different heights on trees in four rows and three blocks in Plot 1.

| Row No. | Height (m) | Spray Coverage (%) |
|---------|------------|--------------------|
|         |            | VRA                | CRA                |
| 1       | 2.5        | 36.6±4.2           | 37.2±3.1           |
| 1       | 1.9        | 31.0±4.6           | 45.6±9.6           |
| 1       | 1.4        | 38.0±5.9           | 15.3±7.3           |
|         | 0.7(a)     | 38.0±5.9           | 15.3±7.3           |
| 2       | 2.5        | 5.8±2.9            | 10.6±8.5           |
| 2       | 1.9        | 7.9±1.8            | 9.4±2.3            |
| 2       | 1.4        | 6.5±0.2            | 7.8±1.5            |
|         | 0.7(a)     | 12.1±3.5           | 20.9±6.9           |
| 3       | 2.5        | 13.2±4.0           | 24.8±5.9           |
| 3       | 1.9        | 8.8±1.3            | 7.8±1.1            |
|         | 1.4        | 5.6±0.8            | 5.5±1.0            |
| 3       | 0.7(a)     | 18.8±4.2           | 36.3±10.9          |
| 4       | 2.5        | 39.9±5.1           | 41.5±8.3           |
| 4       | 1.9        | 36.3±2.4           | 36.3±5.9           |
| 4       | 1.4        | 36.8±2.4           | 31.0±3.8           |
|         | 0.7(a)     | 22.8±19.1          | 44.3±7.6           |

(a)0.7 – sample collect on the trunk

The foliage spray coverage ranged from small droplets on the target with a limited amount of chemicals. The foliage spray coverage varied with plots, rows, blocks and target positions on trees, spray deposition qualities between VRA and CRA were comparable. The average spray coverage with a given amount of spray deposits may not reach 5%.

Despite spray deposits varied with plots, rows, blocks and target positions on trees, spray deposition qualities between VRA and CRA were comparable. The average spray coverage with a given amount of spray deposits may not reach 5%.

Table 4. Average spray coverage of three replications discharged with variable-rate application (VRA) and constant-rate application (CRA) at different heights on trees in six rows and three blocks in Plot 2.

| Row No. | Height (m) | Spray Coverage (%) |
|---------|------------|--------------------|
|         |            | VRA                | CRA                |
| 1       | 2.0        | 39.9±2.0           | 46.0±3.1           |
| 1       | 1.3        | 37.4±0.8           | 42.1±1.7           |
|         | 0.6(a)     | 30.2±5.0           | 44.7±5.6           |
| 2       | 2.0        | 36.0±5.5           | 36.7±5.1           |
| 2       | 1.3        | 17.9±1.4           | 15.8±2.3           |
|         | 0.6(a)     | 17.4±6.1           | 38.6±6.8           |
| 3       | 2.0        | 25.4±5.2           | 34.8±8.0           |
| 3       | 1.3        | 22.2±1.5           | 22.9±2.1           |
|         | 0.6(a)     | 34.3±2.4           | 23.0±10.6          |
| 4       | 2.0        | 18.7±5.5           | 30.7±5.7           |
| 4       | 1.3        | 10.3±2.1           | 13.3±3.1           |
|         | 0.6(a)     | 14.6±3.7           | 33.9±12.2          |
| 5       | 2.0        | 20.4±3.2           | 21.8±4.8           |
| 5       | 1.3        | 14.4±1.5           | 19.3±10.3          |
|         | 0.6(a)     | 35.1±2.5           | 38.4±2.6           |
| 6       | 2.0        | 24.6±3.1           | 24.7±6.0           |
| 6       | 1.3        | 41.4±4.0           | 44.2±0.8           |
|         | 0.6(a)     | 31.3±3.2           | 38.4±5.7           |

(b)0.6 – sample collect on the trunk

Because the distribution of insects and diseases is random in the field, the concept of using spray to carry pesticides to control pests is to take probability of a hit of small droplets on the target with a limited amount of chemicals. The foliage spray coverage ranged from 5.5±1.0% to 46.8±4.1% in entire Plot #1 (Table 3), and from 10.3±2.1% to 48.2±10.2% in Plot #2. These coverage ranges should provide adequate probability for sprays to hit on areas where infestation or infection levels reached 5%.

The foliage spray coverage ranged from 5.5±1.0% to 46.8±4.1% in entire Plot #1 (Table 3), and from 10.3±2.1% to 48.2±10.2% in Plot #2. These coverage ranges should provide adequate probability for sprays to hit on areas where infestation or infection levels reached 5%.

Despite spray deposits varied with plots, rows, blocks and target positions on trees, spray deposition qualities between VRA and CRA were comparable. The average spray coverage with a given amount of spray deposits may not reach 5%.
Spray deposits on foliage of trees in Plot #1 were 1.37 L/cm² for VRA and 1.29 L/cm² for CRA, and 2.15 L/cm² for VRA and 2.72 L/cm² for CRA in Plot #2. The volume median diameter (VMD) of droplets discharged from the sprayer was 223 µm and the volume of a 223 µm droplet was 0.0058 L. These average spray deposits were equivalent to droplet densities as a 1-cm² area covered by 236 droplets of 223 µm with VRA and 222 same size droplets with CRA in Plot #1, and 370 droplets with VRA and 468 droplets with CRA in Plot #2, respectively. Syngenta Crop Protection AG (Basel, Switzerland) recommended the droplet density in the target area be from 20 to 40 droplets per square centimeter for spraying insecticides and 50 to 70 droplets per square centimeter for spraying fungicides (Anonymous, 2004).

Similar to other spray applications under nursery field conditions (Zhu et al., 2006b, 2008; Derksen et al., 2006), there were considerable variations in spray deposits and coverage at different target positions with both CRA and VRA tested in Plot #1 and Plot #2. These variations were reasonable because the canopy structures varied with the heights, trees, rows and blocks. Leaves would intercept sprays and also affect the amount of sprays reaching the sampling targets. Field tests demonstrated that the newly developed laser-guided, air-assisted, variable-rate sprayer coupled with PWM solenoid valve controlled nozzles could significantly reduce the spray volume for multiple-row nursery crop production while providing adequate spray deposition and coverage inside canopies, thereby offering an environmentally responsible spray technology for the nursery industry to protect crops against damage from insects and diseases.

Fig. 7. Percent spray coverage on Water-sensitive papers (WSP) on foliage and trunks discharged from constant-rate application (CRA) and variable-rate application (VRA): (a) in Plot #1, (b) in Plot #2.

Fig. 8. Correlations between spray coverage and spray deposits discharged from variable-rate application (VRA) and constant-rate application (CRA): (a) in Plot #1, (b) in Plot #2.
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