Reducing the Nursery Pesticide Footprint with Laser-guided, Variable-rate Spray Application Technology

Lauren Fessler and Amy Fulcher

Department of Plant Sciences, University of Tennessee, Knoxville, TN 37996

Liesel Schneider

Department of Animal Science, University of Tennessee, Knoxville, TN 37998

Wesley C. Wright

Department of Biosystems Engineering and Soil Science, University of Tennessee, Knoxville, TN 37996

Heping Zhu

Application Technology Research Unit, U.S. Department of Agriculture-Agricultural Research Service, Wooster, OH 44691

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Abstract. Nursery producers are challenged with growing a wide range of species with little to no detectable damage from insects or diseases. Growing plants that meet consumer demand for aesthetics has traditionally meant routine pesticide application using the most time-efficient method possible, an air-blast sprayer, despite its known poor pesticide application efficiency. New variable-rate spray technology allows growers to make more targeted applications and reduce off-target pesticide loss. In this study, a prototype laser-guided variable-rate sprayer was compared with a traditional air-blast sprayer. Pesticide volume, spray application characteristics, and the control of powdery mildew were evaluated over the course of two growing seasons. Spray application characteristics were assessed using water-sensitive cards (WSCs) and DepositScan software. This prototype sprayer reduced pesticide volume by an average of 54% across both years despite being tested against a low rate ($<250 \text{ L}\cdot\text{ha}^{-1}$). In 2016, the conventional sprayer had more than double the deposit density on target WSCs among distal trees than the variable-rate sprayer; however, within proximal trees, there was no difference between the two sprayer types. In 2017, when the trees were larger, within both the distal and proximal trees, the conventional sprayer had greater deposit density on target WSCs than the variable-rate sprayer. In 2016, coverage on target WSCs was nearly 7-fold greater with the conventional treatment than with the variable-rate treatment. In 2017, when trees were larger, there was greater coverage on target WSCs in proximal trees (3.8%) compared with those in distal trees (1.0%) regardless of the sprayer type. This variable-rate spray technology provided acceptable control of powdery mildew severity on individual branches and whole trees and maintained the incidence of powdery mildew to levels comparable to that occurring among trees sprayed with a traditional air-blast sprayer. Therefore, the variable-rate spray technology has the potential to effectively control disease, dramatically reduce the pesticide footprint, and preserve natural resources such as ground and surface water, soil, and beneficial insects found within and around nurseries.

Concerns about pesticide use in agriculture and its negative environmental impact have increased during recent years. Although pesticides are essential for pest management and save $\approx$ \$40 billion worth of crops each year in the United States, it is estimated that the environmental cost of pesticides approaches \$10 billion (Pimentel and Burgess, 2014). Public interest is pushing producers to adopt practices that reduce their environmental impact, specifically their use of and dependency on pesticides. Consumers have demonstrated a willingness to pay more for ornamental, nonfood plants that have been produced using environmentally

friendly production practices (Khachatryan et al., 2017), especially those that minimize the use of pesticides (Getter et al., 2016). Increases in consumers' knowledge of certain systemic insecticides, such as neonicotinoids (Khachatryan et al., 2020), and their preference for pollinator-friendly plants (Khachatryan et al., 2017) further demonstrate their commitment to this issue.

Nursery producers encounter a number of unique challenges regarding pesticide application. One challenge is that, unlike most orchard crops, nursery crops are typically grown in multirow blocks (Zhu et al., 2017a). For this reason, many producers spray to "runoff" in

exterior rows to ensure penetration of interior rows. This practice remains common (Walklate et al., 2006) despite its resulting in pesticide application that is at least four-times the amount needed to control economically important pests (Zhu et al., 2006b, 2008). Another challenge is that producers are tasked with producing plants that meet high aesthetic thresholds, allowing for virtually no visible disease or insect damage. Infestations of certain pests, such as fire blight [*Erwinia amylovora* (Burrill) Winslow et al.] on crabapple (*Malus* spp.), serviceberry (*Amelanchier* spp.), and hawthorn (*Crataegus* spp.) (Jones and Benson, 2001), and trunk and shoot borers on a variety of nursery crops can have devastating economic impacts (Frank and Sadof, 2011; Frank et al., 2013; Seagraves et al., 2013) because they result in plants being culled because of death, extensive damage, or damage affecting the tree structure or form. Additionally, growers are somewhat bound to producing plants for which there is demand, regardless of the pest resistance of these crops. Therefore, some plants that are very popular in the trade are disease-prone or insect-prone. Certain cherries, crabapples, maples, and dogwoods are examples of these pest-prone species (Cappiello and Shadow, 2005; Dirr, 2009; Frank et al., 2013). For these reasons, nursery producers often rely on frequent, heavy pesticide applications to maintain a saleable crop.

Another challenge that nursery producers encounter is the lack of crop uniformity. The nursery industry produces more than 2000 different species of ornamentals with varying shapes, sizes, growth patterns, and harvest schedules in a range of production systems in the United States (Yeager et al., 2013). Additionally, there are few to no sprayers that are designed specifically for nursery crops (Zhu et al., 2011a; Zhu et al., 2006a). Therefore, nursery operators tend to use orchard sprayers that are designed for use on larger, denser apple and citrus crops (Zhu et al., 2006b).

Air-assisted orchard sprayers are known to have low pesticide application efficiency, particularly with drift and off-target applications. Moreover, spray drift from air-blast sprayers used on tree crops is much greater than that of sprayers used in field crops (Ganzelmeier et al., 1995) and other woody crops (Hong et al., 2018). Because the foliage of nursery crops typically does not overlap (Zhu et al., 2006b; Zhu et al., 2008), and because trees are generally devoid of branches within 1 m of ground level (Hong et al., 2018), application inefficiencies caused by overapplication and off-target application are compounded in nurseries. For example, even at a reduced rate of $700 \text{ L}\cdot\text{ha}^{-1}$, tree canopies received four-times to 14.5-times more spray deposit than necessary when treated with a variety of common nursery spray application techniques (Zhu et al., 2006b). More than 70% of the total spray volume applied by an air-blast sprayer can go off-target in a nursery, including more than 34% that is lost on the ground (Zhu et al., 2008). Furthermore, airborne deposits are found 30 m downwind from target nursery crops (Zhu et al., 2006b)

and have been detected as far as 47 m away (Grella et al., 2017).

Flowering dogwood (*Cornus florida* L.) is an important crop in the United States, and particularly in Tennessee. Nationally, it is the third-ranking deciduous flowering tree in the number of plants produced and is responsible for more than \$31 million in sales annually (U.S. Department of Agriculture, 2020). Historically, dogwoods were relatively inexpensive to grow, with no major diseases; disease management costs were ≈\$120/ha/year (Windham et al., 2000). However, in the 1970s, dogwood anthracnose [(*Discula destructiva*) Redlin] became a threat that grew over time (Daughtrey et al., 1996). Eventually, dogwood anthracnose and dogwood powdery mildew, the disease caused by *Microsphaera pulchra* (syn *Erysiphe pulchra*) (Cooke & Peck) and *Phyllactinia guttata* (Wallroth) Léveillé, emerged as major threats to economically viable dogwood production in nurseries, even jeopardizing survival in forests and urban landscapes (Daughtrey et al., 1996; Li et al., 2009). Powdery mildew is now ubiquitous in Tennessee, and environmental conditions favor infections throughout the period when plants are actively growing (i.e., May through August and as late as October in some studies) (Windham et al., 2000). Cultural controls, such as increased spacing, are deemed insufficient; fungicides are required for susceptible dogwood cultivars (Li et al., 2009). Current extension recommendations include spraying every 7 to 14 d during the growing season, which has drastically increased disease management costs by ≈\$1900 per hectare per year (Li et al., 2009; Windham et al., 2000).

To combat issues of overapplication and poor application efficiency, an experimental air-assisted, variable-rate sprayer that uses a high-speed laser scanning sensor to detect the presence, dimensions, and density of crops was developed to match spray output to target tree structures (Chen et al., 2012). Pulse width-modulated (PWM) solenoids are used to adapt nozzle output to the specific characteristics of the detected crop. PWM technology uses duty cycle rather than travel speed,

spray pressure, or nozzle size to vary the spray rate, and it has been proven to achieve uniform spray coverage in field conditions (Grella et al., 2021). With the described technology, this sprayer addresses the two main issues associated with conventional constant-rate sprayers used in nurseries and orchards: 1) the lack of uniformity in spray output within canopies and 2) spray loss to nontarget areas between trees (Fox et al., 2008; Liu et al., 2014). The accuracy of this technology was tested and was verified to be able to (in combination with other sensors) successfully actuate variable-rate flow for multiple nozzles (Liu et al., 2014).

The prototype sprayer was able to deliver uniform spray coverage on ornamental tree species of varying canopy size and foliage density (Chen et al., 2012), as well as to achieve uniform coverage throughout the depth, width, and height of apple tree canopies (Chen et al., 2013a). Additionally, compared with a conventional air-blast sprayer, this sprayer reduced spray losses to the ground by 93%, 93%, and 90% at the leafing, half-foliage, and full-foliage phenological stages of apple trees, respectively (Chen et al., 2013b). At the full-foliage stage, this sprayer reduced airborne drift by 87% and 100% at 15 and 35 m downwind, respectively (Chen et al., 2013b). More recently, PWM technology has been validated in a field setting, providing greater uniformity with 76% less spray volume than constant-rate applications in a multirow apple orchard (Salcedo et al., 2020)).

This laser-guided precision spray technology has the potential to reduce total pesticide volume usage, thereby reducing pesticide input costs as well as reducing off-target pesticide losses and ultimately minimizing the “pesticide footprint” on soil, water, and air. Therefore, the objective of this study was to validate the use of this technology in a commercial nursery setting by comparing the control of a pervasive disease on a highly susceptible host, spray volume, and spray application characteristics of this newly developed sprayer with that of a conventional air-blast sprayer.

Materials and Methods

Test sprayers. The prototype variable-rate, intelligent sprayer, built by the U.S. Department of Agriculture-Agricultural Research Service-Application Technology Research Unit in Wooster, OH, was tested for its effectiveness of disease control, target foliar application characteristics, and total volume output at a commercial nursery in Tennessee. A conventional Durand-Wayland air-blast sprayer (AF 500 CPS, La Grange, GA) owned by the nursery was used as the control.

Variable-rate sprayer. The variable-rate, laser-guided sprayer was equipped with a high-speed, 270° radial and 30-m range laser scanning sensor that was coupled with a non-contact Doppler radar travel speed sensor, an automatic nozzle flow rate controller, an embedded computer, a touch screen, and 40 PWM variable-

rate nozzles on a multiport air-assisted delivery system (Fig. 1A). All 20 nozzles on each side of the sprayer independently discharged variable flow rates to their designated canopy sections (Shen et al., 2017). Nozzles were extended-range flat-fan tips (XR 8004; TeeJet Technologies, Springfield, IL). The tractor was operated to provide a constant power take-off rpm of 540, resulting in the sprayer operating at 240 to 310 kPa, depending on the number of nozzles actuated by the target. The flow rate of each nozzle was automatically calculated in real-time in response to its designated section of canopy volume, the sprayer travel speed, and the preselected spray rate (liters of prepared spray solution per cubic meter of crop volume) (Chen et al., 2012; Liu et al., 2014).

In brief, the technology translates the return distance signals received by the laser scanning sensor mounted between the tractor and sprayer and the sprayer travel speed via an algorithm into a three-dimensional tree surface from which the spray output from each nozzle is actuated (Shen et al., 2017). This enables the sprayer to determine the crop characteristics in real-time, essentially automating a tree row volume calculation, and applying the prescribed volume of pesticide (Zhu et al., 2017b). For this experiment, the sprayer was set to output the default rate of 0.06 L of spray mixture per cubic meter of canopy because this was deemed the appropriate spray rate for nursery crops (Zhu et al., 2017b). Other major components of the sprayer included an axial turbine fan, a 400-L spray tank, and a diaphragm pump.

Conventional sprayer. The conventional sprayer was an 1890-L radial air-blast sprayer with a 10-nozzle lower spray head and a custom 5-nozzle upper spray head (Fig. 1B). The upper spray head remained off during the study because of the low height of the dogwood crop. The nozzle positions on the sprayer were numbered 1 through 15, with 1 being the uppermost nozzle on the upper spray head and 15 being the nozzle closest to the ground on the lower spray head. For the 10 lower nozzles on the body of the sprayer, the upper two (positions 6 and 7) and the lower two nozzles (14 and 15) remained physically closed according to the grower's normal practice for a crop with this canopy architecture. Nozzles in positions 9, 10, and 12 had disc 5, core 2, and those in positions 8, 11, and 13 had disc 4, core 4. The tractor was operated to provide a constant power take-off rpm of 540, resulting in the sprayer operating at 310 kPa.

Test field. Evaluations of the variable-rate and conventional sprayers were conducted at Pleasant Cove Nursery (Rock Island, TN; lat. 35°44'50.1"N, long. 85°39'07.3"W). The test field consisted of six total blocks (five blocks of six rows of trees and one block of five rows of trees). Each block was ≈213.4 m long, with 2.4 m between rows within a block and 4.3 m driveways between blocks. The trees were planted in 2015 at ≈1.2 to 2.1 m apart within the row. The orientation for the two exterior rows on both the east and west sides of the block was defined as proximal, and the orientation for the two interior rows was defined as

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A.F. is the corresponding author. E-mail: afulcher@utk.edu.

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Fig. 1. The two sprayers used to conduct this experiment. (A) Laser-guided, intelligent, variable-rate sprayer and its components. (B) Conventional sprayer (AF 500 CPS; Durand-Wayland, La Grange, GA) including the lower spray head and upper spray head. The individual nozzles status (open/closed) shown is not reflective of their status during the experiment.

distal (Fig. 2). The soil type of this field was a combination of two silt loams, Huntington and Cumberland (Soil Survey Staff, 2019).

The test field was divided in half and flagged for the conventional constant-rate sprayer and the intelligent, variable-rate sprayer. In 2016, the north end of the field was used for the conventional treatment and the south end was used for the variable-rate treatment. In 2017, the treatments were reversed to control for an effect of field location (Fig. 2). The variable-rate sprayer made one pass per driveway, spraying from both sides of the sprayer, which is the normal operation for this sprayer. The conventional sprayer was operated to only discharge from one side, as was the conventional practice for this nursery. Therefore, the operator made two passes per driveway with the conventional sprayer so that the block of trees on each side of the driveway was sprayed on each date. The pesticide volume discharged was determined from spraying the entire field, and disease control and target spray characteristics were assessed on a six-row block of trees on the east side of the field (Fig. 2) because this was the only block planted entirely with the same flowering dogwood cultivar. The volume discharged by each sprayer was determined by aligning the tractor tires with a marked level area of the field before and after spraying and using the graduated

marks on the sprayer tank sight gauge to establish total volume used during each spraying event. The initial height and caliper for each of the trees that were scouted throughout the season (i.e., all six trees in each of four transecting rows in each treatment) were measured on 3 May 2016 and 2 May 2017, and the end-of-season tree measurements were performed on 21 Sept. 2016 and 13 Sept. 2017. An increase in caliper was calculated by subtracting the beginning caliper from the end-of-season caliper, and the same was performed for the increase in height calculation.

Fungicides were sprayed throughout the growing season to control powdery mildew (Table 1). Wind speed, ambient temperature, and relative humidity were measured by a handheld device (Kestrel 3000; Nielsen-Kellerman Company, Boothwyn, PA) when each sprayer was in operation and recorded. Tractor speed remained between 6.0 and 6.1 km·h⁻¹ for all spray events for both sprayers.

Sampling methods. To monitor target spray characteristics, a single back-to-back pair of 5.1- × 7.6-cm WSCs (Syngenta Crop Protection AG, Basel, Switzerland) was placed in each of the six trees in the third, 17th, and 35th transecting rows of the block from the center of the field (Figs. 2 and 3). The WSCs were held in place using electric clips crimped to 14-gauge wire that was twisted around the trunk so that the surface of

the WSC remained perpendicular to the direction of the spray output. The clip was secured to the central leader of the tree at ≈1.1 m from the ground.

In addition to monitoring target spray characteristics, WSCs were used to assess off-target spray perpendicular to the direction of spray output in support of future experiments. Clips, which held back-to-back pairs of WSCs, were added to the central leader of trees beyond the transecting rows being sprayed in the given treatment (off-target trees consisted of all six trees in three rows transecting the block) at a height of ≈1.2 m.

WSCs were placed in the target trees for the variable-rate sprayer treatment and in the off-target trees past the variable-rate sprayer treatment. When spraying was complete, WSCs were collected and placed in labeled envelopes and stored in a sealed bag with desiccant until they could be scanned and analyzed. New WSCs were placed in the corresponding locations for the conventional treatment, the conventional sprayer was operated, and WSCs were collected in the same manner after spraying.

After being transported back to the laboratory, WSCs were scanned at 600 dpi (Epson WorkForce DS-40 Wireless Portable Scanner, Epson, Suwa, Nagano, Japan). Images were saved as jpg files and analyzed in ImageJ (Public Domain) for spray coverage (percent), deposits (microliters per square

Fig. 2. Experimental plot. In 2016, the conventional sprayer treatment was on the northern (yellow) part of the field and the variable-rate sprayer treatment was on the southern (red) part of the field. In 2017, the treatments were reversed (variable rate = yellow; conventional = red).

Table 1. Treatment date, fungicide active ingredient and concentration, weather conditions, and cost for each pesticide application.

Date	Active ingredient	Concentration (g/L)	Variable-rate Sprayer					Conventional Sprayer				
			Air temperature (°C)	Relative humidity (%)	Wind speed (m/s)	Application cost (\$/ha) ^z	Air temperature (°C)	Relative humidity (%)	Wind speed (m/s)	Application cost (\$/ha) ^z		
9 May 2016	Chlorothalonil	1.7	24.5	56.3	3.2	\$3.86	24.1	51.0	3.9	\$10.29		
3 June 2016	Pyraclostrobin	0.5	27.5	55.0	1.7	\$11.06	30.6	66.0	0.7	\$16.76		
17 June 2016	Chlorothalonil	1.7	29.3	62.8	0.9	\$3.86	33.9	44.0	0.8	\$8.57		
14 July 2016	Mancozeb	2.3	33.4	64.0	2.1	\$3.50	29.0	67.0	1.0	\$9.10		
9 May 2017	Chlorothalonil	1.8	25.7	59.2	2.9	\$5.27	23.8	53.3	3.4	\$7.39		
12 June 2017	Mancozeb	2.4	36.0	52.9	0.6	\$3.14	28.1	69.4	1.2	\$6.17		
28 June 2017	Myclobutanil	0.6	29.6	46.4	1.2	\$1.55	32.1	48.5	1.9	\$4.45		
21 July 2017	Chlorothalonil	1.7	31.9	63.0	0.8	\$1.80	34.4	68.0	0.6	\$6.77		

^z/ha = US dollars per hectare.

^z\$/ha = US dollars per hectare.

centimeter), and deposit density (stains per square centimeter) using the DepositScan program (Zhu et al., 2011b). In brief, deposit density is calculated by dividing the total number of spots by the selected area of the WSC, deposits are calculated from the cumulative droplet volume, and coverage is determined by dividing the total spot area by the selected area of the WSC.

There are a few drawbacks to using WSCs to assess deposit density and deposits. Zhu et al. (2011b) acknowledged that the DepositScan program cannot identify coalesced stains as individual deposits, which can, in turn, affect both deposit density and deposit values, particularly when coverage is high. Deposition can be measured more directly either by extracting residues (Hall et al., 2004) or by using a tracer (Çilgi and Jepson, 1992; You et al., 2019); however, these methods are much more costly and time-intensive. WSCs are relatively inexpensive and easy to process, allowing for greater number of samples. Witton et al. (2018) found that although WSCs consistently overestimated deposits, the values were strongly correlated with the deposit values generated through more traditional residue analyses; they ultimately concluded that the digital analysis of WSCs was an acceptable, inexpensive, and efficient alternative.

Powdery mildew disease severity was rated once per week on ‘Cherokee Princess’ flowering dogwood trees from 3 May 2016 to 31 Aug. 2016, and from 2 May 2017 to 11 Aug. 2017. Trees in the 3rd, 17th, 23rd, and 35th transecting rows of the block were rated. The most recently matured, fully expanded pair of leaves on the central leader and two lateral branches was ranked using a scale of 1 to 9 using a modified Horsfall-Barratt scale adapted from the method of Windham and Ross (1985) (Fig. 4). The central leader and the two lateral branches (a branch on the northeast side of the tree and a branch on the southwest side) were tagged to ensure the same branches were rated each week. Additionally, these branches as well as the whole tree were assessed for the incidence of powdery mildew (recorded as either “yes” or “no”). For the whole tree, a visual inspection was conducted while standing ≈1.2 m from the trunk on all sides of the tree.

Data analysis. All analyses were conducted using SAS 9.4 (SAS Institute Inc., Cary, NC). Initial descriptive statistics were performed, including the use of PROC MEANS and PROC FREQ, to visualize the data distributions and determine the frequency of various responses over sprayer type (variable-rate vs. conventional), orientation (proximal vs. distal to sprayer), and week.

To test if there were differences in the sprayer type that affected growth metrics and spray volumes, separate mixed analysis of variance (ANOVA) models for each year were performed to test the fixed effect of the sprayer type. Least square means and SE are reported.

For each year, deposit density, deposits, and coverage on target cards were analyzed using a mixed model ANOVA (PROC GLIMMIX) with the fixed effects of sprayer type, date, and orientation, as well as their two-way and three-way interaction effects. To account for variations attributable to the experimental design, random effects × row nested within the sprayer type, orientation × row nested within the sprayer type, and an autoregressive structure for repeated measures over time were included in each model. As needed, to meet the ANOVA assumptions of normality and homogeneity of variance, deposit density, coverage data, and powdery mildew ratings data were log-transformed. Back-transformed means for these data are presented unless otherwise indicated.

To test whether there were differences in probability for powdery mildew, a multivariable mixed logistic regression model was developed using PROC GLIMMIX with a binary distribution and logit link. The fixed effects tested included sprayer type, orientation, and sprayer type × orientation interaction. Random effects included the transecting row nested within sprayer type, transecting row × orientation within sprayer type, and the week × transecting row × sprayer type × orientation. The least square means statement was used to obtain odds ratios, and the inverse link function was used to obtain model-adjusted probabilities for developing powdery mildew.

Results and Discussion

Growth metrics. In 2016, the increase in caliper during the growing season was unaffected by sprayer type: 7.3 mm for the variable-rate (SE = 0.45) and 7.8 mm for the conventionally sprayed trees (SE = 0.45), respectively ($P = 0.37$). The increase in plant height was greater for the conventional treatment (28.5 cm; SE = 2.9) than for the variable-rate treatment (18.0 cm; SE = 2.9) ($P = 0.02$).

In 2017, the increase in caliper during the growing season was greater for the variable-rate treatment (12.6 mm; SE = 0.56) than for the conventional treatment (9.8 mm; SE = 0.56) ($P < 0.01$). The increase in plant height was unaffected by the sprayer type: 48.8 cm (SE = 3.5) for the variable-rate and 48.3 cm (SE = 3.5) for the conventionally sprayed trees, respectively ($P = 0.91$).

Based on these inconsistent results (e.g., plants sprayed with the conventional sprayer had a greater height increase in 2016 but lower caliper increase in 2017 than plants sprayed with the variable-rate sprayer), it is unlikely that the use of the variable-rate sprayer negatively impacted crop growth. The modest inconsistent differences may be associated with the portion of the field where the trees were grown or variations in timing or execution of production practices such as pruning.

Spray volume. In both 2016 and 2017, the variable-rate sprayer used a lesser volume of pesticide than the conventional sprayer ($P =$

Fig. 3. Water-sensitive card (WSC) positions and branches surveyed for disease ratings. To assess the target spray characteristics, all six trees in three rows transecting the block within the given treatment contained a single pair of back-to-back WSCs held at ≈ 1.1 m. To assess off-target spray characteristics, all six trees in three rows transecting the block beyond the given treatment contained a single pair of back-to-back WSCs held at ≈ 1.2 m. WSCs were secured to the trees with the surface of the WSCs oriented perpendicular to the direction of spray output with electrical clips.

0.02 and $P = 0.01$, respectively). The variable-rate sprayer reduced spray volume by 55% and 53% in 2016 and 2017, respectively (Fig. 5). This translated to an average cost savings of \$5.61 per application per hectare in 2016 and \$3.26 per application per hectare in 2017 (Table 1).

Assuming that spray applications must be performed every 2 weeks from May to October (Li et al., 2009), the average pesticide cost savings per year would be \$57.62 per hectare for the control of powdery mildew. Given a 100-ha field nursery, input savings related to the control of powdery mildew would be \$5762 per year. Other diseases would require fungicides that are not effective against powdery mildew, and some insecticides may need to be applied, potentially necessitating separate applications because of timing or incompatibility; therefore, additional savings are possible. Economic evaluations of this technology estimated annual savings between \$1420 and \$1750 per hectare for season-long insect and disease control in apple orchards and a pay-back period between 1.1 and 3.8 years for orchards up to 20 ha (Manandhar et al., 2020).

Target spray characteristics. In 2016, the deposit density on target WSCs had a significant orientation $\times$ sprayer type interaction ($P = 0.008$) and date $\times$ sprayer type

interaction ($P = 0.01$) (Fig. 6A and B). Within the distal trees, the conventional sprayer had a greater deposit density on target WSCs (an average of 83.9 stains/cm²) than the variable-rate sprayer (an average of 30.2 stains/cm²); however, within the proximal trees, there was no difference between the two treatments. Within the variable-rate treatment there was no date effect; however, within the conventional treatment, the deposit density on target WSCs on 3 June 2016 was greater than that on 17 June 2016 and 14 July 2016. Also, on 3 June 2016, the deposit density on target WSCs was greater for the conventional treatment than for the variable-rate treatment; however, on 9 May 2016, 17 June 2016, and 14 July 2016, there was no difference in the deposit density between treatments.

In 2017, the deposit density on target WSCs again showed a significant orientation $\times$ sprayer type interaction ($P = 0.05$) and date $\times$ sprayer type interaction ($P = 0.0009$) (Figs. 6C and D). Within both the distal and proximal trees, the conventional sprayer had the greater deposit density (86.1 and 65.1 stains/cm², respectively) on target WSCs than the variable-rate sprayer (17.4 and 34.4 stains/cm², respectively). Within the variable-rate treatment, there was a greater deposit density on target WSCs on 12 June

2017 than on 28 June 2017, but all other dates did not differ in the deposit density. In the conventional treatment, there was a greater deposit density on target WSCs on 9 May 2017 than on 12 June 2017 and 28 June 2017; however, the deposit density on 21 July 2017 did not differ from any of the other dates. On 9 May 2017, 28 June 2017, and 21 July 2017, the deposit density on target WSCs was greater with the conventional treatment than with the variable-rate treatment; however, on 12 June 2017, there was no difference in the deposit density on target WSCs between treatments.

The lack of a date effect on the deposit density with the variable-rate treatment in 2016 and having only a single pair of dates differ for deposit density in 2017 within the variable-rate treatment suggest that the variable-rate sprayer is sensing the target density and adjusting its output accordingly to provide a consistent application to a changing canopy, as it is designed to do. On half of all of the spray dates, there was no difference in the deposit density between the variable-rate and conventional treatments, demonstrating that the variable-rate sprayer can supply an application comparable to that of the conventional sprayer on targeted foliage.

In 2016, deposits on target WSCs were affected by the sprayer type ($P = 0.001$) and

Fig. 4. Modified Horsfall-Barratt scale adapted from Windham and Ross (1985) showing the severity of powdery mildew on dogwood leaves. Photo credit: Diana Cochran.

Fig. 5. Pesticide application rate comparison between the variable-rate and conventional sprayers. There was a sprayer type effect in both (A) 2016 ($P = 0.0223$) and (B) 2017 ($P = 0.0123$) for the pesticide application rate. The bars are means $\pm$ SE. Means marked with different letters indicate significant difference ($P < 0.05$).

by the date ($P = 0.0006$) (Figs. 7A and B). Deposits on target WSCs were greater with the conventional treatment ($3.1 \mu\text{L}\cdot\text{cm}^{-2}$) than with the variable-rate treatment ($0.2 \mu\text{L}\cdot\text{cm}^{-2}$). There were fewer deposits on target WSCs on 17 June 2016 than on 9 May 2016 and 3 June 2016.

In 2017, deposits on target WSCs were affected by orientation ($P = 0.03$) and a sprayer type $\times$ date interaction ($P < 0.0001$) (Figs. 7C and D). There were more deposits on target WSCs in proximal trees ($0.5 \mu\text{L}\cdot\text{cm}^{-2}$) than in distal trees ($0.1 \mu\text{L}\cdot\text{cm}^{-2}$). On 9 May 2017 and 12 June 2017, there was

no difference in deposits on target WSCs attributable to the sprayer type. On 28 June 2017 and 21 July 2017, deposits on target WSCs were greater with the conventional treatment (0.4 and $0.8 \mu\text{L}\cdot\text{cm}^{-2}$, respectively) than with the variable-rate treatment (0.0 and $0.0 \mu\text{L}\cdot\text{cm}^{-2}$, respectively).

Fig. 6. Comparisons between deposit density with the variable-rate sprayer treatment and the conventional sprayer treatment. In 2016, there was (A) an orientation $\times$ sprayer type interaction ($P = 0.0076$) and (B) a sprayer type $\times$ date interaction ($P = 0.0143$) for the deposit density on target WSCs. In 2017, there was (C) an orientation $\times$ sprayer type interaction ($P = 0.0488$) and (D) a sprayer type $\times$ date interaction ($P = 0.0009$) for the deposit density on target WSCs. The bars are means $\pm$ SE. Means marked with different letters indicate significant difference ($P < 0.05$).

Fig. 7. Significant effects and interactions on deposits. In 2016, there was (A) a sprayer type effect ($P = 0.0012$) and (B) a date effect ($P = 0.0006$) for deposits on target WSCs. In 2017, there was (C) an orientation effect ($P = 0.0250$) and (D) a sprayer type $\times$ date interaction ($P < 0.0001$) for deposits on target WSCs. The bars are means $\pm$ SE. Means marked with different letters indicate significant difference ($P < 0.05$).

In 2017, sprayer type was no longer a main effect; instead, tree location within the block influenced deposits, possibly because trees were larger in 2017 than in 2016. Average tree height was 41% greater during the second year (126.7 cm in 2016 vs. 178.5 cm in 2017). A larger canopy deflecting droplets was commensurate with the fact that deposits were generally lower in 2017, when the trees were larger (Fig. 7). Deposits observed during the present study (untransformed means ranging from 0.03 to 30.8 $\mu\text{L}\cdot\text{cm}^{-2}$) were comparable with results from another study using variable-rate spray technology retrofitted to a traditional orchard air-blast sprayer with a more typical high-powered fan and operated at or below default rates. Fessler et al. (2020) evaluated spray rates on large apple trees [*(Malus $\times$ domestica)* Borkh.] and found deposits ranging from 0.6 to 128.3 $\mu\text{L}\cdot\text{cm}^{-2}$ on target cards in a range of canopy positions. Additionally, during the present study, deposits on cards in distal trees were reduced 80% in 2017 compared with those on cards in trees in proximal rows. Fessler et al. (2020) found that among large apple trees in single rows, deposits on the target card farthest from the sprayer were reduced by 97.6% to 98.1%,

depending on the spray rate, compared with deposits detected on the most proximal card.

In 2016, coverage on target WSCs was affected by the sprayer type ($P = 0.0007$) and by the date ($P = 0.0014$) (Figs. 8A and B). Coverage on target WSCs was greater with the conventional treatment (14.8%) than with the variable-rate treatment (2.3%). There was lower coverage on 17 June 2016 than on 9 May 2016 and 3 June 2016.

In 2017, coverage on target WSCs was affected by orientation ($P = 0.0267$) and a sprayer type $\times$ date interaction ($P < 0.0001$) (Figs. 8C and D). There was greater coverage on target WSCs in proximal trees (3.8%) than in distal trees (1.0%). On 9 May 2017 and 12 June 2017, there was no difference in coverage on target WSCs between sprayers. However, on 28 June 2017 and 21 July 2017, coverage on target WSCs was greater with the conventional treatment (5.1% and 7.2%, respectively) than with the variable-rate treatment (0.2% and 0.2%, respectively).

Chen et al. (2020b) achieved comparable or better disease and insect control across multiple seasons with the variable-rate sprayer when compared with a conventional, constant-rate sprayer, with pesticide coverage

of 64.0% and 53.7%, respectively, which were both well above the overspray threshold of 30% (Chen et al., 2013a). However, coverage levels in the present study (untransformed means ranging from 4.8% to 31.7%) are generally less than 25%, which is consistent with other research that found that just half of WSCs sprayed using the variable-rate sprayer had coverage more than 15% (Chen et al., 2011); however, these levels were sufficient to prevent even modest powdery mildew infection levels. Although it likely varies with the pathogen, environment, and fungicide, investigating and identifying a minimum coverage threshold to compliment the 30% overspray metric could help spray operators further refine their application rates. Additionally, reducing the spray volume, and thus overspray and off-target loss, to nontarget vegetation may provide a more favorable environment for antagonistic, nonpathogenic fungi that compete with plant pathogens and improve long-term sustainability.

The variable-rate sprayer is designed to apply only the designated quantity of spray output based on the target crop characteristics to avoid the overapplication and low efficiencies of conventional sprayers; therefore, it is

Fig. 8. Significant effects and interactions on coverage. In 2016, there was (A) a sprayer type effect ($P = 0.0007$) and (B) a date effect ($P = 0.0014$) for coverage on target WSCs. In 2017, there was (C) an orientation effect ($P = 0.0267$) and (D) a sprayer type $\times$ date interaction ($P < 0.0001$) for coverage on target WSCs. The bars are means $\pm$ SE. Means marked with different letters indicate significant difference ($P < 0.05$).

logical that both coverage and deposits were greater with the conventional treatment than with the variable-rate treatment in 2016, and on certain dates in 2017. Likewise, during experiments evaluating sprayer performance over a range of grapevine growth stages, coverage from conventional, constant-rate applications was greater than that from intelligent, variable-rate applications during the earliest stage, when plants were smaller and less dense (Nackley et al., 2021). However, this does deviate from some studies in which variable-rate and constant-rate coverage were not different (Chen et al., 2020b; Zhu et al., 2017a). In the present study, because the same field of trees was used in 2016 and 2017, it is not surprising that the effect of orientation on deposits and coverage was evident in 2017, when trees were larger and denser. The orientation (distal vs. proximal row) effect on WSC characteristics could be significant for larger trees, including when sprayed by conventional air-blast sprayers; therefore, it should be further investigated using a range of tree sizes and target pest locations.

Off-target spray characteristics. Off-target spray detected on the WSCs was so minimal that differences were not of practical importance.

No statistical analysis of these data is presented, and untransformed means are reported. The average deposit densities were 4.15 and 4.50 stains/cm² in 2016 and 2017, respectively. The average deposits were 0.03 and 0.05 $\mu\text{L}\cdot\text{cm}^{-2}$ in 2016 and 2017, respectively. The average coverages were 0.27% and 0.55% in 2016 and 2017, respectively.

For this experiment, off-target drift cards were placed perpendicular to the direction of the spray cloud discharged from the sprayer. This suggests that orienting plots in such a way that they are “end-to-end”, as they were in this experiment, results in a minimal amount of off-target spray contamination from one treatment to another. The limited off-target drift in a perpendicular direction can also be used when planning the layout of new nurseries or when replanting existing nurseries to prevent off-target losses onto sensitive crops and other sensitive areas such as ponds, public roadways, and neighboring properties.

Powdery mildew severity and incidence. In 2016, the powdery mildew ratings on the central leader demonstrated an orientation $\times$ week interaction ($P = 0.004$) (Fig. 9A), ratings on the northeast branch had a sprayer type $\times$ orientation $\times$ week interaction ($P = 0.002$)

(Figs. 9B–E), and ratings on the southwest branch had a sprayer type $\times$ week interaction ($P < 0.0001$) (Fig. 9F). For the central leader, during weeks 5 through 8, distal trees had a higher powdery mildew rating than proximal trees; however, the average rating never exceeded 1.7 on this scale of 1 to 9. For the northeast branch, within the variable-rate treatment, distal trees had a higher powdery mildew rating than proximal trees for weeks 5 through 9; however, the average rating never exceeded 2.3 (Fig. 9B). Within the conventional treatment, there was no difference between the distal and proximal trees (Fig. 9C). For the northeast branch, within the proximal trees, during week 9, the conventional treatment had higher powdery mildew ratings than the variable-rate treatment; however, during week 12, the variable-rate treatment had higher ratings than the conventional treatment (Fig. 9D). Within the distal trees, during weeks 5 through 8, the variable-rate treatment had higher ratings than the conventional treatment (Fig. 9E). For the southwest branch, during weeks 4 through 7, trees with the variable-rate treatment had higher powdery mildew ratings than trees with the conventional treatment; however, the average powdery mildew rating never exceeded 2.3.

Fig. 9. The 2016 powdery mildew ratings. Ratings were based on a modified Horsfall-Barratt scale (1–9) for severity. On the central leader, there was (A) an orientation $\times$ week interaction ($P = 0.0037$). On the northeast (NE) branch, there was a sprayer type $\times$ orientation $\times$ week interaction ($P = 0.0023$). (B) Proximal and distal ratings within the variable-rate treatment. (C) Proximal and distal ratings within the conventional treatment. (D) Variable-rate and conventional ratings within the proximal trees. (E) Variable-rate and conventional ratings within the distal trees. On the southwest (SW) branch, there was (F) a sprayer type $\times$ week interaction ($P < 0.0001$). Error bars show SE. Asterisks indicate significant difference ($P < 0.05$).

In 2017, powdery mildew ratings on all branches (central leader, northeast branch, and southwest branch) were affected by week ($P < 0.0001$ for all) (Figs. 10A–C). For the central leader, weeks 9 and 10 had higher ratings than weeks 1 through 7, 11, and 13. For the northeast branch, weeks 9 and 10 had higher ratings than weeks 1 through 5 and 11 through 13. For the southwest branch, weeks 9 and 10 had higher ratings than weeks 1 through 5, 7, and 11 through 13. However, even during weeks 9 and 10, powdery mildew ratings were less than 1.7 for all branches.

Week had the most prevalent effect on powdery mildew ratings, which may be attributable to a series of weeks when environmental conditions were particularly favorable for infection, a period when new and succulent growth was present, and/or when more rapid breakdown in fungicide protection

occurred. Severity began increasing in late May and early June during both years, which is consistent with research that showed that this is when plants become exposed to and infected by airborne inoculum (Mmbaga, 2002). Orientation also had an influence on ratings, which could be attributable to distal trees receiving less spray (Figs. 9A–C) and/or a microclimate effect when there is greater humidity on the interior of blocks, creating higher disease pressure. Although the sprayer type factored into some interactions, with the variable-rate treatment having higher powdery mildew ratings than the conventional treatments in limited instances, both sprayers sufficiently controlled powdery mildew, limiting ratings to 2.8 on any given subset of trees and averaging 1.3. Since becoming established in Tennessee in the

1990s, the fungal organisms that cause dogwood powdery mildew are considered ubiquitous and necessitate fungicide applications bimonthly throughout the growing season to prevent infection (Li et al., 2009). These previously unnecessary pesticide applications increased the cost of dogwood production by $\approx$ \$1900 per hectare per year (Li et al., 2009; Windham et al., 2000) and caused many small dogwood producers to go out of business (Windham et al., 2005). In the present study, both sprayer types were able to apply sufficient fungicide to protect trees during the majority of the season and limit severity to a rating less than 2.8 on a scale of 1 to 9 in 2016 and less than 1.7 throughout 2017.

In addition to severity, the incidence of powdery mildew was also analyzed. Regarding the whole-tree incidence, there was no difference between the two sprayer

Fig. 10. The 2017 powdery mildew ratings. Ratings were based on a modified Horsfall-Barratt scale (1–9) for severity. On the central leader, there was (A) a week effect ($P < 0.0001$). On the northeast (NE) branch, there was (B) a week effect ($P < 0.0001$). On the southwest branch, there was (C) a week effect ($P < 0.0001$). Error bars show the SE. Points marked with different letters indicate significant difference ($P < 0.05$).

types ($P > 0.05$) in 2016 or 2017 (Fig. 11). For individual branches (i.e., central leader, northeast branch, and southwest branch), there was only one instance when the powdery mildew incidence was higher with the variable-rate treatment than with the conventional treatment, which was on the southwest branch in 2016 ($P = 0.02$) (Fig. 11A). For all other comparisons, the powdery mildew incidence did not differ between the variable-rate and conventional treatments.

Because this experiment was conducted at a commercial nursery, there was no untreated control. However, flowering dogwood is well-documented as a highly susceptible host (Li et al., 2009; Windham et al., 2005). The organisms that cause powdery mildew are considered ubiquitous in central Tennessee, the location of this experiment, as is warm, humid weather conducive to infection (Windham et al., 2000). Severe disease pressure for

dogwood powdery mildew is well-researched and established in the literature because of the financial strain this disease causes the Tennessee nursery industry (Li et al., 2009). Additionally, disease management reports from within 30 miles of this location in 2016 and 2017 show substantial disease severity (as high as 80% of the foliage area affected) on untreated controls (Baysal-Gurel and Simmons 2018a, 2018b; Baysal-Gurel et al., 2017a, 2017b).

Both sprayers provided acceptable control of powdery mildew severity and incidence. Although orientation affected spray characteristics monitored by WSCs, both sprayer types provided adequate fungicide applications to keep powdery mildew levels low [i.e., throughout the duration of the experiment, a single assessment never exceeded 4 (raw data point) on the rating scale of 1 to 9 (data not shown)] on both proximal and distal trees.

Additionally, this level of control was achieved even when the variable-rate sprayer did not meet industry recommendations for deposit density guidelines. Specifically, the variable-rate sprayer met the recommended fungicide application deposit density of 50 to 70 stains/cm² (Syngenta AG, 2002) on only one date (9 May 2016), whereas the conventional sprayer met the recommendation on five dates (9 May 2016, 17 June 2016, 14 July 2016, 12 June 2017, and 28 June 2017) but exceeded it on the other three dates (3 June 2016, 9 May 2017, and 21 July 2017). Current recommendations may exceed the spray characteristics required for acceptable control of some diseases. Other studies have reached similar conclusions. Xiao et al. (2020) found that when using an unmanned aerial vehicle to spray pepper (*Capsicum annuum* L.) plants for the control of *Phytophthora capsica* (Leon.), the deposit density did not exceed 40 stains/

Fig. 11. A binary scale was used to record the powdery mildew incidence, which was then analyzed as the probability of powdery mildew occurring. **(A)** In 2016, there was only a sprayer type effect on the SW branch ($P = 0.0206$) for the whole tree, central leader, and northeast (NE) branch ($P > 0.05$). **(B)** In 2017, there was no effect of sprayer type for the whole tree or any of the branches ($P > 0.05$ for all). The bars are means $\pm$ SE. Asterisks indicate significant difference ($P < 0.05$) between paired means.

cm²; however, the control efficacy was more than 95% for a treatment at one-third the normally recommended concentration of active ingredient per hectare and was no different from that of the control electric air-pressure backpack sprayer, for which the deposit density was consistently more than 50 stains/cm² and was applied at the full concentration. Another study that examined different nozzles used for unmanned aerial vehicle spray applications showed that the control efficacy of rice plant hoppers [*Nilaparvata lugens* (Stål), *Sogatella furcifera* (Horváth), and *Laodelphax striatellus* (Fallénat)] at the flowering stage was $78.3 \pm 12.7\%$ for a nozzle type that applied less than the 20 stains/cm² threshold for insecticides at more than half of the sampling sites for the upper layer and did not reach this threshold at all for the lower layer (Chen et al., 2020a). Washington (1997) demonstrated that *Mycosphaerella fijiensis* (Morelet) ascospore germination on banana [*Musa* (L.)] leaves was 0% for two different fungicides when the deposit density was as low as 10 stains/cm².

These results of this experiment that indicate sufficient pest control across a season and a

consistent reduction in spray volume using this intelligent, variable-rate spray technology are supported by similar results of other experiments that demonstrated comparable insect and disease control between variable-rate and conventional sprayers in a nursery and savings on a per-pest basis averaging \$150.16 per hectare (Zhu et al., 2017b). Chen et al. (2019) found that powdery mildew on multirow blocks of ‘Bloodgood’ London planetree (*Platanus acerifolia*) and dogwood was controlled as well or better by the intelligent, variable-rate technology. Additionally, variable-rate technology reduced the spray volume by 52.1% and 25.4% for London planetree and dogwood, respectively. In this same study, for trees sprayed with the variable-rate, intelligent sprayer, apple scab [*Venturia inaequalis* (Cooke)] ratings on crabapple [*Malus ‘Sutyzam’* (Sugar Tyme®) and *M. sargentii*] were significantly higher on a single date in 2017, but not different or lower on the remaining dates in 2017 and on all 19 dates they were ranked in 2018, whereas pesticide use was reduced by 56.3% compared with that of the conventional sprayer. Chen et al. (2021) also effectively and efficiently controlled a range of insects and diseases in both nurseries

and small fruit orchards using variable-rate technology and reduced both foliar fertilizer and pesticide applications up to 65% over a 3-year period.

Conclusion

This study demonstrated that a variable-rate, laser-guided sprayer can be successfully used in a commercial nursery planted in multirow blocks to achieve efficient disease control while reducing the spray volume by more than 50% when compared with an already reduced conventional constant-rate application of 187 L·ha⁻¹. There were no sustained positive or negative effects of the sprayer type on crop growth metrics. Powdery mildew, a ubiquitous and costly disease for dogwood producers, was controlled effectively by both sprayer types throughout the course of both seasons despite the constant-rate sprayer generally providing higher spray coverage and deposit density than the variable-rate sprayer. Although potentially microorganism-specific and pesticide-specific, control was achieved despite deviating from the standard minimum deposit densities for fungicides on all but one spray date, suggesting that

further reductions should be explored. The absence of nearly any detectable spray deposits from either sprayer on drift cards indicates the ability to locate test plots and sensitive plant species perpendicular to the direction of the spray cloud. This variable-rate technology has the potential to reduce total pesticide use, not only dramatically reducing input costs for growers but also decreasing the environmental impact on soil, water, air, and nontarget organisms as well as reducing worker exposure. As a result, Smart Guided Systems (Indianapolis, IN) commercialized this technology as a retrofit kit for conventional air-blast sprayers to achieve variable-rate benefits.

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