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Using Laser-guided Variable-rate Spray Technology with Reduced Rates to Control Pests and Decrease Off-target Movement in a Tall Spindle-trained Apple Orchard

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Abstract. **Apple orchardists in the United States protect their crops from numerous insects and diseases using foliar pesticide applications to produce blemish-free produce; however, doing so incurs significant labor and input costs. Variable-rate spray application technology used at the default spray rate has successfully reduced pesticide volume and, consequently, input costs in orchards and nurseries while effectively controlling several diseases and insects. Our objectives were to evaluate spray characteristics and the pest control efficacy of a sprayer operated in the variable-rate mode at a lower rate than the default rate and compare them with those associated with the conventional constant-rate spray mode. Through preliminary experiments, a reduced spray rate of 0.05 L·m^{-3} of crop volume, which equated to 321.1 L·ha^{-1}, was selected and compared with a conventional constant-rate of 808 L·ha^{-1} using a sprayer retrofitted with variable-rate spray technology and operated in the two different modes throughout two growing seasons. Foliage was scouted biweekly for diseases and two arthropods, and apples were scouted weekly for disease. The variable-rate mode reduced the pesticide volume applied by 58% and maintained pesticide coverage at or above the overspray threshold at all canopy locations except for one. Nontarget ground applications were greatly reduced using the variable-rate mode. Foliar disease measured as leaf spot incidence and leaf spot count severity was unaffected by the spray mode. Fruit rot incidence, fruit rot severity, and disease index for fruit were also unaffected by the spray mode. Fruit disease index, which incorporates both incidence and severity measurements, remained low throughout both seasons. Disease progression was assessed by calculating the area under the disease progress curve (AUDPC). The foliar AUDPC was significantly higher in the variable-rate treatment at the middle of hill location, but not at the bottom or the top of the hill, compared with that of the constant-rate treatment. The fruit AUDPC was unaffected by treatment. Although normally common in apple orchards, neither of the two arthropods was detected on any date. The utility and limitations of existing spray characterization metrics as well as the need for yet-to-be-developed metrics are discussed.**

In the United States, apple production covers approximately 290,200 acres and produces 4,924,250 tons of apples (US Department of Agriculture–National Agricultural Statistics Service 2022), providing \$8 billion in wages and \$22.8 billion in total economic output (US Apple Association 2024). Apple crops, particularly late-maturing cultivars, may be sprayed as many as 25 times per year to achieve adequate pest management (Villani 2023; Walgenbach et al. 2021). These sprays comprise an estimated application of 70 million kg of pesticides per year (Pimentel et al. 1993; US Department of Agriculture–National Agricultural Statistics Service 2018) to control a range of insects and mites (arthropods) and foliar and fruit diseases.

There are several challenges associated with apple production in the southeastern United States. Apples are susceptible to numerous insects, mites, and diseases (Sutton et al. 2014) For example, 10 to 12 arthropods are expected to occur in every North Carolina orchard every year (Sutton et al. 2004). The southeastern growing season is longer than that of more northern growing regions; additionally, it is often warmer and more humid, and therefore more favorable, for several common apple diseases (Villani 2023). For example, fire blight and cedar apple rust infection periods may extend longer in the relatively mild spring in the southeastern United States compared with those in other growing regions, while the hot and humid summers are favorable for fruit rots and foliar diseases such as bitter rot (*Colletotrichum* spp.) and Glomerella leaf spot (*Colletotrichum* spp.) (Schubert 1983; Sutton et al. 2014). Furthermore, harvest may extend well into October for late-maturing cultivars, necessitating an 8-month pest management spray program (Villani 2023). Greater insect and disease pressure and a higher number of pesticide applications increases the labor, fuel, and chemical expense of pest control. In the Southeast, a greater portion of sales is attributed to the fresh market rather than processing (Manandhar et al. 2020), thereby decreasing tolerance for fruit blemishes and making marketability an important consideration in pest management (Pimentel et al. 1993).

As in other apple-growing regions of the United States, apple production in the southeastern United States is transitioning to high and ultra-high planting densities supported by trellises (Robinson 2008). Pesticide use can decrease by up to 70% when switching from standard to dwarfing rootstock (Autio and Cowgill 2016) because of the reduction in crop volume per acre. These systems have greater light penetration and air circulation, thus creating less favorable environments for disease-causing organisms. The reduced tree volume also facilitates greater pesticide penetration into the canopy. However, even with modern high-density production systems, growers remain heavily reliant on pesticide applications for pest management.

Traditional air-blast sprayers can significantly over-apply pesticides in traditional orchards (Fessler et al. 2020) and, therefore, would over-apply pesticides to high and ultra-high density production systems to an even greater extent given their smaller and more sparse trees (Warneke et al. 2021). Variable-rate technology may be an additional means by which growers can reduce pesticide use in high and ultra-high orchard densities. Variable-rate technology uses sensors to detect the crop and travel speed and adjusts spray output in real time, eliminating application to voids between, above, below, and within trees (Chen et al. 2012; Shen et al. 2017). The system automatically adjusts to crop density and, in essence, automates the tree row volume (TRV) calculation (Liu and Zhu 2016). This technology has been tested over several years (Boatwright et al. 2020; Chen et al. 2012; Fessler et al. 2020; Nackley et al. 2021; Shen et al. 2017) since its development by the US Department of Agriculture and commercialization by Smart-Apply LLC. In a medium-density planting of semi-dwarf apple trees, pesticide volume was reduced by 67% to 74% when using variable-rate compared with traditional constant-rate application (Nackley et al. 2021). In a study of apple, peach, blueberry, and raspberry, the pesticide volume applied was reduced up to 53% (Chen et al. 2021), and it was reduced up to 71% in a peach orchard (Boatwright et al. 2020). In addition to reducing the pesticide volume discharged, this technology reduced spray drift by up to 40% and 33% in orchards and vineyards, respectively (Nackley et al. 2021), and nearly 50% in peaches at the bloom stage with no reduction in pest control (Boatwright et al. 2020). Reducing drift not only reduces waste but also can be particularly beneficial to agri-tourism and other operations that are in close proximity to dwellings, businesses, and automobile and pedestrian traffic. The spray technology was initially tested on standard (single trunk) and multistem nursery crops. Rathnayake et al. (2022) used variable-rate spray technology in a high-density commercial apple orchard to compare spray deposition qualities for an application rate of 935 $L \cdot ha^{-1}$ applied with conventional constant-rate spray technology and comparable rates based on the TRV model (0.09 $L \cdot m^{-3}$) and unit crop row (UCR) model (0.10 $L \cdot m^{-3}$) applied using variable-rate technology. The authors found no difference in spray deposition or coverage between these rates and the standard rate, but they did not explore efficacy against pests. The reduced canopy volume of high-density and ultra-high density orchard plantings may allow variable-rate systems to effectively control arthropods and diseases with a further reduction in liters applied per cubic meter of crop canopy.

Therefore, our objectives were to evaluate spray characteristics and pest control efficacy of a sprayer operated in the variable-rate mode using a rate lower than the default rate and compare it with the conventional constant-rate spray mode.

Materials and Methods

Sprayer and instrumentation. This experiment was conducted at The Apple Barn & Cider Mill (Sevierville, TN, USA) using their trailer-mounted air-blast sprayer (AF505; Durand Wayland, LaGrange, GA, USA). The sprayer had a tank volume of 1893 L and a PTO-driven centrifugal pump. Each side of the sprayer had 10 ceramic nozzles (D5 disc and D4 or D5 cores) discharging 2.5 to 3.0 $L \cdot m^{-3}$ at the designated operating pressure 690 kPa. Each nozzle was independently controlled by pulse width-modulated solenoids (e-Chemisaver; TeeJet Technologies, Glendale Heights, IL, USA) using the intelligent system. Only the lower eight nozzles were operational during this study to tailor the application to the height of the crop.

The air-blast sprayer was retrofitted with an intelligent application system developed by the US Department of Agriculture (Chen et al. 2012) that automatically calculated TRV and discharged pesticide solution accordingly in real-time, i.e., intelligent variable-rate mode. The sprayer could also be operated in the conventional constant-rate mode. The intelligent system was composed of a LiDAR sensor (UTM-30LX; Hokuyo Automatic Co., Osaka, Japan) and Doppler radar ground speed sensor (RVSIII radar velocity sensor; Dickey-John Corp., Auburn, IL, USA) that were used to sense the crop presence, size, and density and the sprayer's travel speed, respectively. LiDAR crop volume data and ground speed data were processed (Liu and Zhu 2016) and sent to an automatic flow control box to control (on/off and flow rate) the operation of individual nozzles.

An embedded touch screen interface in the tractor cab was used to enter spray parameters, which were determined based on the crop size and row and driveway spacing (spray width, 4.57 m; vertical maximum, 20 m; vertical minimum, 0.3 m; horizontal maximum, 6.0 m; horizontal minimum, 0.5 m) and designate the spray rate (fluid ounces of spray solution per cubic foot of crop). The spray rate was selected based on experiment results described below. A switch box allowed the operator to select the sprayer mode, i.e., constant- or variable-rate. The tractor was operated at 4.7 to 5.1 $km \cdot h^{-1}$.

A weather station was installed near the Catlett plot on an exposed hilltop to record site-specific air temperature, relative humidity, wind speed and direction, precipitation, solar irradiance, and leaf wetness. The components of the station included an air temperature and humidity sensor (HMP60; Vaisala Corp., Helsinki, Finland), wind monitor (05108-L; Campbell Scientific Inc., Logan, UT, USA), rain gauge (TE525MM; Texas Electronics, Dallas, TX, USA), pyranometer (LI200X; LI-COR, Lincoln, NE, USA), and leaf wetness sensor (237; Campbell Scientific Inc.). Sensors were wired to a data logger (CR1000; Campbell Scientific Inc.) that read and recorded data from the sensors using a CR Basic (Campbell Scientific Inc.) program. The system was powered by a 12V 115-amp-hour deep-cycle battery that was charged by a 130 W/12V photovoltaic panel (KC 130™; Kyocera, Mesa, AZ, USA).

Determining the spray rate for the variable-rate mode. Before beginning the efficacy trial, a preliminary experiment of two different plots in the orchard was conducted to ensure that the selected variable-rate settings would provide sufficient pesticide application

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throughout the orchard. Both plots consisted of trellised Fuji apples (*Malus domestica* Borkh.) grafted onto Budagovsky 9 dwarfing rootstock, but the planting date and driveway width differed between the two plots, with the Catlett plot being the older of the two plots. In the Hilltop plot, there was 7.0 m between rows. In the Catlett plot, there was 5.5 m between rows. In both plots, there was 1.2 m between trees within rows, and the selected trees were in the same row. The driveways on either side of the selected row were deemed the primary and secondary driveways.

To quantify spray characteristics, water-sensitive paper (WSP) was used and later analyzed to determine coverage and deposit density. Commonly, WSP is used to assess spray characteristics (Özlüoymak and Bolat 2020; Zhu et al. 2011) and allow characteristics to be quantified by changing from yellow to dark blue where spray deposits contacted the WSP. Back-to-back pairs of 5.1-cm × 7.6-cm WSP cards (Syngenta Crop Protection AG, Basel, Switzerland) were placed in two locations in the canopy; the "center" cards were placed at the center of the canopy in line with the trunk, and the "near" cards were placed approximately 63.5 cm from the trunk toward the primary driveway. The WSP strips were wrapped around the trunk 30.5 cm from the ground and marked to distinguish cardinal directions. The WSP wraps were created using 2.6-cm × 50-cm WSP strips (Syngenta Crop Protection AG, Basel, Switzerland), which were cut into 21.6-cm sections and stuck to 5.6-cm × 21.6-cm segments of adhesive transparencies using double-sided tape; in the field, the protective film was removed and adhesive was stuck to the tree trunk.

Trees were sprayed in variable-rate mode from both the primary and secondary driveways with a spray rate of 0.009, 0.01, 0.03, or 0.05 L of spray solution per cubic meter of crop detected ($L{\cdot}m^{-3}$). These rates were below the default rate of 0.07 $L{\cdot}m^{-3}$. The sprayer was driven at approximately 5.0 $km{\cdot}h^{-1}$. Because of the low height of the trees, the top two nozzles remained closed.

Sprayed WSP cards were collected in labeled envelopes and stored in a sealed plastic bag with desiccant. The WSP wraps were collected on labeled sheets of paper and then stored in sealed plastic bags with desiccant. New WSP cards and wraps were distributed, and this process was repeated until all four rates had been applied in both plots. The total volume applied when spraying from the primary and secondary driveways was recorded using the monitor.

The WSP was scanned at 600 dpi (HP Photosmart Plus All-in-One Printer B209; Hewlett-Packard, Palo Alto, CA, USA) and saved as a .jpg file. Then, these files were analyzed to determine spray coverage (%) and deposit density (droplets/cm^2) using DepositScan software (Zhu et al. 2011).

Efficacy trial. The efficacy trial was conducted at the Catlett plot, which was planted in 2017 and consisted of Nonaburg channery silt loam soil type (Soil Survey Staff 2021). The plot was divided approximately in half from north to south. The eastern side was sprayed using the intelligent variable-rate mode, and the western side was sprayed using the conventional constant-rate mode throughout the season in 2021 and 2022. With the variable-rate mode, the spray rate was set to 0.05 $L{\cdot}m^{-3}$ and the other spray parameters were the same as those listed previously. With the constant-rate mode, the sprayer was calibrated to 808 $L{\cdot}ha^{-1}$. The top two nozzles were closed in both modes to tailor the application to the maximum crop height. The volume of solution applied to each treatment was recorded after each pesticide treatment. The volume of water was recorded when spraying WSP to characterize the two treatments.

In each treatment, the plot was blocked into the following three zones because of the difference in topography: bottom of the hill; middle of the hill; and top of the hill. In each zone, four representative trees were selected to be monitored for pests and used to assess spray characteristics. Tree characteristics, including height, width (parallel and perpendicular to row), canopy volume, and percent of full sun able to penetrate the canopy were measured and compared between treatments. Dates and weather conditions during spray characterization trials with water and WSP are listed in Table 1. Pesticide application dates and products applied are listed in Table 2. Pesticides were chosen by the grower and represent a typical commercial apple pest management program for the Southeast.

Starting on 27 May 2021 and 25 May 2022, biweekly foliar scouting was conducted until 8 Sep 2021 and 16 Sep 2022, respectively. Leaves were scouted in the field for lesions that were characteristic of any type of fungal leaf spot. On the first foliar scouting date in each season, a branch that was between the first and second wire (approximately 100 cm from the ground) was tagged on each of the 12 trees in both treatments and was used for foliar scouting for the duration of the season. The distal 30.5 cm of each branch were assessed to determine the following scouting data: total number of leaves; number of leaves with at least one lesion; and total number of lesions. These data were used to calculate leaf spot incidence as follows:

$$\frac{number\ of\ leaves\ with\ at\ least\ one\ lesion}{total\ number\ of\ leaves} \times 100\% \qquad [1]$$

and leaf spot count severity as follows:

$$\frac{total\ number\ of\ lesions}{number\ of\ leaves\ with\ at\ least\ one\ lesion} \qquad [2]$$

where leaf spot count severity represents the average number of lesions per leaf with at least one lesion within the defined evaluation area.

Additionally, a leaf that showed the same symptoms as those present on the scouted branch was collected from each tree and sent to the University of Tennessee Soil, Plant, and Pest Center (Nashville, TN, USA) for disease identification. Leaves were also scouted for European red mite (*Panonychus ulmi*); five leaves on each tagged branch were inspected using a hand lens and the number of leaves infested with one or more mites was recorded (Walgenbach et al. 2021).

Starting on 18 Aug 2021 and 21 Jul 2022, weekly fruit scouting was conducted until 15 Sep 2021 and 21 Sep 2022, respectively. Apples were scouted in the field for lesions that were characteristic of any type of fungal fruit rot. On the first fruit scouting date in each season, four apples that were not a part of a cluster and spanned approximately the vertical middle two-thirds of the canopy were tagged on each selected tree. These apples were scouted for the duration of the season unless the fruit dropped or incurred some type of physical damage (e.g., bird pecks), in which case another fruit at a comparable position was tagged and scouted. Each of these fruits was assessed to determine the presence or absence of lesions and percent of fruit

Table 1. Ambient weather conditions during spray characterization trials with water sensitive paper[i,ii].

		Air temp (°C)		Relative humidity (%)		Wind speed ($m{\cdot}s^{-1}$)	
Date	Product applied	Min	Max	Min	Max	Avg	Max
6 Jul 2021	Variable-rate	18.1	32.7	39.0	90.5	1.4	3.0
6 Jul 2021	Constant-rate	18.1	32.7	39.0	90.5	1.4	2.4
20 Jun 2022	Variable-rate	10.7	31.1	23.4	84.4	1.3	1.7
20 Jun 2022	Constant-rate	10.7	31.1	23.4	84.4	1.3	1.9

[i] Air temperature and relative humidity are reported for the time of the application using data collected during 15-min intervals. Wind speed is reported using data collected during 60-s intervals.

[ii] Caution should be exercised when interpreting these data because of the more exposed location of the weather station than that at the Catlett plot where experiments were conducted.

Table 2. Pesticide applications in 2021 and 2022[i].

Date	Product type	Product applied (brand name)	Common name	Date	Product type	Product applied (brand name)	Common name
19 Jun 2021	Fungicide	Roper	Mancozeb	17 Jun 2022	Fungicide	Captan	Captan
	Fungicide	Captan	Captan		Fungicide	Koverall	Mancozeb
	Insecticide	Tombstone	Cyfluthrin		Fungicide	Rampart	Potassium phosphite
	Surfactant	LI700	N/A		Fungicide	Merivon	Fluxapyroxad, Pyroclostrobin
24 Jun 2021	Fungicide	Roper	Mancozeb		Fertilizer	Calcium	Calcium
	Fungicide	Captan	Captan		Fertilizer	Boron	Boron
	Insecticide	Imidan	Phosmet		Surfactant	LI700	N/A
16 Jul 2021	Fungicide	Captan	Captan	1 Jul 2022	Fungicide	Captan	Captan
	Fungicide	Merivon	Fluxapyroxad, Pyroclostrobin		Fungicide	Koverall	Mancozeb
	Insecticide	Tombstone	Cyfluthrin		Fungicide	Rampart	Potassium phosphite
	Fertilizer	Calcium	Calcium		Fungicide	Merivon	Fluxapyroxad, Pyroclostrobin
24 Jul 2021	Fungicide	Captan	Captan		Fertilizer	Calcium	Calcium
	Fungicide	Merivon	Fluxapyroxad, Pyroclostrobin		Fertilizer	Boron	Boron
	Insecticide	Tombstone	Cyfluthrin		Surfactant	LI700	N/A
	Fertilizer	Calcium	Calcium	12 Jul 2022	Fungicide	Captan	Captan
	Fertilizer	Boron	Boron		Fungicide	Rampart	Potassium phosphite
7 Aug 2021	Fungicide	Captan	Captan		Fertilizer	Calcium	Calcium
	Fungicide	Rampart	Potassium phosphite		Fertilizer	Boron	Boron
	Insecticide	Imidan	Phosmet		Insecticide	Beseige	Chlorantraniliprole, Lambda-cyhalothrin
	Fungicide	Pristine	Boscalid, Pyraclostrobin		Surfactant	LI700	N/A

[i] Applications recorded are those conducted during the period of the experiments. In each year, fire blight applications were made before initiating variable-rate and constant-rate spray treatment.
N/A = not applicable.

surface covered by lesions. These data were used to calculate fruit rot incidence as follows:

$$\frac{number\ \ of\ \ fruit\ \ with\ \ at\ \ least\ \ one\ \ lesion}{4\ \ tagged\ \ fruit} \times 100\% \qquad [3]$$

and fruit rot severity as follows:

$$\frac{sum\ \ of\ \ percentage\ \ of\ \ fruit\ \ surface\ \ covered\ \ by\ \ lesions}{number\ \ of\ \ fruit\ \ with\ \ at\ \ least\ \ one\ \ lesion} \times 100\% \qquad [4]$$

Additionally, on each scouting date, an untagged fruit with the same symptoms as those present on the scouted fruits was collected from each tree and sent to the University of Tennessee Soil, Plant, and Pest Center for disease identification.

The disease index for fruit was calculated using the following equation:

$$\frac{Fruit\ \ rot\ \ incidence\ \ \times\ \ Fruit\ \ rot\ \ severity}{100} \qquad [5]$$

To evaluate disease progression, the area under the disease progress curve (AUDPC) was calculated separately for foliar disease and fruit disease using the following equation:

$$A_k = \sum_{i=1}^{N_t-1} \frac{(y_i + y_{i+1})}{2} (t_{i+1} - t_1) \qquad [6]$$

where t is the order of disease severity observation, y_i is the disease level at $t = i$, y_0 is the initial infection or the disease level at $t = 0$ (i.e., the first disease severity observation), and A_k is the total accumulated disease level for AUDPC until $t = t_k$ (Madden et al. 2007).

To determine whether invasive brown marmorated stink bug (*Halyomorpha halys*) was present in the orchard, three trees at the northernmost end of each treatment (closest to mature woods adjacent to the orchard) were visually inspected for eggs, nymphs, and adults for a total of 3 min. If hatched eggs were found, then they were removed. Additionally, for one of these three trees in each treatment a sheet was held below one limb on the east side and one limb on the west side of the tree. The limbs were struck, and the number of stink bugs that fell onto the sheet was recorded. These methods were adapted from the work of Leskey et al. (2012) and conducted in conjunction with biweekly leaf scouting.

On 6 Jul 2021 and 20 Jun 2022, WSP cards were used to assess spray characteristics. In each of the 12 trees in each treatment, electrical "Alligator" clips were placed in the following three locations in the canopy: near (approximately 35.6 cm below the second wire and 63.5 cm out from the trunk on the east side of the tree); far (approximately 35.6 cm below the second wire and 63.5 cm out from the trunk on the west side of the tree); and high (on the central leader approximately 30.5 cm above the second wire). A fourth electrical clip was placed

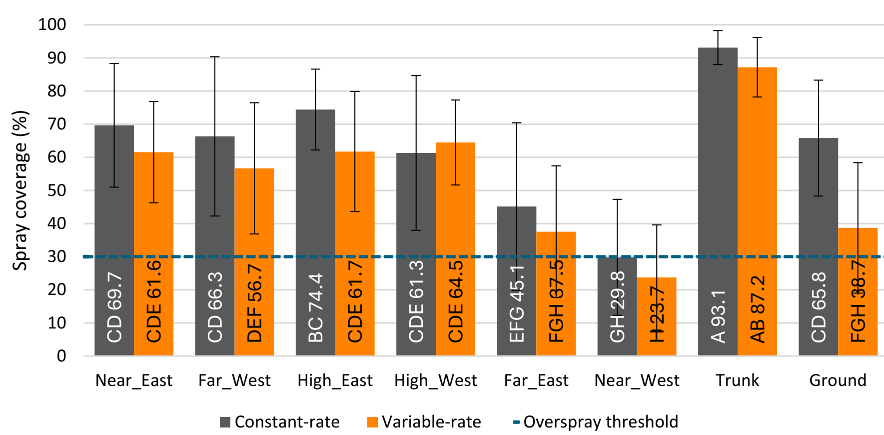

Fig. 1. Comparison of spray coverage on water-sensitive cards (WSCs) between the constant-rate and variable-rate treatments at eight card locations. The dotted line represents the overspray threshold, i.e., 30% coverage. Means with the same letter are not significantly different (Tukey's honestly significant difference, $P < 0.05$). Uncertainty intervals represent the standard deviation.

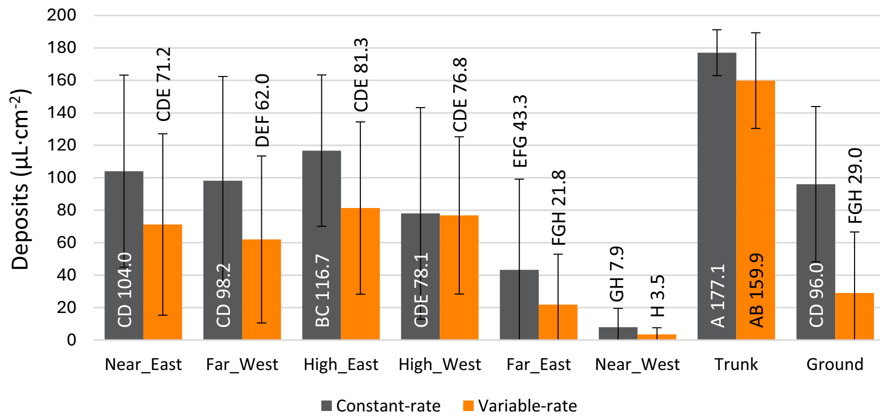

Fig. 2. Comparison of spray deposits on water-sensitive cards (WSCs) between the constant-rate and variable-rate treatments at eight card locations. Means with the same letter are not significantly different (Tukey's honestly significant difference, $P < 0.05$). Uncertainty intervals represent the standard deviation.

on the trunk at the graft union. A board with a binder clip was placed on the ground below the near WSP card to capture off-target spray on the orchard floor. First, two back-to-back WSP cards facing east and west were placed in each canopy clip, and a single WSP card was placed on the east side of the trunk and on the ground board in the variable-rate treatment. The selected row was then sprayed in the variable-rate mode from both adjacent driveways. The spray volume was recorded and WSP cards were collected in labeled envelopes and placed in sealed plastic bags with desiccant. This process was then repeated with the sprayer operating in constant-rate mode. The WSP cards were scanned and analyzed for coverage (%), deposit density (droplets/cm^2), and deposits (μL·cm^{-2}) using DepositScan software (Zhu et al. 2011).

Statistical analysis. Tree measurements and leaf AUDPC were analyzed using treatment and blocked on field position using an analysis of variance (ANOVA). The effect of treatment on spray volume was analyzed using an ANOVA. The effects of treatment, block (field position), and date for foliar disease and fruit disease data, including the leaf spot count severity, leaf spot incidence, foliar AUDPC, fruit rot incidence, fruit rot severity, fruit rot index data, and fruit AUDPC, were analyzed using a mixed model analysis for repeated measures with date as the repeated factor. Block was initially included in the aforementioned foliar disease and fruit disease data analysis but was removed after determining that it was not significant. Data were reanalyzed without block. Spray characterization data were analyzed using a split plot design with treatment as the whole plot effect and card location as the split effect factor. Block was initially included in the aforementioned spray application characterization analysis but was removed after determining block was not significant. The data were reanalyzed without block. Rank data transformation was applied when a diagnostic analysis of residuals exhibited violation of normality and equal variance assumptions using the Shapiro–Wilk test and Levene's test. Post hoc multiple comparisons were performed with Tukey's adjustment. Statistical significance was identified at $P < 95\%$ confidence. Analyses were conducted using SAS 9.4 TS1M7 (SAS institute Inc., Cary, NC, USA). Means are presented with the standard deviation.

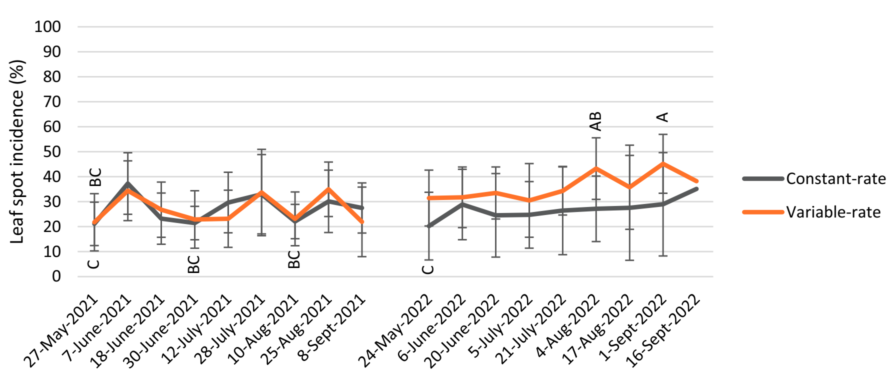

Fig. 3. Leaf spot incidence observed in 2021 and 2022 reported as the percentage of leaves in the defined evaluation area with at least one disease lesion. Means with the same letter are not significantly different (Tukey's honestly significant difference, $P < 0.05$). Sample dates without mean separation letters are not significant; letters are not presented for visual clarity. Uncertainty intervals represent the standard deviation.

Results

Determining the spray rate for the variable-rate mode. Rate significantly affected spray volume ($P = 0.04$), spray coverage, and deposit density ($P < 0.0001$). Spray volume was higher at the 0.05 L·m^{-3} rate compared with the 0.01 L·m^{-3} rate ($P = 0.0492$). There were no other differences in spray volume among treatments ($P \geq 0.0521$) (Supplemental Fig. 1). Rates of 0.009 L·m^{-3} and 0.01 L·m^{-3} resulted in 12.8% ± 5.1% and 11.0% ± 5.8% coverage, respectively, and were lower than the higher two rates tested ($P < 0.0001$). The 0.03 L·m^{-3} rate resulted in 28.5% ± 9.5% coverage. The 0.05 L·m^{-3} rate resulted in 41.7% ± 12.7% coverage and was the only rate to exceed the overspray threshold of 30%. Additionally, the 0.05 L·m^{-3} rate had significantly higher coverage than that of the other three rates tested ($P \geq 0.0021$) (Supplemental Fig. 2). Because of significant interactions between plot-by-card location and rate-by-card location, these factors could not be collapsed in the statistical analysis for deposit density. However, deposit density ranged from 50 ± 24.6 droplets/cm^2 to 133 ± 18.9 droplets/cm^2, meeting or exceeding the deposit density target rate for fungicides (50–70 droplets/cm^2) (Supplemental Fig. 3). The rate of 0.05 L·m^{-3} was chosen because it was a slight decrease from the default, which was important to the grower cooperator in this initial experiment of using a lower rate than the default spray rate, and because it met or exceeded the deposit density target rate for fungicides (50–70 droplets/cm^2), which was a mutually agreed upon goal of the research team and grower cooperator.

Efficacy trial. There were no consistent differences in tree characteristics between the two sets of treatment plots. For height, variable-rate trees were significantly taller than constant-rate trees ($P < 0.0001$) in the bottom of hill block (302 ± 28.9 cm and 253 ± 26.6 cm, respectively), but they were significantly shorter ($P < 0.0001$) in the top of hill block (228 ± 7.2 cm and 298 ± 19.5 cm, respectively). Constant-rate trees were wider (255 ± 45.1 cm) than variable-rate trees (187 ± 50.5 cm) in the top of hill block ($P = 0.0096$), but trees in the bottom of hill block did not have different widths ($P = 0.1046$), with constant-rate trees measuring 219 ± 40.0 cm and variable-rate trees measuring 270 ± 53.1 cm wide. Tree canopy volume, which was calculated using height and width data, was higher for the variable-rate trees (19.5 ± 6.6 m^3) than for the constant-rate trees (12.1 ± 3.4 m^3) in the bottom of hill block ($P = 0.0054$), whereas constant-rate trees had a higher volume (16.0 ± 5.6 m^3) than that of variable-rate trees (9.2 ± 3.8 m^3) in the top of hill block ($P = 0.0010$).

Spray volume was 58% lower in the variable-rate mode compared with the constant-rate mode ($P < 0.0001$) over the course of the trial (27 May 2021–8 Sep 2021; 25 May 2022–16 Sep 2022). The constant-rate mode sprayed an average of 768 ± 13.4 L·ha^{-1} and the variable-rate mode sprayed an average of

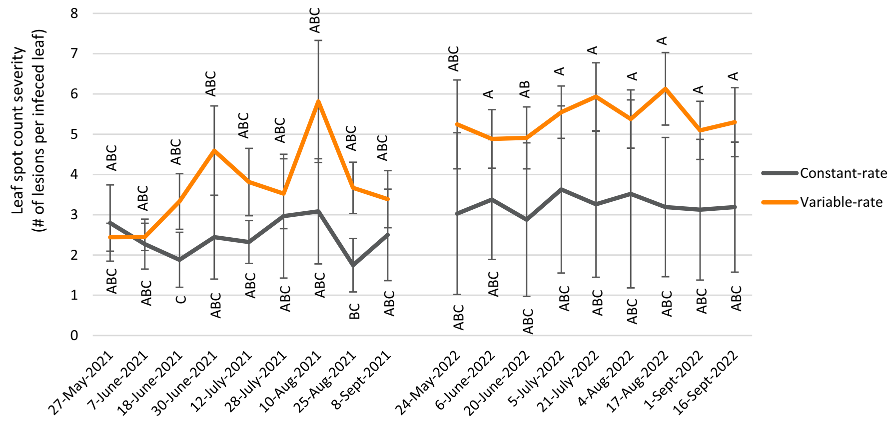

Fig. 4. Leaf spot count severity observed in 2021 and 2022 reported as the total number of lesions divided by the number of leaves with at least one lesion. Means with the same letter are not significantly different (Tukey's honestly significant difference, $P < 0.05$). Uncertainty intervals represent the standard deviation.

321 ± 16.3 L·ha^{-1}. In comparison, an application based on TRV would have applied 1871 L·ha^{-1}. Percent coverage on WSP cards met or exceeded the 30% overspray threshold in both treatments at all card locations except the near west card location in the variable-rate treatment, which had 23.7% ± 15.9% coverage. The only difference in spray coverage between treatments occurred at the nontarget ground card location, where the constant-rate averaged 65.8% ± 17.5% coverage and the variable-rate averaged 38.7% ± 19.7% coverage ($P = 0.001$) (Fig. 1). Both treatments exceeded deposit density target ranges for fungicides (50–70 droplets/cm^2) and insecticides (20–30 droplets/cm^2). Deposit density was significantly higher in the variable-rate treatment (81.1 ± 45.3 droplets/cm^2) than in the constant-rate treatment (58.8 ± 40.0 droplets/cm^2) ($P = 0.0005$). There were differences in deposits between card locations, but not between treatments, with the exception of the ground card, an off-target location, where the constant-rate treatment had more than three-times the deposits than the variable-rate treatment (96 ± 47.9 μL·cm^{-2} and 29 ± 37.6 μL·cm^{-2}, respectively) ($P < 0.0001$) (Fig. 2).

Diseases diagnosed on foliage and fruit are reported for 2021 and 2022 (Supplemental Tables 1–4). There were no differences in leaf spot incidence or leaf spot count severity between treatments on any of the rating dates in either trial year ($P \geq 0.7724$) (Figs. 3 and 4). Leaf spot incidence ranged from 20% to 45%, and leaf spot count severity ranged from two to six lesions per diseased leaf. Because of a significant treatment × block interaction, marginal means were analyzed for foliar disease AUDPC. The foliar AUDPC was higher in the variable-rate treatment at the middle of hill location compared with that in the constant-rate treatment ($P = 0.0390$) (Fig. 5). There were no differences in foliar AUDPC between treatments at the bottom of hill or top of hill locations ($P > 0.0945$).

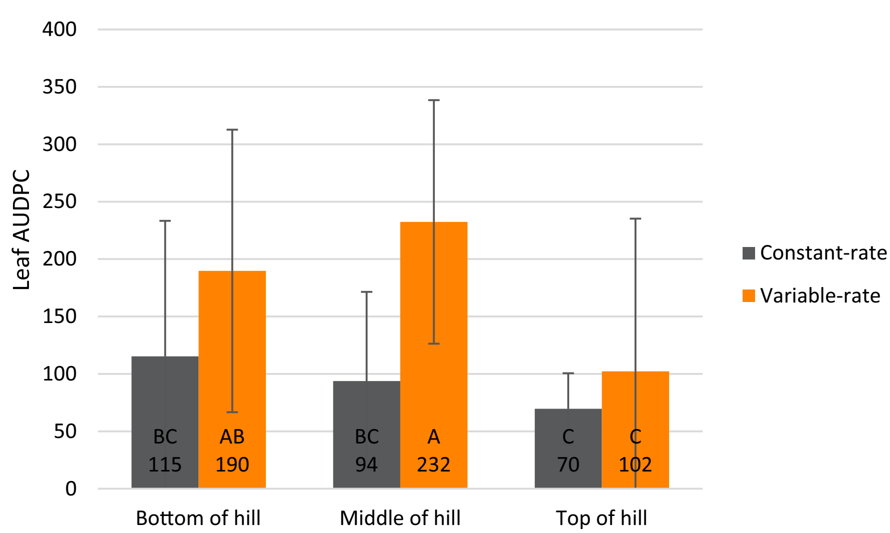

Fig. 5. Area under the disease progress curve (AUDPC) from severity ratings observed in 2021 and 2022 reported as $A_k = \sum_{i=1}^{N_i-1} \frac{(y_i + y_{i+1})}{2}(t_{i+1} - t_1)$, where t is the order of disease severity observation, y_i is the disease level at $t = i$, y_0 is the initial infection or the disease level at $t = 0$ (i.e., the first disease severity observation), A_k is the total accumulated disease level for AUDPC until $t = t_k$ (Madden et al. 2007). Means with the same letter are not significantly different (Tukey's honestly significant difference, $P < 0.05$). Uncertainty intervals represent the standard deviation.

Treatment did not influence fruit rot incidence ($P = 0.4385$), fruit rot severity ($P = 0.3425$), fruit disease index ($P = 0.2826$), or AUDPC ($P = 0.5595$) (Figs. 6–9). Fruit disease index, which incorporates both incidence and severity measurements, remained low throughout both trials. Average disease index values ranged from 0 to 0.82 ± 1.6 and 0 to 1.01 ± 1.5 in 2021 and 2022, respectively (Fig. 8).

In both treatments in both years, no European red mites or brown marmorated stink bugs were detected during scouting; therefore, statistical analysis was not performed, and these data are not presented. Both arthropod pests are typically found in apple orchards in the region (Walgenbach et al. 2021), making their absence noteworthy. Because we could not rule out the population being zero at this location, we made no treatment-based conclusions using these data.

Discussion

Modern US apple orchards consist of dwarf and semi-dwarf trees grown in a variety of production systems (Rathnayake et al. 2022). Such orchards may use lower application rates, like 935 L·ha^{-1}, to reduce the overall volume of chemicals sprayed, off-target loss, and input costs (Rathnayake et al. 2022). In contrast, orchardists growing apples using traditional training types and orchard layouts may apply 1540 L·ha^{-1} as their standard rate (Fessler et al. 2020; Walgenbach et al. 2021). In the present study, the rate of 0.05 L·m^{-3}, which equated to 321.1 L·ha^{-1}, suggested that further reductions may be possible in the southeast United States.

There were no differences between the variable-rate and constant-rate treatments in any of the disease metrics on any of the rating dates. Both treatments managed disease well, as evidenced by the relatively low levels of foliar and fruit disease at the end of each trial. Although foliar and fruit disease incidence ranged from 20% to 45% and 0% to 20%, respectively, severity values were much lower at two to five lesions per diseased leaf and 0.1% to 3% per fruit, respectively. These values correspond to a relatively minor level of disease and would generally be considered a good level of disease control in a southeastern commercial orchard (personal communication with grower cooperator and author observations). Additionally, fruit disease index was a maximum of 1.01, which is also indicative of a very low level of disease (Fig. 8). For example, a maximum disease index of 100 indicates 100% of evaluated fruit had disease, and those fruit were 100% covered by disease.

In contrast, the foliar AUDPC at the middle of hill location had poorer performance in the variable-rate treatment than that in the constant-rate treatment. The AUDPC captures the cumulative disease intensity over the course of the entire trial (Madden et al.

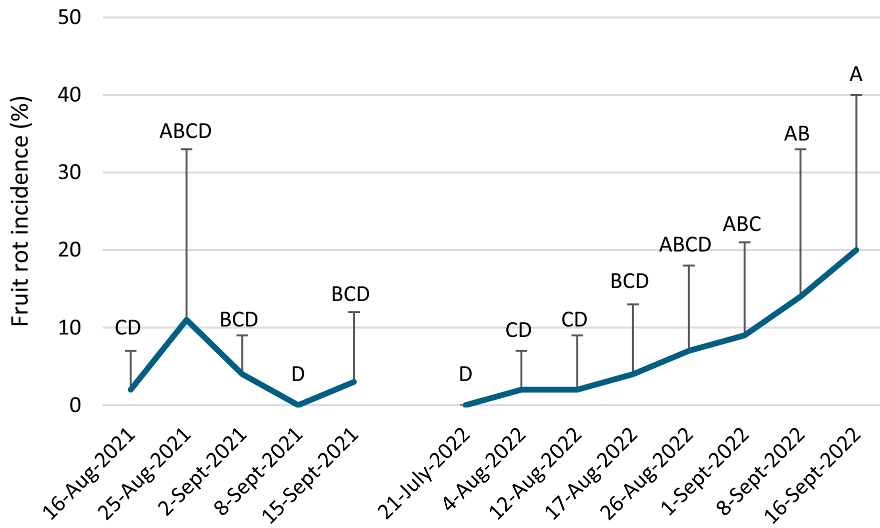

Fig. 6. Fruit rot incidence observed in 2021 and 2022 reported as the percentage of fruit in the defined evaluation area with at least one disease lesion. Means with the same letter are not significantly different (Tukey's honestly significant difference, $P < 0.05$). Uncertainty intervals represent the standard deviation.

2007). As such, it is possible for disease intensity between treatments to not be statistically different at each individual rating date, whereas the cumulative disease over the course of the trial can be significantly different. This was the case at the middle of hill location. Indeed, leaf spot incidence and severity were numerically higher in the variable-rate treatment compared with the constant-rate treatment at many rating dates, especially in 2022. Although these differences were not significant at individual rating dates, they became significant when accumulated into the AUDPC value. The underlying mechanism driving the difference is unclear because all but one WSP card location indicated that the 30% overspray threshold had been reached in both treatments, and deposit densities for fungicides and insecticides were reached in all WSP card locations for both treatments.

The overspray threshold is the only established metric to gauge spray coverage and should be interpreted carefully. It was established in previous studies using artificial targets, but it has not been empirically tested for correlation with pest control (Zhu et al. 2008). It is possible that a lower pesticide-conserving overspray threshold, i.e., one that allows greater coverage, would result in better cumulative disease control indicated by the AUDPC value. Moreover, there is no lower threshold counterpart to establish the minimum coverage needed for pest control. This is an aspect of pesticide application that warrants further study. Effective use of metrics including overspray, a future underspray threshold, and deposit density targets may require field calibration because plant taxa susceptibility to a given pest varies, as do the inherent level of difficulty in controlling a given pest and pesticide mode of action. As an example of spray metrics not characterizing the needed level of spray, powdery mildew control was achieved in dogwood trees despite lower than recommended fungicide deposit densities (Fessler et al. 2021). In that study, the target of 50 to 70 droplets/cm^2 for deposit density was only reached on one date over two growing seasons, and on the remaining dates it ranged from 12.7 to 38.4 droplets/cm^2, suggesting that the deposit density target may not be a universal value for all crops, all diseases, and all pesticides, nor is it a pesticide-conserving value; instead, it is a "safe" target that should lead to pest control if the spray interval, pest life stage susceptibility to control measures, and pesticide mode of action are appropriate. Furthermore, it should be noted that when measuring deposit density with WSP, the reported values may be lower than the actual values, especially when coverage is high, because of the tendency of droplets to coalesce into larger droplets on WSP as seen in the current study. This must be considered when further exploring deposit density as a spray metric.

In this study, there was a single location, i.e., the ground card, at which the spray coverage differed between the variable-rate and constant-rate treatments. In this nontarget location, the variable-rate treatment averaged 38.7%, and the constant-rate treatment averaged 65.8%. Cross et al. (2001) examined spray deposits and off-target movement from an axial-fan sprayer discharging three spray rates (3.8, 11, and 29 L·min^{-1}) using apple trees of different sizes and spacings. The study found that despite the more than sevenfold difference in the spray rate, orchard floor deposits were not different. However, ground deposits were greater when spraying smaller trees than larger trees because smaller trees did not intercept as much of the spray. Vercruysse et al. (1999) demonstrated that nontarget ground deposits by conventional airblast sprayers in semi-dwarf pears and apples account for 39% to 29% of the total spray volume when foliage is not fully developed and during full-leaf stages, respectively.

Variable-rate technology is designed to detect changing canopy densities over the course of a growing season and adjust the spray output accordingly while maintaining sufficient levels of coverage and deposits. With variable-rate technology, the spray rate (i.e., liters of spray solution per cubic meter of crop volume) is selected by the operator. Because the system sprays the crop, and not the gaps between plants, it generally reduces the total volume sprayed without reducing spray characteristic metrics (i.e., coverage and deposit density). There have been instances of both spray volume and metrics being lower when variable-rate technology was compared with conventional constant-rate technology for canopy applications (Chen et al. 2013; Fessler et al. 2021; Salcedo et al. 2020; Shen et al. 2017; Wodzicki et al. 2023). However, in these cases, either the conventional constant-rate exceeded the overspray threshold (Chen et al. 2013; Salcedo et al. 2020; Wodzicki et al.

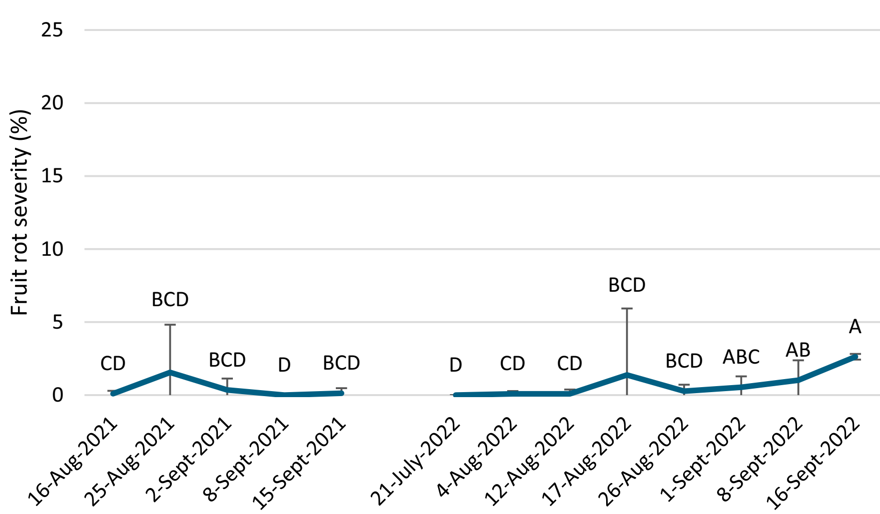

Fig. 7. Fruit rot severity observed in 2021 and 2022 was calculated using the following equation: $\frac{\textit{sum percentage of fruit surface covered by lesions}}{\textit{number of fruit with at least one lesion}} \times 100\%$. Means with shared letters next to them were not significantly different (Tukey's honestly significant difference, $P < 0.05$). Uncertainty intervals represent the standard deviation.

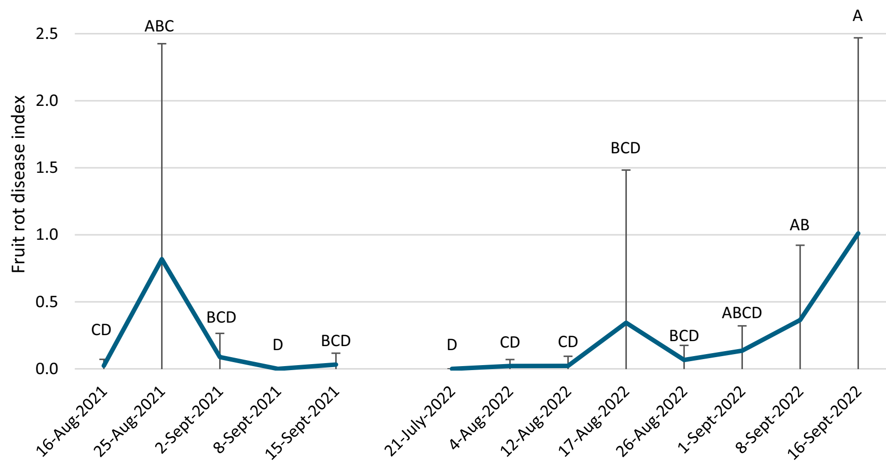

Fig. 8. Fruit disease index observed in 2021 and 2022. Disease index was calculated using the following equation: $\frac{Fruit\ rot\ incidence\ \times\ Fruit\ rot\ severity}{100}$. Means with the same letter are not significantly different (Tukey's honestly significant difference, $P < 0.05$). Uncertainty intervals represent the standard deviation.

2023) or control was unaffected by the lower variable-rate application (Fessler et al. 2021). According to Fessler et al. (2021), a "low" conventional constant-rate of approximately 187 L·ha^{-1} instead of the typical 935 L·ha^{-1} was applied.

Spraying in variable-rate mode increased application efficiency but reduced off-target ground spray as well as aerial drift by up to 40% in an apple orchard and up to 33% in a vineyard (Nackley et al. 2021). Our study supports the findings that variable-rate spray technology can reduce nontarget pesticide application to the ground compared with a conventional sprayer while maintaining similar levels of coverage on the crop. Although the 41% reduction in ground spray in the present study is a positive aspect of the variable-rate treatment from an input cost reduction standpoint, reducing off-target movement to the orchard floor can also have ecological benefits, for example, reducing pesticide exposure to nontarget organisms such as beneficial insects and pollinators. Beneficial insects were not monitored in the present study; however, in a companion study at another Tennessee apple orchard, Fessler et al. (2023) documented bees, butterflies, wasps, beetles, flies, and other insects and found as many as 31 insects foraging in a 1-m^{-2} area of the orchard floor during a 15-min interval.

The WSP cards on the proximal face of tree trunks received more than 87% coverage regardless of spray mode. These cards were located in a nontarget location because the intended targets were tree canopies, thus highlighting the opportunity to further reduce pesticide waste by closing the lower nozzles, either manually or by using the touch screen user interface (when in variable-rate mode). However, this high coverage may also indicate that it is possible to use variable-rate technology as a labor-efficient alternative to hand-held "spray guns" for pesticide application to tree trunks. Research of the viability of making trunk applications using variable-rate technology is necessary.

Spray volume was significantly reduced (58% lower) in the variable-rate mode compared with the constant-rate mode. This result agreed with that of previous research of variable-rate spray technology in apple orchards (Fessler et al. 2020; Nackley et al. 2021) and other woody crop production systems (Boatwright et al. 2020; Llorens et al. 2010; Zhu et al. 2017). Although spray material costs vary widely between orchards based on factors such as cultural practices, disease pressure, planting type, and products used, a 2022 apple production budget by Michigan State University Extension estimated material costs between \$364 and \$486 per hectare per season (Schwallier et al. 2022). Using these estimates, the variable-rate treatment would reduce material costs by \$211 to \$282 per hectare per year. This reduction does not represent the total reduction in cost. A study performed by Manandhar et al. (2020) in Ohio apple orchards of 4 and 20 ha quantified and compared annual pesticide application savings between spraying with a conventional sprayer and spraying with variable-rate technology; they found that orchards of these sizes could reduce the amount spent annually on pesticide application between \$1420 and \$1750 per hectare by using variable-rate technology. These reductions included a 60% to 67% reduction in pesticide costs, a 27% to 32% reduction in application time, and a 28% reduction in labor and fuel compared with conventional sprayers. Reduced pesticide output also provides additional benefits to environmental health and worker safety that are difficult to quantify, while the reductions in application time and labor also benefit growers who require more efficient production in the face of debilitating labor shortages and demand for high-quality horticultural products (Fulcher et al. 2023; Rihn et al. 2022).

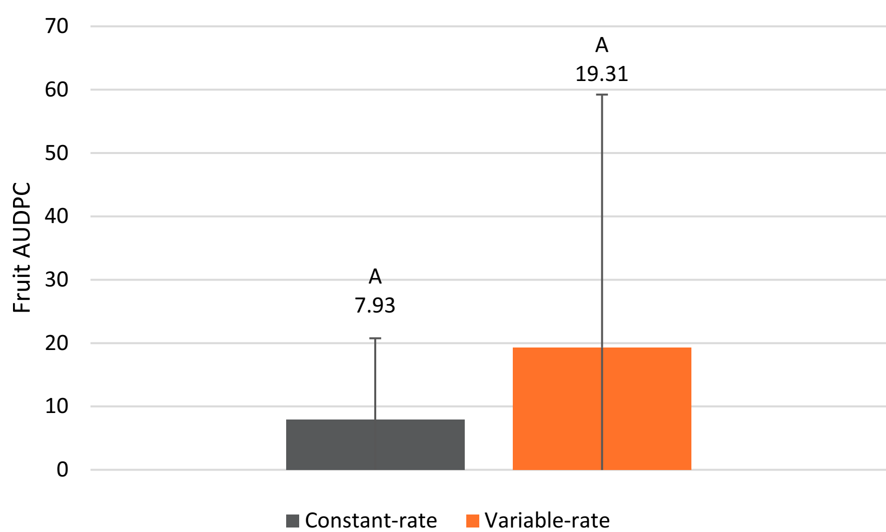

Fig. 9. Area under the disease progress curve (AUDPC) was calculated using the following equation: $A_k = \sum_{i=1}^{N_i-1} \frac{(y_i + y_{i+1})}{2}(t_{i+1} - t_1)$, where t is the order of disease severity observation, y_i is the disease level at $t = i$, y_0 is the initial infection or the disease level at $t = 0$ (i.e., the first disease severity observation), A_k is the total accumulated disease level for AUDPC until $t = t_k$ (Madden et al. 2007). Means with the same letter are not significantly different (Tukey's honestly significant difference, $P < 0.05$). Uncertainty intervals represent the standard deviation.

Conclusions

This study evaluated pest control efficacy of variable-rate spray technology operated at a rate below the default rate compared with a conventional constant-rate sprayer in a commercial apple orchard. The variable-rate treatment reduced spray volume by 58% compared with the constant-rate treatment, and both treatments managed disease well and to a commercially acceptable level. Although disease levels were not different at individual rating dates, the variable-rate treatment did have cumulatively more foliar disease (i.e., higher AUDPC) at one of three plot locations compared with that of the constant-rate treatment. Further studies are necessary to determine the reason behind this observation, especially because WSP card data indicated comparable and commercially acceptable spray coverage and deposit characteristics for both treatments. Arthropod control was not analyzed nor interpreted because neither arthropod was detected on any scouting date. Results from this study showed that variable-rate spray technology operated at a reduced rate had the potential to reduce overall spray volumes while providing disease control comparable to conventional constant-rate sprayers in commercial apple production.

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