

Assessment of Three Commercial Over-the-Row Sprayer Technologies in Eastern Washington Vineyards

Margaret L. McCoy,¹ Gwen-Alyn Hoheisel,² Lav R. Khot,³
and Michelle M. Moyer^{1*}

Abstract: Washington winegrape growers are rapidly adopting vineyard management technologies such as mechanical pruners and harvesters, but they have been slower to adopt new chemical application technologies. This study generated technical information about commercial over-the-row sprayers and their deposition and drift to allow growers to select and optimize sprayers for different vineyard systems and winegrape canopies. Three commercial sprayer technologies (multi-fan heads, pneumatic, and electrostatic) were evaluated for canopy deposition and drift in the 2016 and 2017 production seasons. Data were collected in *Vitis vinifera* Chardonnay and Riesling vineyards at two application timings, early season and midseason, to determine sprayer deposition patterns in opposed and unopposed applications and in-field aerial and ground drifts. All sprayer technologies showed consistent in-canopy deposition and drift patterns at both application timings. Regardless of sprayer technology, the most deposition was in the upper canopy rather than in the fruiting zone. Similarly, the most aerial and ground drift occurred in the row closest to the sprayed row, indicating that drift is relatively low with all three evaluated sprayer technologies.

Key words: air-assistance, over-the-row sprayer, spray deposition, spray drift, technology optimization

Perennial specialty crop industries have used the axial fan airblast sprayer since the late 1940s, with no substantial modernization to reflect current horticultural systems (Fox et al. 2008). In recent years, new sprayer technologies have been introduced (Landers 2004, Fox et al. 2008, Pergher et al. 2013), but there is little data on how these technologies perform in today's horticultural settings and evolving management practices. Canopy sprayer application technology has been studied in other perennial crop growing regions (Grella et al. 2017), but there is a general lack of awareness of how

these technologies perform and function in modern vineyards within the Pacific Northwest growing region.

In-season vineyard pest management relies on proper timing, selection, and application of products. Pertinent research often focuses on region-specific timing and selection of products. Little is known about how existing and emerging sprayer technologies beyond the axial fan airblast sprayer perform in the varied vineyard sites around Washington State. Washington growers are adopting advanced vineyard management technologies such as mechanical pruners and harvesters rapidly, but the adoption of new chemical application technologies has been slower (Dokoozlian 2013). Many growers still use the relatively inexpensive axial fan airblast sprayer for chemical applications because they grow a diversity of crops and it is adaptable to multiple crop canopies. However, the air volume and direction produced by the axial fan are not wholly matched to modern winegrape canopy structures. Recognizing the mismatch between applicator and crop may be problematic, especially as it relates to drift.

Manufacturers have developed several over-the-row air-assisted sprayers which can direct spray droplets into the grapevine canopy using less air volume. Changes or adoption of new agricultural technology often correlates with how much risk growers are able or willing to accept (Nowak 1992, Marra et al. 2003). Growers may be asking for solutions to old problems, but are hesitant to take on new technology unless it has been proven to perform reliably and have minimal, easy maintenance (Franson 2010). Assessments provide useful information to develop best use practices for these sprayer technologies. This in turn allows individuals to better select or adapt existing technologies for various site limitations.

These assessments also provide critical information to regulatory agencies. For example, as application exclusion zones become stricter (40 CFR § 170.405), growers will need

¹Department of Horticulture, Washington State University, Irrigated Agriculture Research and Extension Center, 24106 North Bunn Rd, Prosser, WA 99350; ²WSU Extension, Washington State University, 1121 Dudley Avenue, Prosser, WA 99350; and ³Department of Biological Systems Engineering, Washington State University, Irrigated Agriculture Research and Extension Center, 24106 North Bunn Rd, Prosser, WA 99350.

*Corresponding author (michelle.moyer@wsu.edu)

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updated information so they can adjust spray application practices for legal compliance. Currently, most air-assisted sprayer technologies require the largest regulated exclusion zone (30.5 m) and have a droplet size larger than the medium classification (volume medium diameter, $DV_{0.5} > 294 \mu\text{m}$; ASABE 2009; 40 CFR § 170.405). To assist with potential drift mitigation, several new sprayer technologies that use air-assistance have adopted strategies such as the use of directed air.

Directed air sprayers, like the Croplands Quantum Mist (standard hydraulic nozzles) or Gregoire Speedflow Progress (air shear/pneumatic nozzles) models, use opposing fans or air assistance to direct air into the canopy. These sprayers can produce very fine to fine droplets ($DV_{0.5}$ between 60 to 225 μm ; ASABE 2009) which can result in many small droplets covering the entire leaf surface (ASABE 2009), but are prone to drift. Small droplets, $DV_{0.5}$ between 30 to 50 μm , can easily drift away from the target even under relatively calm conditions (Pregler 2009). Electrostatic sprayer technology, which produces similarly-sized droplets surrounded by a slight electrical charge, is marketed as improving deposition on foliar or fruit surfaces facing away from the sprayer (Pregler 2009), but there are mixed findings regarding coverage quality (Oakford et al. 1994, Pascuzzi and Cerruto 2015). Regardless of charge, when small droplets are exposed to high temperature and low humidity, they can evaporate quickly and disappear before coming into contact with the target (Ozkan and Zhu 2016).

Thus, it is important to conduct regional studies to evaluate sprayer performance based on local canopy architecture and environmental differences. This study assessed three commercially available, over-the-row, air-assisted sprayers to gather data that can be used for sprayer optimization in winegrape canopies.

Materials and Methods

General experimental design. For all sprayers (Figure 1), canopy deposition, aerial drift, and ground drift were evaluated at two timings: early-season (BBCH 55 or 65), and midseason (BBCH 75, 77, or 79; Lorenz et al. 1994). Specific canopy and drift assessment methods are described below in the “Spray deposition and drift collection and processing” section. Sprayer evaluation comparisons were made only within a single sprayer type. Thus, no comparisons are made among sprayer types.

A summary of sprayer operation information, including dates of sprays, vine growth stage, and sprayer-specific operating metrics, is presented (Tables 1 and 2). At each of the two sites (described below), evaluations for vine development stage were repeated both spatially and temporally. At site 1, two different vineyard blocks (2.5 ha each) were used for sprayer evaluation: a south quadrant and a north quadrant. In 2016, only the north quadrant was used on each sprayer evaluation date, and in 2017, both quadrants were used. In 2016 at site 1, the early-season evaluation timing was conducted on day of the year (DOY) 144 and in 2017, it was conducted on DOY 136 and 142. In 2016, midseason evaluation timing at site 1 was conducted on DOY 174 and 210 and in 2017, it was conducted on DOY 206 and 227. At site 1, between the two

years and two different vineyard quadrants, each sprayer and timing combination was evaluated three different times. At site 2 (6.6 ha), sprayer evaluation was conducted in 2017 only. The early-season evaluation timing was conducted on DOY 157 and the midseason evaluation timing was conducted on DOY 208. On each day, two different locations in the vineyard block at site 2 were used for evaluation, so the sprayer and timing combination was evaluated two times.

Site and equipment descriptions. *Site 1 description.* Site 1 was a commercial vineyard in the Horse Heaven Hills AVA (45°59'N; 119°38'W) in Paterson, WA. The vineyard was established in a Warden very fine sandy loam soil (coarse-silty, mixed, superactive, mesic Xeric Haplocambids) and Hezel loamy fine sand soil (sandy over loamy, mixed, superactive, nonacid, mesic Xeric Torriorthents [USDA-NRCS 2019]). The

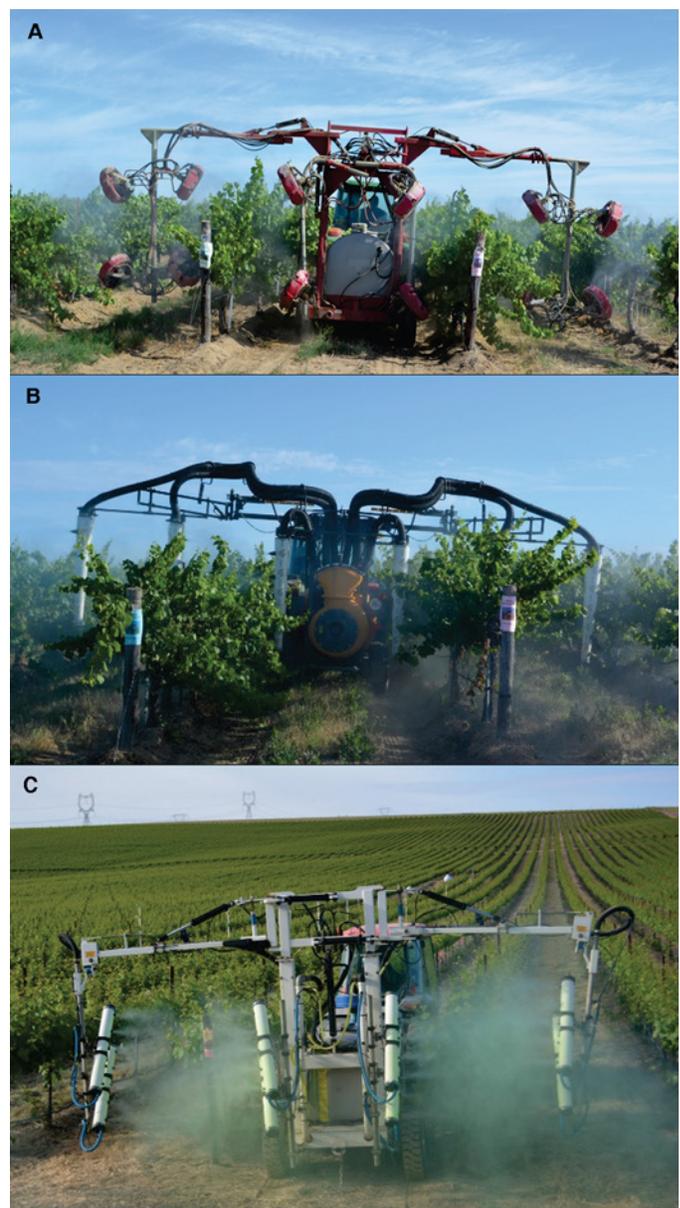


Figure 1 Over-the-row commercial sprayers evaluated in this study in Washington state in 2016 and 2017. (A) VineTech Quantum Mist; (B) Blue-line Gregoire SpeedFlow; and (C) On Target Spray Systems electrostatic.

Table 1 Operational parameters of three commercial over-the-row sprayer technologies used in Washington State field trials in 2016 and 2017. Day of year (DOY) from 1 Jan.

Sprayer	# of rows sprayed ^a	Nozzle type	Year	# of nozzles open during application	DOY (vine growth stage-BBCH) ^b	Tractor travel speed (km/hr)	Operating pressure (pascal)
Quantum Mist	3	Teejet VisiFlo TX-VK08	2016	6 per fan head; 12 fan heads	144 (65) 174 (77)	4.7	620,528
			2017	4 per fan head; 12 fan heads	136 (55)	5.6	620,528
				6 per fan head; 12 fan heads	206 (75)	5.2	
Gregoire	3	DynaDiff Air-sheer	2016	3 per tube; 6 tubes	144 (65)	4.0	282,685
				5 per tube; 6 tubes	174, 210 (77, 79)	4.7	399,896
			2017	3 per tube; 6 tubes	142 (55)	2.9	399,896
				5 per tube; 6 tubes	206, 227 (75, 77)	2.0	
On Target	2	Pneumatic electrostatic	2017	5 per tube; 8 tubes	157 (55) 208 (75)	5.2	89,632

^aThree-row sprayers consisted of two rows with opposing spray applications, and two half rows with unopposed spray. Two-row sprayers consisted of only opposed spray rows. See Figure 2E and 2F. All sprayers were over-the-row.

^bGrowth stages were based on the extended BBCH scale (Lorenz et al. 1994). BBCH 55 and 65 were defined as early-season application timing; BBCH 75, 77, and 79 are defined as mid-season application timing.

Table 2 Additional operational parameters of three over-the-row commercial sprayer technologies used in Washington State field trials in 2016 and 2017.

Sprayer/year	Application timing	Engine (rpm)	Application rate (L/ha)	Rate controller
Quantum Mist				
2016	Early and mid	2000	701.6	TeeJet 844-AB
2017	Early	2000	467.7	TeeJet 844-AB
	Mid	1800	701.6	
Gregoire				
2016	Early	2200	233.9	Arag Bravo 180s
	Mid	2400	467.7	
2017	Early	2400	233.9	Arag Bravo 180s
	Mid	2400	467.7	
On Target	Early and mid	1600	198.3	None

vineyard was planted in 1980 in a north-south row orientation to own-rooted *Vitis vinifera* Chardonnay on a 1.8 m × 3.1 m vine by row spacing. The vine canopy was trained to a modified vertical shoot-positioned (VSP) system with a single, centered catch wire allowing both east and west sides of the canopy to flop out and downward. Vine-row-volume measurements were taken within a 3 m area in a non-data row. Canopy width and height (edge to edge of the canopy growth and from the top of the cordon to the top of the canopy growth, respectively) were calculated from five measurements of each type (Tables 3 and 4). Vineyard irrigation and pest management programs followed grower standard practices for the site.

Site 1 sprayers. Two commercial sprayers were examined in this vineyard. Both the Quantum Mist and Gregoire sprayers were fitted with a rate controller, TeeJet 844-AB and Arag Bravo 180s, respectively, during sprayer evaluations for both seasons.

The first sprayer was a Croplands Quantum Mist, distributed by VineTech (65 horsepower requirement), a three-row, over-the-row sprayer operated by a John Deere 5100M tractor (100 horsepower). The sprayer had 12 axial fan heads, equally divided on six hydraulic arms: that is, two fan heads per arm (Figure 1A). Each fan head had six locations for nozzles and used hydraulic, grey hollow cone Teejet VisiFlo TX-VK8 nozzles. In 2016, due to rapid early-season growth at the time of application, six nozzles were used for all application dates at a spray volume rate of 702 L/ha. In 2017, the early-season applications occurred when canopy sizes were smaller, so only four nozzles arranged in a square pattern were used at a spray volume rate of 468 L/ha. In the late-season applications, six nozzles were used with a spray volume rate of 702 L/ha (Table 2). Sprayer calibration and optimization were done with direct on-site assistance of manufacturer representatives, according to their regional specifications. Fan heads were set facing forward, toward the front of the sprayer, at an ~45° angle into the canopy, not facing directly toward the opposing fan head (Figure 1A). Air velocity was recorded ~0.5 m from the nozzle to represent the distance from the sprayer to the canopy at the canopy closest to the sprayer on the opposed row (24 km/hr) and the unopposed row (17 km/hr).

The second sprayer was a Gregoire Speedflow Progress, distributed by BlueLine Manufacturing (50 to 80 horsepower requirement), a three-row, over-the-row sprayer operated by a John Deere 5520 tractor (89 horsepower; Figure 1B). Sprayers were donated for use from the manufacturer and a different machine of the same model was donated in each year. The sprayer was equipped with a FLEXIspray system, consisting of six flexible PVC-coated polyester fabric tubes on hydraulic arms with five nozzles per arm. To accommodate the height of the canopy and nozzle selection while preventing the tubes from touching the ground, a simple modification of switching inlet tubes was made so that the bottom three nozzles operated in a group and the top two operated

as a group. Original tubing had the top three nozzles clustered independently from the bottom two. In both seasons, only the bottom three nozzles were used in the early-season applications at a spray volume rate of 234 L/ha and all five nozzles were used in late-season applications at a spray volume rate of 468 L/ha (Table 2). This pneumatic sprayer was equipped with a Gregoire air-shear, DynaDiff diffuser

nozzle. The sprayer calibration and optimization were done with direct on-site assistance of manufacturer representatives, according to their regional specifications. The fabric tubes were set facing backwards, away from the front of the sprayer, at an ~20 to 30° angle into the canopy, not facing directly toward the opposing fabric tubes and nozzles (Figure 1B). Air velocity was recorded ~0.5 m from the nozzle to

Table 3 Day of year (DOY), weather conditions, and vine-row-volume measurements for data collections during Quantum Mist assessment field trials in Washington State in 2016 and 2017.

Year/application timing ^a	Spray row	Avg temp (°C)	Avg relative humidity (%)	Avg wind speed (km/hr)	Avg wind direction (°) ^a	Vine-row-volume ^b (m ³ /ha)
2016						
Early	Opposed	18.2	48.7	14.0	SSW (200)	–
	Unopposed	19.4	46.4	12.5	SSW (195)	
Mid	Opposed	24.2	49.0	3.1	*SSW (200)	
	Unopposed	25.1	47.6	4.0	*NW (315)	
2017						
Early	Opposed; N Quadrant	12.1	68.0	10.8	SSW (212)	519.2
	Opposed; S Quadrant	12.0	68.3	10.4	SSW (209)	
	Unopposed; N Quadrant	13.8	62.2	7.8	SSW (199)	
	Unopposed; S Quadrant	14.0	62.9	8.2	S (189)	
Mid	Opposed; N Quadrant	21.9	59.0	8.6	*SE (128)	3997.5
	Opposed; S Quadrant	23.2	42.0	7.4	*SE (124)	
	Unopposed; N Quadrant	25.9	38.5	5.0	*SE (138)	
	Unopposed; S Quadrant	27.0	40.0	8.1	*SE (146)	

^aEarly-season collections occurred on DOY 144 in 2016 and DOY 136 in 2017. Weather data were collected from an on-site ATMOS weather station. Midseason collections occurred on DOY 174 in 2016 and on DOY 206 in 2017. Weather data were collected from the WSU AgWeatherNet (weather.wsu.edu) Paterson West station, located within 5.6 km of the site, with an elevation difference of 3 m, as noted with an *.

^bVine-row-volume was not collected in 2016.

Table 4 Day of year (DOY), weather conditions, and vine-row-volume measurements for data collections during Gregoire assessment field trials in Washington State in 2016 and 2017.

Year/application timing ^a	Spray row	Avg temp (°C)	Avg relative humidity (%)	Avg wind speed (km/hr)	Avg wind direction (°) ^a	Vine-row-volume ^b (m ³ /ha)
2016						
144	Opposed	15.2	62.5	10.6	SSW (213)	–
	Unopposed	16.3	58.9	9.5	SW (226)	
174	Opposed	17.3	52.5	2.7	*SE (137)	
	Unopposed	17.9	57.5	3.7	*ESE (118)	
210	Opposed	28.5	46.8	1.4	SW (227)	
	Unopposed	30.0	40.3	2.7	ENE (59)	
2017						
142	Opposed; N quadrant	18.8	67.0	3.8	ESE (109)	458.2
	Opposed; S quadrant	18.6	68.2	3.6	E (101)	
	Unopposed; N quadrant	22.8	52.1	3.7	S (170)	
	Unopposed; S quadrant	23.2	51.1	3.2	SE (132)	
206	Opposed; N quadrant	30.8	30.2	4.0	*S (178)	3997.5
	Opposed; S quadrant	31.2	35.3	5.2	S (179)	
	Unopposed; N quadrant	31.6	26.3	5.0	S (183)	
	Unopposed; S quadrant	33.3	36.1	5.8	S (189)	
227	Opposed; N quadrant	15.4	58.0	4.7	E (95)	3997.5
	Unopposed; N quadrant	19.2	47.0	5.3	*ESE (109)	

^aEarly-season collections occurred on DOY 144 in 2016 and 142 in 2017; weather data were collected from an on-site ATMOS weather station. Midseason collections occurred on 210 in 2016 (weather data were collected from an on-site ATMOS weather station), on DOY 174 in 2016, and DOY 206 and 227 in 2017. Weather data were collected from Washington State University AgWeatherNet (weather.wsu.edu) Paterson West station, located within 5.6 km of the site, with an elevation difference of 3 m, as noted with an *.

^bVine-row-volume was not collected in 2016.

represent the distance from the sprayer to the closest canopy on the opposed row (26 km/hr) and the unopposed row (23 km/hr). Though individual sprayers and rate controllers differed between years, the application rate, engine speed, and operating pressure were all maintained at a consistent rate.

Site 2 description. Evaluations were also conducted in 2017 on a commercial vineyard located in the Columbia Valley AVA (46°32'N; 119°49'W) in Mattawa, WA. The vineyard has Ritzville silt loam soil (coarse-silty, mixed, superactive, mesic Calcic Haploxerolls) (USDA-NRCS 2019). The vineyard was planted in 2011 in a north-south row orientation to own-rooted *V. vinifera* Riesling on a 1.5 m × 2.4 m vine by row spacing. The canopy was trained to a strict VSP and the vineyard's irrigation and pest management programs followed grower standard practices for the site. Vine-row-volume measurements were also taken at site 2, as previously described.

Site 2 sprayer. The On Target sprayer, manufactured by On Target Spray Systems Inc. (20 to 32 horsepower requirement), is a two-row, over-the-row electrostatic sprayer (Figure 1C). This sprayer was operated by a Kubota M8540 tractor (86 horsepower). The sprayer was equipped with eight PVC tubes, each with five electrostatic pneumatic nozzles. All nozzles were used the entire season for both applications at a rate of 198.3 L/ha (Table 2). Prior to field tests, the nozzles were checked with a voltmeter (ASIMT33D-CA, AstroAI) to ensure 1000 V electricity was present at each nozzle as is required for electrostatic charge of the droplets. This sprayer did not use a rate controller and was calibrated and optimized with direct onsite assistance of manufacturer representatives, according to their regional specifications. PVC tubes, and thus nozzles, were oriented at 90° to the vine row, directly opposite the opposing tube and nozzles (Figure 1C). Air velocity was not recorded for this sprayer.

Travel speed calculations. For all sprayers, tractor speed was calculated before each spray trial application. The tractor was operated at the same settings during a tracer application with the power take-off (PTO) engaged and at the rotations per minute (rpm) of the intended application with a full sprayer tank. The specified gear and tractor rpm for each application was recorded (Table 2) and adjusted to account for changes during the growing season, including spray volume delivered and canopy size. The tractor speed was timed over a set-length course (91.44 m) and calculated as kilometers per hour (km/hr).

Weather and canopy measurements. Environmental parameters, including wind speed (km/hr), wind direction (°), relative humidity (RH, %), and air temperature (°C), were collected continuously during spray applications. During spray applications, either a handheld Kestrel Instruments 3000 anemometer or an all-in-one weather station (ATMOS 41; METTER Group Inc.) connected to a data logger (CR1000; Campbell Scientific) was used to acquire environmental data at 0.02 Hz (Tables 3 to 5). The weather station was mounted ~3 m aboveground. On days that the all-in-one ATMOS 41 weather station did not record weather data, the corresponding wind direction data was pulled from Washington State University's AgWeatherNet (weather.wsu.edu) weather station network, since the handheld anemometer does not collect that type of data. At site 1, the AgWeatherNet Paterson West station was used at the first midseason evaluation (DOY 174) in 2016 and at both midseason applications (DOY 206, 227) in 2017. This station is located within 5.6 km of the site and has an elevation difference of 3 m. For site 2, the AgWeatherNet McClure station was used at midseason (DOY 208) in 2017. This station is located within 19.6 km of the site and has an elevation difference of 312 m. Collected environmental parameters conformed to ISO standards ($\pm 25\%$ deviation for wind speed, $\pm 10\%$ deviation for RH, and $\pm 5\%$ deviation for temperature between the tests being compared) on all days except Gregoire midseason in 2017 (ISO 2007). On those particular days (DOY 206 and 227), the deviation during spray application was 23% in temperature, 26% in RH, and 49% in wind speed.

Spray deposition and drift collection and processing. A 500 mg/L solution of fluorescent tracer (Keystone Pyranine 10G; Milliken) dissolved in water was applied during field trials. Tank samples were collected pre- and post-application to determine tracer concentration and to normalize data across spray dates. Canopy deposition, aerial drift, and ground drift were determined by collecting spray deposition on 5 × 5 cm plastic cards (card placement described below). This method of using plastic cards is appropriate at low to moderate volume spray applications and for in-field (short distance) drift studies (Forster et al. 2014, Rathnayake et al. 2021). Cards were made from Stark Boards Disposable Cutting Boards.

Canopy spray deposition – Experimental design. To collect spray deposition within the canopy, collection poles facilitated placement of plastic cards throughout different zones of interest. Poles were constructed from schedule 40 2-cm

Table 5 Day of year (DOY), weather conditions, and vine-row-volume measurements for data collections during On Target assessment field trials in Washington State in 2016 and 2017.

Year/application timing ^a	Spray row	Avg temp (°C)	Avg relative humidity (%)	Avg wind speed (km/hr)	Avg wind direction (°) ^a	Vine-row-volume (m ³ /ha)
2017						
157	Row 10	22.5	29.7	7.5	N (14)	349.8
	Row 20	19.6	34.1	3.0	N (11)	
208	Row 10	25.9	34.3	8.5	*WSW (255)	3181.6
	Row 20	23.7	40.2	12.7	*WSW (253)	

^aEarly-season collections occurred on DOY 157; weather data were collected from an in-field ATMOS weather station. Midseason collections occurred on DOY 208. Weather data were collected from a Washington State University AgWeatherNet (weather.wsu.edu) McClure station, located within 19.6 km of the site, with an elevation difference of 312 m, as noted with an *.

PVC pipe and metal alligator clips (5.1 cm × 1.1 cm; Figure 2A and 2B) to attach the plastic collection cards. At site 1, 15 canopy poles were placed in two rows (opposed spray row and unopposed spray row) to accommodate the three-row sprayers (Figure 2E). Site 2 had 15 canopy poles in a single row, since it was a two-row sprayer (Figure 2F). Collection zones in the canopy included west upper canopy (WUPP), middle upper canopy (MidUPP; site 1 only), east upper canopy (EUPP), west fruiting zone (WFZ), and east fruiting zone (EFZ) (ISO 22522:2007 2007). Distance between plastic cards in the up-

per canopy and fruiting zone was ~17 cm at both sites. The larger canopy at site 1 necessitated an additional card in the MidUPP, positioned halfway between EUPP and WUPP and raised 3 cm (Figure 2A). Site 2 had a more tightly trained canopy, so MidUPP was excluded (Figure 2B). The unopposed row was sprayed on one side in the first pass, and the other side in a second pass. Thus, both sides of the canopy received spray deposition, but with unopposed air applications.

Aerial and ground drift – Experimental design. Aerial drift poles with similar construction as those used for collecting

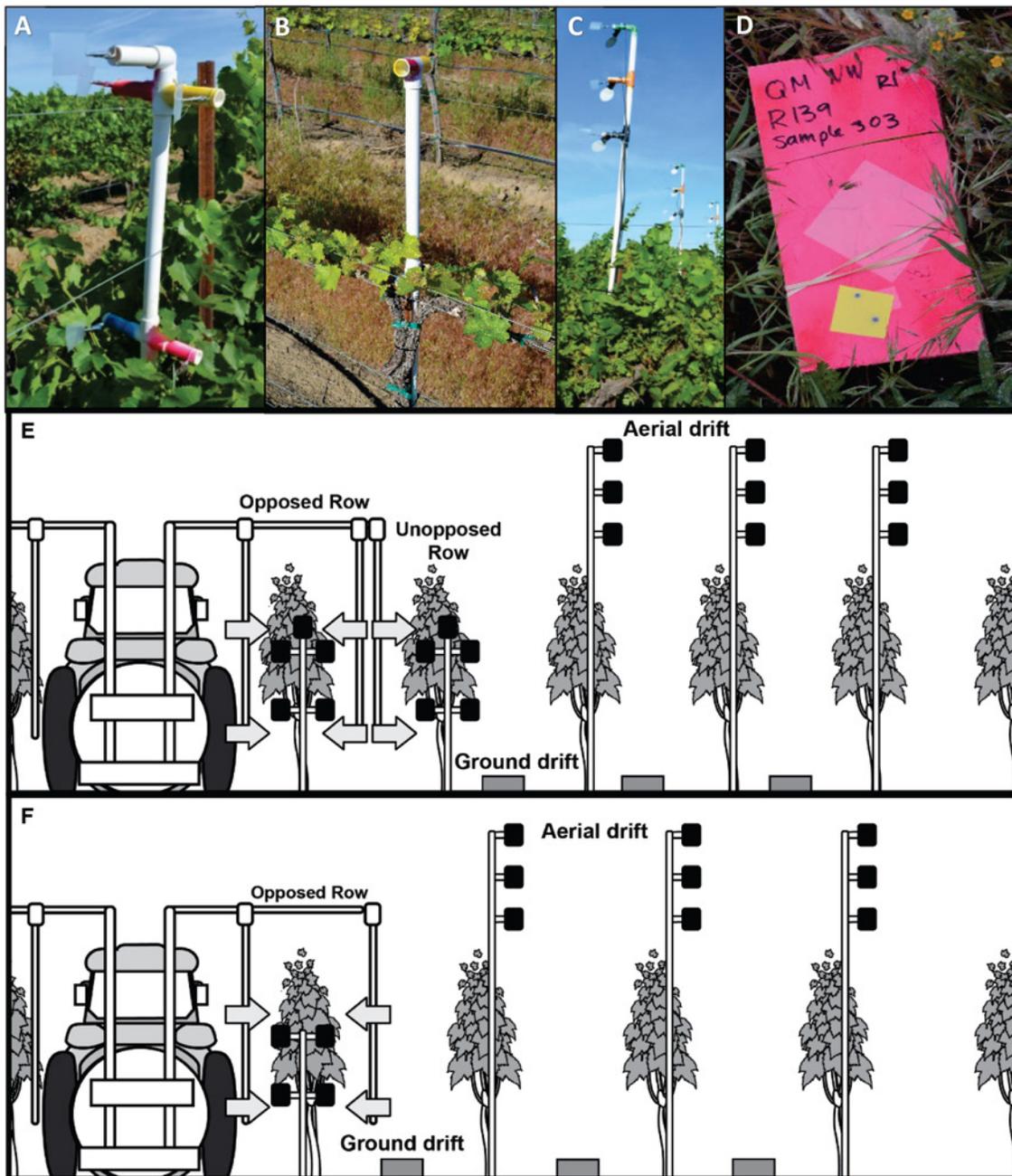


Figure 2 Field collectors and vineyard collection locations for sprayer evaluations in Washington State in 2016 and 2017. (A) Canopy deposition collection pole with five collection zones for Quantum Mist and Gregoire sprayers at Site 1; (B) Canopy deposition collection pole with four collection zones for On Target sprayer at Site 2; (C) aerial drift collection poles; and (D) ground drift collection block. Field trial configuration for (E) Site 1 and (F) Site 2 for 2016 and 2017 trials, showing in-canopy (opposed and unopposed rows), aerial drift, and ground drift collection points in the vineyard during data collection after tracer applications. Graphic art by Dr. Charlotte Oliver, Washington State University.

canopy deposition (Figure 2C) were placed in the first three rows downwind from the sprayed row (Figure 2E and 2F). Aerial drift was collected at 0.3, 0.6, and 0.9 m above the canopy. To collect ground drift, wooden blocks (10 × 17 cm) were placed in the middle of the interrow (equal distance from either neighboring vine row), downwind of the spray application row and upwind of aerial poles (Figure 2D). Plastic cards were affixed under a rubber band.

Deposition and drift collection procedures. Post application, tracer solution was allowed to dry for ~10 min on the plastic cards before collection, and each card was placed into an individual bag (Uline). General best practice protocols (such as changing gloves and discarding compromised cards) were followed to prevent contamination between samples. All samples (tank and cards) were immediately placed in a dark, thermally insulated cooler with ice packs to avoid tracer degradation during transport back to the lab, where they were stored at 1.6°C within 5 hrs of field collection. At this temperature, samples can be stored up to 90 days with minimal deterioration (Nairn and Forster 2015). All samples were analyzed within 60 days of collection.

Deposition quantification. An aliquot of deionized water was added to each individual collection bag or tank sample, then shaken for 1 min at 180 oscillations/min (Model: 6010, Eberbach shaker). A sample of this solution was poured into borosilicate glass cuvettes and analyzed using a fluorometer (10-AU, Turner Design). The concentration reading (parts per billion; µg/L) was recorded for each sample. All samples with concentrations exceeding the upper limit of the fluorometer (1000 µg/L) were diluted to read again in the linear range of developed calibration curves. Each sample reading was corrected using a calibration curve produced from tracer standards made from each chemical lot of tracer specific to a trial (Khot et al. 2012).

Powdery mildew disease ratings. Cluster disease ratings of grapevine powdery mildew, *Erysiphe necator*, were conducted for each sprayer in both years. Disease ratings were estimated visually as percent surface area infected. Ratings were collected in-field on 30 clusters per treatment replicate typically collected between 25 Aug and 1 Sept each year; typically immediately preharvest. The level of disease present at all sites and both years were considered acceptable by the associated commercial entity. In 2016 at Site 1, clusters in the Quantum Mist trial had an average incidence and severity of powdery mildew of 1% and 0.3%, respectively. In 2016 at Site 1, clusters sprayed by the Gregoire had an average incidence and severity of powdery mildew of 3% and 0.3%, respectively. In 2017 at Site 1, clusters in the Quantum Mist trial had an average incidence and severity of powdery mildew of 80% and 16%, respectively. In 2017 at Site 1, clusters sprayed by the Gregoire had an average incidence and severity of powdery mildew of 62% and 15%, respectively. In 2017 at Site 2, clusters sprayed by the On Target had an average incidence and severity of powdery mildew of 70% and 10%, respectively.

All partnering growers used systemic fungicides as a part of their routine fungicide program. Systematic products are generally absorbed by the plant, which can overcome disease

management limitations related to deposition patterns of the applied product (Wise et al. 2010). Because of this, we could not compare how spray deposition from each sprayer may have influenced powdery mildew disease control in those sprayed blocks.

Statistical analyses. Fluorometry readings were normalized for tank sample concentrations across all sprayers and application days to allow comparison within a sprayer type. No comparisons were made among sprayer types or across dates. Deposition differences between and within canopy zones and drift was analyzed with an analysis of variance and least standard squares, followed by post-hoc comparison of means using Tukey's honest significant difference (JMP; ver. 14.0.0, SAS Institute, Inc.). Significant differences ($\alpha = 0.05$) were examined by sprayers across application growth timings and between spray dates, position of spray card target within the vineyard, and overall amount of deposition from each sprayer.

Results

Quantum Mist. Early season. In both years, significantly more deposition was collected in the upper canopy zones of opposed and unopposed row applications (Table 6). Total collected canopy deposition in the opposed row (88.0 ng/cm²) was less than the unopposed row (110.5 ng/cm²) in 2016 ($p < 0.0001$), but deposition was not different between rows in 2017 ($p = 0.44$; opposed 132.8 ng/cm²; unopposed 128.5 ng/cm²). In 2017, vineyard quadrant data were pooled within vineyard collection area as no significant difference was seen in canopy deposition (opposed row, $p = 0.09$; unopposed row, $p = 0.92$) or aerial drift ($p = 0.22$).

The interaction between height above the canopy and distance from the sprayer was not significant ($p = 0.97$ in 2016 and $p = 0.06$ in 2017). Height above the canopy (0.3 to 0.9 m) did not influence aerial drift either ($p = 0.81$ in 2016 and $p = 0.08$ in 2017), so aerial drift data were analyzed as distance (rows) from the sprayer (Table 6). In 2017, ground drift data were different between the two quadrants of the vineyard ($p = 0.04$) and were analyzed separately. The amount of ground drift did not differ statistically by distance from sprayer in 2016 or in the south quadrant in 2017 (Table 6), but it was significant in the north quadrant in 2017. While not always statistically significant, the most ground drift was collected in the row closest to the sprayed row, and the least in the third row from the sprayed row.

Midseason. In both years of the study, significantly more deposition was collected in the upper canopy zones of opposed and unopposed row applications (Table 7). Total collected deposition in the opposed row (42.4 ng/cm²) was less than in the unopposed row (81.7 ng/cm²) in 2016 ($p < 0.0001$), but deposition was not different between rows in 2017 ($p = 0.45$; opposed 55.6 ng/cm²; unopposed 52.9 ng/cm²). In 2017, vineyard quadrant data was pooled within collection area as no significant difference was seen in canopy deposition between quadrants (opposed row, $p = 0.71$; unopposed row, $p = 0.40$) or ground drift between quadrants ($p = 0.56$).

The interaction between height above canopy and distance from the sprayer were not different for aerial drift in

2016 ($p = 0.35$) or in 2017 (north quadrant, $p = 0.45$ and south quadrant, $p = 0.37$). Height above the canopy also did not influence aerial drift in 2016 ($p = 0.76$) or in the north quadrant in 2017 ($p = 0.40$). In the south quadrant in 2017, aerial drift was significantly greater at 0.9 m above the canopy than at 0.3 m ($p = 0.03$). However, overall drift was very low (0.016 ng/cm², 0.008 ng/cm², and 0.009 ng/cm², for 0.9 m, 0.6 m, and 0.3 m above the canopy, respectively) relative to canopy deposition. Distance from the sprayer did not influence aerial drift in 2016 ($p = 0.89$) or in 2017 (north quadrant, $p = 0.82$ and south quadrant, $p = 0.27$). Distance from the sprayer influenced ground drift (Table 7) and in

both years, the row closest to the sprayed row had more drift than the rows further away.

Gregoire. Early season. In 2016, both the opposed and unopposed rows had more spray deposition in the upper canopy than in the fruit zones (Table 8). Total collected canopy deposition in the opposed row (86.8 ng/cm²) was greater than in the unopposed row (64.2 ng/cm²) in 2016 ($p < 0.0001$). Total canopy spray deposition was not different between rows in 2017 ($p = 0.67$; opposed 50.5 ng/cm²; unopposed 52.5 ng/cm²). In 2017, vineyard quadrant data were pooled within vineyard collection area, as no significant difference was seen in opposed row canopy deposition ($p = 0.15$), aerial drift

Table 6 Early-season canopy deposition, aerial drift, and ground drift for the Quantum Mist sprayer. Lowercase letters across rows indicate significant difference in means using Tukey's honest significant difference at $\alpha = 0.05$ across individual rows. WFZ: west fruit zone; EFZ: east fruit zone; WUPP: west upper canopy; MidUPP: middle upper canopy; and EUPP: east upper canopy.

Canopy deposition (ng/cm ²)							
Year ^a	Spray row	WFZ	EFZ	WUPP	MidUPP	EUPP	<i>p</i> value
2016	Opposed	53.9 b	31.5 b	112.9 a	124.2 a	117.7 a	<0.0001
2017	Opposed	101.5 b	102.2 b	153.9 a	147.6 a	158.6 a	<0.0001
2016	Unopposed	60.3 b	35.3 b	135.8 a	145.9 a	119.1 a	<0.0001
2017	Unopposed	94.5 b	80.5 b	161.2 a	156.5 a	160.6 a	<0.0001
Aerial drift (ng/cm ²)							
Year ^a	1 row from sprayer	2 rows from sprayer	3 rows from sprayer	<i>p</i> value			
2016	37.4 a	25.8 ab	14.7 b	0.003			
2017	12.8 a	5.8 b	4.2 b	<0.0001			
Ground drift (ng/cm ²)							
Quadrant	1 row from sprayer	2 rows from sprayer	3 rows from sprayer	<i>p</i> value			
2016	13.3	6.7	2.7	0.07			
2017; N quadrant ^b	2.8 a	1.0 b	0.4 b	0.01			
2017; S quadrant ^b	45.6	13.7	7.6	0.08			

^aIn 2016, spray data was collected on day of year (DOY) 144 and in 2017, it was on DOY 136.

^bGround drift data in 2017 was significantly different by quadrant ($p = 0.04$).

Table 7 Mid-season canopy deposition, aerial drift, and ground drift for the Quantum Mist sprayer. Lowercase letters across rows indicate significant difference in means using Tukey's honest significant difference at $\alpha = 0.05$. WFZ: west fruit zone; EFZ: east fruit zone; WUPP: west upper canopy; MidUPP: middle upper canopy; and EUPP: east upper canopy.

Canopy deposition (ng/cm ²)							
Year ^a	Spray row	WFZ	EFZ	WUPP	MidUPP	EUPP	<i>p</i> value
2016	Opposed	19.1 b	23.0 b	61.1 a	56.1 a	52.8 a	<0.0001
2017	Opposed	16.7 c	16.7 c	81.8 ab	92.5 a	70.3 b	<0.0001
2016	Unopposed	30.2 b	38.1 b	113.8 a	116.3 a	110.7 a	<0.0001
2017	Unopposed	22.7 b	14.7 b	64.8 a	90.2 a	72.0 a	<0.0001
Aerial drift (ng/cm ²)							
Year ^a	1 row from sprayer	2 rows from sprayer	3 rows from sprayer	<i>p</i> value			
2016	0.04	0.03	0.03	0.89			
2017; N quadrant ^b	0.02	0.03	0.02	0.83			
2017; S quadrant ^b	0.01	0.008	0.01	0.27			
Ground drift (ng/cm ²)							
Year ^a	1 row from sprayer	2 rows from sprayer	3 rows from sprayer	<i>p</i> value			
2016	10.7 a	0.2 b	0.03 b	0.004			
2017	3.6 a	0.1 b	0.1 b	0.02			

^aIn 2016, spray data was collected on day of year (DOY) 174 and in 2017, it was on DOY 206.

^bHeight above canopy was significantly different between quadrants in 2017 ($p = 0.0005$).

($p = 0.08$), or ground drift ($p = 0.06$). In 2017, unopposed row data were significantly different between the two quadrants ($p = 0.002$) and were not pooled. In 2017, opposed row and north quadrant unopposed row had more canopy spray deposition in the fruiting zone than in the upper canopy zones (Table 8). However, there were no differences in canopy zone deposition in the south quadrant.

Aerial drift had no interaction between height above the canopy and distance from the sprayer ($p = 0.97$ in 2016 and $p = 1.0$ in 2017), and no direct influence of height was evident

above the canopy (0.3 to 0.9 m) alone ($p = 0.92$ in 2016 and $p = 0.98$) in 2017 (Table 8). Ground drift between vineyard quadrants was not significantly different in 2017 ($p = 0.08$) and was pooled. Ground drift in downwind rows was significant in 2016, but not in 2017 (Table 8).

Midseason. In 2016, except for DOY 210, both the opposed and unopposed rows had more spray deposition in the upper canopy than in the fruit zones (Table 9). Total collected canopy deposition on DOY 174 and 210 in the opposed row (72.5 ng/cm² and 54.8 ng/cm², respectively) was more than in the

Table 8 Early-season canopy deposition, aerial drift, and ground drift for the Gregoire sprayer. Lowercase letters across rows indicate significant difference in means using Tukey's honest significant difference at $\alpha = 0.05$. WFZ: west fruit zone; EFZ: east fruit zone; WUPP: west upper canopy; MidUPP: middle upper canopy; and EUPP: east upper canopy.

Canopy deposition (ng/cm ²)							
Year ^a	Spray row	WFZ	EFZ	WUPP	MidUPP	EUPP	p value
2016	Opposed	48.9 b	48.4 b	103.1 a	126.4 a	107.3 a	<0.0001
2017	Opposed	85.9 a	67.4 ab	43.6 bc	25.6 c	30.6 c	<0.0001
2016	Unopposed	45.2 b	33.2 b	94.4 a	77.2 a	71.1 a	<0.0001
2017; N quadrant ^b	Unopposed	81.7 a	46.3 b	36.6 b	20.7 b	23.5 b	<0.0001
2017; S quadrant ^b	Unopposed	79.0	58.7	66.8	47.8	62.4	0.52
Aerial drift (ng/cm ²)							
Year ^a	1 row from sprayer	2 rows from sprayer		3 rows from sprayer		p value	
2016	2.0	2.7		2.4		0.71	
2017	0.5	0.01		0.004		0.06	
Ground drift (ng/cm ²)							
Year ^a	1 row from sprayer	2 rows from sprayer		3 rows from sprayer		p value	
2016	28.9 a	2.2 b		0.4 b		0.003	
2017	0.5	0.5		0.3		0.66	

^aIn 2016, spray data was collected on day of year (DOY) 144 and in 2017, it was on DOY 142.

^bUnopposed canopy deposition data in 2017 was significantly different by quadrant (0.002).

Table 9 Mid-season canopy deposition, aerial drift, and ground drift for the Gregoire sprayer. Lowercase letters across rows indicate significant difference in means using Tukey's honest significant difference at $\alpha = 0.05$. WFZ: west fruit zone; EFZ: east fruit zone; WUPP: west upper canopy; MidUPP: middle upper canopy; and EUPP: east upper canopy.

Canopy deposition (ng/cm ²)							
Year ^a	Spray row	WFZ	EFZ	WUPP	MidUPP	EUPP	p value
2016-1	Opposed	40.9 c	44.4 c	107.0 a	99.8 ab	70.5 bc	<0.0001
2016-2	Opposed	40.7 bc	35.5 c	70.9 a	64.3 ab	62.8 ab	<0.0001
2017	Opposed	35.3 bc	39.3 bc	79.5 a	58.3 ab	27.5 c	<0.0001
2016-1	Unopposed	37.5 b	37.8 b	88.6 a	64.9 ab	74.1 a	0.0002
2016-2	Unopposed	39.9	34.1	53.3	47.3	54.3	0.24
2017; N quadrant	Unopposed	38.4 b	32.9 b	82.7 a	100.0 a	77.0 a	<0.0001
2017; S quadrant	Unopposed	36.4 ab	35.0 b	72.8 a	66.5 ab	46.7 ab	0.01
Aerial drift (ng/cm ²)							
Year ^a	1 row from sprayer	2 rows from sprayer		3 rows from sprayer		p value	
2016-1	0.08	0.01		0.03		0.12	
2016-2	0.6 a	0.3 b		0.2 b		0.007	
2017	0.2	0.1		0.07		0.09	
Ground drift (ng/cm ²)							
Year ^a	1 row from sprayer	2 rows from sprayer		3 rows from sprayer		p value	
2016	14.0 a	0.6 b		0.2 b		<0.0001	
2017	11.3 a	0.3 ab		0.3 b		0.03	

^aIn 2016, spray data was collected twice, with 2016-1 on day of year (DOY) 174 and 2016-2 on DOY 210. In 2017, collections occurred on DOY 206 and 227, but there was no difference between the 2017 collection dates, so data was pooled between collection dates.

unopposed row (60.6 ng/cm² and 45.8 ng/cm², respectively) in 2016 ($p = 0.03$ and $p = 0.04$, respectively). Total collected deposition in the opposed row was significantly less than in the unopposed row in 2017 ($p < 0.0001$; opposed 47.9 ng/cm²; unopposed 58.9 ng/cm²). In 2017, vineyard quadrant data for opposed row applications were pooled as no significant differences were seen between quadrants in canopy deposition ($p = 0.10$), aerial drift ($p = 0.17$), or ground drift ($p = 0.35$). In 2017, unopposed row application was different between quadrants ($p = 0.02$), but followed the pattern of greater deposition in the upper canopy than in the fruiting zone.

There was no interaction between height above the canopy and distance from the sprayer ($p = 0.61$ and $p = 0.95$ in 2016 on DOY 174 and 210, respectively, and $p = 0.94$ in 2017) in aerial drift, and no direct effect of height above the canopy on aerial drift ($p = 0.60$ and $p = 0.84$ in 2016 on DOY 174 and 210, respectively, and $p = 0.82$ in 2017). In only one instance (DOY 210 in 2016) did distance from the sprayer influence aerial drift: more drift was collected in the row closest to the sprayer (Table 9). In 2017, the data on aerial drift from the two quadrants were not different from each other ($p = 0.17$) and were pooled. Distance away from the sprayer also influenced ground drift (Table 9), and more drift was collected in the row closest to the sprayer. Ground drift between vineyard quadrants was not significantly different 2017 ($p = 0.35$) and was pooled.

On Target. Early season. Opposed canopy deposition data collected in two different areas of the vineyard in 2017 (rows 10 and 20) were significantly different ($p = 0.01$) and hence not pooled. The row 10 canopy deposition pattern was highly variable: the least deposition was in the fruit zone nearest the sprayer (EFZ) and the greatest, in the opposite fruiting zone (WFZ; Table 10). A similar pattern was not observed in row 20, where there was a more even deposition pattern throughout the canopy (Table 10).

Aerial and ground drift were not significantly different between the two rows ($p = 0.64$ and $p = 0.68$, respectively) and were pooled for analysis. There was no interaction between height above the canopy and distance from the sprayer ($p = 0.86$), and height above the canopy alone did not significantly

influence aerial drift ($p = 0.84$). Distance from the sprayer did influence aerial drift, with a gradient of more drift collected in the rows closest to the sprayer (Table 10). Distance from the sprayed row influenced ground drift (Table 10), with more drift in the closest row.

Midseason. Opposed canopy deposition data collected in the vineyard were not significantly different between rows 10 and 20 ($p = 0.07$), but were analyzed separately to keep consistent data presentation. In row 10, the canopy deposition pattern was variable: the least deposition was observed in the upper canopy furthest from the sprayer (WUPP), while the upper canopy on the opposing side, closest to the sprayer, had the most deposition (EUPP; Table 11). Canopy in row 20 had more deposition on the side closest to the sprayer (EFZ and EUPP) than on the opposite side of the canopy, furthest from the sprayer (Table 11).

Aerial and ground drift were not significantly different between the two rows ($p = 0.21$ and $p = 0.71$, respectively) and were pooled for analysis. There was no interaction between height above the canopy and distance from the sprayer ($p = 0.56$), and height above the canopy alone did not significantly influence aerial drift ($p = 0.44$). Aerial drift was greatest in the row closest to the sprayer (Table 11). Distance from the sprayer influenced ground drift (Table 11), with more drift in the row closest to the sprayer.

Discussion

All sprayers evaluated in this study performed well under manufacturer recommended settings and the local weather conditions. Across all sprayers, the majority of the applied tracer (80.0 to 99.3% of total spray collected) was deposited onto the vine canopy, with minimal ground and aerial drift. Of that minimal drift, there was more ground drift than aerial drift (0.23 to 16.0% and 0.01 to 7.3% of total spray collected, respectively), and most of this drift was generally captured in the row closest to the sprayer. Off-target drift is also frequently attributed to the air assistance provided by the sprayer; the fan size and direction of air flow contribute to air assistance output for a sprayer type. A traditional airblast sprayer axial fan (90 cm diam) can produce air volumes up

Table 10 Early-season canopy deposition, aerial drift, and ground drift for the On Target. Lowercase letters across rows indicate significant difference in means using Tukey's honest significant difference at $\alpha = 0.05$. WFZ: west fruit zone; EFZ: east fruit zone; WUPP: west upper canopy; and EUPP: east upper canopy.

Canopy deposition (ng/cm ²)							
Year ^a	Row	Spray row	WFZ	EFZ	WUPP	EUPP	<i>p</i> value
2017	Row 10	Opposed	80.2 a	36.3 b	54.9 ab	53.0 ab	0.001
2017	Row 20	Opposed	64.7	62.1	72.0	85.2	0.21
Aerial drift (ng/cm ²)							
Year	1 row from sprayer		2 rows from sprayer		3 rows from sprayer		<i>p</i> value
2017	0.6 a		0.4 ab		0.1 b		0.005
Ground drift ^b (ng/cm ²)							
Year	1 row from sprayer		2 rows from sprayer		3 rows from sprayer		<i>p</i> value
2017 ^b	17.2 a		3.8 b		0.6 b		0.013

^aIn 2017, spray data was collected on day of year (DOY) 157.

^bGround data was pooled by row because year and DOY were not significant.

to 47 m³/sec, in contrast to the Croplands SARDI fans (38 cm diam) on the Quantum Mist sprayer, which can produce 3.35 m³/sec each when operated at 2000 rpm (Furness 2005). Higher air outputs are more suited for larger canopies and can create more drift in smaller canopies (Pergher and Gubiani 1995, Grella et al. 2017, Sinha et al. 2019). Drift on the ground may be attributed additionally to differences in foliage density over the vertical height of the vine. More vegetation above the cordon can capture spray, but the generally low-vegetation zone between the ground and the vine cordon allows spray directed into that area to pass through.

The canopy deposition pattern observed across all sprayers was consistent, where more spray was generally deposited on the upper canopy than in the fruiting zone. The typical canopy training systems evaluated here were either modified or strict VSP. These training systems often result in a greater volume of canopy higher in the upper trellis than is typically encountered at or below the fruit zone. Depending on general canopy management practices such as fruit-zone leaf removal, there is typically very little foliage at and below the fruiting zone. Because increased vegetation is often associated with increased spray deposition due to air eddies created by vine-air interaction (Panneton et al. 2005), increased upper canopy spray deposition relative to the fruiting zone is expected. Even with less deposition throughout the fruiting zone, compared to the upper canopy, the applied pesticide may still provide adequate pest control. Water volume and sprayer choice were less influential on disease control than the mode of action of the fungicide (Wise et al. 2010).

Growers often desire sprayers that can cover more than one row in a single pass (Franson 2010), as the greatest efficiencies can be gained in multi-row machines (Niederholzer 2013, Landers 2014). However, most over-the-row sprayer deposition assessment studies have not compared opposed and unopposed row applications (Soriano et al. 2005, Gil et al. 2015, Salcedo et al. 2020), or if a comparison is made, it is not from the same sprayer (Pergher et al. 2013). Experiments that do not collect data from opposed and unopposed rows do not provide a full picture of sprayer performance as it relates to deposition and drift. In our experiments, there was

variable canopy deposition between the opposed and unopposed rows, but those differences were not always consistent (that is, we did not always see consistently greater deposition in opposed relative to unopposed rows). While there have been concerns about spray deposition with multi-row sprayers (Franson 2010), our results indicate that concerns about lack of deposition in unopposed rows are not warranted. In fact, in several instances we found equal or greater deposition in the unopposed rows, perhaps due to the time between passes, which can allow droplets from the first spray pass to dry before the second pass, increasing deposition (Deveau 2016). However, it should be noted that the application evaluations were conducted under generally optimal spray conditions (moderate wind speeds) and that spray deposition in unopposed rows could be altered if sprays were made under higher wind speed conditions that were stronger than the air generated by the sprayers.

Quantum Mist. In general, the opposed and unopposed row canopy deposition patterns were similar, with more deposition in the upper canopy than the fruiting zone. This suggests that the manufacturer should have an operator controller to adjust the fan speed from the top to bottom of the fans on each side, not only on one side of fans or the other. The opposing fan heads on this machine target deposition into the canopy and use a low air speed, both of which help keep spray droplets within the canopy. Yet, the total canopy deposition for the unopposed row was significantly greater than in the opposed row in 2016, but not in 2017 at both season timings. In our study, regardless of small weather changes or fan placement, the unopposed row application had either equal or more canopy deposition than the opposed row application.

For this machine, nozzle placement within the fan is also a critical component to sprayer set-up and optimization, as nozzle placement can influence canopy deposition patterns. When the nozzles are symmetrically placed within the fan head, then the air from the fan produced an even deposition pattern. When nozzles were not symmetrically distributed, the deposition pattern on the canopy became banded (data not shown).

Table 11 Mid-season canopy deposition, aerial drift, and ground drift for the On Target sprayer. Lowercase letters across rows indicate significant difference in means using Tukey’s honest significant difference at $\alpha = 0.05$. WFZ: west fruit zone; EFZ: east fruit zone; WUPP: west upper canopy; and EUPP: east upper canopy.

Canopy deposition (ng/cm ²)							
Year ^a	Row	Spray row	WFZ	EFZ	WUPP	EUPP	p value
2017	Row 10	Opposed	28.0 bc	42.7 b	19.2 c	65.7 a	<0.0001
2017	Row 20	Opposed	19.9 b	48.8 a	17.5 b	38.6 a	<0.0001
Aerial drift (ng/cm ²)							
Year	1 row from sprayer		2 rows from sprayer		3 rows from sprayer		p value
2017	3.6 a		2.2 b		1.5 b		0.001
Ground drift ^b (ng/cm ²)							
Year	1 row from sprayer		2 rows from sprayer		3 rows from sprayer		p value
2017	23.9 a		3.3 b		1.2 b		0.0002

^aIn 2017, spray data was collected on day of year (DOY) 208.

^bGround data was pooled by row because year and DOY were not significant.

Gregoire. Stationary nozzles are regarded as an advantage of pneumatic technology because they do not require nozzles to be changed regularly; however, this also eliminates the ability to manipulate individual nozzle flow. The measured flow rate from the nozzles ranged from 1.02 to 1.55 L/min in 2016 and 0.38 to 0.68 L/min in 2017, possibly leading to uneven spray patterns. Each year, the sprayer was set as described to target the spray arms and nozzles to account for canopy size. However, different machines were used in the two years and each machine and rate controller combination is unique. Rate controllers were calibrated within their limitations, but travel speeds had to differ each season to achieve similar application rates. The difference in tractor speed (Table 1) may have been enough to alter air movement through the canopy and thus change the deposition pattern.

Being able to modify the spray boom so that the three-nozzle arrangement can target the small canopy along the cordon is an advantage of this machine. During early-season applications, when the canopy was smaller, the collection cards in the upper canopy were actually above the existing canopy, which was still close to the cordon. The early-season sprayer set-up adapted the typical five-nozzle arrangement of the machine to use only three nozzles, directed toward the cordon and lower canopy, increasing deposition in the fruiting zone. With this arrangement, canopy coverage for the opposed and unopposed rows had similar deposition patterns, with more deposition in the upper canopy and less in the fruiting zone.

Environmental conditions and the nature of variable flow among nozzles in pneumatic sprayers may have contributed to variances observed in drift. The most aerial drift was collected during midseason on DOY 210 in 2016, which was warmer, with lower humidity and calmer winds. ‘Very fine’ droplets (ASABE 2009), like those produced by pneumatic nozzles, are prone to increased evaporation at high temperatures, resulting in reduced deposition. As with all sprayers that produce small droplets, environmental conditions should be considered during applications.

Aerial drift was low at all years and application timings relative to the spray deposited to the canopy, with almost no difference as distance increased from the sprayer. In contrast, there was typically more ground drift collected in the row closest to the sprayer. There was only one instance where distance from the sprayer did not influence ground drift (Table 8), but relative to other observation dates for ground drift, overall drift at this time point was very low relative to canopy deposition across all collection distances ($<1 \text{ ng/cm}^2$).

On Target. The uneven canopy deposition seen at both application timings is surprising (Tables 10 and 11), since other studies observed fairly even canopy deposition in other cropping systems (Mermer et al. 2020). Differences observed in this trial may be attributed to the canopy shape and density in this vineyard, the use of an older model sprayer, or variance individual nozzle flow. Mermer et al. (2020) used a different model and there are clear mechanical advantages to some models, like having the capability to swivel the nozzle arm horizontally to be parallel to the cordon in early season, optimizing the delivery of spray to the intended crop.

As with other pneumatic sprayers, individual nozzle flow cannot be manipulated. In the study, measured flow from individual nozzles in our sprayer model ranged from 0.08 L/m to 0.30 L/m. The total measured nozzle output from the 10 nozzles that sprayed the east side of the canopy was 52.0 L/m compared to an output of 34.4 L/m from the 10 nozzles that sprayed the west side of the canopy. This difference could explain why there was generally more deposition on the east side of the canopy than on the west during several applications: more spray was applied to the east side. The only exception occurred during early season (row 10), where the west fruit zone had greater deposition than the east fruit zone, but this pattern was not seen in the upper canopy. The ground and aerial drift for the On Target were similar to the other sprayers, where more drift was collected closest to the sprayer.

Conclusions

The sprayer technologies evaluated in this study had very low aerial and ground drift relative to the quantity of spray deposited on the grapevine canopies. The canopy spray deposition patterns had more spray in the upper sections than in the fruiting zones, which was expected since there is often less vegetation in the fruiting zone to capture spray. Under moderate weather conditions, both opposed and unopposed spray rows in our multi-row sprayers had no consistent pattern of more or less canopy deposition, indicating that adjustment to the orientation of fan heads or nozzle arms to target the canopy is critical. The inability to alter individual nozzle flow rate on pneumatic sprayers may lead to some unevenness in spray. However, all tested modern multi-row sprayers performed well, with more canopy deposition and minimal drift when configured appropriately and used under recommended spray conditions.

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