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Research Article

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

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Abstract: Washington wine grape growers are rapidly adopting vineyard management technologies such as mechanical pruners and harvesters but have been slower to adopt new chemical application technologies. Therefore, this study was aimed at generating technical information about commercial over-the-row sprayers deposition and drift, which could be used by growers during sprayer selection and optimization for different vineyard systems and wine grape canopies. Three commercial sprayer technologies, i.e. multi-fan heads, pneumatic, and

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electrostatic sprayer, were evaluated for their 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 mid-season, to determine sprayer deposition patterns in opposed and unopposed application spray row canopy and in-field aerial as well as ground drift. 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 compared to the fruiting zone of the vines. Similarly, the most aerial and ground drift was in the row closest to the sprayed row, indicating that drift is relatively low with the three evaluated sprayer technologies.

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

Introduction

Perennial specialty crop industries have used the axial fan airblast sprayer without any substantial modernization to reflect current horticultural systems since the late 1940s (Fox et al. 2008). In recent years, new sprayer technologies have been introduced (Landers 2004, Fox et al. 2008, Pergher et al. 2013) but limited data has been collected on how these technologies perform in today's more advanced 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.

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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 perform in the varied vineyard sites around Washington State beyond the axial fan airblast sprayer. Washington growers are rapidly adopting advanced vineyard management technologies, such as mechanical pruners and harvesters, 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 wine grape canopy structures. Recognizing the mismatch between applicator and crop may be problematic especially as it relates to drift.

Manufacturers have thus developed a number of over-the-row air-assisted sprayers which can direct the spray droplets into the grapevine canopy using less air volume. Changes or adoption of new types of agricultural technology is often strongly related to how much risk growers are able or willing to take on with the intended change (Marra et al. 2003, Nowak 1992). 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 either better select or use the technologies they have for various site limitations.

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These assessments also provide critical information to regulatory agencies. For example, as application exclusion zones become stricter (40 CFR § 170.405), growers will need updated information so they can adjust spray application practices to be legally compliant. 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 µm; ASABE 2013; 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, direct the air with opposing fans or air assistance into the canopy. These sprayers can produce very fine to fine droplets ($DV_{0.5}$ between 60 to 225 µm; ASABE 2013) which can result in many small droplets covering the entire leaf surface (ASABE 2009) but prone to drift. Small droplets, $DV_{0.5}$ between 30 to 50 µm, can easily drift away from the target even in relatively calm conditions (Pregler 2009,). Electrostatic sprayer technology, which produce similarly sized droplets surrounded by a slight electrical charge, is marketed as improving deposition on the surface of foliage or fruit faced away from the sprayer (Pregler 2009), but the literature has reported 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 quickly evaporate and disappear before coming in-contact with the target (Ozkan and Zhu 2016).

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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 wine grape 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 mid-season (BBCH 75, 77, or 79; Lorenz et al. 1994). Specific canopy and drift assessment methods are described below in "***Spray deposition and drift collection and processing.***" Sprayer evaluation comparisons are 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 are presented in Tables 1 and 2. At each of the two sites (described below), evaluations for each vine development stage were repeated both spatially and temporally. At site 1, there were two different vineyard blocks (2.5 hectares each) 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, mid-season 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

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118 two years and two different vineyard quadrants, each sprayer and timing combination was
119 evaluated three different times. At site 2 (6.6 hectares), sprayer evaluation was conducted in 2017
120 only, and the early season evaluation timing was conducted on DOY 157, and mid-season
121 evaluation timing was conducted on DOY 208. On each day, two different locations in the vineyard
122 block at site 2 were used for evaluation, so the sprayer and timing combination was evaluated two
123 times.
124
125 ***Site and equipment descriptions.***
126 *Site 1 description.* Site 1 was a commercial vineyard in the Horse Heaven Hills AVA (45°59 'N;
127 119°38 'W) in Paterson, WA, USA. The vineyard was established in a Warden very fine sandy
128 loam soil (coarse-silty, mixed, superactive, mesic Xeric Haplocambids) and Hezel loamy fine sand
129 soil (sandy over loamy, mixed, superactive, nonacid, mesic Xeric Torriorthents (USDA-NRCS
130 2019). The vineyard was planted in 1980 in a north-south row orientation to own-rooted *Vitis*
131 *vinifera* 'Chardonnay' on a 1.8 m by 3.1 m, vine by row spacing. The vine canopy was trained to
132 a modified vertical shoot positioned (VSP) system with a single, centered catch wire allowing both
133 the east and west sides of the canopy to flop out and downward. Vine-row-volume measurements
134 were taken within a 3 m area in a non-data row. Canopy width and height (edge to edge of the
135 canopy growth and from the top of the cordon to the top of the canopy growth, respectively) were
136 calculated from five measurements of each type (Tables 3 and 4). Vineyard irrigation and pest
137 management programs followed grower standard practices for the site.
138

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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; Prosser, WA, USA), a three-row, over-the-row sprayer operated by a John Deere 5100M tractor (100 horsepower; Waterloo, IA, USA). The sprayer had 12 axial fan heads, equally divided on six hydraulic arms, that is, two fan heads per arm (Fig. 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 applications dates at a spray volume rate of 702 L/ha. In 2017, the early season applications occurred when canopy sizes were smaller, therefore 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). The sprayer calibration and optimization were done with direct onsite assistance of manufacturer representatives, and done so according to their regional specifications. Fan heads were set facing forward, towards the front of the sprayer, at an approximately 45° angle into the canopy, not facing directly towards the opposing fan head (Fig. 1A). Air velocity was recorded approximately 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).

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The second sprayer was a Gregoire Speedflow Progress, distributed by Blueline Manufacturing (50-80 horsepower requirement; Yakima, WA, USA), a three row, over-the-row sprayer operated by a John Deere 5520 tractor (89 horsepower; Waterloo, IA, USA; Fig. 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 onsite assistance of manufacturer representatives, and done so according to their regional specifications. The fabric tubes were set facing backwards, away from the front of the sprayer, at an approximately 20 to 30° angle into the canopy, not facing directly towards the opposing fabric tubes and nozzles (Fig. 1B). Air velocity was recorded approximately 0.5 m from the nozzle to represent the distance from the sprayer to the closest canopy r on the opposed row (26 km/hr) and the unopposed row (23 km/hr). Though individual sprayers and rate controllers differed between years changed, application rate, engine speed, and operating pressure were all maintained at a consistent rate.

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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, USA. The vineyard has Ritzville silt loam soil (coarse-silty, mixed, superactive, mesic Calcidic Haploxerolls) (USDA-NRCS 2019). The vineyard was planted in 2011 in a north-south row orientation to own-rooted *V. vinifera* 'White Riesling' on a 1.5 m by 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. (20-32 horsepower requirement; Mt. Angel OR, USA), was a two row, over-the-row electrostatic sprayer (Fig. 1C). This sprayer was operated by a Kubota® M8540 tractor (86 horsepower; Gainesville, GA, USA). The sprayer was equipped with eight PVC tubes, each with five electrostatic pneumatic nozzles. All nozzles were used the entire season for application at a rate of 198.3 L/ha (Table 2). Prior to field tests, the nozzles were checked with a voltmeter (ASIMT33D-CA, AstroAI, Brea, CA, USA) to ensure 1000 V of electricity was present at each nozzle as is required for electrostatic charge of the droplets. This sprayer did not utilize a rate controller, and was calibrated and optimized with direct onsite assistance of manufacturer representatives, and done so 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 (Fig. 1C). Air velocity was not recorded for this sprayer.

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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 throughout 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 to kilometer per hour (km/hr).

Weather and canopy measurements.

Environmental parameters including wind speed (km/hr), wind direction (°), relative humidity (RH, %), and air temperature (ºC) were collected continuously during spray applications. During spray applications either a handheld anemometer Kestrel® Instruments 3000 (Boothwyn, PA, USA) or an all-in-one weather station (ATMOS 41; METER Group Inc., Pullman, WA, USA) connected to a data logger (CR1000; Campbell Scientific, Logan, UT, USA) was used to acquire environmental (Tables 3, 4, and 5) data at 0.02 Hz. The weather station was mounted approximately 3 m above ground level. 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 mid-season evaluation (DOY 174) in 2016, and both mid-season 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 on at mid-season

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(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 (± 25% deviation for wind speed, ± 10% deviation for RH, and ± 5% deviation for temperature between the tests being compared) on all days except Gregoire mid-season 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. All environmental data recorded during experiments can be found in Tables 3, 4 and 5.

Spray deposition and drift collection and processing.

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

Canopy spray deposition – Experimental design. To collect spray deposition within the canopy, collection poles facilitated the placement of plastic cards throughout different zones of interest. Poles were constructed from schedule 40 2-cm PVC pipe and metal alligator clips (5.1 cm by 1.1 cm) (Fig. 2A and B) to attach the afore mentioned plastic collection cards. At site 1, 15 canopy

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poles were placed in two rows (opposed spray row and unopposed spray row) to accommodate the three-row sprayers (Fig. 2E). Site 2 had 15 canopy poles in a single row since it was a two-row sprayer (Fig. 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 upper canopy and fruiting zone was approximately 17 cm at both sites. The larger canopy at site 1 necessitated an additional card in the upper middle canopy (MidUPP), positioned halfway between EUPP and WUPP and raised 3 cm (Fig. 2A). Site 2 had a more tightly trained canopy, so MidUPP was excluded (Fig. 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 canopy deposition (Fig. 2C) were placed in the first three rows downwind from the sprayed row (Fig. 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 (Fig. 2D). Plastic cards were affixed under a rubber band.

Deposition and drift collection procedures. Post application, tracer solution was allowed to dry for approximately 10 min on the plastic cards before collection, and each card was placed into individual bags (Uline, Pleasant Prairie, WI, USA). General best practices protocols (such as

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270 changing gloves and discarding compromised cards) were followed to prevent contamination
271 between samples. All samples (tank and cards) were immediately placed in a dark, thermally
272 insulated cooler with ice packs to avoid tracer degradation during transport back to the lab where
273 they were stored at 1.6 ºC within 5 hrs of field collection. At this temperature, samples can be
274 stored up to 90 days with minimal deterioration (Nairn and Forster 2015). All samples were
275 analyzed within 60 days of collection.
276
277 *Deposition quantification.* An aliquot of deionized water was added to each individual collection
278 bag or tank sample, then shaken for 1 min at 180 oscillations/min (Model: 6010, Eberbach shaker,
279 Belleville, MI, USA). A sample of this solution was poured into borosilicate glass cuvettes and
280 analyzed using a fluorometer (10-AU, Turner Design, San Jose, CA, USA). The concentration
281 reading (parts per billion; µg/L) was recorded for each sample. All samples with concentrations
282 exceeding the upper limit of the fluorometer (1,000 µg/L) were diluted to read again in the linear
283 range of developed calibration curves. Each sample reading was corrected using a calibration curve
284 produced from tracer standards made from each chemical lot of tracer specific to a trial (Khot et
285 al. 2012).
286
287 ***Powdery mildew disease ratings.***
288 Cluster disease ratings of grapevine powdery mildew, *Erysiphe necator*, were conducted for each
289 sprayer in both years. Disease ratings were visually estimated as percent surface area infected.
290 Ratings were collected in-field on 30 clusters per treatment replicate typically collected between
291 (25 Aug and 1 Sept each year; typically immediately pre-harvest). The level of disease present at

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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 for comparison within a sprayer type. No comparisons were made among sprayer types or across any dates. Deposition differences between and within canopy zones and drift was analyzed with an ANOVA and Least Standard Squares, followed by post-hoc comparison of means using Tukey's HSD (JMP; ver. 14.0.0, SAS Institute Inc., Cary, NC, USA). Significant

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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 of the study, 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/cm^2) was less than the unopposed row (110.5 ng/cm^2) in 2016 ($p < 0.0001$), but deposition was not different between rows in 2017 ($p = 0.44$; opposed 132.8 ng/cm^2; unopposed 128.5 ng/cm^2). 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 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 statistically differ by distance from sprayer in 2016 or the south quadrant in 2017 (Table 6), but it was significant in the north quadrant in 2017. While not always statistically significant, most ground drift was collected in the row closest to the sprayed row, and the least in the third row from the sprayed row.

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Mid-season. 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/cm^2) was less than the unopposed row (81.7 ng/cm^2) in 2016 ($p < 0.0001$), but deposition was not different between rows in 2017 ($p = 0.45$; opposed 55.6 ng/cm^2; unopposed 52.9 ng/cm^2). In 2017, vineyard quadrant data was pooled within vineyard 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 more at 0.9 m above the canopy than at 0.3 m ($p = 0.03$). However, overall drift was very low (0.016 ng/cm^2, 0.008 ng/cm^2, and 0.009 ng/cm^2, 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

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358 row (86.8 ng/cm^2) was more than the unopposed row (64.2 ng/cm^2) in 2016 ($p < 0.0001$). Total
359 canopy spray deposition was not different between rows in 2017 ($p = 0.67$; opposed 50.5 ng/cm^2;
360 unopposed 52.5 ng/cm^2). In 2017, vineyard quadrant data were pooled within vineyard collection
361 area as no significant difference was seen in opposed row canopy deposition ($p = 0.15$), aerial drift
362 ($p = 0.08$), or ground drift ($p = 0.06$). In 2017, unopposed row data were significantly different
363 between the two quadrants ($p = 0.002$), thus were not pooled. In 2017, opposed row and north
364 quadrant unopposed row had more canopy spray deposition in the fruiting zone than the upper
365 canopy zones (Table 8). However, there were no differences in canopy zone deposition in the south
366 quadrant.
367
368 Aerial drift had no interaction between height above the canopy and distance from the sprayer (p
369 $= 0.97$ in 2016 and $p = 1.0$ in 2017), and no direct influence of height was evident above the
370 canopy (0.3 to 0.9 m) alone ($p = 0.92$ in 2016 and $p = 0.98$) in 2017 (Table 8). Ground drift
371 between vineyard quadrants was not significantly different in 2017 ($p = 0.08$), and therefore
372 pooled. Ground drift in downwind rows was significant in 2016, but not in 2017 (Table 8).
373
374 *Mid-season.* In 2016, except for DOY 210, both the opposed and unopposed rows had more spray
375 deposition in the upper canopy than in the fruit zones (Table 9). Total collected canopy deposition
376 on DOY 174 and 210 in the opposed row (72.5 ng/cm^2 and 54.8 ng/cm^2, respectively) was more
377 than the unopposed row (60.6 ng/cm^2 and 45.8 ng/cm^2, respectively) in 2016 ($p = 0.03$ and $p =$
378 0.04, respectively). Total collected deposition in the opposed row was significantly less than the
379 unopposed row in 2017 ($p < 0.0001$; opposed 47.9 ng/cm^2; unopposed 58.9 ng/cm^2). In 2017,

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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 increased deposition pattern in the upper canopy than fruiting zone pattern.

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) for 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, and in this instance 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 pooled as they were not different from each other (p = 0.17). Distance away from the sprayer also influenced ground drift (Table 9), and more drift was collected in the row closet to the sprayer. Ground drift between vineyard quadrants was not significantly different 2017 (p = 0.35), and therefore 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. Row 10 canopy deposition pattern was highly variable; the lowest deposition in the fruit zone nearest the sprayer (EFZ) and the most in the opposite fruiting zone (WFZ; Table 10). A similar pattern was

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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.

Mid-season. 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), whereas 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), compared to 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 highest in the row closest to the

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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 under the weather conditions they were evaluated in. 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 diameter) can produce air volumes up to 47 m^3/sec, compared to the Croplands SARDI fans (38 cm diameter) on the Quantum Mist^{TM} sprayer which can produce 3.35 m^3/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 additionally attributed to the 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 can allow spray that is directed into that area to pass through.

The canopy deposition pattern observed across all sprayers was consistent, where more spray was generally deposited in the upper canopy than in the fruiting zone. The typical canopy training

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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 what is typically encountered in the fruit zone or lower. Depending on general canopy management practices, such as fruit-zone leaf removal, there is typically very little foliage at and below the fruiting zone. Given that 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 lower deposition throughout the fruiting zone, compared to the upper canopy, chemistries may still provide adequate pest control. Wise et al. (2010) found that water volume and sprayer choice were less influential on disease control, than the mode of action of the fungicide.

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 (Gil et al. 2015, Salcedo et al. 2020, Soriano et al. 2005), 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 higher 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 is

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not warranted. In fact, in several cases we found equal to more deposition in the unopposed rows, and this could be explained by the time between passes, which can allow droplets from the first spray pass to dry before the second pass which can lead to increased deposition (Deveau 2016). However, it should be noted that the application evaluations were conducted in 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 one side of fans or the other. The opposing fan heads on this machine target deposition into the canopy and uses a low air speed, both of which aid to keep spray droplets within the canopy. Yet, the total canopy deposition for the unopposed row was significantly higher than in the opposed row in 2016, but not in 2017 for 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

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pattern. When nozzles were not symmetrically distributed, the deposition pattern on the canopy became banded (*data not shown*).

Gregoire

Stationary nozzles are regarded as an advantage of pneumatic technology because they do not require nozzles to be changed regularly, but this also eliminates the ability to manipulate individual nozzle flow. The measured flow rate (liters per minute, L/min) from the nozzles ranged from 1.02 L/min to 1.55 L/min in 2016 and 0.38 L/min to 0.68 L/min in 2017, possibly leading to uneven spray patterns. Each year, the sprayer was set so that the spray arms and nozzles were targeted to account for canopy size, as described in materials and methods. However, in each year, a different machine was used, 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 3-nozzle arrangement to target the small canopy along the cordon is an advantage of this machine. During early season when the canopy was smaller, the collection cards in the upper canopy were actually above the existing canopy that was still close to the cordon. The early season sprayer set up adapted the typical 5-nozzle arrangement of the machine to only use three nozzles that were directed towards the cordon and lower canopy, thus increasing deposition in the fruiting zone. With this arrangement, canopy coverage for the

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opposed and unopposed rows had a 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 mid-season on DOY 210 in 2016 which was warmer, had lower humidity, and calmer winds. 'Very fine' droplets (ASABE 2009), like those produced by pneumatic nozzles, are prone to increased evaporation at higher temperatures, resulting in reduced deposition. As with all sprayers that produce small droplets environmental conditions should be considered during applications.

Aerial drift was low in all years and application timings relative to the spray deposited to the canopy, with almost no difference as distance increased from the sprayer. This was not the case for ground drift, where there was typically more drift collected in the row closest to the sprayer. However, 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 ng / cm^2).

On Target

The uneven canopy deposition seen at both application timings (Tables 10 and 11) is surprising since other studies have observed fairly even canopy deposition (Mermer et al. 2019) in other cropping systems. Differences that were 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

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flow. Mermer et al. (2019) 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 early season. This should help to optimize the delivery of spray application 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 ten 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 ten 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 compared to the west during several of the applications– simply 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 relative to the fruiting zones which may be expected as 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

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553 sprayers may lead to some unevenness in spray. However, all of the tested modern multi-row
554 sprayers performed well with more canopy deposition and minimal drift when configured
555 appropriately and used under recommended spray conditions.

556 Literature Cited

557 40 CFR § 170.405 - Entry restrictions associated with pesticide applications. United States Code
558 of Federal Regulations. [Online]: https://www.govinfo.gov/content/pkg/CFR-2019-
559 title40-vol26/xml/CFR-2019-title40-vol26-sec170-405.xml. Accessed 04-22-2020.

560 ASABE. 2009. ASABE S572.1 Droplet size classification. Am Soc Agric Biol Eng. [Online]:
561 https://cdn2.hubspot.net/hub/95784/file-32015844-
562 pdf/docs/asabe_s572.1_droplet_size_classification.pdf. Accessed 18 June 2020.

563 Deveau J. 2016. Airblast 101: A Handbook of Best Practices in Airblast Spraying. Sprayers 101.
564 [Online]: https://sprayers101.com/airblast101/.

565 Dokoozlian N. 2013. The evolution of mechanized vineyard production systems in California.
566 Acta Hortic 978:265–278.

567 Forster WA, Gaskin RE, Strand TM, Manktelow DWL, Van Leeuwen RM. 2014. Effect of target
568 wettability on spray droplet adhesion retention spreading and coverage artificial
569 collectors versus plant surfaces.

570 Fox RD, Derksen RC, Zhu H, Brazee RD, Svensson SA. 2008. A History of Air-Blast Sprayer
571 Development and Future Prospects. Trans ASABE 51:405–410.

572 Franson P. 2010. "Almost Satisfied With Sprayers". *Wines Vines Analytics*. [Online]:
573 https://winesvinesanalytics.com/columns/section/19/article/74746/Almost-Satisfied-
574 With-Sprayers.

575 Furness G. 2005. Optimizing Set Up and Operation: Head Placement for Vertical Shoot Position
576 (VSP) Canopies. Quantum Mist^{TM} Grape Sprayer Test Report Number 2. South
577 Australian Research and Development Institute Loxton Research Centre.
578 http://www.croplands.co.nz/content/download/5843/56826/file/QMReport.pdf.

579 Gil E, Llop J, Gallart M, Valera M, Llorens J. 2015. Design and evaluation of a manual device
580 for air flow rate adjustment in spray application in vineyards. In SuproFruit 2015 – 13th

American Journal of Enology and Viticulture (AJEV). doi: 10.5344/ajev.2021.20058
AJEV Papers in Press are peer-reviewed, accepted articles that have not yet been published in a print issue of the journal or edited or formatted, but may be cited by DOI. The final version may contain substantive or nonsubstantive changes.

Workshop on Spray Application in Fruit Growing, Lindau, Germany, 15-18 July 2015. pp. 8–9. https://upcommons.upc.edu/bitstream/handle/2117/80624/4736-18282-1-PB.pdf?sequence=6&isAllowed=y

Grella M, Gallart M, Marucco P, Balsari P, Gil E. 2017. Ground Deposition and Airborne Spray Drift Assessment in Vineyard and Orchard: The Influence of Environmental Variables and Sprayer Settings. Sustainability 9:728–753.

Hislop EC. 1988. Electrostatic Ground-Rig Spraying: An Overview. Weed Technology 2:94–105.ISO 22522:2007. 2007. ISO 22522: Crop protection equipment — Field measurement of spray distribution in tree and bush crops.

Khot LR, Ehsani R, Albrigo G, Larbi PA, Landers A, Campoy J, Wellington C. 2012. Air-assisted sprayer adapted for precision horticulture: Spray patterns and deposition assessments in small-sized citrus canopies. Biosyst Eng 113:76–85.

Kruger GR, Klein RN, Ogg CL, Vieira BC. 2019. Spray Drift of Pesticides. University of Nebraska Extension Publication #G1773.

Landers A. 2004. Prevention is better than cure - Reducing Drit from Vineyard Sprayers. In Invited Presentation Article - International Conference on Pesticide Application for Drift Management. Waikoloa, Hawaii, 27-29 October. pp. 116–124. Kona, Hawaii.

Landers A. 2014. "Multi-row sprayers offer great improvements in timeliness." *Good Fruit Grower.* 24 Oct 2014. [Online]: https://www.goodfruit.com/multi-row-sprayers/.

Lorenz, D. H., Eichhorn, K. W., Blei-Holder, H., Klose, R., Meier, U., & Weber, E. (1994). Phänologische Entwicklungsstadien der Weinrebe (*Vitis vinifera* L. ssp. *vinifera*). Viticulture and Enology Science, 49,66e70.

Marra M, Pannell DJ, Abadi Ghadim A. 2003. The economics of risk, uncertainty and learning in the adoption of new agricultural technologies: Where are we on the learning curve? In Agricultural Systems. pp. 215–234. Elsevier.

Nairn JJ, Forster WA. 2015. Photostability of pyranine and suitability as a spray drift tracer. New Zeal Plant Prot 68:32–37.

Niederholzer F. 2013. "Ways to Save On Grape Spraying." *Growing Produce.* 11 January 2013. https://www.growingproduce.com/fruits/ways-to-save-on-grape-spraying/.Nowak P. 1992. Why farmers adopt production technology. J Soil Water Conserv 47:14–16.

Oakford M, Jones K, Bound S, O'Rielly L. 1994. A comparison of air-shear and electrostatic spray technology with a conventional air-blast sprayer to thin apples. Aust J Exp Agric 34:669.

American Journal of Enology and Viticulture (AJEV). doi: 10.5344/ajev.2021.20058
AJEV Papers in Press are peer-reviewed, accepted articles that have not yet been published in a print issue of the journal or edited or formatted, but may be cited by DOI. The final version may contain substantive or nonsubstantive changes.

Ozkan H, Zhu H. 2016. Effect of Major Variables on Drift Distances of Spray Droplets. The Ohio State University Extension Publications #FABE-525.

Panneton B, Lacasse B, Piché M. 2005. Effect of air-jet configuration on spray coverage in vineyards. Biosyst Eng 90:173–184.

Pascuzzi S, Cerruto E. 2015. Spray deposition in "tendone" vineyards when using a pneumatic electrostatic sprayer. Crop Prot 68:1–11.

Pergher G, Gubiani R. 1995. The Effect of Spray Application Rate and Airflow Rate on Foliar Deposition in a Hedgerow Vineyard. J Agric Eng Res 61:205–216.

Pergher G, Gubiani R, Cividino SRS, Dell'Antonia D, Lagazio C. 2013. Assessment of spray deposition and recycling rate in the vineyard from a new type of air-assisted tunnel sprayer. Crop Prot 45:6–14.

Pregler B. 2009. "Product Review: Electrostatic Sprayers". *Wine Business Monthly* Sept 2009:36–43. https://www.winebusiness.com/wbm/?go=getArticle&dataId=68062

Rathnayake, A.P., Khot, L. R., Hoheisel, G. A., Thistle, H. W., Teske, M. E., Willett, M. J.Appl. Engi. of Argri. In Review. Downwind spray drift assessment for airblast sprayer applications in a modern apple orchard system. MS 14324 ASABE.

Salcedo R, Llop J, Campos J, Costas M, Gallart M, Ortega P, Gil E. 2020. Evaluation of leaf deposit quality between electrostatic and conventional multi-row sprayers in a trellised vineyard. Crop Prot 127:104964.

Sinha R, Ranjan R, Khot LR, Hoheisel GA, Grieshop MJ. 2019. Drift potential from a solid set canopy delivery system and an axial–fan air–assisted sprayer during applications in grapevines. Biosyst Eng 188:207–216.

Soriano AP, Soriano MLP, Piedra AP, Martin MLS. 2005. Comparison of the pesticide coverage achieved in a trellised vineyard by a prototype tunnel sprayer, a hydraulic sprayer, an air-assisted sprayer and a pneumatic sprayer - Dialnet. Spanish J Agric Res 3:175–181.

U.S. Department of Agriculture - Natural Resources Conservation Service (NRCS). 2019. Official Soil Series Description. [Online]: https://soilseries.sc.egov.usda.gov/osdname.aspx. Accessed 14 October 2019.

Wise JC, Jenkins PE, Schilder AMC, Vandervoort C, Isaacs R. 2010. Sprayer type and water volume influence pesticide deposition and control of insect pests and diseases in juice grapes. Crop Prot 29:378–385.

American Journal of Enology and Viticulture (AJEV). doi: 10.5344/ajev.2021.20058
AJEV Papers in Press are peer-reviewed, accepted articles that have not yet been published in a print issue of the journal or edited or formatted, but may be cited by DOI. The final version may contain substantive or nonsubstantive changes.

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

Sprayer	Number of rows sprayed[a]	Nozzle type	Year	Number 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)	4.7	620,528
					174 (77)	4.7	
			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)	5.2	89,632
					208 (75)		

[a] Three-row sprayers consist of two rows with opposing spray applications, and two half rows with unopposed spray. Two-row sprayers consist of only opposed spray rows. See Fig. 2E and F. All sprayers were over-the-row.
[b] Growth stages 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	2017	Early and mid	1600	198.3	None

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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	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)	3,997.5
		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)	

[a] Early season collections occurred on DOY 144 in 2016 and DOY 136 in 2017, weather data were collected from an on-site ATMOS weather station. Mid-season collections occurred on DOY 174 in 2016, and DOY 206 in 2017, weather data were collected from WSU AgWeatherNet (weather.wsu.edu) "Paterson West" station, located within 5.6 km of the site, and has an elevation difference of 3 m, as noted with an *.
[b] Vine-row-volume not collected in 2016.

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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 (m^3/ha)[b]
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)	3,997.5
		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)	3,997.5
		Unopposed; N Quadrant	19.2	47.0	5.3	*ESE (109)	

[a] Early season collections occurred on DOY 144 in 2016 and 142 in 2017, weather data were collected from an on-site ATMOS weather station. Mid-season 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, and has an elevation difference of 3 m, as noted with an *).
[b] Vine-row-volume not collected in 2016.

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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)	3,181.6
		Row 20	23.7	40.2	12.7	*WSW (253)	

[a] Early season collections occurred on DOY 157, weather data were collected from an in-field ATMOS weather station. Mid-season 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, and has an elevation difference of 312 m, as noted with an *.

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 HSD at α=0.05 across individual rows. WFZ = west fruit zone; EFZ= east fruit zone; WUPP = west upper canopy; MidUPP = middle upper canopy; EUPP = east upper canopy.

Canopy deposition (ng/cm^2)							
Year [a]	Spray row	WFZ	EFZ	WUPP	MidUPP	EUPP	*p*-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	*p*-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	*p*-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

[a] In 2016, spray data was collected on DOY 144, and in 2017 it was on DOY 136.
[b] Ground drift data in 2017 was significantly different by quadrant (p = 0.04).

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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 HSD at α=0.05. WFZ = west fruit zone; EFZ= east fruit zone; WUPP = west upper canopy; MidUPP = middle upper canopy; EUPP= east upper canopy.

Canopy deposition (ng/cm^2)							
Year[a]	Spray row	WFZ	EFZ	WUPP	MidUPP	EUPP	*p*-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	*p*-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	*p*-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

[a] In 2016, spray data was collected on DOY 174, and in 2017 it was on DOY 206.
[b] Height above canopy was significantly different between quadrants in 2017 (*p*=0.0005).

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 HSD at α=0.05. WFZ = west fruit zone; EFZ= east fruit zone; WUPP = west upper canopy; MidUPP = middle upper canopy; 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

[a] In 2016, spray data was collected on DOY 144, and in 2017 it was on DOY 142.
[b] Unopposed canopy deposition data in 2017 was significantly different by quadrant (0.002).

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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 HSD at α=0.05. WFZ = west fruit zone; EFZ= east fruit zone; WUPP = west upper canopy; MidUPP = middle upper canopy; 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

[a] In 2016, spray data was collected on DOY 2016-1 is DOY 174 and 2016-2 is DOY 210. In 2017, collection occurred on DOY 206 and 227; but there was no difference between the 2017 collection dates, so data is pooled between collection dates.

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 HSD at α=0.05. WFZ = west fruit zone; EFZ= east fruit zone; WUPP = west upper canopy; EUPP= east upper canopy.

Canopy deposition (ng/cm^2)							
Year[a]	Row	Spray row	WFZ	EFZ	WUPP	EUPP	*p*-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	*p*-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	*p*-value
2017[b]	17.2 a	3.8 b	0.6 b	0.013

[a] In 2017, spray data was collected on DOY 157.
[b] Ground data was pooled by row because year and DOY were not significant.

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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 HSD at α=0.05. WFZ = west fruit zone; EFZ= east fruit zone; WUPP = west upper canopy; 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

[a]In 2017, spray data was collected on DOY 208.
[b]Ground data was pooled by row because year and DOY were not significant.

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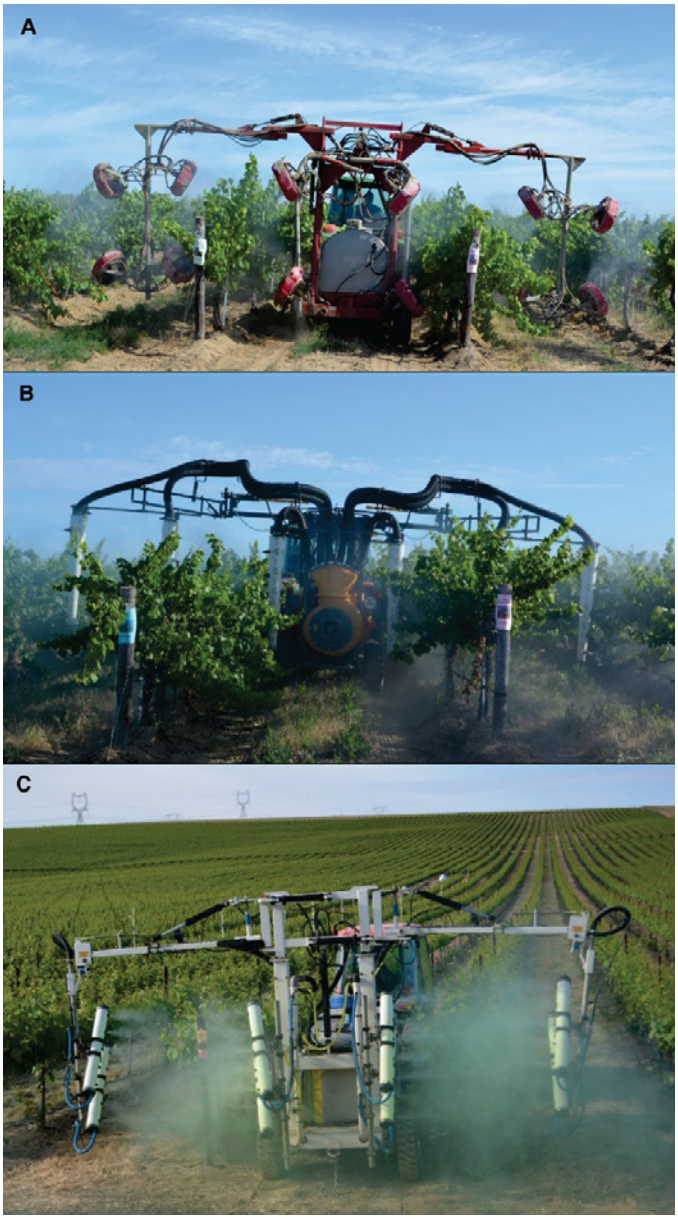

Figure 1 Over-the-row commercial sprayers evaluated in this study in Washington state in 2016 and 2017. (**A**) VineTech Quantum Mist^{TM}; (**B**) Blueline Gregoire SpeedFlow; and (**C**) On Target Spray Systems electrostatic**.**

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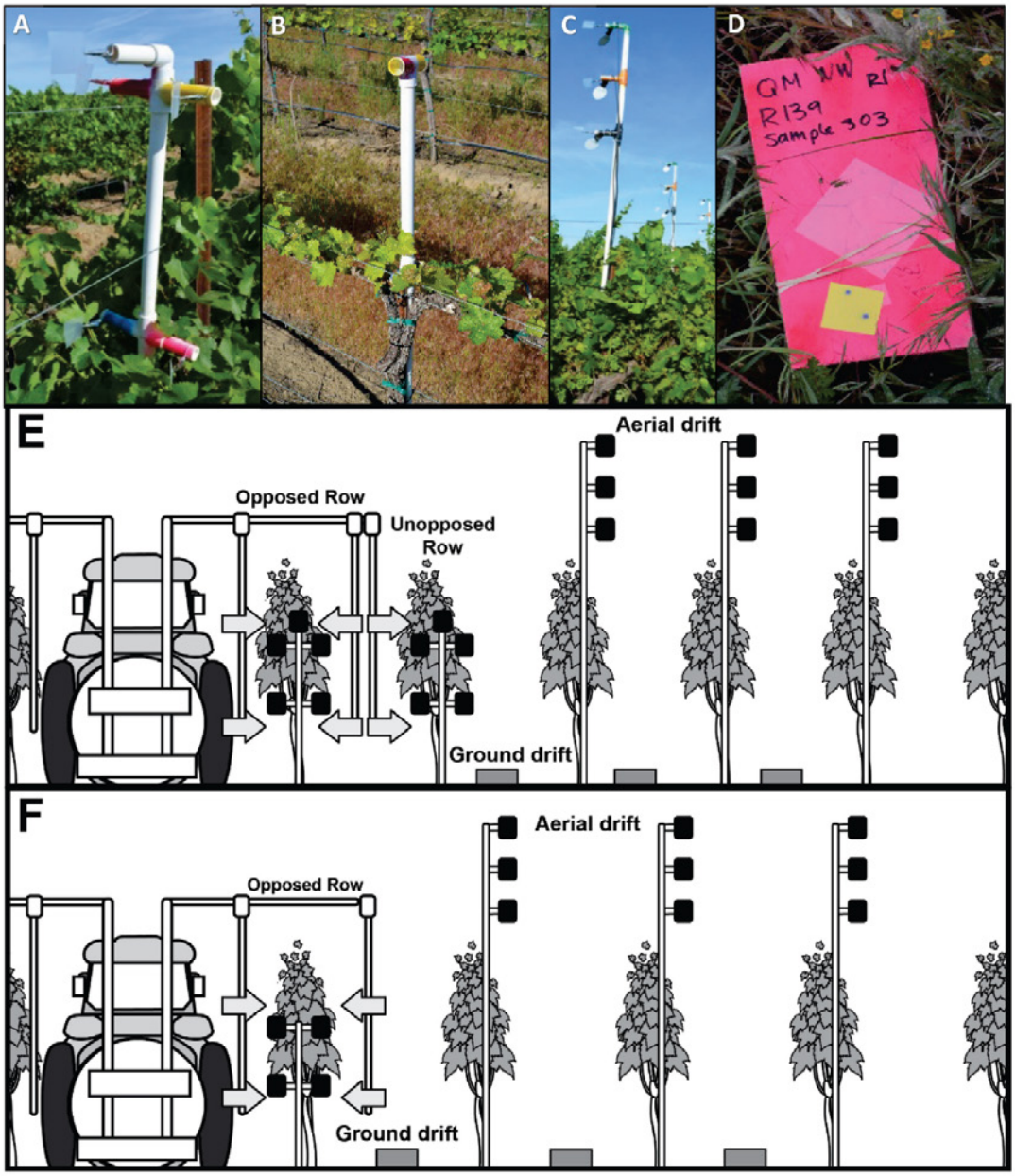

Figure 2 Field collectors and vineyard collection locations for sprayer evaluations in Washington State in 2016 and 2017. (**A**) Canopy deposition collection pole with five collection zones at for Quantum Mist^{TM} and Gregoire sprayers at Site 1; (**B**) Canopy deposition collection pole with four collection zones at for On Target sprayer at Site 2; (**C**) aerial drift collection poles; and (**D**) ground drift collection block. (**E**) Field trial configuration for Site 1; and (**F**) and 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**.**