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Management of Grape Powdery Mildew with an Intelligent Sprayer and Sulfur

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Abstract

Wine grapes are an important agricultural commodity in the Pacific Northwest, where grape powdery mildew (GPM) is one of the main disease problems. The efficacy of various sulfur concentrations and output volumes from an air blast sprayer retrofitted with the Intelligent Spray System (ISS) were evaluated for the management of GPM. The ISS consists of a LiDAR sensor, Doppler speed sensor, embedded computer, flow controller, and individual pulse-width-modulation solenoid valves at each nozzle. GPM cluster severity ranged from 55 to 75% across all trials in the study when the ISS was used at its default spray rate of 62.5 ml/m^3 with micronized sulfur at 6 g/liter, which was significantly higher than all other fungicide treatments but lower than nontreated controls. Similarly, leaf incidence values were highest on nontreated vines, followed by micronized sulfur at 6 g/liter applied at 62.5 ml/m^3, with all other fungicide treatments being significantly lower in all trials. Using the ISS at the 62.5 ml/m^3 rate and a rotation of locally systemic fungicides resulted in the lowest observed GPM leaf incidence and average cluster severity of 11% in both 2019 and 2020, the lowest cluster severity of all fungicide treatments tested. GPM control with the ISS and micronized sulfur was equivalent to a constant-rate air blast treatment at 6 g/liter when the spray rate of the ISS was increased to 125 ml/m^3 or the concentration of sulfur was increased to 24 g/liter. In those cases, the amount of sulfur applied to vines was at or above the minimum label rate from bloom until the end of the season, or the entire season, respectively. This study has shown that sufficient disease control cannot always be expected when pesticides are mixed at the same rate as would be used for a constant-rate sprayer in a variable rate sprayer, especially when contact fungicides such as sulfur are used. With appropriate adjustments, the variable-rate ISS can be a useful tool to reduce pesticide quantities, water needed for mixing, and as a result labor, because fewer trips to refill for a given spray event are needed.

Keywords: crop protection, precision agriculture, sensors, viticulture

Wine grapes are an important agricultural commodity in the Pacific Northwest (PNW), with Washington and Oregon producing a combined 306,000 tons in 2017 (USDA NASS 2020). In Oregon and Washington, wine grape plantings go back to the 19th and early 20th century, with serious commercial development beginning in the 1970s (Gregutt 2010; Hellman 2003). Oregon wine grape production is estimated at a value of $238 million, with a total economic impact related to the wine grape industry of $7.2 billion in 2019 (Economics Forensics and Analytics Inc. 2021). The wine grape industry in the PNW is now well established, with grapes produced predominantly in the arid central and eastern areas of Washington and many geographic areas of Oregon.

One of the most important diseases that threaten grape production in the PNW is grape powdery mildew (GPM; *Erysiphe necator* Schweinitz) (Pscheidt and Ocamb 2021). GPM pressure is high in the PNW, with the long, mild growing season common in PNW viticultural areas favoring reproduction and dispersal of the pathogen. Fungicide applications and vine training dominate growing season activities, many of which are focused on the management of GPM. Conventional fungicide applications for GPM management start in late April to mid-May, before the pre-bloom phenophase (Biologische Bundesanstalt, Bundessortenamt and Chemical Industry 57), and continue through to veraison (Biologische Bundesanstalt, Bundessortenamt and Chemical Industry 81; Lorenz et al. 1995). The use of organically acceptable products such as sulfur can require weekly application intervals, whereas many modern synthetic fungicide intervals can be from 14 to 21 days. The large amounts of water needed to apply fungicide spray programs that involve 6 to 12 applications per season present a challenge for the many vineyards in the PNW that do not have direct access to water. GPM management has been estimated to cost as much as 37% of the gross value of production in places where GPM pressure is significant (Sambucci et al. 2014).

Vineyard sprayers are typically air-assisted systems with designs including over-the-row tunnel sprayers, electrostatic-based sprayers, and radial air blast sprayers. The radial air blast sprayer is the most common design used in vineyards around the world (Warneke et al. 2021). Although radial air blast sprayers are effective at achieving adequate pesticide coverage and deposition on grapevines, they are not efficient. Spray losses to the ground by radial air blast sprayers are commonly 20 to 30% and as great as 70% (Jensen and Olesen 2014; Pergher et al. 1997). Spray losses to the air, also known as pesticide drift, range from 2% of applied volume to 10% (Gil et al. 2007; Jensen and Olesen 2014). This results in estimates of applied spray that gets deposited on the crop of somewhere between 15 and 70% depending on the nozzles, spray volume, vine type, and vine growth stage at the time of application (Jensen and Olesen 2014; Pergher et al. 1997). Standard sprayers emit a constant rate of pesticide determined by the tractor ground speed, nozzles in use, and pump pressure. Sensor-controlled sprayers are a technology that has been emerging as a way to retrofit existing radial air blast sprayers to make them more efficient (Warneke et al. 2021). Sensor-controlled sprayers that use ultrasonic sensors have been commercially available since the mid-1990s and work by turning the sprayer fully on when a plant is sensed, then fully off when the sprayer is passing gaps between plants. Although ultrasonic sensor sprayers reduce pesticide use by 15 to 40% and ground deposition by ≤72%, they are still not widely used (Giles et al. 2011).

Variable-rate sprayers are the newest entrants into the sensor-controlled sprayer market. Variable-rate sprayers typically use a LiDAR sensor to detect plant presence and plant characteristics such as foliage density, to adjust spray volume output in real time to match plant canopy characteristics. These sprayers can reduce spray losses to the ground by 68 to 90%, losses blown through tree canopies by 70 to 92%, airborne spray drift by 70 to 100%, and applied spray volume by 31 to 73% compared with a standard radial air blast sprayer (Chen et al. 2013, 2020). LiDAR integrated sprayers are also capable of taking plant growth data such as canopy density in addition to counting the number and size of plants. As a result of applying less pesticide, variable-rate LiDAR sprayers use less water,

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labor, and diesel because fewer sprayer fill-ups are needed to complete a given spray area. This has multifaceted benefits: Sprays are easier to fit into short periods (such as good weather or when a pest or pathogen is vulnerable), wear and tear on the tractor is reduced, pesticide load on the environment is reduced, and sprayer operators are less fatigued because shorter times are needed for spraying (Warneke et al. 2019).

The only variable rate sprayer using LiDAR that is commercially available in the United States is called the Intelligent Spray Control System (ISS; Smart Guided Systems, Indianapolis, IN). The ISS was developed by the U.S. Department of Agriculture before its commercialization and was tested extensively in nurseries and orchards to validate the technology as robust and effective (Zhu et al. 2017). Subsequently, kits that include all the components of the ISS that could be retrofitted onto most standard air-assist sprayers were introduced. These ISS retrofit kits have been demonstrated to increase efficiency without reducing efficacy compared with a standard air blast sprayer at controlling a wide variety of pests and pathogens on crops such as apple, peach, blueberry, raspberry, and a variety of nursery crops (Boatwright et al. 2020; Chen et al. 2019, 2020). Most studies using the ISS have evaluated a variety of different pesticides in a grower's standard schedule and compared the grower's standard sprayer to the ISS. No research on the ISS has examined how the efficacy of contact action protectant fungicides could be affected by the variable rate technology of the ISS. In addition, no research has evaluated the efficacy of the ISS in wine grapes. Our goal was to compare the efficacy of different sulfur concentrations and output volumes from the ISS retrofitted onto a standard air blast sprayer for the management of GPM on wine grapes.

Materials and Methods

Sprayer and tractor. The sprayer used for this research was a 189-liter (50 gallon) air-blast sprayer (Pak-blast; Rears Mfg., Coburg, OR) retrofitted with the ISS. The ISS consisted of a LiDAR laser sensor, Doppler speed sensor, embedded computer, flow controller circuitry box, and individual pulse width modulation (PWM) solenoid valves at each sprayer nozzle. These components adjust pesticide application volume in real time to match plant canopy density (Zhu et al. 2017). A spray console wired to the system allowed the use of either the ISS components, where the sensors modulated spray volume in real time, or standard operation, where the sprayer emitted a constant rate of the pesticide. The spray rate parameter controls the volume of pesticide applied per unit canopy volume. The default spray rate setting for the ISS was 62.5 ml/m^3 of canopy. When the ISS was used it will hereafter be referred to as "ISS," and when the ISS was off and standard operation occurred it will hereafter be referred to as "standard." Fungicide suspensions were applied at 552 kPa from the sprayer nozzles (TeeJet ceramic D3 discs and DC25 cores). Only one side of the sprayer was used, such that two passes (one on each side of the row) were needed to fully spray a single row of grapes. The sprayer control system was mounted in the tractor (Kubota M5N-111) that pulled and powered the sprayer.

Plots and experimental design. The vineyard used for the study was located at the Botany and Plant Pathology Field Laboratory, Oregon State University, in Corvallis, Oregon. This vineyard consisted of cultivar rows positioned between a buffer row of hedged rootstock vines to help minimize row–row interference, with cultivar rows randomized at the time of planting. Within each cultivar row a single rootstock vine was trained between each plot of cultivar vines to minimize plot–plot interference. Rows of Pinot noir (2018 to 2020) and Pinot gris (2019 to 2020) planted in 1998 on *V. rupestris* × *V. riparia* 101-14 rootstock with 2.13 × 2.44 m spacing were used in the study. Cultivar vines were trained to a Guyot (vertical shoot position) system and pruned by 15 March each year. Shoot thinning by hand occurred in May of each year, and sucker removal by hand was continuous throughout the season. Shoots were cut above the top wire in mid-June each year and maintained at that height throughout the rest of the growing season.

During the 3 years of the study (2018 to 2020), fungicide treatments (Table 1) were arranged in a randomized complete block design in both cultivars. Within each cultivar trial, each fungicide treatment was replicated on four sets of five vines. The experiments tested types of fungicides, rates of fungicides, and rates of applications (Table 1).

Fungicides and rates were determined in collaboration with a group of local wine grape grower collaborators. From these discussions we selected micronized sulfur (Microthiol Disperss 80%; United Phosphorus Inc., King of Prussia, PA) applied every 7 to 12 days depending on plant growth stage and disease pressure as measured by the Gubler–Thomas powdery mildew risk index (Gubler et al. 1999). Shorter spray intervals (7 to 8 days) corresponded to bloom and times of high disease pressure, and longer (10 to 12 days) spray intervals corresponded to times of fruit development and lower disease pressure. We selected two Microthiol Disperss (MD) concentration-based rates (6 and 24 g/liter) and one area-based rate (5.6 kg/ha). The area-based approach (5.6 kg/ha) results in a higher concentration of product being applied earlier in the season when the canopy is small, whereas the concentration-based approach (6 g/liter) results in a lower amount of product applied per area because the same concentration is maintained early in the season when application volume is its lowest. Both rates (6 g/liter and 5.6 kg/ha) eventually result in the same volume of pesticide being applied when the vines are at full canopy and approximately the same amount of product per area. The high concentration rate (24 g/liter) was suggested by our viticulture industry collaborators, who sometimes use this rate early in the season when application volume is low. For the 2019 to 2020 Pinot gris we compared the default ISS spray rate of 62.5 ml/m^3 with a higher spray rate of 125 ml/m^3; we designate these modes as ISS-low and ISS-high, respectively (Table 1). Additionally, we

Table 1. Treatments applied to vines during the 2018 to 2020 seasons

2018–2020 Pinot noir			2019–2020 Pinot gris		
Tractor speed (m/s)[t]	**Sprayer mode[u]**	**Treatment[v,w]**	**Tractor speed (m/s)**	**Sprayer mode[u]**	**Treatment[v,w]**
N/A	N/A	Nontreated	N/A	N/A	Nontreated
0.85	ISS-low	6 g/liter MD	0.85	ISS-low	6 g/liter MD
0.85	Standard	6 g/liter MD	0.85	Standard	6 g/liter MD
0.85	Standard	5.6 kg/ha MD[x]	0.85	ISS-high	6 g/liter MD
0.85	ISS-low	24 g/liter MD[y]	0.85	ISS-low	Vivando-Endura alt. Quintec-Torino[z]
2.01	Standard	24 g/liter MD	–	–	–

[t] 0.85 m/s and 2.01 m/s, equivalent to 1.9 and 4.5 miles/h, respectively.

[u] Intelligent low (ISS-low) and high (ISS-high) treatments applied at 62.5 and 125 ml/m^3 (0.06 and 0.12 fl. oz./ft.^{3}), respectively.

[v] All treatments were applied at 552 kPa (80 psi) at tractor power take-off rated speed. MD, Microthiol Disperss (80% sulfur, FRAC M2).

[w] Treatments of 6 g/liter, 5.6 kg/ha, 24 g/liter are equivalent to 5 lb./100 gal., 5 lb./A., and 20 lb./100 gal., respectively.

[x] Treatment applied only in 2018 Pinot noir trial.

[y] Treatment applied in 2019 to 2020 Pinot noir trials.

[z] Treatment applied at the highest label rates per area. Active ingredients and FRAC codes are as follows: metrafenone (Vivando, FRAC U8), boscalid (Endura, FRAC 7), quinoxyfen (Quintec, FRAC 13), and cyflufenamid (Torino, FRAC U6).

selected a rotation of synthetic fungicides (Table 1), mixed at the highest label rate, that are commonly used by the wine grape industry in the Willamette Valley of Oregon: Metrafenone (Vivando; BASF, Florham Park, NJ) was tank mixed with boscalid (Endura; BASF, Florham Park, NJ) and alternated on a 2-week interval with cyflufenamid (Torino; Gowan Company, Yuma, AZ) tank mixed with quinoxyfen (Quintec; Gowan Company, Yuma, AZ).

Data collection and analysis. Leaves and clusters were evaluated for GPM incidence and severity, respectively, by a single individual. The middle three vines of each plot were examined in the field for GPM by arbitrarily selecting 25 clusters or leaves on both the east and west sides of the row for a total of 50 units examined per plot. The visual incidence (presence or absence) of GPM on leaves was recorded weekly from mid-June through mid-August in each year. The severity of GPM on clusters (percentage coverage of GPM on the cluster surface) was visually estimated and recorded in late July or early August each year, just before the onset of veraison. Weekly leaf incidence levels were used to calculate absolute area under the disease progress curve (AUDPC) in the agricolae package in R (de Mendiburu 2020). Data collected from the 2018 Pinot noir trial were analyzed separately from the 2019 and 2020 data because treatments were not fully standardized between 2018 and 2019 to 2020. The 2018 leaf incidence AUDPC data were analyzed with a generalized least squares model to accommodate nonhomogenous variance between treatments. The 2018 Pinot noir cluster severity was used as binomially distributed probability of berry infection and modeled via a generalized linear mixed model (GLMM) in the lme4 package in R with block fitted as a random effect (Bates et al. 2015). Leaf incidence AUDPC data from the 2019 to 2020 Pinot noir trials and the 2019 to 2020 Pinot gris trials were combined, and each cultivar was analyzed separately with a generalized least squares model to accommodate nonhomogenous variance between treatments. Cluster severity data from 2019 to 2020 Pinot noir trials and the 2019 to 2020 Pinot gris trials were combined, and each cultivar was analyzed separately via a GLMM in the lme4 package with block fitted as a random effect (Bates et al. 2015). Treatments in cluster severity and leaf AUDPC analyses were contrasted via estimated marginal means (emmeans package), and the fit of all GLMMs was checked with an overdispersion function and the DHARMa package in R (Bolker et al. 2009; Hartig 2020; Lenth 2020). Any overdispersion caused by extrabinomial variation in the cluster severity GLMMs was corrected for an observational level random effect (Harrison 2014). Uncertainty was estimated via asymptotic 95% confidence intervals. All data were analyzed in R version 4.0.3 (R Core Team 2020).

Spray coverage. Spray coverage was evaluated in the cluster zone and midcanopy on 22 June 2018 on the same Pinot noir vines from the fungicide trials. Water-sensitive cards (TeeJet Technologies, Wheaton, IL) were clipped back to back with a sign holder (Versa-Grip; Deflecto LLC, Indianapolis, IN) and attached to vines just above the fruiting wire, in the cluster zone, located near the base of the grapevine canopy. Three pairs of these back-to-back cards were evenly dispersed lengthwise along the middle three vines of each five-vine plot. One of the cards faced the east side of the row, and the other faced the west side of the row. Two of the pairs were clipped to the vines from the east side of the row, such that the east-facing card was more exposed than the west-facing card and vice versa for the pair that was clipped on the west side of the row. Cards that were more exposed (such as cards clipped on the east side of the row facing east) were called outer-facing cards, and cards that faced the canopy were called inner-facing cards. In addition to the cluster zone cards, a single water-sensitive card was placed midway up the canopy on the adaxial surface of a leaf in each plot. Tractor and sprayer settings tested mirrored the settings in the 2018 Pinot noir sulfur trial (Table 1) and included ISS-low at 0.85 m/s and standard mode at 0.85 and 2.01 m/s. Water was applied as the spray mixture, and after application the water-sensitive cards dried for 30 min, then were collected into zip-top plastic bags. Water-sensitive cards were then scanned and analyzed for spray coverage (percentage coverage of card) and deposit density (spray deposits per square centimeter) in the image analysis software DepositScan (Zhu et al. 2011). Spray coverage percentages were modeled with a generalized linear model with a quasi-binomial distribution. Deposit density was analyzed via a linear model. Uncertainty for both spray coverage and deposit density was estimated via asymptotic 95% confidence intervals, and treatment comparisons were conducted in the emmeans package (Lenth 2020).

Results

Pinot noir trials. In the 2018, 2019, and 2020 trials, the greatest leaf AUDPC was observed on nontreated vines, which was significantly greater than for all other treatments (Table 2). In 2018, 2019, and 2020 trials the 6 g/liter MD ISS-low treated vines had significantly greater AUDPCs than all other MD treatments but significantly lower AUDPCs than nontreated vines. Vines treated with the three remaining MD rates (6 g/liter, 5.61 kg/ha, 24 g/liter, all standard mode) had AUDPCs that were not significantly different from each other in 2018, 2019, and 2020 trials.

In 2018 the cluster severity data showed the same trend of significance where nontreated vines had significantly higher cluster severity than vines treated with 6 g/liter MD ISS-low, which had significantly higher cluster severity than vines treated with all three other MD treatments (Table 2). Cluster severity data were more variable in 2019 and 2020, but nontreated vines still had significantly higher cluster severity than all fungicide treatments. Treatment with 6 g/liter MD ISS-low resulted in significantly lower cluster severity than nontreated vines in both years but significantly higher cluster severity than vines treated with all other MD treatments (Table 3). During 2019 and 2020 trials the lowest cluster severities were assessed on vines treated with 6 g/liter MD-standard, although in 2020 cluster severities from those vines were not significantly different from those of vines treated with 24 g/liter MD standard mode in 2019 and 2020 and the 24 g/liter MD ISS-low treatment from 2019. In 2020, vines treated with 24 g/liter MD ISS-low had significantly lower cluster severity than vines treated with 6 g/liter MD ISS-low from 2019 and 2020 and were not significantly different from vines treated with 24 g/liter MD standard mode from 2019 and 2020.

Pinot gris trials. The greatest AUDPC value was observed on nontreated vines in 2020, with the AUDPC from nontreated vines in 2019 being slightly less (Table 3). Vines treated with 6 g/liter MD ISS-low in 2019 and 2020 had a significantly lower AUDPCs than nontreated vines in both years, but vines treated in 2020 with 6 g/liter MD ISS-low had a significantly greater AUDPCs than vines treated in 2019 with 6 g/liter MD ISS-low. When vines were treated with 6 g/liter MD with ISS-high (125 ml/m^3) in 2020, the AUDPC was not significantly different than when vines were treated with 6 g/liter MD ISS-low in 2019. The AUDPC on vines treated with 6 g/liter MD ISS-high in 2019 was not significantly different from the AUDPC of vines treated with 6 g/liter MD standard in 2019 or 2020. The synthetic fungicide rotation applied to vines in ISS-low mode resulted in significantly lower AUDPCs than when vines were treated

Table 2. Leaf incidence area under the disease progress curve (AUDPC) and average cluster severity from the 2018 Intelligent Sprayer trial on Pinot noir at the Botany and Plant Pathology field lab

Treatment[y]	AUDPC[z]	Cluster severity[z]
Nontreated	2,689 (2,503–2,876) a	93 (88–96) a
6 g/liter MD ISS-low	2,194 (2,008–2,380) b	55 (40–69) b
6 g/liter MD Std	1,210 (1,024–1,397) c	10 (6–16) c
5.6 kg/ha MD Std	942 (755–1,128) c	10 (6–16) c
24 g/liter MD Std	938 (751–1,124) c	10 (6–17) c

[y] All treatments were applied at 552 kPa (80 psi) at tractor power take-off rated speed. ISS-low, intelligent spray, low mode (62.5 ml/m^3); MD, Microthiol Disperss (80% sulfur); Std, standard mode.

[z] Estimates are followed by 95% confidence intervals in parentheses. Treatments followed by different letters are significantly different from each other; marginal means contrast ($P < 0.05$) with P values adjusted via Tukey method.

with any of the MD treatments in both 2019 and 2020; however, vines treated with the synthetic rotation in 2020 had a significantly greater AUDPC than vines treated with the synthetic rotation in 2019.

The nontreated vines had significantly higher cluster severity than vines treated with any of the fungicides in both 2019 and 2020, and there was no significant difference in cluster severity between 2019 and 2020 for that treatment (Table 3). Vines treated with 6 g/liter MD ISS-low had significantly higher cluster severity than vines treated with other fungicides in 2019 and 2020, with no significant differences in cluster severity between years for that treatment. There were no significant differences in cluster severity between vines treated with 6 g/liter MD-standard or 6 g/liter MD ISS-high in either 2019 or 2020. Vines treated with the synthetic fungicide rotation ISS-low had significantly lower cluster severity than vines treated with any other fungicide treatments in 2019 and 2020 (Table 3).

Spray coverage in 2018. In the cluster zone, there were no significant differences in percentage coverage of water sensitive cards among all three sprayer settings within the outer-facing group (Table 4). For the inner-facing cards however, when water was applied in standard mode at 0.85 m/s, significantly higher percentage coverage on water sensitive cards was observed than when water was applied in either ISS-low mode at 0.85 m/s or standard mode at 2.01 m/s (Table 4). There were no significant differences in deposit density between the three sprayer settings on the outward-facing cards placed in the cluster zone (Table 4). For the inner-facing cluster zone cards, significantly higher deposit density was observed on cards when water was applied in ISS-low mode at 0.85 m/s (65 ml/m^3) than on cards when water was applied in standard mode at 0.85 m/s (Table 4). Among cards placed on leaves in the midcanopy above the cluster zone there were no significant differences in percentage coverage (Kruskal–Wallis test, P = 0.437) or deposit density (Kruskal–Wallis test, P = 0.618) between all three sprayer settings tested (Table 4).

Spray quantities, Pinot noir trials. The volume of fungicide mixture applied in the 6 g/liter MD-standard treatment averaged 1,017 liters/ha and ranged from 919 liters/ha in 2019 (applied early in the season) to 1,094 liters/ha in 2020 applied at full canopy (Fig. 1). The 5.61 kg/ha MD treatment that was applied only in 2018 resulted in a similar amount, with a minimum spray volume of 979 liters/ha and a maximum of 1,083 liters/ha. The 24 g/liter MD-standard treatment (applied at a faster ground speed) resulted in a lower spray volume, with a minimum of 406 liters/ha in 2019 and a maximum of 478 liters/ha in 2020 (Fig. 1). The first application of the 24 g/liter MD-standard treatment in 2018 resulted in 1,043 liters/ha, which was greater than the label rate of formulated MD per hectare. To apply 24 g/liter MD within the label specifications, it was necessary to increase the tractor speed from 0.85 to 2.01 m/s. The 6 g/liter MD ISS-low treatment was applied at a minimum of 131 liters/ha and ranged up to a maximum of 497 liters/ha, with the volume increasing steadily through the season as the ISS adjusted output volume to accommodate canopy growth (Fig. 1). In 2018 to 2020 the ISS-low treatment resulted in a total application volume of 3,506, 3,435, and 4,477 liters/ha, compared with 10,212, 9,663, and 12,676 liters/ha, respectively, in standard mode, representing a 66, 64, and 65% decrease in volume in those seasons. The 24 g/liter MD ISS-low treatment showed a similar increase in spray volume through the season as the 6 g/liter MD ISS-low treatment, with a minimum of 143 liters/ha applied early in the season in both 2019 and 2020 and a maximum of 482 liters/ha in 2020.

Table 3. Leaf incidence area under the disease progress curve (AUDPC) and average cluster severity from the 2019 and 2020 Intelligent Sprayer trials at the Botany and Plant Pathology field lab

Pinot noir				Pinot gris			
Treatment^{w,x}	Year	AUDPC^y	Cluster severity^y	Treatment^{w,x}	Year	AUDPC^y	Cluster severity^y
Nontreated	2019	2,743 (2,689–22,797) a	97 (96.1–97.6) a	Nontreated	2019	2,700 (2,678–2,721) b	94 (92.5–95.6) a
	2020	2,790 (2,736–22,844) a	97 (96.5–97.9) a		2020	2,778 (2,756–2,800) a	94 (92.3–95.4) a
6 g/liter MD-standard	2019	797 (638–956) c	23 (18.6–27.4) e	6 g/liter MD-standard	2019	1,013 (758–1,268) gh	26.4 (21.5–32.2) c
	2020	844 (685–1,003) c	25 (20.2–29.5) de		2020	1,092 (837–1,346) ef	26 (20.9–31.3) c
6 g/liter MD ISS-low	2019	1,929 (1,771–2,087) b	73.1 (67.8–77.7) b	6 g/liter MD ISS-low	2019	1,963 (1,620–2,307) d	67 (61.0–73.0) b
	2020	1,976 (1,819–2,134) b	75 (70.1–79.5) b		2020	2,042 (1,698–2,386) c	67 (60.2–72.3) b
24 g/liter MD-standard	2019	789 (622–956) c	27 (22.1–31.9) cde	6 g/liter MD ISS-high	2019	1,194 (919–1,468) fh	38 (31.3–44.1) c
	2020	836 (669–1,003) c	29 (24.0–34.3) cde		2020	1,273 (999–1,547) deg	37 (30.6–43.2) c
24 g/liter MD ISS-low	2019	676 (433–918) c	37 (31.5–43.1) cd	Synthetic rotation ISS-low^z	2019	81 (21–142) j	11 (9.0–14.6) d
	2020	723 (480–966) c	40 (33.8–45.8) c		2020	160 (100–221) i	11 (8.7–14.2) d

[w] All treatments were applied at 552 kPa (80 psi) at tractor power take-off rated speed. MD, Microthiol Disperss (80% sulfur, FRAC M2).

[x] Intelligent low (ISS-low) and high (ISS-high) treatments applied at 62.5 ml/m^3 and 125 ml/m^3 (0.06 and 0.12 fl. oz./ft.^{3}), respectively.

[y] Estimates are followed by 95% confidence intervals in parentheses. Treatments followed by different letters are significantly different from each other; marginal means contrast (P < 0.05) with P values adjusted via Tukey method.

[z] Synthetic rotation: metrafenone (Vivando, FRAC U8) mixed with boscalid (Endura, FRAC 7) alternated with quinoxyfen (Quintec, FRAC 13) mixed with cyflufenamid (Torino, FRAC U6), all mixed at their highest label rates if they were applied in standard mode.

Table 4. Percentage coverage and droplets/cm^2 on water-sensitive cards placed in the cluster zone and midcanopy during the Pinot noir coverage trial in 2018

Card position	Treatment^x	Coverage (%)^y	Deposit density (deposits/cm^2)^y
Outer facing	Standard (0.85 m/s)	58 (48–68) a	45 (28–62) a
	Standard (2.01 m/s)	65 (54–74) a	43 (27–60) a
	Intelligent (0.85 m/s)^z	60 (50–70) a	44 (28–61) a
Inner facing	Standard (0.85 m/s)	57 (47–67) b	52 (35–69) a
	Standard (2.01 m/s)	35 (26–45) a	72 (56–89) ab
	Intelligent (0.85 m/s)	34 (25–45) a	82 (65–99) b
Midcanopy^z	Standard (0.85 m/s)	25.8 ± 9.2	88.8 ± 6.5
	Standard (2.01 m/s)	17.1 ± 4.9	81.0 ± 11.4
	Intelligent (0.85 m/s)	35.2 ± 11.4	85.6 ± 19.9

[x] Outer facing, inner facing, and midcanopy cards were tested separately to determine statistical differences among treatments. All treatments applied at 552 kPa (80 psi) at tractor power take-off rated speed. Intelligent mode treatments applied at a rate of 62.5 ml/m^3 (0.06 fl. oz./ft.^{3}) water.

[y] Means followed by 95% confidence intervals for outer- and inner-facing cards. Means and standard error for midcanopy cards.

[z] There were no significant differences in percentage coverage (Kruskal–Wallis test, P = 0.437) or deposit density (Kruskal–Wallis test, P = 0.618) between treatments in midcanopy cards.

The amount of MD applied per hectare was calculated based on the amount of spray volume applied for each treatment and the concentration of MD in the tank. The 6 g/liter MD-standard treatment resulted in a minimum of 5.6 kg/ha of MD and a maximum of 6.6 kg/ha of MD (Fig. 2). The 5.61 kg/ha MD standard mode treatment resulted in a minimum of 5.7 kg/ha and a maximum of 6.9 kg/ha of MD (Fig. 2). The 24 g/liter MD standard mode treatment resulted in a minimum of 9.9 kg/ha that occurred in 2019 and a maximum of 11.44 kg/ha of MD that occurred in 2020 (Fig. 2). The 6 g/liter MD ISS-low treatment resulted in a minimum of 0.80 kg/ha of MD applied early in the season in 2019 to a maximum of 3.0 kg/ha in 2020. The 24 g/liter MD ISS-low treatment started the season with a minimum of 3.4 kg/ha and a maximum of 11.5 kg/ha later in the season in 2020. In 2018 to 2020 the ISS-low treatment resulted in a total applied sulfur of 21.2, 20.9, and 27.2 kg/ha, respectively, compared with 61.7, 58.7, and 76.0 kg/ha in standard mode, representing a 66, 64, and 65% decrease in applied sulfur in those seasons.

Spray quantities, Pinot gris trials. The volume of fungicide solution applied with the 6 g/liter MD standard mode treatment ranged from 907 liters/ha early in the season in 2019 to a maximum of 1,102 liters/ha that occurred at full canopy in 2020 (Fig. 3). For the 6 g/liter MD ISS-low treatment spray volume applied ranged from 131 liters/ha early in the season in 2019 to a maximum of 481 liters/ha at full canopy in 2020 (Fig. 3). For the 6 g/liter MD ISS-high treatment, spray volume applied ranged from 171 liters/ha early in the season in 2019 to 732 liters/ha in 2020. In 2019 to 2020 the ISS-low treatment resulted in a total application volume of 3,419 and 4,306 liters/ha, respectively, compared with 9,364 and 12,716 liters/ha in standard mode, representing a 63 and 66% decrease in volume in those seasons. For ISS-high, total application volume in 2019 and 2020 was 5,182 and 6,829 liters/ha, respectively, representing 45 and 46% less total volume applied than the standard mode treatment. Vines treated with the synthetic rotation using ISS-low were sprayed with a minimum volume of 135 liters/ha that occurred with the first application of 2019 up to a maximum of 509 liters/ha that was the last application of 2020.

The 6 g/liter MD-standard treatment resulted in a minimum of 5.5 kg/ha of MD and a maximum of 6.8 kg/ha of MD (Fig. 4). The 6 g/liter MD ISS-low treatment resulted in a minimum of 0.80 kg/ha and a maximum of 2.9 kg/ha of MD (Fig. 4). The 6 g/liter MD ISS-high treatment resulted in a minimum of 1.0 kg/ha MD in 2019 and a maximum of 4.4 kg/ha MD in 2020. In 2019 to 2020 the ISS-low treatment resulted in a total applied sulfur of 20.8 and 26.2 kg/ha, respectively, compared with 56.9 and 77.6 kg/ha in standard mode, representing a 63 and 66% decrease in applied sulfur in those seasons. For ISS-high total applied sulfur in 2019 and 2020 was 31.5 and 41.6 kg/ha, respectively, representing 45 and 46% less total applied sulfur than the standard mode treatment.

Discussion

The ISS-low (62.5 ml/m^3) spray mode resulted in acceptable GPM control with systemic fungicide rotations but did not result in acceptable control when the MD micronized sulfur was used. When MD was applied with the ISS, equivalent GPM control to a standard air blast sprayer was achieved when the spray rate was

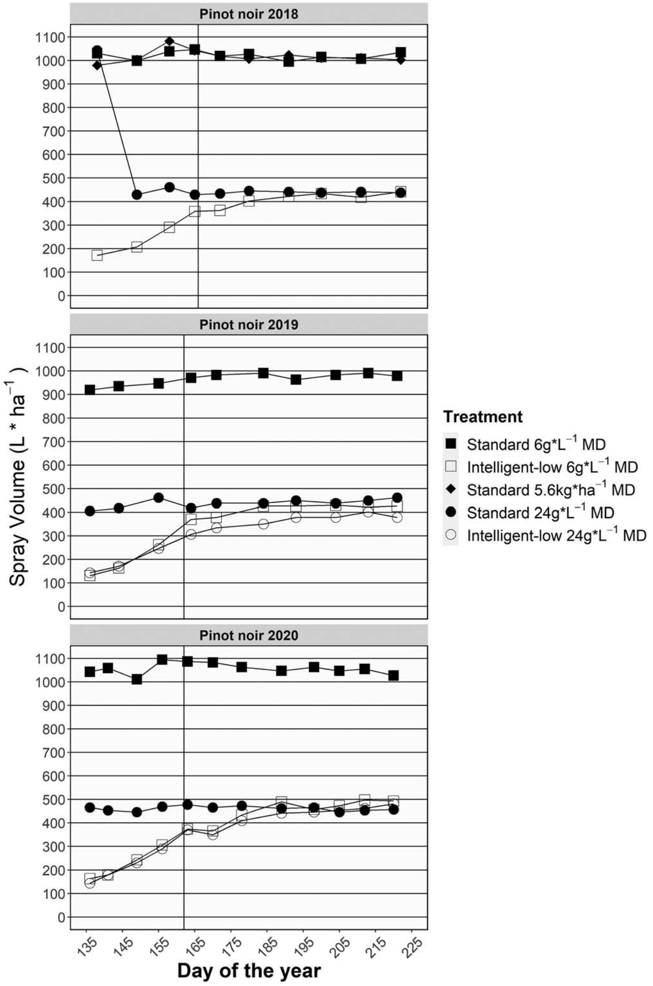

Fig. 1. Applied spray volume (liters/ha) during each application in the Pinot noir trials from 2018 to 2020. Vertical lines indicate the date of 50% cap fall (Biologische Bundesanstalt, Bundessortenamt and Chemical Industry 65).

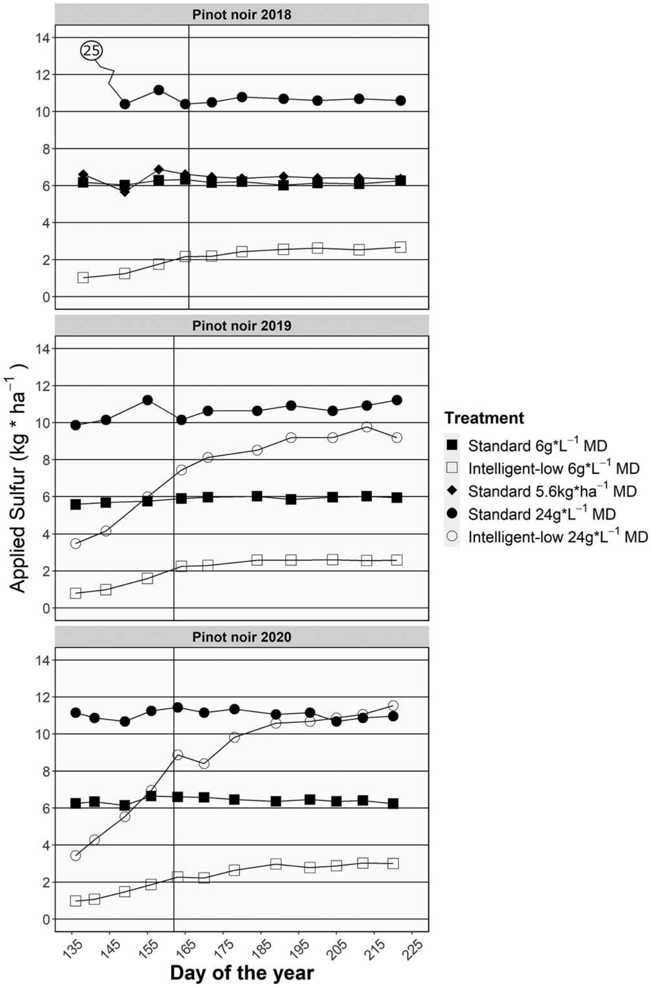

Fig. 2. Formulated 80% micronized sulfur (Microthiol Disperss, kg/ha) applied during each application in the Pinot noir trials from 2018 to 2020. Vertical lines indicate the date of 50% cap fall (Biologische Bundesanstalt, Bundessortenamt and Chemical Industry 65).

high (125 ml/m^3) or when the MD was mixed at a higher concentration (24 g/liter).

A lower quantity of MD was applied per unit area at the default (62.5 ml/m^3) ISS-low spray rate, which explains, in part, the lower GPM efficacy. Mixing an industry standard rate of MD (6 g/liter) and applying it with ISS-low mode resulted in per area application rate that remained lower than the lowest label recommendation of 3.4 kg/ha for the entire season (Figs. 2 and 4). However, the same concentration of MD (6 g/liter) when used in standard mode resulted in almost 6 kg/ha across years for the entire season and acceptable GPM control. When the concentration of MD was increased to 24 g/liter in ISS-low mode or when the spray rate in the ISS user controls was increased to apply more volume per unit canopy (ISS-high mode), these changes resulted in better control of GPM on leaves and clusters. The amount of formulated MD applied per area in each of those cases was at or above the minimum recommended rate all season or from bloom through the rest of the season, respectively (Figs. 2 and 4).

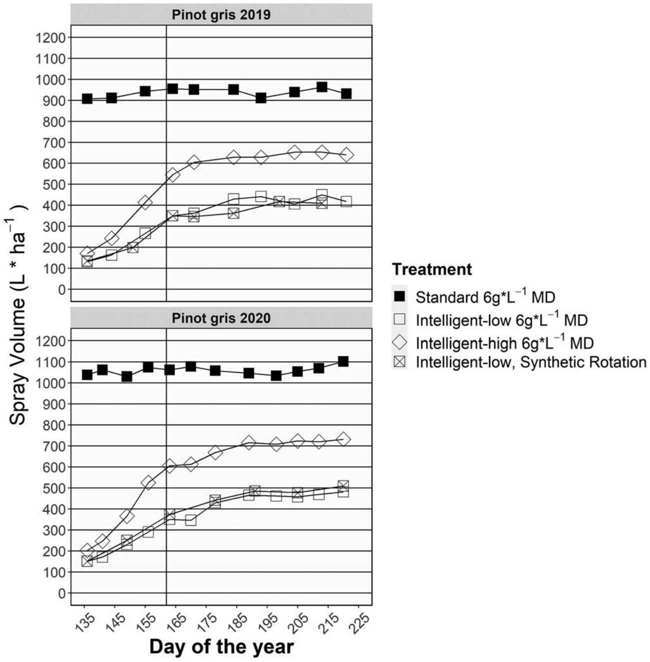

Fig. 3. Applied spray volume (liters/ha) of spray mixture applied during each application in the Pinot gris trials from 2019 to 2020. Vertical lines indicate the date of 50% cap fall (Biologische Bundesanstalt, Bundessortenamt and Chemical Industry 65).

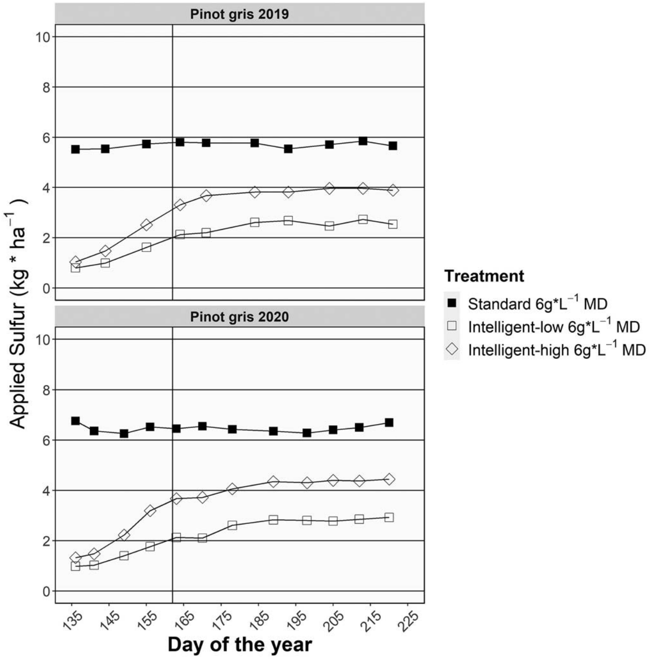

Fig. 4. Formulated 80% micronized sulfur (Microthiol Disperss, kg/ha) applied during each application in the Pinot gris trials from 2019 to 2020. Vertical lines indicate the date of 50% cap fall (Biologische Bundesanstalt, Bundessortenamt and Chemical Industry 65).

Less spray coverage occurred on the inside of the canopy when the ISS-low setting was used, which can also explain, in part, the lower GPM efficacy. In 2018, coverage of cluster zone cards facing outwards was not significantly different between the sprayer settings tested; however, inner-facing cards in the cluster zone sprayed with ISS-low at 0.85 m/s had significantly lower coverage than cards in 0.85 m/s standard mode plots. This indicates that the lower volume of spray used in ISS-low mode probably resulted in lower coverage of leaves and clusters. Nonventuri nozzles using PWM valves do not have markedly different droplet size spectra than when the same nozzles are used without PWM at ≥40% duty cycles; therefore, differences in droplet spectra between standard mode and ISS mode treatments probably did not markedly contribute to differences in coverage or deposit density (Butts et al. 2019). Nonsystemic contact action fungicides such as sulfur work best when target plant structures are well covered (Williams and Cooper 2004; Wise et al. 2010). The coverage of cards in standard mode at the higher speed (2.0 m/s) was also significantly lower than the coverage of cards in standard mode at 0.85 m/s, but cluster severity and leaf AUDPCs were similar between sulfur treatments applied with those settings. The higher rate of MD per area in that treatment probably explains, in part, the similar control of GPM to the 6 g/liter treatment applied in standard mode.

The uniformity of spray distribution, as measured by deposit density, is also important in the efficacy of pesticide applications. In contrast to the spray coverage data, the deposit density of the ISS-low treatment was significantly higher than the 0.85 m/s standard mode treatment on the inner-facing cards. There is a reciprocal relationship between percentage coverage and deposit density whereby as percentage coverage increases, spray deposits start to overlap, leading to a decrease in deposit density. The data from the coverage trial in this study did not indicate that higher values of deposit density were advantageous when sulfur was applied. However, when systemic fungicides were applied with those same settings, efficacious control of powdery mildew was achieved. The ability of systemic fungicides to absorb into plant tissues and redistribute, providing even protection of the tissues, probably compensated for the lower coverage but more evenly dispersed droplets on leaf and cluster surfaces (Klittich 2014). Although higher spray application volumes can improve pesticide coverage and thus efficacy, there is a tipping point where excess spray will run off plants or blow through canopies, resulting in waste (Wise et al. 2010). The most efficacious balance between coverage and droplet density is different for every pesticide product and has been little studied.

There currently are no standardized metrics that relate the combination of coverage and deposit density to pest or disease control. Some agriculturists have suggested that thresholds such as 10 to 15% coverage in combination with 85 or more deposits/cm^2 are good for control, whereas Syngenta AG has suggested 20 to 30 droplets/cm^2 for insecticides and 50 to 70 droplets/cm^2 for fungicides (Deveau 2016; Salcedo et al. 2020). Some fungicides, such as micronized sulfur, rely on contact activity with the target pathogen, where they will be efficacious only when in contact or in very close proximity to the target organism. The coverage trial in combination with the disease data indicates that the main factor leading to higher disease levels in ISS-low plots in 2018 could have been a low application rate of active ingredient applied with the ISS because of the low volumes applied with ISS-low. Spray volume has been shown to be more important in the efficacy of nonsystemic protectant fungicides than systemic fungicides (Wise et al. 2010). In that study, Ziram (a contact fungicide) was applied at the same rate per unit area in two different volumes of spray. When the higher volume was applied, significantly better control of phomopsis cane and leaf spot (*Phomopsis viticola*) and GPM was achieved than the lower application volume (Wise et al. 2010). However, when a systemic fungicide was applied at the two different volumes, there was no significant difference in control of phomopsis cane and leaf spot, grape downy mildew (*Plasmopara viticola*), or GPM (Wise et al. 2010). The disparity in efficacy between the fungicidal products as the spray application volume changed was probably caused by their mode of action and redistribution properties.

Our results suggest that an increase in the efficacy against GPM as the amount of sulfur per area increased is probably caused by the mode of action of sulfur. Sulfur is most active at inhibiting the growth of GPM when it is in close contact with the fungus or fungal spores, slowing growth and inhibiting conidia germination (Williams and Cooper 2004). Sulfur also inhibits fungal growth as it vaporizes on plant surfaces, improving GPM control in a localized area around sulfur deposits (Warneke et al. 2020). The lower quantity of sulfur applied per area at 6 g/liter in the ISS-low mode may have resulted in too little sulfur deposition to reliably inhibit GPM conidia from infecting leaf and cluster tissues. In addition, the deposited sulfur may have been too little to augment GPM control with sulfur vaporization.

The synthetic fungicide rotation probably was mixed at a concentration high enough to compensate for the lower application volume of the ISS, whereas the micronized sulfur concentration was probably too low when applied with the same settings. The 6 g/liter sulfur treatment was mixed so that it was applied at about 6 kg/ha in standard mode, which is near the middle of the rate range of 3.4 to 11.2 kg/ha, as listed on the MD label. This result is in contrast to the synthetic fungicide rotation in the Pinot gris trials in this study, where two products were applied simultaneously and were mixed at the highest rate per area on the label. Pesticides rates are formulated to be high enough to kill the most tolerant pest or disease on the label, and therefore the recommended rates are often higher than needed for other species on the label (Duke 2017). However, <0.1% of applied pesticides are estimated to reach their target organism (Pimentel 1995). When the sprayer was used in ISS-low mode, an inadequate dose of sulfur was applied to the vines, leading to the poor disease control that was observed in this study. Growers starting to use variable rate technology should calibrate the technology to get a rough estimate of the volumes that will be applied at different times of the year to mix pesticides at concentrations that will result in appropriate doses on their crops.

The difficulty in deciding on a rate of pesticide to mix when using a variable rate sprayer such as the ISS lies in the need to reconcile the stated per area rate on the pesticide label with the variable amount of spray volume applied on a given date or plant phenological stage. The ISS is effective at applying a specified amount of spray volume to a plant canopy, reducing drift and off-target waste; however, it assumes that the concentration of pesticide in the tank is enough to get efficacious disease or pest control (Chen et al. 2013). This study has shown that when a fungicide is mixed at a rate that would be commonly used in conventional spraying equipment, acceptable control of GPM cannot always be expected. Most literature that has been published on controlling plant pests and diseases by using ISS technology has shown that the ISS systems achieve similar or better control of insects and plant diseases to that of standard sprayers (Boatwright et al. 2020; Chen et al. 2019, 2020). Studies using ISS technology have examined its use primarily with conventional pesticide programs that consist of a large proportion of synthetic pesticides.

As variable rate technologies such as the ISS become more widespread in the market, it will become more prudent for chemical manufacturers to consider adding alternative dosing models such as concentration based rates or unit canopy rates to facilitate pesticide use in variable rate spraying equipment. This will help producers avoid control failures due to the currently largely inadequate rate statements on labels. Although the majority of specialty crop growers use conventional pesticide programs, increasing market demand for sustainably produced products continues to drive use of natural or biological pesticide products. For example, today the biopesticide market is about 5% of the total crop protection market (about $3 billion), but it is forecasted to grow to >7% of the market (about $4.5 billion) by 2023 (Olson 2015). Growers using organic or contact pesticide-heavy spray programs will probably need to mix higher concentrations or set their sprayer to apply larger volumes per canopy area to compensate for the lower volumes of pesticide applied per unit area with the ISS. Despite these complications of using variable rate technology such as the ISS, the benefits, including lower water requirements of the ISS for pesticide mixing and higher pesticide use efficiency of using these technologies, may outweigh the other issues.

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