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Coverage of hazelnut shoot tips using an Intelligent sprayer, 2019.

Hazelnut shoot tips are the site of infection of *Anisogramma anomola* (Eastern Filbert Blight (EFB)), which infects meristematic tissue in spring when rains and warm temperatures release ascospores from cankers. To manage this disease 4 fungicide sprays are applied to susceptible cultivars beginning at bud break and continuing for 8 weeks. It is also suggested to apply fungicides for the first year after planting resistant trees. At field demonstrations in 2018 hazelnut growers reported using speeds up to 10mph during applications in order to complete their sprays in windows of good weather on large acreage farms. Use of standard sprayers in young (<7 years old) hazelnut orchards leads to overspray and off target drift due to large gaps between trees. The Intelligent Spray System (ISS) uses a Lidar sensor, Doppler ground speed sensor, embedded computer, and individual pulse width modulation valves at each nozzle to release spray only when a target is sensed, which can lead to significant savings in a hazelnut orchard system. The goal of this study was to evaluate the ability of the ISS to cover shoot tips at different speeds.

The spray coverage trial was conducted on 25 April 2019 in an orchard of 5 year old Jefferson hazelnut trees located at the Botany and Plant Pathology Field Lab in Corvallis, OR. Plots consisted of single trees separated from adjacent plots by at least one non-treated tree. The sprayer used (50 gallon Pak-blast, Rears Mfg., Coburg, OR) was a standard "off-the-shelf" sprayer retrofitted with the components of the ISS. The sprayer was operated using a Kubota M5N-111 tractor, and Surround WP (Kaolin clay) was mixed in the spray tank at the rate of 0.5# Surround/1 gallon water.

Table 1. Sprayer settings used in the hazelnut coverage trial, and observed volumes per acre from the trial.

Tractor Speed (mph)	Nozzle Set	Sprayer Mode[xy]	Mean Spray rates from trial (GPA)[z]
1.9	TeeJet D5, DC46-HSS	Standard	112 (±4)
		Automated	42 (±6)
3.2	TeeJet D10, DC45-HSS	Standard	97 (±3)
		Automated	50 (±0.6)
4.7	Teejet D10, DC46-HSS	Standard	116 (±3)
		Automated	63 (±5)

[x]All standard treatments were calibrated to apply 100gal/A at tractor PTO rated speed.
[y]Treatments in automated mode applied at a spray volume setting of 0.06fl oz/ft^3 of canopy.
[z]Rates calculated from an assumed spray area of 300ft^2 per replicate, actual sprayed areas varied in size, means followed by standard error in parentheses.

On each tree two water sensitive cards were placed midway and near the center of the canopy, one facing due east, and one facing due west. Shoots were sampled from three areas of the sprayed trees, the leading edge, mid-canopy, and lagging edge. The leading edge of the canopy was where the sprayer first passed as it travelled down the row, the mid-canopy was roughly in line with the trunk when looking perpendicular to the hazelnut row, and the lagging edge was where the sprayer last passed the tree as it travelled down the row. Shoot tips were sampled by clipping several small lateral branches 5 ft off the ground that contained at least three buds total at a similar growth stage from within the aforementioned zones. Sampled branches and shoots were placed into plastic bags then into Styrofoam coolers, and finally a refrigerator.

Once in the lab three shoot tips of similar growth stage per sampling zone (three leaves unfolded) were removed from the small branches using forceps. Excised shoot tips were placed in a custom light box designed for taking photos of plant samples, and photographed under four (4)-43W white light bulbs using a Canon Powershot A2500. Both the top and bottom of each shoot tip was photographed with a background of white paperboard using auto white balance and an ISO of 100. Images were subsequently analyzed for percent coverage and other spray parameters using a custom, automated macro in ImageJ.

Spray coverage data was divided into three separate analyses. Coverage on the tops (adaxial) of shoots was analyzed using a generalized linear model with a binomial distribution, to account for the bounded percentage nature of the data. Spray coverage on the bottoms (abaxial) of shoots could not be analyzed using a generalized linear model because the data all contained small values that when rounded to integers for the binomial analysis, depleted all of the variation in the data. A linear model was used to analyze the percent coverage on the bottoms of shoots. A final analysis on the shoot tip spray coverage data was done where the total coverage (top + bottom coverage) was analyzed using a generalized linear model with a binomial distribution. Water sensitive cards were analyzed to examine the effect of sprayer speed, sprayer setting, and card orientation on both the percent coverage on cards, and the DV 0.5 values. To examine spray coverage on water sensitive cards a generalized linear model with a quasibionmial distribution was fit to the percent coverage data, due to overdispersion. To examine DV 0.5 values, due to heteroscedasticity, the values were natural log transformed then a linear model was fit to the data. Contrasts were conducted using least squared means (marginal means) using the emmeans package, all data was analyzed in R version 3.5.1.

Table 2. Percent coverage on hazelnut shoot tips from each sampling location.

Sampling Location	Tractor Speed (mph)	Sprayer Setting[xy]	Percent coverage Shoot Top[z]	Percent Coverage Shoot Bottom[z]
Leading Edge	1.9	Automated	6.6 (5.1-8.4) A	1.2 (0.9-1.5) A
		Standard	11.7 (9.3-14.6) B	1.5 (1.2-1.7) B
	3.2	Automated	3.5 (2.5-4.9) A	0.9 (0.7-1.5) A
		Standard	6.5 (4.7-8.7) B	1.2 (0.9-1.5) B
	4.7	Automated	4.2 (3.1-5.7) A	1.0 (0.8-1.3) A
		Standard	7.6 (5.7-10.0) B	1.3 (1.0-1.6) B
Mid-canopy	1.9	Automated	5.2 (3.9-6.8) A	0.9 (0.6-1.2) A
		Standard	9.3 (7.2-12.0) B	1.2 (0.9-1.4) B
	3.2	Automated	2.5 (1.7-3.7) A	0.7 (0.4-0.9) A
		Standard	4.7 (3.3-6.7) B	0.9 (0.6-1.2) B
	4.7	Automated	4.3 (3.1-5.8) A	0.8 (0.5-1.0) A
		Standard	7.7 (5.8-10.2) B	1.0 (0.7-1.3) B
Lagging Edge	1.9	Automated	4.4 (3.2-5.9) A	1.4 (1.1-1.6) A
		Standard	7.9 (6.0-10.4) B	1.6 (1.3-1.9) B
	3.2	Automated	4.1 (3.0-5.6) A	1.1 (0.8-1.4) A
		Standard	7.4 (5.6-9.8) B	1.4 (1.1-1.6) B
	4.7	Automated	5.8 (4.4-7.6) A	1.2 (0.9-1.5) A
		Standard	10.4 (8.2-13.2) B	1.4 (1.2-1.7) B

[x]All treatments were applied at 100gal/A at tractor PTO rated speed.
[y]Treatments in automated mode applied at a spray volume setting of 0.06fl oz/ft^3 of canopy.
[z]Means followed by 95% confidence intervals in parentheses, means within columns followed by different letters are significantly different at $p<0.05$.

Coverage on both tops and bottoms of shoot tips at all sampling locations and tractor speeds was significantly lower when the spray was applied in automated mode compared to standard mode (Table 2). On the tops of shoot tips there were no significant differences in coverage among sampling locations within sprayer settings and speeds (Supplementary Table 1). On the bottom of shoot tips, coverage on tips sampled from the lagging edge of the canopy had significantly higher coverage than the mid-canopy shoots, while the leading edge shoots had coverage that was not significantly different from either other location in all sprayer setting and speed combinations (Supplementary Table 1). Coverage values were also averaged across sampling locations and compared to each other (Table 3). On both tops and bottoms of shoots when all settings and speeds were compared to each other, the standard sprayer mode applied at 1.9mph resulted in the highest coverage, while automated mode at 3.2mph resulted in the lowest coverage (Table 3). On the tops of shoots, the 1.9mph, 4.7mph, and 3.2mph treatments applied in standard mode respectively had the highest coverage levels, while the 1.9mph treatment applied in automated mode was not significantly different from the 3.2mph standard treatment (Table 3). On the bottoms of shoot tips the treatment applied in standard mode at 1.9mph had significantly higher coverage than the treatment applied in automated mode at 3.2mph, while all other treatments were not significantly different from either of those treatments (Table 3).

Coverage was not significantly different among all sprayer setting and speed groups on water sensitive cards when automated mode was compared to standard mode (Table 4). However, within 1.9mph and 3.2mph standard and 1.9mph automated sprayer mode and

Table 3. Percent coverage on hazelnut shoot tips when averaged over sampling location.

Tractor Speed	Sprayer Setting[xy]	Percent Coverage Shoot Tops[z]	Percent Coverage Shoot Bottoms[z]
1.9	Automated	5.3 (4.4-6.4) C	1.2 (0.9-1.4) AB
	Standard	9.5 (8.1-11.1) A	1.4 (1.2-1.6) A
3.2	Automated	3.3 (2.7-4.1) D	0.9 (0.7-1.1) B
	Standard	6.1 (5.0-7.4) BC	1.2 (0.9-1.4) AB
4.7	Automated	4.7 (3.9-5.7) DC	1.0 (0.8-1.2) AB
	Standard	8.5 (7.2-10.0) AB	1.3 (1.0-1.5) AB

[x]All treatments were applied at 100gal/A at tractor PTO rated speed.
[y]Treatments in automated mode applied at a spray volume setting of 0.06fl oz/ft^3 of canopy.
[z]Means followed by 95% confidence intervals in parentheses, means within columns followed by different letters are significantly different at $p<0.05$.

Table 4. Percent coverage on water sensitive cards in the hazelnut shoot tip trial.

Card Facing Direction	Tractor Speed (mph)	Sprayer Setting[xy]	Percent coverage[z]	Sprayer Setting[xy]	Tractor Speed (mph)	Card Direction	Percent coverage[z]
East	1.9	automated	35 (22-50)	Standard	1.9	East	46 (32-61)
		standard	46 (32-61)			West	21 (11-36) *
	3.2	automated	14 (6-27)		3.2	East	28 (17-44)
		standard	28 (17-44)			West	7 (2-19) *
	4.7	automated	18 (9-32)		4.7	East	22 (12-37)
		standard	22 (12-37)			West	9 (3-22)
West	1.9	automated	15 (7-29)	Automated	1.9	East	35 (22-50)
		standard	21 (11-36)			West	15 (7-29) *
	3.2	automated	3 (0.3-15)		3.2	East	14 (6-27)
		standard	7 (2-19)			West	3 (0.3-15)
	4.7	automated	3 (1-15)		4.7	East	18 (9-32)
		standard	9 (3-22)			West	3 (1-15)

[x]All treatments were applied at 100gal/A at tractor PTO rated speed.
[y]Treatments in automated mode applied at a spray volume setting of 0.06fl oz/ft^3 of canopy.
[z]Means followed by 95% confidence intervals in parentheses, asterisk indicates significantly lower coverage at $p<0.05$.

Table 5. DV 0.5 values for the water sensitive cards from the hazelnut shoot tip trial.

Tractor Speed (mph)	Sprayer Setting[wx]	DV 0.5 (µm)[yz]
1.9	automated	1871 (1358-2850)
	standard	2573 (1867-3547)
3.2	automated	572 (415-788)
	standard	786 (570-1083)
4.7	automated	795 (577-1096)
	standard	1093 (793-1507)

[w]All treatments were applied at 100gal/A at tractor PTO rated speed.
[x]Treatments in automated mode applied at a spray volume setting of 0.06fl oz/ft^3 of canopy.
[y]Values averaged over the card facing direction.
[z]Means followed by 95% confidence intervals in parentheses, asterisk indicates significantly lower coverage at $p<0.05$.

Table 6. Median droplet diameter on water sensitive cards.

Tractor Speed	Sprayer Setting[xy]	DV 0.5 (µm)[z]
1.9	Automated	1872 (1358-2580) AB
	Standard	2573 (1867-3547) A
3.2	Automated	572 (415-788) C
	Standard	786 (570-1083) C
4.7	Automated	795 (577-1096) C
	Standard	1093 (793-1507) BC

[x]All treatments were applied at 100gal/A at tractor PTO rated speed.
[y]Treatments in automated mode applied at a spray volume setting of 0.06fl oz/ft^3 of canopy.
[z]Means followed by 95% confidence intervals in parentheses, means followed by different letters are significantly different at $p<0.05$.

speed groups there was significantly lower coverage on cards facing the west side of the row, as compared to those facing east (Table 4). There was no significant difference between automated and standard mode groups when the median drop size (DV 0.5) was compared among sprayer settings within speed groups (Table 5). The cards in the 1.9mph group had significantly larger DV 0.5s than all other settings except for 4.7mph standard which was not significantly different than 1.9mph automated (Table 6).

When spray was applied in automated mode it resulted in significantly lower coverage on tops and bottoms of hazelnut shoots than when compared to spray applied in standard mode among all speeds. However, for both automated and standard modes, on both tops and bottoms of shoots, poor coverage was observed. Based on grape powdery mildew efficacy trials, over 30% coverage for systemic products and over 50% coverage for contact products would be considered good coverage (which depends on more than just percentage of covered tissue such as number of spray deposits per unit area). One explanation is that using the sprayer in automated mode at a spray rate of 0.06fl oz/ft^3 did not result in enough volume for sufficient coverage on hazelnut shoots, however the treatments applied in standard mode were applied at nearly double the volume and still resulted in poor coverage. The treatments applied in standard mode were all calibrated to be applied at the spray rate of 100 gallons/Acre, which is an industry standard rate for trees of that size. The low amount of coverage observed could suggest that either the sprayer fan was underpowered for the given tree size and row spacing, or the spray quality was not of the correct type for the application.

Coverage on water sensitive cards was higher than that of shoots, notably on the cards that were facing eastward. The pairs of water sensitive cards were placed from the east side of the canopy, and in doing so, were more on the east side of the tree, which is likely the reason for the higher coverage observed on those cards. While the observed amounts of coverage on the hazelnut shoots would not be enough to result in sufficient disease control, the coverage on most of the east side of cards was sufficient for disease control. Water sensitive cards were positioned perpendicular with the plane of spray, and unlike shoots, did not require agitation to receive spray. The water sensitive cards in the 1.9mph treatment groups had the highest coverage of all speed groups within the sprayer setting groups. When the sprayer was moving at 1.9mph, the fan had more time to displace the stagnant air between the sprayer and the water sensitive cards with spray-laden air, as compared to the 3.2 or 4.7mph speeds. If the sprayer fan was able to displace a higher volume of air, coverage on water sensitive cards in the 3.2 and 4.7mph groups may have been higher, however the droplet sizes observed on the water sensitive cards illuminate other spray quality issues.

While Teejet does not supply a recommended pressure range for its disc-core nozzles, a general rule of thumb is not to spray below 40 psi to facilitate complete atomization of the spray fluid, and industry air blast spraying pressures routinely exceed 100psi. The DV 0.5s from the nozzle sets were mostly categorized as Ultra Coarse (3.2mph automated was characterized as Extremely Coarse), which is the highest DV 0.5 classification according to ASABE Standard S572.1, the primary pesticide application droplet size standard in the USA. Smaller droplets are known to result in better coverage for a given spray volume in general, and Fine droplets (DV 0.5 of 106 to 235) are recommended for contact acting fungicides, as would be commonly used in hazelnut shoot spraying. If the solenoids could have been operated at higher pressures to where the droplet spectra were within the Fine range, those droplets may have been more effectively transported by the sprayer fan, resulting in better coverage. Based on the spray coverage data from water sensitive cards and shoot tips, in combination with the droplet size data, a larger fan and/or operating the sprayer at higher pressures would have likely improved the spray quality on hazelnut shoots and water sensitive cards.

When examining the DV 0.5 data, the mean DV 0.5s from the 1.9mph group were higher than all other groups. These differences in droplet size are likely due to the different pressures used for the nozzle sets. To standardize the volume sprayed at 100GPA, the D5-DC46 nozzle set from the 1.9mph group were used at 45psi, while the D10-DC45 and D10-DC46 from the 3.2 and 4.7mph groups, respectively, were used at 65psi. These pressures were used in this study because the solenoids used on the ISS are only reliable up to around 100psi, and above this they can become irregular in opening and closing. Using the high volume nozzles in this study, there was a significant pressure drop from when the sprayer nozzles were shut to when they were open (~30-50psi), so the pressures in the study were the highest possible given the restrictions of the solenoids and desired speeds. Future coverage trials should use nozzles that produce fine droplets at lower pressures and possibly driving the tractor closer to the trees being sprayed.

Supplementary Table

Supplementary Table 1. Percent coverage on tops of hazelnut shoot tips.

Tractor Speed (mph)	Sprayer Setting	Sampling Location	Percent coverage Shoot Tops[z]	Percent coverage Shoot Bottoms[z]
1.9	Automated	Leading Edge	6.6 (5.1-8.4) A	1.2 (0.9-1.5) AB
		Mid Canopy	5.2 (3.9-6.8) A	0.9 (0.6-1.2) A
		Lagging Edge	4.3 (3.2-5.9) A	1.4 (1.1-1.6) B
	Standard	Leading Edge	11.7 (9.3-14.6) A	1.5 (1.2-1.7) AB
		Mid Canopy	9.3 (7.2-12.0) A	1.2 (0.9-1.4) A
		Lagging Edge	7.9 (6.0-10.4) A	1.6 (1.3-1.9) B
3.2	Automated	Leading Edge	3.5 (2.5-4.9) A	0.9 (0.7-1.2)AB
		Mid Canopy	2.5 (1.7-3.7) A	0.7 (0.4-0.9) A
		Lagging Edge	4.1 (3.0-5.6) A	1.1 (0.8-1.4) B
	Standard	Leading Edge	6.5 (4.7-8.7) A	1.2 (0.9-1.5) AB
		Mid Canopy	4.7 (3.3-6.7) A	0.9 (0.6-1.2) A
		Lagging Edge	7.4 (5.6-9.8) A	1.4 (1.1-1.6) B
4.7	Automated	Leading Edge	4.2 (3.1-5.7) A	1.0 (0.8-1.3) AB
		Mid Canopy	4.3 (3.1-5.8) A	0.8 (0.5-1.0) A
		Lagging Edge	5.8 (4.4-7.6) A	1.2 (0.9-1.5) B
	Standard	Leading Edge	7.6 (5.7-10.0) A	1.3 (1.0-1.6) AB
		Mid Canopy	7.7 (5.8-10.2) A	1.0 (0.7-1.3) A
		Lagging Edge	10.4 (8.2-13.2) A	1.4 (1.2-1.7) B

[x]All treatments were applied at 100gal/A at tractor PTO rated speed.
[y]Treatments in automated mode applied at a spray volume setting of 0.06fl oz/ft^3 of canopy.
[z]Means followed by 95% confidence intervals in parentheses, means followed by