Variable rate spraying in varied micro-meteorological conditions

L. R. Khot[1], R. Ehsani[2], L. G. Albrigo[2], W. Swen[2], J. C. Neto[3], J. M. Campoy[4], C. Wellington[4]

(1. *Biological Systems Engineering, Washington State University, Pullman, Washington, USA*;
2. *Citrus Research and Education Center, IFAS, University of Florida, Lake Alfred, Florida, USA*;
3. *Embrapa Agriculture Informatics, Campinas, Sao Paulo, Brazil*;
4. *National Robotics Engineering Center, Robotics Institute, Carnegie Mellon University, Pittsburgh, Pennsylvania, USA*)

Abstract: This study evaluated effects of crosswind on the variable rate sprayer application treatments spray coverage and deposition on different citrus canopy sizes. The axial-fan airblast sprayer retrofitted with variable liquid- and air-assist rates was field-tested with different crosswind conditions on small (about 2 m tall and < 1.5 m wide) and medium-sized (about 3 m tall and < 2.5 m wide) canopies. Crosswinds of 1.3, 2.7, and 4.0 ms^{-1} on the canopies being sprayed were generated using the stationary conical air shaker as the air blower unit. Water sensitive papers (WSPs) were used to collect droplet deposits and image processing software was used to analyze the WSPs scanned at 600 dpi. Percent spray coverage on the WSPs was found to be one of the most suited parameters to evaluate the effectiveness of spray application treatments. Overall, the variable rate spray application treatments had comparable spray coverage on respective canopies (front, middle, and across WSP locations in the canopy) during all crosswind conditions. For both types of canopies, spray coverage was higher on the canopy front and decreased as the spray penetrated inside (i.e. canopy middle) and across. Due to coalescing, larger droplets ($D_{v,0.5}$ [volume median diameter] = 838 to 2,624 μm) were formed on the WSPs located on canopy front, whereas coalescing reduced as the spray penetrated inside ($D_{v,0.5}$ = 391 to 1,625 μm on canopy middle) and across the canopy ($D_{v,0.5}$ = 307 to 508 μm).

Keywords: airblast sprayer, adjustable air-assistance, crosswind, spray coverage, citrus

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1 Introduction

For horticultural crops, Variable Rate Application (VRT) of fertilizers and pesticides is one of the best ways to reduce production costs, increase profitability, and have a positive environmental impact. Usually smaller trees require fewer inputs than larger trees; therefore, application rates can vary based on canopy foliage density or variation of tree size within a single row. Variable rate systems used in precision horticulture consist of different sensors, control systems and actuators mounted on an agricultural vehicle for tree-specific spray applications. Large amount of scientific literature is available on this topic. For example, Gil et al. (2007) used three ultrasonic sensors to detect variability in crop width and accordingly, varied the flow rates of the sprayer nozzles in real-time using solenoid electro-valves. Alternatively, Pai et al. (2009) measured citrus foliage density using a laser scanner mounted on the front of an airblast sprayer and used the resulting information to control the air-assistance to the spray droplets via an automated electro-mechanical air deflector plate. Recently, Pérez-Ruiz et al. (2011) used a geospatial prescription map prepared for Spanish olive trees along with Real Time Kinematic-Global Positioning System (RTK-GPS) based sprayer positioning information to control spray application rate. Jeon and Zhu (2012) developed an experimental VRT sprayer for nursery trees

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***Corresponding author: Reza Ehsani,** Citrus Research and Education Center, IFAS, University of Florida, Lake Alfred, Florida, USA. Email: ehsani@ufl.edu, phone: 863-956-8770.

that adjusted spray output in real-time based on ultrasonic sensor scanned canopy sizes.

In an overview of airblast sprayer developments, Fox et al. (2008) highlighted the need for tree size-specific optimization of the spray volume, air-jet velocities, and spray patterns for effective spray applications. Pertinent to airblast sprayers, Pergher and Gubiani (1995) experimented with varied spray and air output rates of a conventional sprayer to investigate resulting spray deposition, ground losses and drift in vineyards. They reported that the high spray and air output rates resulted in the reduced spray deposition, increased ground losses as well as drift as compared to other combinations of spray and air output rates.

With the aim of developing a precision airblast sprayer for use in citrus orchards, researchers at the University of Florida, in collaboration with the Carnegie Mellon University and Cornell University, have retrofitted an axial-fan airblast sprayer to increase spray targeting accuracy and potentially reduce chemical use and ground losses (Khot et al., 2012a). This retrofitted sprayer can adjust the spray output rate using pulse width modulation controlled solenoid valves. An innovative component of this new system is the use of air-diverting louvres to change the amount of air-assistance on the spray mix based on canopy size.

For effectiveness, good agricultural spraying practices require use of sprayers in typical micro-metrological conditions when wind is steady, yet not very calm, in the ranges of 1 to 4 ms^{-1}, with the temperature below 25°C, and relative humidity (RH) greater than 40% (Deveau, 2009). However, in most practical operating conditions, these general guidelines would not be available while operating a VR-based air blast sprayer in varied canopies, especially in citrus orchards of varied stages and orchards with a higher rate of replanted trees (Figure 1). It is well known that the combination of higher sprayer ground speed and increased crosswind primarily reduces airblast spray penetration inside the canopy (Fox et al., 1985). Rapid changes in atmospheric stability conditions could also increase drift of airblast sprayer applications, to about two to six times that of stable conditions (Miller et al., 2000). Thus, the variable liquid- and air-assistance rates need to account such instantaneous micro-metrology, i.e. crosswind and downwind speeds.

Therefore, the key objectives of this study were: 1) to evaluate the effect of crosswind on the spray coverage and deposition on different citrus canopy sizes due to VRT sprayer application treatments, and 2) to investigate the use of water sensitive paper targets along with image processing approach for spray deposit quantification.

Figure 1 a) Two-year young sparse, and b) 10+ years old hedged citrus canopies

2 Materials and methods

Experiments were conducted in orchards managed by the Citrus Research and Education Center (CREC), University of Florida, Lake Alfred, Florida (Lat: 28.1037, Long: 81.7070). The retrofitted sprayer was tested for spray efficiency with small (about 2 m tall and < 1.5 m wide) and medium-sized (about 3 m tall and < 2.5 m wide) citrus canopies.

An axial-fan air blast sprayer (Supersprayer 1000, Durand Wayland, GA), which had been retrofitted for precision spray applications in citrus orchards was used in this study. Figure 2 depicts the experimental setup. A conical citrus mechanical harvesting air shaker was used as the "blower" to generate different crosswind speeds during the spray treatments. The blower unit consisted of a circular axial fan (diameter = 1.37 m) center-lined at a height of about 2.5 m from ground and "a rotatable air outlet assembly" (Coppock and Donhaiser, 1981). In this study, the blower was stationed about 1 6 m away from the test tree centerline with about 1.5 m tall intervening tree in-between (Figure 2) and was operated without rotating the air outlet such that wind was blown on to the test canopy counteracting the spray material released by the sprayer (Figure 2). The blower axial-fan rotations were adjusted to about 600, 1,000, or 1,400 rpm, to have intended wind speeds of 1.3 (3), 2.7 (6), and 4.0 (9) ms^{-1} (mph) on the test tree canopy. For consistent blower speed settings, the throttle of the blower unit was locked during each of the experimental runs and speeds from the dial indicators were monitored.

In the selected orchard, tree lines were south-north and treatments were applied such that the trees on the west side were sprayed during each of the treatments. The sprayer was operated at 4 km h^{-1} for all spray treatments. Note that spray treatments involved single spray passes with water as the spray liquid.

Spray treatments involved testing the VRT sprayer decision rules on 2 m and 3 m tall canopies. The spray decision rules were formulated after the detailed spray patterns evaluation of individual and combination of the variable nozzle flow rates (0% to 100%) from either-side of the sprayer at varied air-assist settings (0% to 100%) (Khot et al., 2012a; Khot et al., 2012b). Formulated rules are summarized in Table 1. The spray decision rules for 1.3 ms^{-1} crosswind were formulated based on the spray pattern evaluation results and were modified for 2.7 and 4.0 ms^{-1} crosswind conditions based on the hypothesis that increased crosswind may need increased air-assistance for spray mix to reach to the target canopies. The crosswind treatments of 1.3, 2.7, and 4.0 ms^{-1} are henceforth referred as 'Low', 'Med', and 'High' wind treatments, respectively.

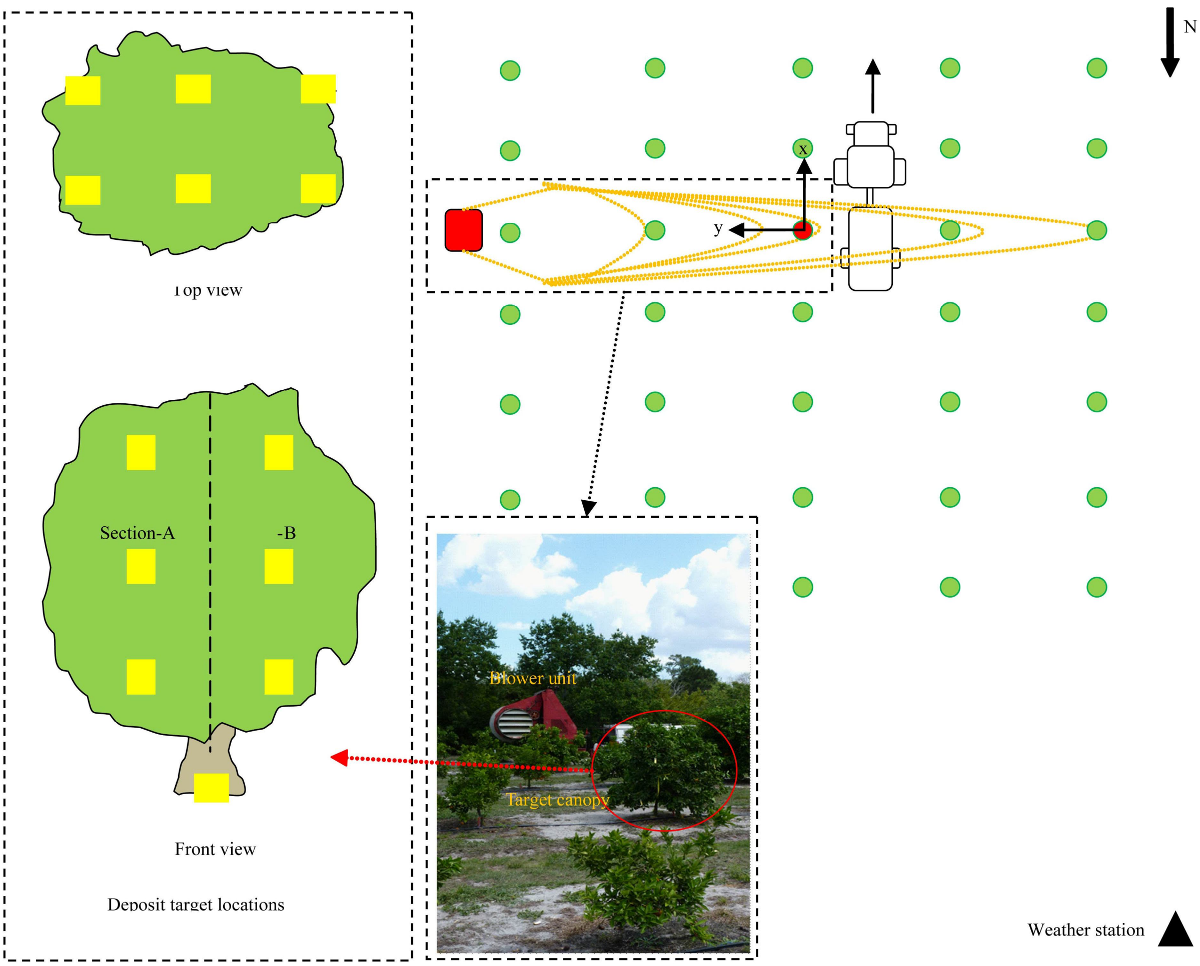


Figure 2 Schematic of the field experiment with inserts of target locations (front and top view of 2 m tall canopies)

Table 1 Variable rate spray decision rules formulated based on detailed spray patterns evaluation of the developed sprayer

Nozzles (flow rate, %)	Air-assist/%		
	Crosswind→ 1.3 ms^{-1} (3 mph)	2.7 ms^{-1} (6 mph)	4.0 ms^{-1} (9 mph)
Tree height- 2 m			
2-4 (100)	70	80	100
Tree height- 3 m			
2-6 (100)	80	90	100

Water sensitive papers (WSPs) (size: 26×76 mm) from TeeJet® Technologies (Spraying Systems Co., Wheaton, IL) were used as artificial targets. The tree canopy was divided into two sections (A and B). For 2 m tall canopies, in the A section, WSPs were placed at three vertical heights of 0.6, 1.2, and 1.8 m (Figure 2) and at three lateral locations, i.e., canopy front, canopy middle, and canopy back (Figure 2). This sequence was repeated for the remaining half of the tree (section B). Additionally, to evaluate spray drift, WSPs were placed on wooden blocks on the ground in adjacent row middles from the test tree at -3, 0, 3, 10, 16 m downwind. Thus, each treatment run involved 23 deposits. In case of 3 m tall canopies, the above procedure was repeated with additional sampling at 2.5 m, i.e., total of 29 deposits for each of the treatment runs.

Experiments involved three wind treatments (‘Low’, ‘Med’, and ‘High’) that were randomized and replicated three times per canopy size. About zero to three minutes before each spray run, the maximum wind speed at each of the spray deposit (WSP) location was recorded using a handheld ultrasonic wind meter (Wind Scribe, Davis Instruments, Hayward, CA). This study doesn’t attempt to compare wind measurement and respective deposition at each of the WSP location; rather wind measurements were to develop overall idea of the amount of crosswind penetration into the 2 m and 3 m tall canopies. Similar to any spray application treatments in field conditions, local wind guest and wind turbulence would affect spay material transportation and deposition.

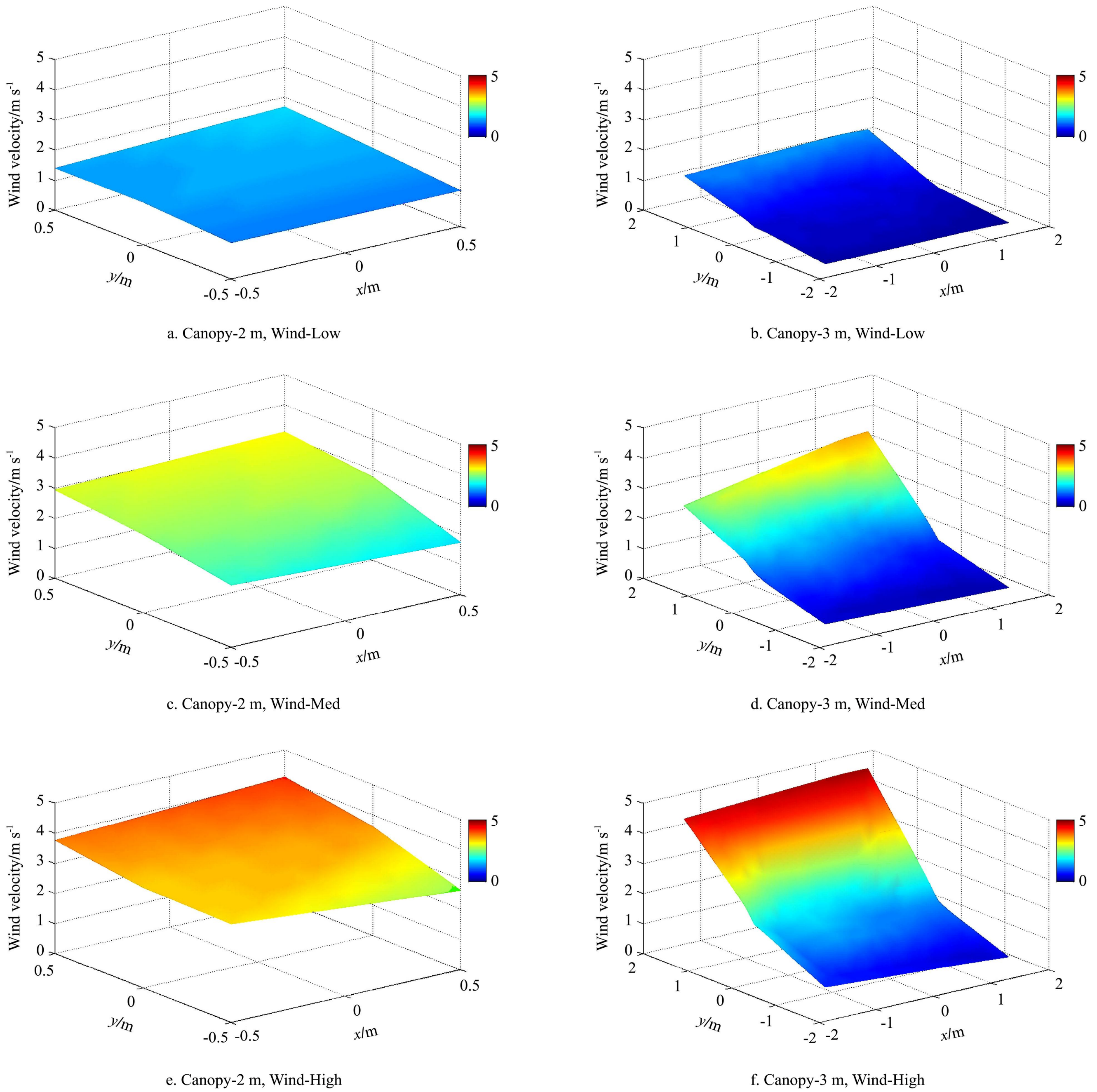
A weather station was also set up in an open field to record wind speed and wind direction at 2 m above ground during the spray applications. A two-axis sonic anemometer was used to record wind parameters at a rate of 4 Hz. During ‘Low’, ‘Med’ and ‘High’ crosswind treatments on 2 m tall canopies, the average wind speed (standard deviation) and direction were 1.7(0.8), 1.9(0.8), 1.8(0.8) m s^{-1} and 140(30), 152(35), 149(30)° from north, respectively. Similarly, for respective treatments on 3 m tall canopies, the average wind speed and direction were 1.5(0.8), 1.7(0.8), 1.5(0.8) ms^{-1} and 220(91), 240(65), 206(49)° from north. Other micro-metrological parameters such as air temperature (2 m above ground), soil temperature, and humidity recorded by Florida Automated Weather Station (FAWN) ranged from 18°C to 30°C, 23°C to 30°C, and 37% to 66% during the period of experiments. The FAWN was about 300 m away from the experiment plots.

After each spray run, each of the WSPs was collected and placed in a resalable plastic bag (size: 7.6×12.7 cm). Afterwards, each WSP was scanned at a resolution of 600 dpi and stored as a bitmap image. These images were processed using a computer program developed by Chaim et al. (2002). For each scanned image, the program outputs the number of droplets, volume median diameter (µm), spray density (droplets cm^{-2}), and coverage (%). These parameters were stored in an Excel file format for further statistical analysis.

Statistical Analysis Software (SAS®) (ver. 9.2, SAS Institute Inc. Cary, NC) was used to perform descriptive as well as ANOVA analysis. Significant effects of various treatment combinations were inferred at the 5% level and the ‘LSMEANS’ option was used to compare least square mean differences.

3 Results and discussion

Figure 3 depicts the crosswind to sprayer travel path (x-direction) on the canopies. The y-direction represents canopy width perpendicular to sprayer travel and $\{x, y = (0, 0)\}$ represents the tree trunk. Maximum wind measurements at 0.6, 1.2, 1.8 m (for 2 m tall canopies), and 2.5 m (for 3 m tall canopies) vertical locations were interpolated to depict the sheet of crosswind onto the test canopies as shown in Figure 3. During 'Low' wind treatment, the average (of three heights and three replication treatments) maximum crosswind entering the 2 m canopy was 1.5±0.6 ms^{-1} (± Std. Dev.) and the average maximum crosswind which penetrated across the canopy was 1.2±0.5 ms^{-1}. Similarly, during 'Med' and 'High' wind treatments, average crosswind of 3.0±0.6 ms^{-1} and 3.9±0.8 ms^{-1} entered the 2 m canopy and penetrated across with speeds of 1.9±0.5 ms^{-1} and 2.9± 0.5 ms^{-1}, respectively. The 2 m tall canopy foliage was not dense, allowing most of the crosswind to penetrate across. However, same was not true for 3 m tall dense canopy and crosswind entering was at a higher rate than the wind penetrated across the canopy. For example, at 'High' wind treatments, the average maximum crosswind at the entrance and across the 3 m tall canopy was 3.8±1.8 ms^{-1} and 0.7±0.6 ms^{-1}, respectively. For the same treatments, the crosswind at the middle of the canopy was 1.5±0.6 ms^{-1}.



a. Canopy-2 m, Wind-Low

b. Canopy-3 m, Wind-Low

c. Canopy-2 m, Wind-Med

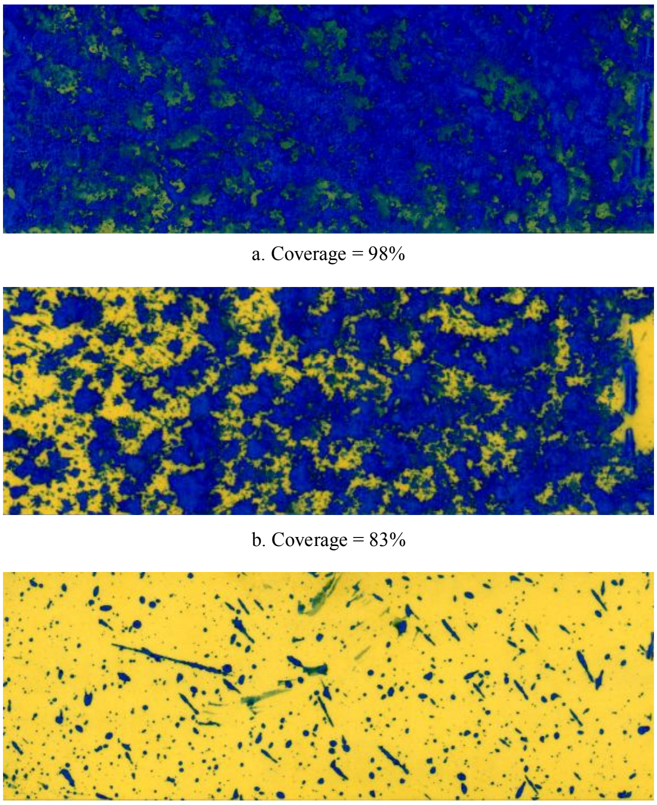
d. Canopy-3 m, Wind-Med

e. Canopy-2 m, Wind-High

f. Canopy-3 m, Wind-High

Figure 3 Wind speed measured on test canopies during various crosswind treatment conditions. Figures (a, c, e) and (b, d, f) represent 'Low', 'Med', and 'High' crosswind treatments on 2 m and 3 m tall canopies, respectively. Tree trunk is (x, y) = (0, 0) with the x-axis as the sprayer travel path, the y-axis as the canopy width perpendicular to sprayer travel, and the z-axis as the canopy height from the ground

During the spray treatments, the wind entered from the back of the canopy and passed through-and-across the foliage leaving from the front of the canopy; hence it was termed as crosswind perpendicular to the sprayer travel path. Figure 4 shows the typical WSPs after a spray run and image analysis based spray coverage results for WSPs located at canopy front, canopy middle and canopy back during one of the spray treatments. The image processing software developed by Chaim et al. (2002) analyzed the WSPs scanned at 600 dpi to detect the droplet stains 48 μm in diameter and higher.



a. Coverage = 98%

b. Coverage = 83%

c. Coverage = 9%

Figure 4 Sample of water sensitive papers with spray deposition on two-meter tall (a) canopy front, (b) canopy middle, and (c) canopy back during 'high' crosswind spray application

Reliability of WSP image processing software depends mainly on the scan resolution and droplet spread factor. Zhu et al. (2011) reported that for 2,400 dpi scanned WSP images; the developed 'DepositScan' software could detect droplet spots up to 17 μm and that the denser overlapped spray deposition limits the droplet recognition ability of such software. Hoffmann and Hewitt (2004) compared three different software programs to analyze the WSP targets and reported that the three software programs provided comparable droplet size results with Pearson's correlation coefficients for $D_{v,0.5}$ droplet size in the ranges of 0.58 to 0.70. They also suggested that the image analysis to estimate the droplet size would not be affected by the spread factor for droplets smaller than 500 μm. Salyani and Fox (1999) assessed that amongst the output parameters from WSPs image analysis, percent area coverage is a more reliable parameter for quantitative analysis and that WSPs would have limited use in evaluating high volume spray applications. Also, Panneton (2002) reported that the percent area coverage estimates using WSP-based imaging analysis may have some estimation errors, up to 3.5% in the reported example study. Thus, the image analysis output data presented in this section was interpreted considering above limitations.

Figure 5 represents the percent spray coverage data averaged for various vertical heights, at canopy front, canopy middle, and canopy back. Similar to previous sprayer evaluation studies (Salyani and Fox, 1999; Chen, 2010; Zaman et al., 2011), large intrinsic variability in the percent spray coverage data was observed in this study. Overall, except for WSPs at canopy front on 3 m tall trees, coverage was not significantly different at 5% level for low, medium and high wind treatments. Trends suggest that the increased air-assistance to the spray droplets might have helped to reduce the adverse effect of crosswinds (1.3 to 4.0 ms^{-1}) on 2 m tall canopies. In the case of 3 m tall canopies, crosswind combined with dense foliage might have governed the spray coverage at most of the canopy front and canopy middle WSP locations.

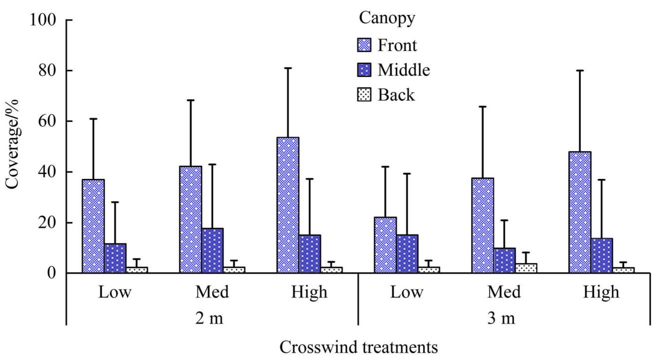


Figure 5 Spray coverage on 2 m and 3 m canopies during increased air-assistance to counter the crosswind conditions. Data for each of the canopy types was analyzed separately

For 2 m tall canopies, spray coverage of the canopy front was comparable for all the crosswind conditions of 1.3, 2.7, and 4.0 ms^{-1}. Overall, average spray material coverage on the canopy front ranged from 37% to 54%, and reduced considerably as it reached the canopy middle (11% to 15%) and substantially across the canopy (< 2%). A similar trend was observed for a 3 m tall and dense canopy where respective average coverage ranged between 22% to 48%, 10% to 15%, and 2% to 4% on canopy front, middle, and back, respectively.

Overall, the spray coverage on the canopy front was higher than at the canopy middle and the canopy back where crosswind was predominantly higher (Figure 3 b, d, f). Table 2 details the spray coverage and droplet characteristics at individual target heights during three crosswind conditions and on both types of canopies. Coalescing of multiple spray droplets per unit area resulted in much larger volume median droplet sizes, ($D_{v,0.5}$) (range: 838 to 2,624 μm) on canopy front; whereas for inside and across the canopy, the decreased spray material penetration resulted in much smaller (range: 307 to 508 μm) and less overlapping of droplets per unit area. In general, as the rate of droplets coalescing increased, denser was the deposition.

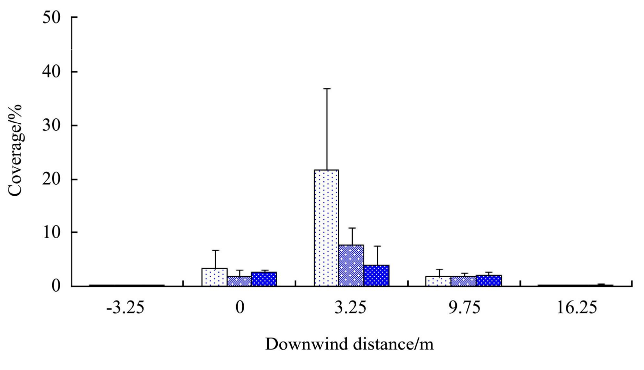
Table 2 Spray coverage and droplet characteristics at varied crosswind conditions within studied canopies

Wind treatment	Target height/m	2 m Tall Canopy*			3 m Tall Canopy*		
		Coverage/%	Droplets/cm^{-2}	$D_{v,0.5}$/μm	Coverage/%	Droplets/cm^{-2}	$D_{v,0.5}$/μm
Canopy front							
Low	0.6	18	34	940	31	286	1736
	1.2	52	122	2464	28	357	1326
	1.8	40	117	1858	15	357	930
	2.5				16	94	838
Med	0.6	31	77	1292	46	117	1770
	1.2	44	130	2039	47	200	1824
	1.8	51	80	1911	37	213	1455
	2.5				21	94	1011
High	0.6	39	86	1757	57	80	2173
	1.2	69	143	2624	55	162	2122
	1.8	52	99	2047	56	147	2041
	2.5				24	124	1001
Canopy middle							
Low	0.6	6	24	710	3	41	456
	1.2	17	26	916	6	36	499
	1.8	11	42	713	43	135	1519
	2.5				9	64	463
Med	0.6	5	39	576	10	90	533
	1.2	35	47	1625	6	90	503
	1.8	13	89	735	18	114	909
	2.5				6	63	391
High	0.6	8	90	673	7	96	541
	1.2	33	120	1461	9	95	677
	1.8	5	73	537	34	121	1272
	2.5				5	100	396
Canopy back							
Low	0.6	2	19	483	2	22	321
	1.2	2	11	409	2	24	423
	1.8	3	33	361	1	21	378
	2.5				4	65	307

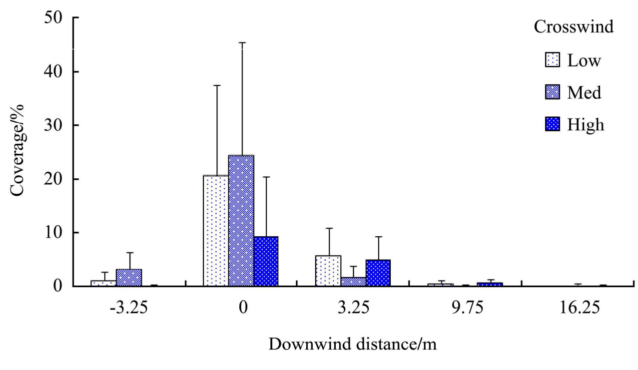
Wind treatment	Target height/m	2 m Tall Canopy*			3 m Tall Canopy*		
		Coverage/%	Droplets/cm^{-2}	$D_{v,0.5}$ /µm	Coverage/%	Droplets/cm^{-2}	$D_{v,0.5}$ /µm
Med	0.6	2	19	442	2	36	320
	1.2	1	25	467	2	33	405
	1.8	4	58	340	5	51	478
	2.5				6	90	315
High	0.6	2	46	444	1	38	349
	1.2	2	40	439	1	30	525
	1.8	3	104	366	2	37	508
	2.5				4	84	406

Note: * represented are averages for coverage, density and droplet size parameters at a given target location. $D_{v,0.5}$ = volume median diameter of droplets deposited on WSP.

Figure 6 shows the percent spray coverage on WSPs, located on the ground, at various downwind locations. The zero-meter downwind distance represented ground deposits beneath the tree (near trunk). As the spray volume was doubled for 3 m tall and dense canopies compared to 2 m canopies, the spray material deposited on the WSPs was also higher, and was highest at a crosswind speed of 2.7 ms^{-1}. Overall, except for the row that was being sprayed, not much of the material drifted to neighboring row-middles, especially when applications were performed in 3 m tall dense canopies. Note that the crosswind was generated primarily on the target tree (i.e., local effect) and had minimal effect on drift. This trend might change in normal metrological conditions with higher winds in the entire orchard. Nonetheless, less spray material might have drifted downwind due to the fact that the spray rate was almost 40% to 70% less compared to conventional airblast spraying in studied canopies. During the spray applications in 2 m tall canopy, droplets drifted at 10 m and 16 m downwind were sized ($D_{v,0.5}$) about 264 and 181 µm, respectively. Similarly, for applications at the 3 m tall canopy, droplets drifted at above respective downwind locations were 247 µm and 213 µm diameter ($D_{v,0.5}$). Some of these droplets might also have coalesced on WSP targets. Overall, droplets with $D_{v,0.5}$<200 µm might drift downwind (16 m or farther) in studied canopies with set spray decision rules.



a. 2 m tall canopy



b. 3 m tall canopy

Figure 6 Downwind spray drift on ground deposits during spray treatments on 2 m and 3 m tall canopies

4 Conclusions

1) Amongst the various output parameters from the analyzed WSP deposits, percent spray coverage was more suited parameter to evaluate the effects of spray application treatments.

2) Overall, the spray coverage with variable rate sprayer application treatments was comparable, significantly not different at 5% level, for all crosswind conditions on 2- and 3 m tall canopies. Spray coverage was higher on the canopy front and was decreased as spray mix entered the canopies. Due to coalescing,

larger droplets ($D_{v,0.5}$ = 838 to 2624 μm) were formed on the canopy front, whereas coalescing reduced as the droplets penetrated inside the canopy with $D_{v,0.5}$ ranging between 391 to 1,625 μm on canopy middle and 307 μm to 508 μm on canopy back deposits.

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