Assessment of spray distribution with water-sensitive paper

Masoud Salyani[1*], Heping Zhu[2], Roy D. Sweeb[1], Naresh Pai[1]

(1. *University of Florida, CREC, Lake Alfred, FL 33850, USA*; 2. *USDA-ARS, ATRU, Wooster, OH 44691, USA*)

Abstract: The purpose of this article is to highlight the limitations of water-sensitive paper in characterizing spray droplet distribution and deposition in field application. Spatial distributions of spray droplets discharged from an airblast sprayer were sampled on pairs of absorbent paper (AP) and water-sensitive paper (WSP) targets at several distances from the sprayer. Spray solutions, containing a fluorescent tracer, were discharged from two nozzle sizes to achieve low and high volume rates commonly used in citrus applications. Spray deposits on AP targets were measured by fluorometry and spray coverage areas on WSP cards were assessed by three independent image analysis systems. Generally, there were good correlations (R^2 = 0.9085 to 0.9748) among the three imaging systems in measuring WSP percent area coverage. Lower volume rate (smaller droplets) provided more useful WSP targets than higher volume rate (larger droplets). Overall, there were somewhat weak correlations between WSP area coverage and AP spray deposition measurements. Volume median diameter and number of droplet stains on WSP cards, obtained by only two imaging systems, showed noticeable differences between the measurements of the two systems.

Keywords: WSP, image analysis, spray volume rate, spray coverage, spray droplet size

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1 Introduction

Spatial distribution of spray droplets, discharged from orchard sprayers, signifies the potential of sprayers for on-canopy deposition and drift. Normally, the orientations of air deflectors and nozzles on sprayers are adjusted so that spray discharge is confined to the height and depth of tree canopy (Gracia et al., 1996). Such adjustments could increase on-canopy deposition while minimizing spray drift (Salyani et al., 2007). Assessment of spray distribution usually involves the use of a quantitative method for determining spray deposition and/or drift. Generally, the choice of a particular method depends on the availability of capital and human resources, biological and physical characteristics of the target crop, and expected accuracy for evaluation of the test variables. Literature review of spray sampling methods reveals that none of the existing techniques is suitable for all application scenarios; therefore, the problems and limitations associated with each technique must be well understood before choosing an appropriate method for a particular application. In general, quantitative methods involving colorimetry (Hoffmann and Salyani, 1996), fluorometry (Pergher and Gubiani, 1995), spectrometry (Derksen and Gray, 1995), etc. are more accurate but they are costly and time consuming; therefore, a fast and inexpensive technique could offer a useful alternative for spray deposition assessment.

Water-sensitive paper (WSP) card has been on the market for about 30 years (Ciba-Geigy Ltd., 1985). The cards have been used by spray researchers, farmers, and others to visualize and/or quantify spray distribution and/or deposition from ground and aerial applications. Any aqueous spray droplet can leave a blue stain (speck or spot) on the yellow surface of WSP under appropriate laboratory or field conditions. The stained cards can be assessed visually (Hall et al., 1987; Theriault et al., 2001; Nuyttens et al., 2004; Khot et al., 2011a), by a

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*** Corresponding author: Masoud Salyani,** University of Florida, CREC, Lake Alfred, FL 33850, USA. Email: msi@ufl.edu.

colorimetric method (Giles et al., 1989), or an image analysis system (Salyani et al., 1987; Fox et al., 2001; Panneton, 2002; Hoffmann and Hewitt, 2005; Zhu et al., 2011b; Cunha et al., 2012).

In laboratory studies, WSP cards have been used to calibrate the droplet density for insecticide application onto leaf targets (Hall et al., 1987), investigate the deposition efficiency of different droplet sizes (Salyani et al., 1987), compare the drift potential of spray tips in a wind tunnel (Wolf, 2003), study spray deposition characteristics of conventional and air-induction nozzles (Guler et al., 2007), or visualize the droplet distribution on the targets prepared for evaluating fluorescent dye degradation (Khot et al., 2011b). In the field settings, the cards have been used to compare spray coverage quality among various sprayers, nozzles, or operating variables in several crops including: citrus (Salyani and Fox, 1999), apples (Holownicki, et al., 2002), soybeans (Zhu et at., 2008), greenhouse plants (Derksen et al., 2010), and wheat (Ozkan et al., 2012). WSP has also been used to determine optimal spray volume for conventional nursery sprayers (Zhu et al., 2011a), evaluate spray deposition consistency inside ornamental nursery canopies for variable-rate sprayer development (Jeon et al., 2011), adjust sprayer output for optimal control of pests (Zhu et al., 2011c), or monitor spray distribution patterns of aerial applications (Fritz et al., 2006).

In evaluating spray coverage with WSP targets, Theriault et al. (2001) and Fox et al. (2003) compared visual rating with image analysis of the stained cards. Both reported a 4^{th} order relationship between the two methods which indicated the limitation of the image analysis in reading densely stained targets. Panneton (2002) developed a field portable image analysis system to overcome the problem of changing WSP background color due to varying droplet density. Hoffmann and Hewitt (2005) compared three image analysis systems using WSP for droplet sizing. They found high correlations between the three systems for the droplet size spectra parameters but slight to no correlations for the droplet relative span. Similarly, Cunha et al. (2012) compared several image analysis systems in assessing spray coverage, droplet density, and droplet size spectrum. Among all the measured parameters, spray coverage and droplet density were the most and least consistent measurements, respectively.

The aforementioned reports and others have shown that the use of WSP involves several practical limitations. Generally, WSP needs special image analysis system with trained operator and a spread factor to convert spot size to droplet size. Furthermore, yellow coating can turn blue/green in high humidity environment, and small droplets cannot make detectable stains on coating.

The main objective of this study was to explore the usefulness of water-sensitive paper in characterizing spray droplet distribution and quantitative assessment of spray deposition in field applications. Specific objectives were to: a) verify the effect of volume rate (nozzle size/capacity) on the droplet spectra parameters, b) compare WSP area coverage, droplet volume median diameter (VMD), and number of droplets obtained by different image analysis systems, c) study the effect of spray droplet spectrum on the WSP percent area coverage, and d) establish the relationship between droplet spot area coverage on WSP and spray deposition on absorbent paper targets.

2 Materials and methods

2.1 Spray applications

A conventional orchard airblast sprayer (PowerBlast 500, Rear's Manufacturing Co., Eugene, OR) was used with five airflow rates, ranging from 1.9 to 7.6 m^3/s, and six open nozzles on lower manifold of one side only (Pai et al., 2009). The nozzles were either Blue or Lilac Albuz APT cone nozzles (Ceramiques Techniques Desmarquest, Evreux, France). At a nominal pressure of about 1000 kPa, the measured discharge rates for the Lilac and Blue nozzle banks (6 nozzles) were 2.9 and 21.4 L min^{-1}, respectively. The sprayer was operated within a citrus orchard at 2.7 km/h ground speed. Each treatment (combination of airflow rate- nozzle type) was replicated four times, which amounted to 40 spray runs. Spray solutions contained a fluorescent tracer dye (Pyranine-10G; Keystone Aniline Inc., Chicago, IL) at a nominal concentration of 500 mg L^{-1}. The volume median diameters (VMD)s and standard deviation of the

Lilac and Blue nozzles at 1000 kPa pressure, obtained earlier by a laser droplet-sizing instrument (Helos/Vario H3100A; Sympatec Inc., Lawrenceville, NJ), were 104 ± 3 and 164 ± 5 μm, respectively.

2.2 Spray targets

Spray targets included pairs of WSP cards and absorbent paper (AP) sheets wrapped over semi-rigid plastic cards. Both were 5×7.5 cm in size. They were positioned vertically (facing spray) at 1.5 m height and nine distances (2.4-10.8 m) from the operating nozzles (Figure 1). These arrangements along with different spray treatments provided varying amounts of deposition and droplet densities from each application (9×4 WSP and AP samples per treatment). Shortly after spraying (1-5 min), dried targets were collected individually, placed inside sealable plastic bags, and stored in a cooler for later transfer to the lab. The collected absorbent paper targets were analyzed by fluorometry (Salyani, 2000) and the detailed results of spray deposition were reported earlier in Pai et al. (2009). The corresponding WSP targets were read by the following image analysis systems.

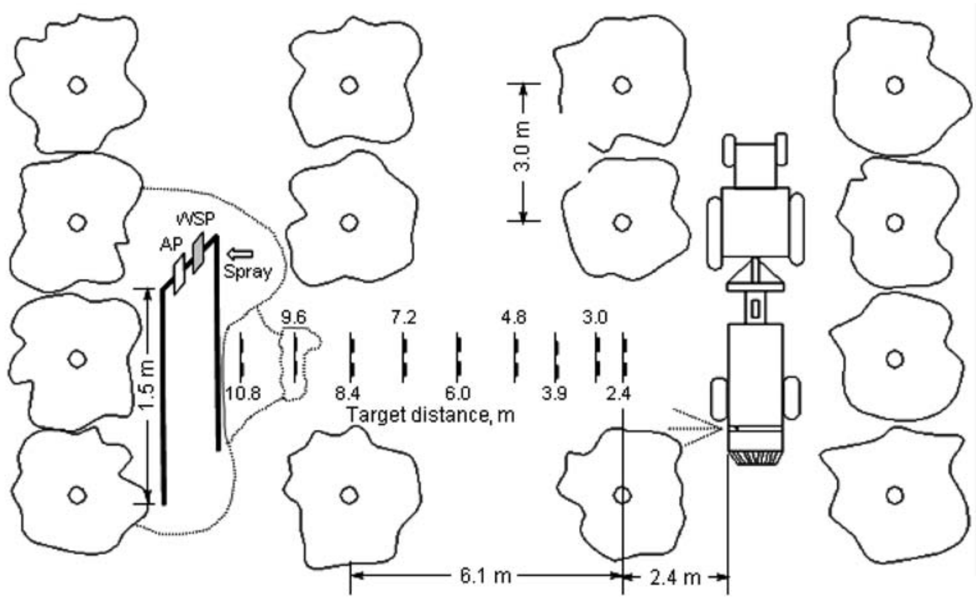


Figure 1 Layout of the spray targets

2.3 Image analysis of WSP targets

The set of WSP cards were analyzed independently by three different image analysis systems located in three laboratories, hereafter identified as AM1, DS2, and PS3. At all locations, only a 20×20 mm sample area at the center of each card was used for image analysis.

AM1 system was a modified area meter (Delta-T Devices Ltd., Cambridge, England) equipped with an RCA 2014X digital camera and monitor. The resolution of the camera was 1/300 of field of view width and height, i.e., 67 μm/pixel. It could only report the stain area in mm^2. Using three combinations of the camera height (5.2 or 8.0 cm), monitor calibration index (2.48, 2.61, or 3.26), and background threshold setting (2.8 or 3.0), each card was read three times. The average of the three measurements was reported as the percent of area coverage.

DS2 system consisted of a flatbed scanner, with resolution of 30 μm/pixel, and the DropletScan™ software (WRK of Oklahoma, Stillwater, OK). This software could provide droplet VMD, number of droplets, and droplet distribution (area coverage) statistics using a droplet spread factor (SF), i.e., $D_s/D_d = 1.5237 + 0.0006\, D_s$, where, D_s and D_d are spot and droplet diameters (μm), respectively.

PS3 system included a photo-smart scanner (Model Scanjet 5530, Hewlett-Packard, Palo Alto, CA) with 600 dpi imaging resolution (42 μm/pixel) and an image processing software (Image Tool 3.0, The University of Texas Health Science Center, San Antonio, TX). Depending on the background color of each card, the upper threshold of the image analysis was set between 140 and 180 but the lower threshold was always set at zero. The software was also capable of calculating the droplet size parameters using the equation (D_d=0.95$D_s^{0.91}$) to convert the spot diameter to the droplet diameter.

The relationships among the area coverage measurements in three laboratories and between those measurements and spray deposition were expressed by linear regression lines. These relationships were further refined for the Lilac and Blue nozzles.

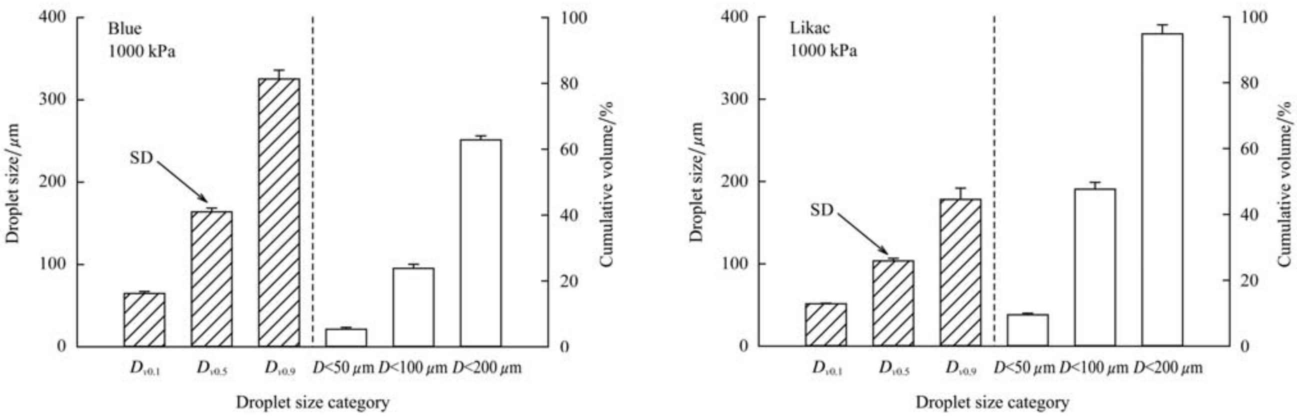
3 Results and discussion

3.1 Nozzle droplet size parameters

Figure 2 shows the droplet size spectra of the Blue and Lilac nozzles Albuz APT cone nozzles. The VMDs ($D_{v0.5}$) of those nozzles at about 1,000 kPa pressure and 1.4 m distance from the laser beam were 164 ± 5 and 104 ± 3 µm, respectively. Nearly 63% of the Blue and 95% of Lilac nozzle droplet volumes had diameters less than 200 µm. The “relative span” of the two nozzle types was 1.6 and 1.2, respectively.

3.2 WSP percent area coverage

Figures 3-5 show general relationships among the percent area coverage measurements obtained with the three image analysis systems. Evidently, there were some irrational data, particularly with the PS3 measurements (Figures 4 and 5). Combining the results of WSP image analysis from the three labs and visually comparing each three sets of the area coverage data with the actual droplet stain density on the corresponding WSP card, it was noticed that some measurements do not make sense. For example, one set of matching data included 2.2, 1.5, and 42.9% for the AM1, DS2, and PS3 measurements, respectively. Obviously, the PS3 reading was too high and incorrect (Figure 6) and the error was most likely from the operator’s typing mistake. Therefore, after removing all noticeable incorrect data and separating the results for the two nozzles (volume rates), the relationships between each two systems were established with improved precision (Figures 7-9).



Note: The $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ are droplet diameters which indicate that 10%, 50%, and 90%, respectively, of spray volume contain these or smaller size droplets. D refers to droplet size (diameter).

Figure 2 Droplet size spectra of the Blue and Lilac Albuz APT cone nozzles

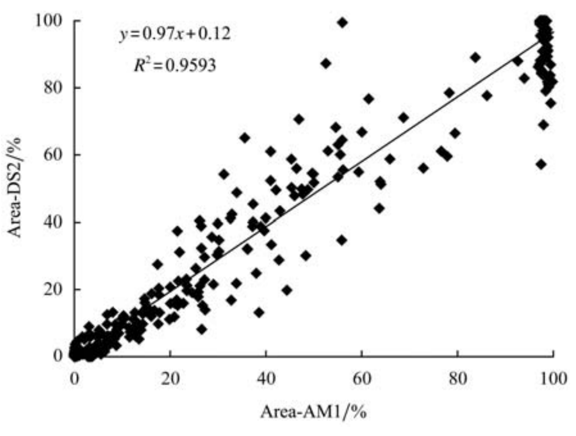


Figure 3 General relationship between area coverage measurements obtained by AM1 and DS2 image analysis systems

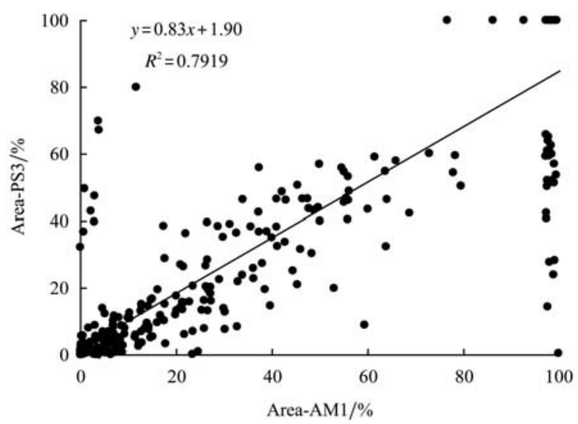


Figure 4 General relationship between area coverage measurements obtained by AM1 and PS3 image analysis systems

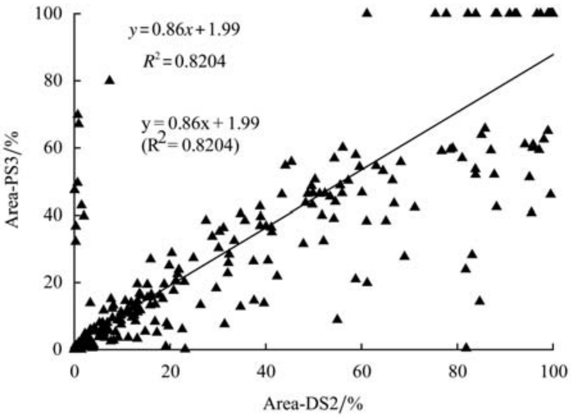


Figure 5 General relationship between area coverage measurements obtained by DS2 and PS3 image analysis systems

Figure 6 A WSP card with an erroneous area coverage measurement of 42.9% within 20×20 mm sample area at the center of the card

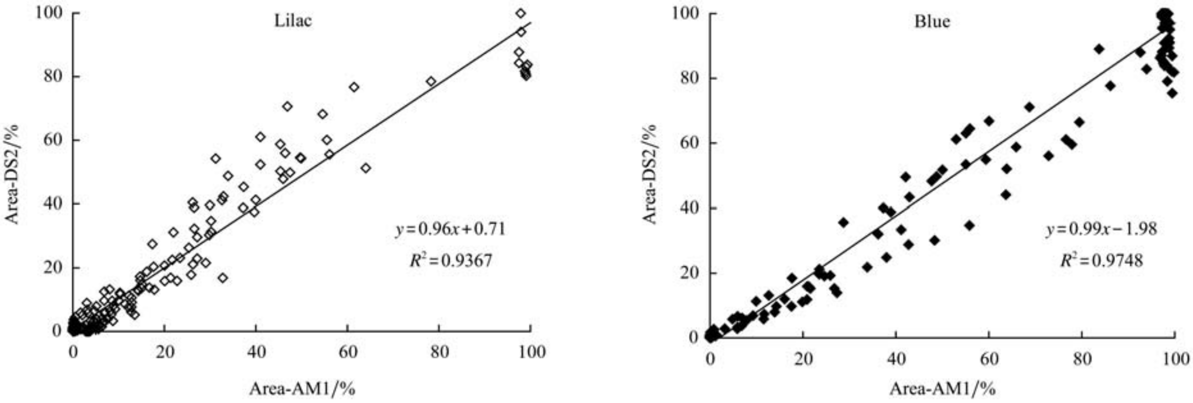


Figure 7 Refined relationships between area coverage measurements obtained by AM1 and DS2 image analysis systems

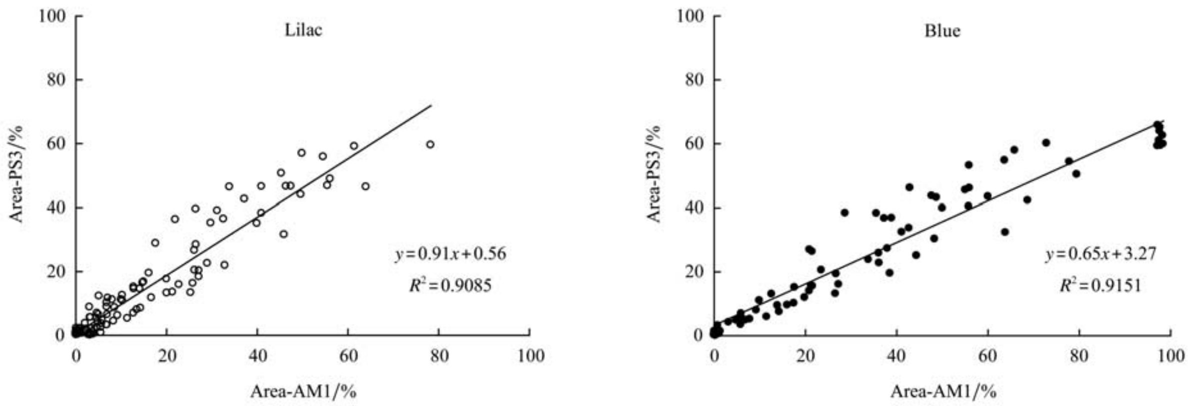


Figure 8 Refined relationships between area coverage measurements obtained by AM1 and PS3 image analysis systems

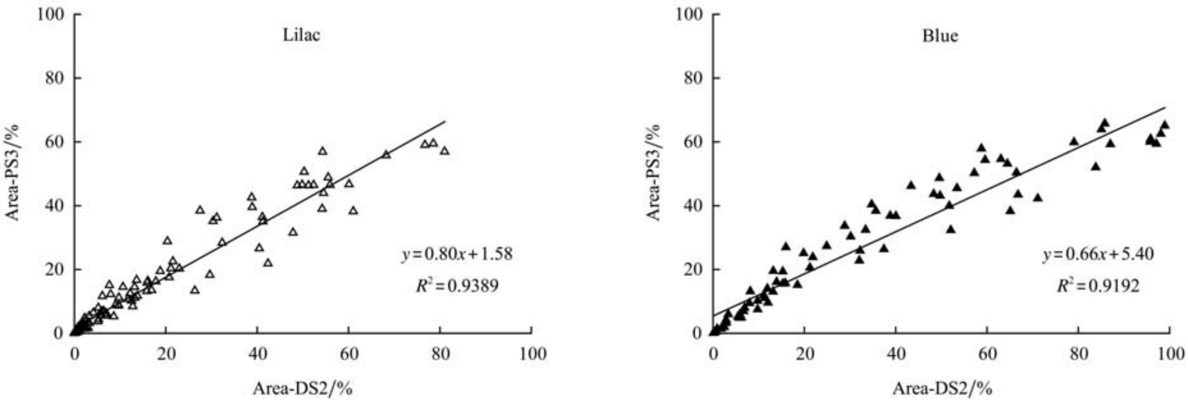


Figure 9 Refined relationships between area coverage measurements obtained by DS2 and PS3 image analysis systems

Overall, there were good correlations (R^2 = 0.9085 to 0.9748) among the three imaging systems in measuring percent area coverage on WSP cards. The AM1 and DS2 results agreed well for most measurements, particularly for the targets produced by higher volume rate of blue nozzles (Figure 7). However, the PS3 measurements were generally lower than the other two (Figures 8 and 9) although they showed good correlations with both AM1 and DS2 measurements.

The plots of Figures 3-5 and 7-9 show that while there could be a very good agreement between some measurements also there might be many dissimilar data points in any given matching set. This discrepancy may be attributed to the inherent limitations of the image analysis systems as explained in Salyani and Fox (1994) or operator errors. Because of scanner resolution limitation and random locations of spots on the WSP cards, the accuracy of any imaging program using pixel recognition technique would decrease with the decreased size of the spot (Zhu et al., 2011b). Any spot with its coverage area smaller than one pixel area could be reported as covering two, three, or four pixels if it was not perfectly centered in one pixel. With the 600 dpi resolution, a 50 µm diameter spot could be measured as 95 µm in diameter and a 100 µm spot could be 165 µm. In general, small droplets with light stains and large droplets with heavy coverage could not provide accurate results.

The plots of Figures 10-12 put the data in perspective and display the distributions of the difference in area coverage measurements. Figure 10 illustrates the difference between AM1 and DS2 measurements. The differences ranged from -47.5% to +42.5%. Evidently, about 50% of the differences were less than 2.5%. While the data for the Lilac nozzle (lower volume/smaller droplet size) showed nearly normal distribution for the differences the Blue nozzle (higher volume/larger droplets) data were somewhat skewed toward higher reading by the AM1 system. The difference between AM1 and PS3 measurements ranged from -27.5% to +52.5% (Figure 11). Again, most of the differences were confined to ±2.5% and the AM1 system recorded slightly larger measurements for the Blue nozzle stains. The differences between DS2 and PS3 area coverage measurements ranged from -22.5% to +47.5% (Figure 12). For these systems, nearly 60% of the differences were within ±2.5% of the recorded area coverage.

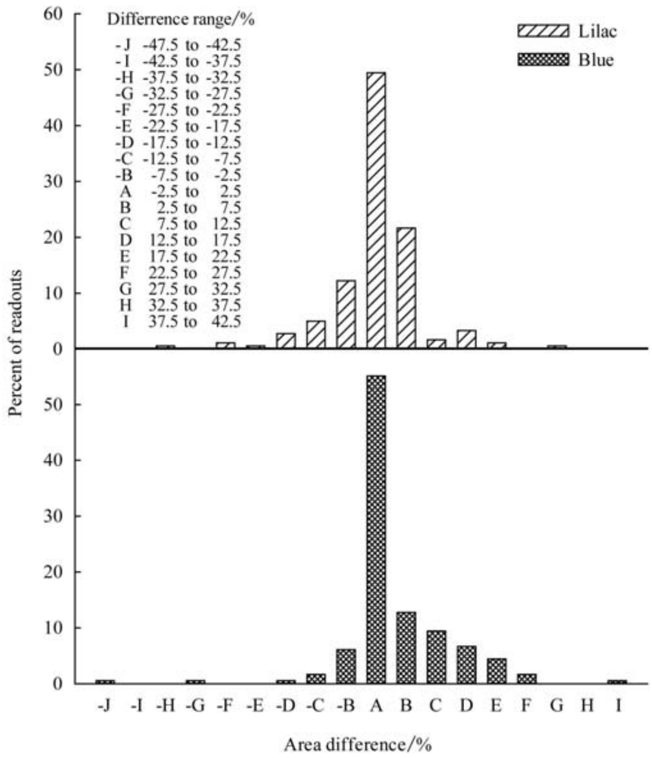


Figure 10 The difference between area coverage measurements obtained by AM1 and DS2 image analysis systems

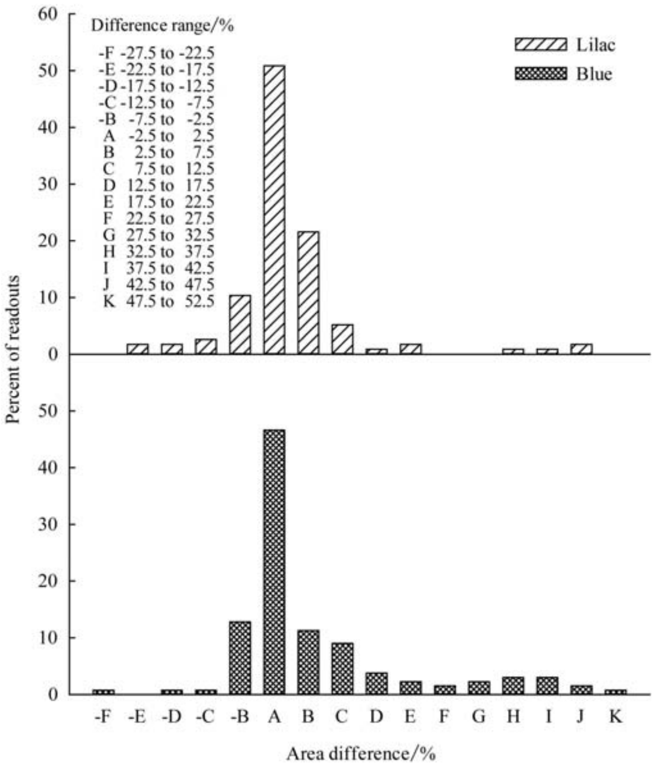


Figure 11 The difference between area coverage measurements obtained by AM1 and PS3 image analysis systems

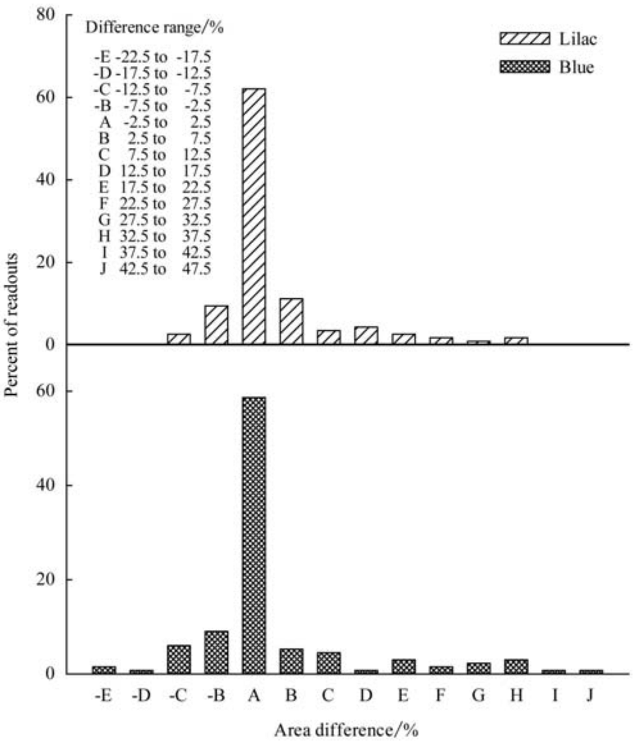


Figure 12 The difference between area coverage measurements obtained by DS2 and PS3 image analysis systems

3.3 Relationship between WSP area coverage and spray deposition

Figure 13 shows the relationships between percent area coverage of WSP and spray deposition on absorbent paper targets. Closer observation of data segments revealed somewhat erratic deposition results for very lightly and very heavily stained targets (area coverage: 0-5% and 80-100%) with nearly no correlation between the two factors in those ranges. Obviously, there were clear differences between the results of the Lilac (lower volume) and Blue (higher volume) nozzles with all image analysis systems. WSP deposits produced by the higher volume showed weak correlations (R^2: 0.4109 – 0.5034) between the area coverage and spray deposition. Correlations were much better (R^2: 0.6982 – 0.7572) for the lower volume because of less droplet overlaps on WSPs. These results revealed that WSP area coverage (2-dimentional data, i.e., spot surface area) may not be a good indicator of the amount of spray deposition

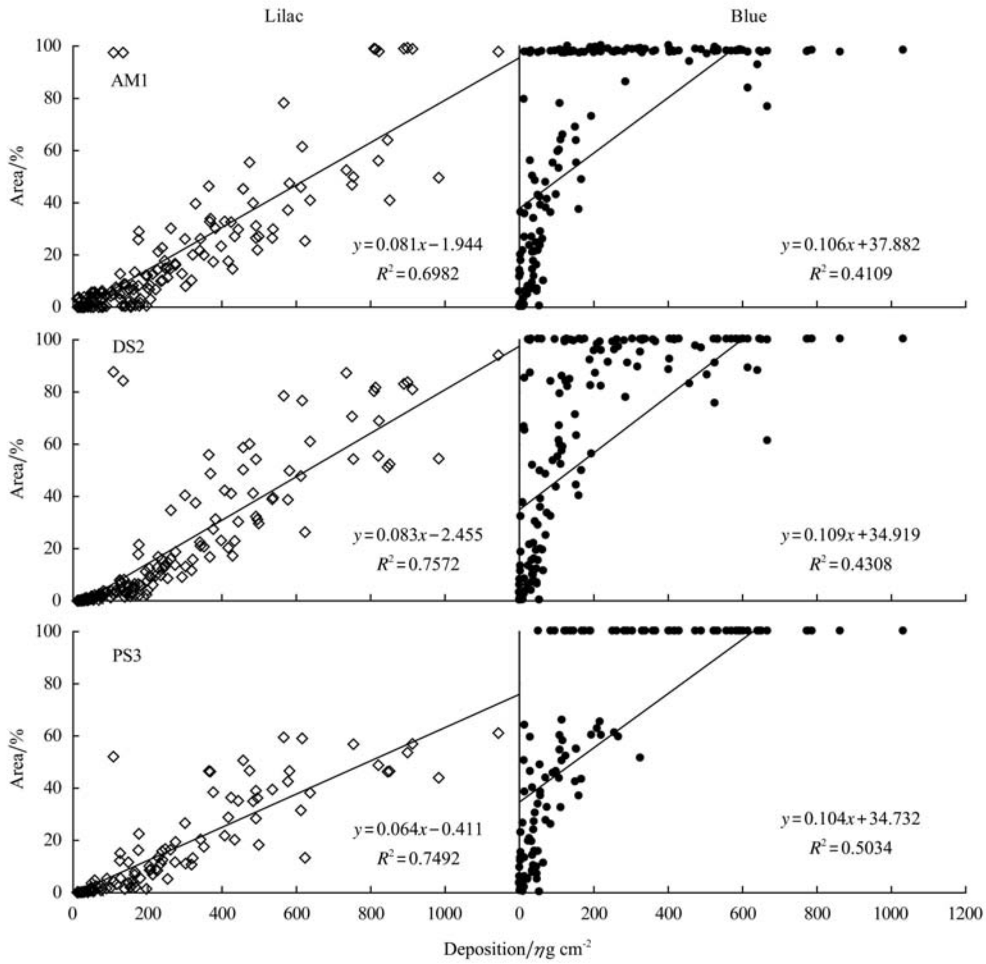


Figure 13 Relationships between spray deposition (on absorbent paper) and spray coverage (on WSP) obtained by three image analysis systems

(3-dimentional data, i.e., spray volume) in most field applications. Given the wide range of WSP coverage in any field spraying (from sparse, small light blue spots to dense, large dark blue stains), particularly in high volume orchard applications, it appears that WSP could not provide accurate information for assessing the amount of spray deposition.

3.4 Droplet VMD measurements with WSP

Using the DS2 system, the range and mean ± Standard deviation (in parentheses) of droplet VMDs were recorded as 29−830 (200±151) µm and 73−840 (279±179) µm for the Lilac and Blue nozzle targets, respectively. With the PS3 system, the corresponding results were, respectively, 18−954 (134±136) µm and 41−752 (194±163) µm. Clearly the VMDs obtained by image analysis of WSP targets did not reflect the droplet distributions shown in Figure 1, although the means showed correct trends. Apparently, the measurements were affected by the target distance, imaging resolution, and the presence of touching or overlapping droplet stains. As has been explained in Zhu et al. (2011b), given the imaging resolutions of 30 and 42 µm/pixel for the DS2 and PS3 systems, the minimum diameter of visible droplets should be 33 and 47 µm, respectively. This means that any registered spot diameter smaller than those minimum sizes could not be theoretically correct and may be attributed to the imaging algorithm error.

Overall, the VMD measurements of the two systems were not correlated (R^2: 0.0699) although excluding the outlier data could improve the correlation to some extent (R^2: 0.5389). The differences ranged from -325 to +575 µm (Figure 14). These differences could partially originate from the use of dissimilar spread factors with the two systems. Overall, DS2 system gave larger VMD sizes compared to corresponding PS3 droplet sizes. Nearly 60% of smaller droplets, produced by Lilac nozzles, and 50% of larger droplets, produced by Blue nozzles, were recorded 25-75 µm larger with the DS2 system. With both systems, the measured VMDs were generally smaller for more distant targets. This observation could be explained by droplet evaporation, settling of larger droplets, and the presence of fewer touching stains.

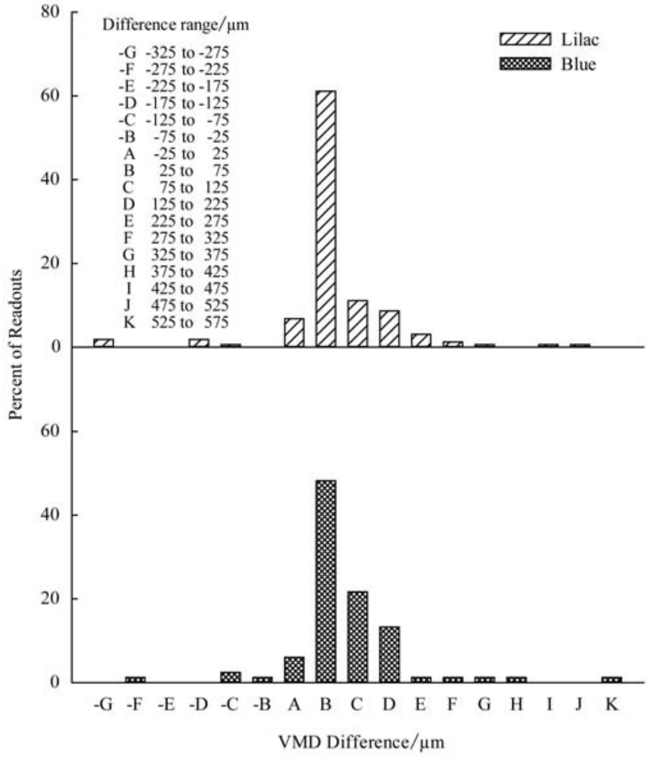


Figure 14 The difference between droplets VMD measured by DS2 and PS3 image analysis systems

3.5 Number of droplet stains on WSP (droplet density)

For the DS2 imaging system, the recorded number of droplet stains (within the 20×20 mm sample area) ranged from 5 to 6051 and 5 to 3496 for the Lilac and Blue nozzle targets, respectively. Each droplet stain might be formed by one or multiple overlapped droplet deposits For the PS3 system, the corresponding numbers were, respectively, 2-2265 and 5-1756. The results indicated some correlation (R^2: 0.4835) between number of droplets measured with the two systems. Although omitting the outlier data could increase the R^2 value to 0.6877, there were marked differences between the two measurements of the number of droplet stains. The difference (DS2-PS3) ranged from -900 to +3100 (Figure 15). Overall, the DS2 system recorded higher numbers compared to the PS3 system where nearly 25% of the differences were within ±100 counts. These differences could be attributed to the imaging resolutions of the systems and touching or overlapping of droplet deposits as explained in Salyani and Fox (1994) and Zhu et al. (2011b). In general, both systems showed lower number of droplet stains for more distant targets, primarily due to the settling of larger droplets before reaching the targets. It should be mentioned that, the droplet density information could be used as a complementary measure of spray treatment quality in some pest control applications (Boina et al., 2012).

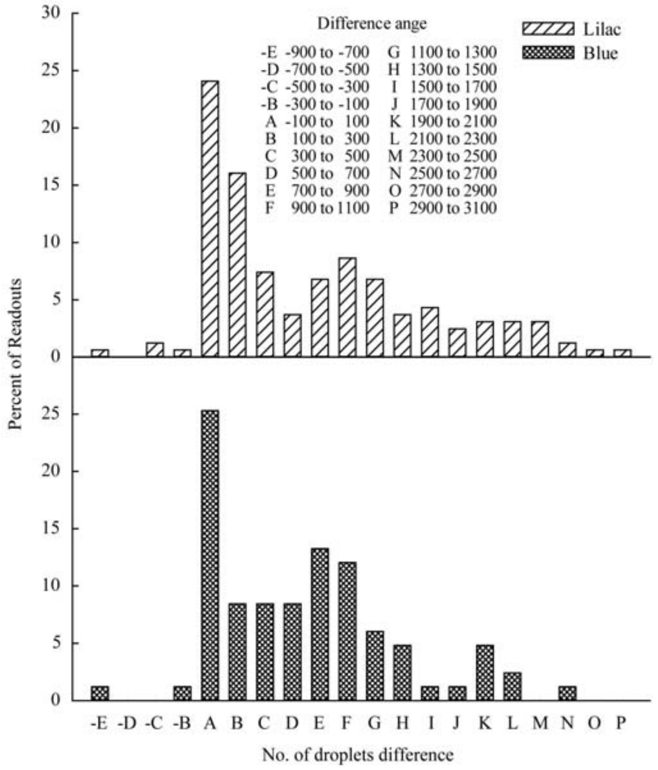


Figure 15 The difference between numbers of droplet stains obtained by DS2 and PS3 image analysis systems

Overall, it may be said that the use of WSP cards to quantify the amount of spray deposits and droplet size distributions in spray applications is generally questionable; although, repeated sampling with high number of replications might show a useful trend. Droplet size spectra of the spray and resulting droplet specks could affect the accuracy of the measurements. Very small droplets cannot generate detectable spots while very large droplets may runoff and result in distorted droplet spots. High droplet densities could generate many connected or overlapped spots that cannot be sized accurately by any imaging system.

4 Conclusions

1) Overall, there were good correlations (R^2: 0.9085 – 0.9748) among the three imaging systems in measuring percent area coverage on WSP cards; however, some matching measurements contained unacceptable data that degraded the overall performance of the systems.

2) Lower volume rate (smaller droplet size range) provided more useful targets than higher volume rate (larger droplets) for image analysis. Very low and very high area coverage measurements were not accurate.

3) Overall, there were somewhat weak correlations between WSP area coverage measurements and spray deposition. Therefore, WSP may provide reasonably accurate estimation of area coverage but could not be used to quantify the amount of spray deposits in most field applications.

4) Spray droplet VMDs obtained by image analysis of WSP targets could not reliably characterize the size of droplets generated by the tested nozzles. There was no or a weak correlation between droplet size data obtained by the DS2 and PS3 image analyzers. Overall, the former gave larger VMD sizes compared to corresponding PS3 droplet sizes.

5) The correlation between number of droplet stains obtained by the DS2 and PS3 systems was reasonably good (R^2: 0.6877) even though the DS2 system gave greater number of droplet stains compared to the PS3 measurements.

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