TECHNICAL NOTE:

ENVIRONMENTAL AND SPRAY MIXTURE EFFECTS ON DROPLET SIZE REPRESENTED BY WATER-SENSITIVE PAPER USED IN DRIFT STUDIES

S. J. Thomson, M. E. Lyn

ABSTRACT. *Water-sensitive paper (WSP) cards are frequently used to provide visual representation of droplet size and density for spray drift and deposition studies. Droplets collected on WSP spread out on the surface of the paper, and standard "spread factor" equations are used to compensate for spread to characterize actual droplet size. To date, no data have been presented to consider the effects of ambient conditions and formulation on droplet size represented by WSP. These data would be useful for creation of more accurate spread factor equations, and significant effects on droplet size could be modeled into new equations to account for these variables. A study was conducted using a newly constructed enclosed chamber that allows independent control of temperature and relative humidity (RH) to determine the effects of temperature, RH, spray formulation, and droplet volume on droplet diameter as represented by WSP. Droplets of a known diameter were placed on several WSP cards using five mixtures of Domark® fungicide, Syl-Tac® surfactant, and water while RH, temperature, and droplet volume were varied at three levels each. The WSP were optically scanned to obtain droplet size. Statistical procedures were used to determine the effect of temperature, RH, droplet volume, and spray mixture on stain area, and a model was developed over the droplet size range applied. A useful relationship of the influence of ambient conditions was derived, which indicated a linear 0.24%/1% ΔRH influence on stain diameter. The effect of mixture on stain size was significant at the 1% level, and use of a surfactant was seen to increase the average stain diameter on WSP by as much as 40% over the application of water alone.*

Keywords. *Drift measurement, Spray drift, Spray droplet, Spray sampling, Water-sensitive paper.*

Drift measurement and analysis is a complex task because of interrelated multi-dimensional dynamic processes that occur between the time of spray release and droplet deposition. All drift measurements currently require samplers to collect representative samples of drift deposits close to ground level and samplers for collecting airborne spray drift.

The ASABE drift measurement standard (*ASABE Standards*, 2004) specifies that drift deposits be collected on a flat collector, with the exposed surface level and located approximately at the top of the soil surface, grass, or crop that is in the downwind area. This type of collector (fallout sheet) has been widely used (Bouse et al., 1994; Carlton and Bouse, 1988; Hatterman-Valenti et al., 1995; Bui et al., 1998; Kirk, 2000; Smith et al., 2000; Fox et al., 1993, Lan et al., 2008, Thomson et al., 2004, 2005) with several types of sample media that include alpha-cellulose, Mylar, and photographic film.

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The authors are **Steven J. Thomson, ASABE Member,** Research Agricultural Engineer, USDA-ARS Crop Production Systems Research Unit, Stoneville, Mississippi, and **Margaret E. Lyn,** Graduate Assistant, College of Management, Georgia Institute of Technology, Atlanta, Georgia. **Corresponding author:** Steven J. Thomson, USDA- ARS Crop Production Systems Research Unit, P.O. Box 350, Stoneville, MS 38776; phone: 662-686-5240; fax: 662-686-5372; e-mail: steve. thomson@ars. usda.gov.

Mylar sheets have a non-reactive surface that is easily rinsed with small volumes of solvent; therefore, they are well suited for use as sample media. Water-sensitive paper (WSP) cards have also been used to quantify spray coverage and droplet size distribution of drift deposits. However, droplet stain diameters must be adjusted through the use of a spread factor to determine the actual droplet diameters associated with the stain. Degre et al. (2001) concluded that water-sensitive cards were useful for qualitative comparisons due to the variability in spread factor associated with very large droplets (1240 and 985 μm diameter). While this variability was probably greater than for droplets less than 200 μm in diameter, field use of water-sensitive card data to determine droplet spectra has been suspect because the moisture content of the card affects the spread factor.

The size of the droplet on WSP and the formulation are also thought to influence actual droplet size. Cards located within the canopy of transpiring plants absorb moisture from the air and may produce a larger stain (due to the longer time required to absorb the droplet) than a dry card. Card data are also highly dependent on the color threshold level used when processing the card images to measure the stain areas. Studies by Wolf et al. (1999), Panneton (2002), Sánchez-Hermosilla and Medina (2004), and Hoffmann and Hewitt (2005) highlighted the importance of careful image interpretation and analysis of card data. To our knowledge, no data have been presented to determine actual droplet size on spray cards as a function of ambient air temperature and moisture levels, droplet volume, or formulation. These data would be useful to create more accurate spread factor equations.

Figure 1. Controlled environment chamber (CEC) and associated hardware.

Materials and Methods

Controlled Environment Chamber

A controlled environment chamber or CEC (model 5506C, Electro-Tech Systems, Inc., Glenside, Pa.) was used to perform the experiment. The CEC was an O-ring sealed benchtop chamber equipped with a heating and cooling microprocessor system that automatically maintains the experimental temperature and humidity. To enable automatic control of humidity, the CEC was equipped with a heated-water reservoir, a vacuum pump, and a desiccant (fig. 1).

During an experiment, the microprocessor automatically activated the vacuum pump if an increase in humidity was detected or supply power to the water reservoir to compensate for low humidity. Although the CEC comes equipped with a temperature and humidity readout, two additional hygrometers/thermometers (model 35519-047, VWR, West Chester, Pa.) were positioned inside the CEC at different locations.

Prior to establishing the environmental settings, the following items were placed inside the CEC: 26 mm × 500 mm strips of WSP (Ciba-Geigy, Spraying Systems, Inc., Wheaton, Ill.), the five formulations, an adjustable 0.1 to 2.5 μL volume pipette (model EW-24505-00, Eppendorf AG, Hamburg, Germany), and replacement micropipette tips. The experiment was performed at five different environmental settings. There were two low-temperature settings (20°C at 40% or 80% RH), two high-temperature settings (35°C at 40% or 80% RH), and one intermediate setting (30°C at 60% RH). At both the low and high temperature settings, a low (40%) and high (80%) humidity setting was established. Since the CEC took a longer time to adjust from a high to low humidity relative to the opposite direction, low-humidity experiments were generally conducted first.

Formulations and Application

Each of the formulations shown in table 1 was prepared using 100 mL of deionized water. For each formulation, the respective amount of Syl-Tac® surfactant (Wilbur-Ellis, Fresno, Cal.) and Domark® fungicide (Valent USA, Walnut Creek, Cal.) was added, and the mixture was then stirred until homogeneous. Four different formulations were evaluated in addition to a water or control treatment.

Table 1. Formulation percent composition.

Treatment	Constituent Composition (%)		
	Syl-Tac®	Domark®	Water
1	1.54	0	98.46
2	1.50	2.26	96.24
3	0.62	0	99.38
4	0.62	0.92	98.46
5	0	0	100.00

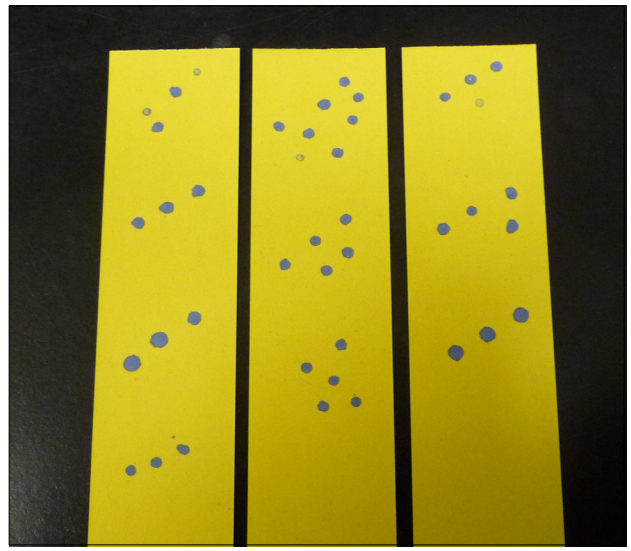

Figure 2. Typical placement of droplets on WSP.

For each treatment, at a given temperature and RH setting, three different droplet volumes (0.1, 0.3, and 0.5 μL) were applied to a strip of WSP divided into three sections. Within each section, a minimum of three droplets of a given volume were carefully applied. This was done by ejecting the formulation before touching the pipette tip to the WSP at an optimal angle to minimize smudging. The optimal angle, a subjective parameter, was dependent on the person applying the droplets, and distance of application was set close to the strip so that the droplet would make a clean break from the pipette tip. The sizes were randomly placed onto the strips. Although more than three droplets were applied per droplet volume, only three droplets with no signs of smudging were analyzed (fig. 2). WSP were allowed to dry inside the CEC for 10 min before removing. For each treatment, at a given temperature and RH setting, there were three droplet volumes and three stains analyzed per droplet volume on each of three WSP strips.

Analysis of WSP

After the experiment was completed, the WSP strips were analyzed for geometrical parameters using an image scanning system. The image analysis system consisted of a JVC CCD camera with RGB output and an Integral Technologies Flashpoint Intrigue frame grabber (Pelco Worldwide, Clovis, Cal.) mounted in a Dell Dimension desktop computer running MS Windows 98. The WSP were scanned using SigmaScan 5.0 (Aspire Software International, Ashburn, Va.), and programmed macros were used to process and export droplet area and diameter to a text file for spreadsheet analysis.

Results

Effects on Droplet Stain Size

Table 2 illustrates the effect of RH, temperature, size (droplet volume), and treatment (mixture) on actual droplet size for a known applied droplet volume. The SAS 9.1.3 pro–

Table 2. Effects on droplet stain area determined from WSP.

Effect	Numerator df	Denominator df	F Value	Pr > F
Treatment	5	63	373.21	<0.0001
RH	1	63	20.20	<0.0001
Temperature	1	63	2.82	0.0980
Size × Treatment	5	63	69.07	<0.0001

cedure Proc Mixed (SAS Institute, Inc., Cary, N.C.) was used to analyze the data and provide a model solution with [RH-temperature combination × treatment × size] set as random effects. Non-significant main effect and interaction terms were progressively dropped out, resulting in final output (table 2). Treatment (or mixture), RH, and size × treatment (the interaction between droplet size and treatment) were all significant effects on droplet stain area (p = 0.01). A model solution was developed, and coefficients for all treatment mixtures are illustrated.

$$\log(\text{area}) = C_1 + C_2(\text{RH}) + C_3(\text{Temp}) + C_4(\text{Size}) \quad (1)$$

where RH is relative humidity, Temp is ambient temperature, Size is droplet size volume or the known volume of mixture applied to WSP, and coefficients C_1 through C_4 are as follows:

C_2 = 0.001999; C_3 = 0.001970.

Treatment 1: C_1 = -1.7773; C_4 = 0.9472

Treatment 2: C_1 = -1.8065; C_4 = 0.9218

Treatment 3: C_1 = -1.8052; C_4 = 0.9154

Treatment 4: C_1 = -1.8460; C_4 = 0.7139

Treatment 5: C_1 = -2.2619; C_4 = 1.1525.

The error sum of squares (SS) was small in proportion to the model sum of squares, as the model explained 89% of the total variance ($R^2 = (SS_{Model}/SS_{Corrected\ total}) = 0.89$).

Figure 3 illustrates a relationship between droplet volume applied to WSP vs. stain area, along with a representation of the model solution for treatment 1. Log model results illustrate a range of model fits at each applied volume, representing the combined effects of RH (40%, 60%, and 80%) and temperature (20°C, 30°C, and 35°C). These effects were consistent if expressed as a percentage of actual stain area.

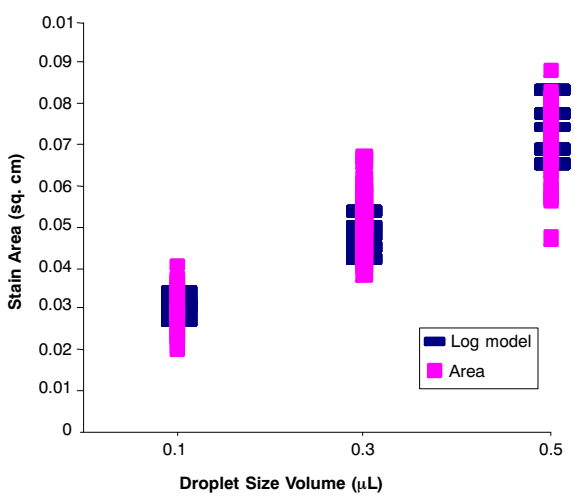

Figure 3. Droplet size volume vs. stain area for treatment 1.

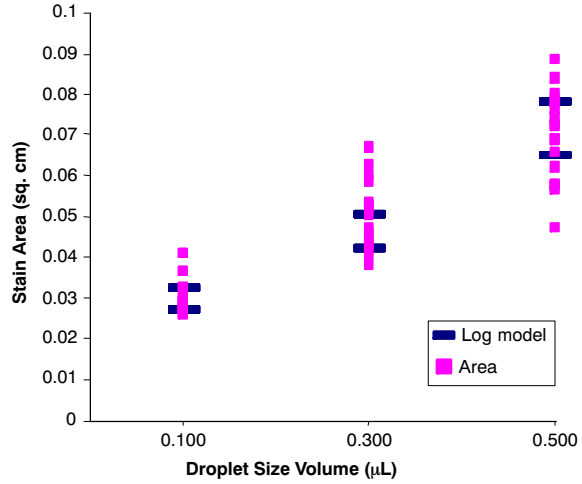

Figure 4. Droplet size volume vs. stain area for treatment 1 showing actual data and model results between the two extremes of RH (40% and 80%).

To illustrate a typical response due to RH alone (with temperature fixed at 20°C), model responses between the extremes of RH (40% and 80%) are illustrated in figure 4. For the model fit corresponding to the subset of data shown, percentage increase in stain area caused by an increase in RH between the extremes (40% and 80%) was 20% at all three stain sizes, or +0.5%/1% ΔRH. This corresponds to an increase in stain diameter of 0.24%/1% ΔRH. Using this relationship, the same droplet scanned from a card as 200 µm in diameter at 40% RH would scan as 219 µm at 80% RH. A 500 µm droplet at 40% RH would scan as 548 µm at 80% RH.

Spread Factor Equations

Droplet spread on the Ciba-Geigy brand WSP at fixed conditions can be approximated by the equation of Hill and Inaba (1989):

$$y = 0.51x + 53\ \mu\text{m} \quad (2)$$

where y is the actual diameter, and x is the stain diameter (µm). Equation 2 was derived with a Decis 5.0 (EC) spray solution at 42% RH.

Another approximation (the USDA-ARS equation; Hoffmann and Hewitt, 2005) can be used for a wider range of stain diameters:

$$y = 0.53549306x - (0.000084839x^2) \quad (3)$$

where y is the actual diameter, and x is the stain diameter (µm).

Documentation on the test parameters used to derive equation 3 is not readily available, but figure 5 presents several equations to determine spread factor regenerated from a chart presented by Hoffmann and Hewitt (2005). The relationship presented by Hill and Inaba (1989) (eq. 2) has been added for comparison, along with quadratic curve fits to our data (r = 0.96) with surfactant/active ingredient (A.I.) combination (treatment 1) and with water only (treatment 5). We selected all runs at 20°C and 40% RH for the curve fits and to compare with the only relationship having test conditions we could document (Hill and Inaba, 1989).

The relationship with water only (treatment 5 in this study) appears to continue the Hill and Inaba (1989) relationship at larger droplet sizes nicely, but it should be noted that

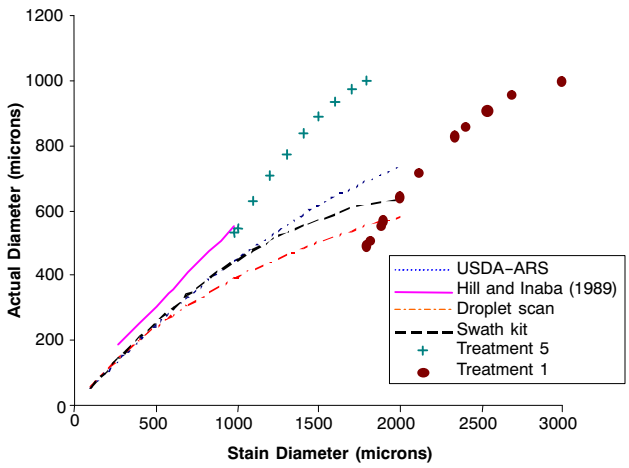

Figure 5. Spread factor relationships.

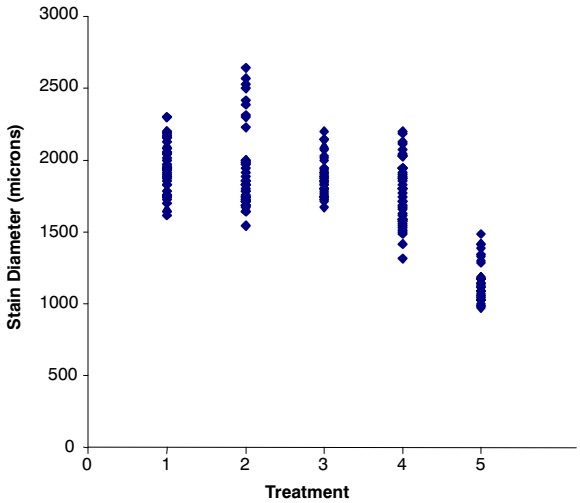

Figure 6. Stain diameter as a function of treatment for the smallest droplet volume applied to WSP (size = 1).

the latter was derived using a Decis 5.0 solution (no additional surfactant). The differences between the curves for surfactant/A.I. (treatment 1) and water (treatment 5) are quite pronounced, indicating the importance of deriving curves for each spray mixture. These differences can be illustrated in an alternate way. Figure 6 illustrates stain diameter for size 1 (smallest droplet) by treatment pooled across the variables RH and temperature values for our experiment. Total reduction in mean diameter between treatments 1 and 4 (all containing surfactant and/or A.I.) was only 9%, but the total reduction from treatments 1 to 5 was 40%. For all droplet volumes pooled together, these reductions were 15% and 34%, respectively. It is not clear if any of the relationships expressed in figure 5 besides that of Hill and Inaba (1989) used a surfactant in their derivation, but we suspect that they did not. All curves represented in figure 5 except the one derived by Hill and Inaba (1989) appear to fall between our curves, and this could be seen as a compromise between a response using surfactant and one using water only. However, it is not clear if these relationships, when derived, were actually meant to represent such a compromise.

In derivation of their relationship, Hill and Inaba (1989) gave no indication of test replications or syringe imprecision. The latter would be extremely important, especially for the smallest volume the authors applied (0.01 μL). We have observed this volume to be obtainable using the smallest minor graduation of a Hamilton 7000 0.5 μL syringe (Hamilton Company, Reno, Nev.). However, additional human error would be introduced using a syringe by its application method. It can also be noted that in figure 5, except for the 0.1 μL volume (576 μm diameter) spotted onto WSP, the droplets applied for our experiment were larger than those derived by others (fig. 5). For our experiment, we were limited by the smallest volume available using commercial micropipettes. The Eppendorf pipette used to produce the smallest droplet has a stated accuracy of ±12.5% and imprecision of 6% at 0.1 μL. Our procedures could be used to develop a final droplet size model that could include smaller droplet sizes than were possible to generate herein. These droplets could be applied in the lab to WSP using microliter syringes (as indicated above for manual application) or by a precision droplet generator. If using a droplet generator, droplet sizes would need to be verified by laser diffraction or similar means. Based on our experimental and analytical procedures, a protocol could then be established to obtain data for any spray mixture as required for a field experiment. A library of equations could then be developed as new spray mixtures are required.

Summary and Conclusions

Water-sensitive paper (WSP) is frequently used in spray drift and deposition studies to characterize the size and density of droplets applied by ground or aerial spraying systems. A study was conducted using a controlled environment chamber to determine and model the effects of RH, ambient temperature, spray mixture, and droplet size on droplet diameter obtained from WSP. Results of this study illustrated significant effects of RH, droplet size, and spray mixture on actual droplet area by statistical analysis. Model solutions were developed for the five mixtures tested, and an example solution was illustrated. The following practical conclusions can be drawn from this study:

1. The effect of RH on droplet stain size was statistically significant but of modest magnitude for our study. A +0.24%/1% ΔRH would translate into only a 5% difference in diameter over a typical 20% range of daily humidity values. Thus, the degree of this difference may not be great enough to warrant compensation for RH in the field.

2. The effect of formulation on droplet area on WSP is pronounced and must be considered in the derivation of spread factor relationships.

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