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ENGINEERING

Chemical Application Equipment for Improved Deposition in Cotton

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INTERPRETIVE SUMMARY

Some insects that attack cotton, including aphids, spider mites, and whiteflies, feed on the undersides of leaves or beneath the plant canopy. Pesticides applied to control these insects must be deposited within the plant canopy where they feed.

Air-assisted electrostatic and hydraulic sprayers have been developed in recent years to improve pesticide penetration and coverage within the plant canopy. These sprayers need to be evaluated to determine their effectiveness when compared with conventional sprayers.

This study compared within-canopy penetration and leaf side coverage of spray materials applied using the following spray technologies: (i) air-assisted sprayer; (ii) over-the-top hydraulic nozzles plus drop nozzles; (iii) electrostatic air-assisted sprayer; (iv) over-the-top hydraulic nozzles; (v) over-the-top nozzles plus shielded drop.

We used water-sensitive cards that collect spray droplets and spray residue washed from the topsides and undersides of leaves, and fluorescent dye collected on cotton strings placed within the plant canopy to determine the effect of sprayer application method on spray penetration (i) into the plant canopy; (ii) to the top- or underside of cotton leaves; (iii) in the top and middle of plants.

Spot diameters generated by all five sprayers in cotton and collected on water-sensitive cards were larger on upper than on lower leaf surfaces, and coverage was greater on leaf topsides than on undersides. Coverage was also greater in the top than the middle of the plant canopy.

The air-assisted sprayer had better coverage than other sprayers on leaf undersides and good coverage on leaf topsides. Hydraulic nozzle sprayers deposited more spray material, measured by the spray residue washed from leaves, on leaves where nozzles were positioned to direct the spray solution. The air-assisted sprayer deposited spray material throughout the plant canopy and on the topsides and undersides of leaves.

Total net dye fluorescence deposited on collector strings decreased from top to bottom of plant canopy and was high in locations where the hydraulic nozzles directed spray materials. Because sprayer methods influence spray penetration and leaf coverage in cotton, the applicator can select sprayers that optimize control of specific insect pests in the plant canopy where insects feed.

ABSTRACT

Air-assisted electrostatic and hydraulic sprayers developed in recent years to improve pesticide deposition within the plant canopy and on the undersides of cotton leaves were evaluated to determine their effectiveness compared with conventional sprayers. The study determined and compared within-canopy deposition of spray from conventional hydraulic nozzle, air-assisted, and electrostatic sprayers in cotton plants. Water-sensitive paper, residue washed from leaves, and fluorescent dye collected on strings were used to determine the effect of sprayer method on spray deposition within the canopy and on cotton leaf surface. Spot diameters generated by all five sprayers in cotton and collected on water-sensitive paper were larger on the top than on the lower surfaces of leaves. Coverage was greater on leaf topsides than on undersides and in the top portion of the plant canopy. The air-assisted sprayer offered better coverage than other sprayers on the undersides of the leaves and good coverage on the topsides. The hydraulic nozzle sprayers deposited

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more spray material, measured by the leaf-wash method, on leaves at locations where the nozzles were directed. The air-assisted sprayer deposited spray material throughout the plant and on both leaf surfaces better than other sprayers did. Total net fluorescence on collector strings generally decreased from the top to the bottom of plants, and was highest where hydraulic nozzles directed spray. Sprayer methods influenced spray deposition and coverage in cotton canopies, and can be selected to provide improved application in the plant canopy where optimum coverage is needed.

The amount of pesticide deposited by sprayers on an intended target depends on the interaction of crop, environment, application equipment, and pesticide formulation. To control aphids, spider mites, and whiteflies in cotton, pesticides need to be deposited within the plant canopy and on the undersides of leaves.

In recent years, application equipment has been developed to improve pesticide deposition within the plant canopy and on the undersides of leaves. Air-assisted electrostatic and hydraulic sprayers, marketed for use as improved application equipment, need to be compared with conventional hydraulic-nozzle sprayers and evaluated for effectiveness of pesticide deposition within the plant canopy and on the undersides of leaves.

Mulrooney and Skjöldager (1997) found that air-assistance significantly enhanced the efficacy of insecticides to control boll weevils and beet armyworms in cotton. These pests were difficult to control with conventional application methods. Compared with over-the-top sprayers and drop-nozzle sprayers, an air-assisted sprayer provided greater canopy penetration and deposition of fluorescent tracer on Mylar® sheets and water-sensitive paper (Womac et al.; 1992).

Compared with other sprayers, the air-assisted sprayer also increased deposition of bifenthrin on leaves and squares within the canopy. Howard et al. (1994) reported that three different air-assisted sprayers deposited more bifenthrin on both the topsides and undersides of leaves in the middle of the cotton canopy and gave a higher percentage of coverage than conventional over-the-top hydraulic sprayers provided.

Law et al. (1993) investigated canopy penetration of three application methods. Compared with air-assisted uncharged and hydraulic sprayers, an air-assisted electrostatic-charged spray increased deposition onto vertical surfaces in cotton plants by a factor of 1.5 in the top canopy and 3-fold in the bottom. Air-assisted electrostatic-charged spray also increased deposition onto leaf undersides by 1.9 fold more than an air-assisted uncharged spray did, and 2.5-fold more than hydraulic spray methods.

Results in silverleaf whitefly (*Bemisia argentifolii*) control suggests that air-assisted electrostatically-charged sprayers may reduce insecticide usage by 50% (Palumbo and Coates, 1996; Herzog et al.,1983). Therefore, efficient application systems such as the air-assisted and electrostatic air-assisted sprayers could reduce the amount of insecticides required for insect management and improve application effectiveness of biological/biorational insecticides.

This study determined and compared spray deposition in cotton plants using new and/or improved application technology. The objectives were: (i) to compare within-cotton-canopy deposition of water-dye sprays applied by conventional hydraulic nozzles, air-assisted, and electrostatic air-assisted sprayers, and (ii) to determine the efficiency of equipment and systems for the application of insecticides to the undersides of cotton leaves.

MATERIALS AND METHODS

Field tests were conducted in plots (8 rows, 0.91 m wide by 15 m long) of mature cotton at the Coastal Plain Experiment Station, Tifton, GA, in 1994, 1995, and 1996 to determine spray deposition applied with: (i) Berthoud[1] (Berthoud Sprayers, South Haven, MI) air-assisted sprayer (hereafter called air-assisted); (ii) hydraulic sprayer with one nozzle over-the-top and two nozzles on 38-cm long drops directed 45° downward into the plant canopy (drops); (iii) sprayer equipped to place by air-assisted electrostatic-charged spray droplets (Electrostatic Sprayer Systems, Watkinsville, GA; (iv) hydraulic nozzles on over-the-top sprayer (over-top); (v) hydraulic nozzles with shielded drops

[1] Mention of a proprietary product does not constitute an endorsement by USDA-ARS or the University of Georgia.

(shielded). The shielded sprayer was a conventional hydraulic sprayer boom modified to place spray nozzles on 'V' shaped-shields, which allowed placement of spray nozzles between cotton rows and within the plant canopy. The arrangement directed spray solutions within the plant canopy to the undersides of cotton leaves. The drop shields were 15 cm wide by 76 cm long and spring-loaded to allow backward deflection when needed. Two nozzles on each side of the row were positioned to spray 45° upward into the plant canopy. One nozzle over each row directed spray down into the plant canopy. The boom assembly sprayed 8 rows. Sprayer nozzle arrangement and spray direction toward cotton plants for the three hydraulic nozzle sprayers and the two air-assisted sprayers are illustrated in Figs. 1 and 2.

Sprayer equipment and operating specifications are presented in Table 1. Water-sensitive paper, dye residue washed from leaves (leaf wash), and fluorescent dye collected on strings placed within the plant canopy were methods used to determine the effect of application method on spray deposition within the canopy and/or on the topsides or undersides of cotton leaves.

Water-sensitive paper (cards 76 by 26 mm) (Spraying Systems, Inc., Wheaton, IL) were attached to 38 by 51 mm Post-it® sticky notes (3M Corp., St. Paul, MN) and placed at random in 15-m long plots in the top and mid-area of cotton plants. The sticky notes were stapled to the topsides and undersides of 10 cotton leaves in each location. Plots then were sprayed with water using each of the five sprayers.

After spraying, the cards were collected and placed into Zip-Lock® bags for later evaluation. Sprayer applications were replicated three times in 1995 and 1996. The cards were evaluated for percentage of card covered with spots and spray spot diameter. Spray coverage and size distribution of spots on the cards were determined with a Scanman hand-held optical scanner (Logiteck, Inc., Fremont, CA) and analyzed with software developed by Franz (1993).

Smudges or globs of stain on cards resulted in extremely large spot diameters that were not representative of sprayer performance and were removed from the data set before analysis of percent coverage and mean spot diameters. The design was a split-split-split plot in time and space (Steel and Torrie, 1960), where the main plot was years, first split was a randomized complete block design consisting of five sprayers and three sampling areas. The second split was two locations in the plant canopy with 10 leaves at each location as sampling units. The third split was the leaf side. Mean spot diameters and percent coverage were separated by Duncan's new multiple range test.

In the dye wash test, three plot areas in mature cotton were sprayed with 49 g ha^{-1} (0.49 μg cm^{-2}) FD&C blue dye (Warner Jenkinson, St. Louis, MO). Sprayer applications were replicated three times. Ten leaves from the top and 10 leaves from the middle of the plants were picked from each of the 15 sprayed areas. Dye residues were washed (with 3 mL of methanol) from the topsides and undersides of leaves with a dual-side leaf washer developed by Carlton (1992). Dye solutions washed from the topsides and undersides of leaves were evaluated for transmittance with a Milton Roy Spectronic 20D spectrophotometer (Spectronic Instruments, Inc., Rochester, NY) and compared with a calibration from known washed deposits to determine dye deposition by each sprayer, leaf side, and location within the plant canopy. Mean dye deposits as

Table 1. Application methods and sprayer specifications for cotton sprayer deposition test conducted in 1994, 1995, and 1996 in Georgia.

Sprayer †	Volume	Pressure	Nozzle Type ‡	Nozzle	Velocity §
	L ha^{-1}	kPa		mL min^{-1}	m min^{-1}
Air-assisted	187	103 ¶	2-Blue	686	80
Drops	136	552	3-TX10	458	107
Electrostatic	37	103–241 #	3-STD	103	91
Over-top	78	414	2-TX6	384	107
Shielded	187	379	5-TX4	260	75

† Air-assisted = Berthoud air-assisted sprayer; Drops = hydraulic sprayer with over-top and drop nozzles; Electrostatic = electrostatically charged sprayer; Over-top = hydraulic nozzles over-the-top sprayer; and Shielded = hydraulic nozzles over-the-top and shielded drops.

‡ Blue = Berthoud 15/10 nozzle with 1.5 mm diameter orifice; 3-TX10 = Three TX10 nozzles (Spraying Systems Co., Wheaton, IL);STD = Electrostatic Spraying Systems single-port induction-charging nozzle; 2-TX6 = two Spraying SystemsTX6 nozzles;5-TX4 = five Spraying SystemsTX4 nozzles, one over-the-top and four directed into the canopy.

§ Travel velocity of the sprayers

¶ Air velocity of 93 km h^{-1}

Air pressure of 241 kPa

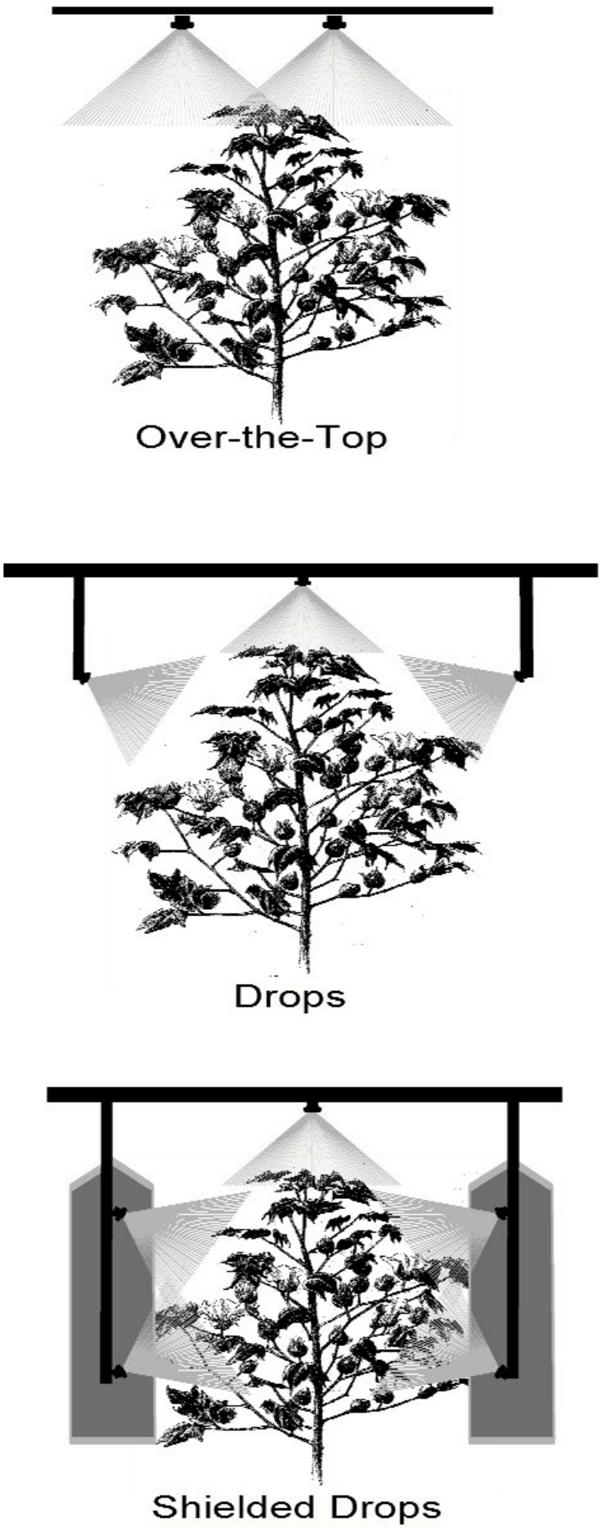

Fig. 1. Sprayer nozzle arrangement and spray direction for the three hydraulic nozzle sprayers.

Fig. 2. Sprayer nozzle arrangement and spray direction for the air-assisted sprayers.

measured by transmittance were separated by Duncan's new multiple range test.

In the string collector test, three plots (two rows treated and evaluated together) were established in a field of mature cotton to compare the five sprayers for spray penetration into the plant canopy. Strings (13 m long) were threaded through the plant canopy parallel to the row at the top, middle (25 cm in from top), and bottom of the plants (50 cm from top) near the center plant stem. After treating each row, untreated strings were attached to the end of the treated strings and the previous treated strings were removed. Untreated strings were pulled into place to provide strings at the same plant location for the next spraying.

All six rows with clean strings were treated with the five sprayers with 6.2 mL ha^{-1} of rhodamine WT liquid dye (Keystone Aniline Corp., Chicago, IL). Strings for each position and machine were evaluated by the method developed by Whitney and Roth (1985) for net fluorescence of a 12-m section of each string. A low-speed string door analysis system and software (WRK, Inc., Manhattan, KS) was set up and calibrated to analyze the sprayed strings. For each year, the design was a split-plot where the main plots were replications and sprayers, and the subplots were positions in the plant canopy with two rows as sampling units. Treatment means of net fluorescence were separated by Duncan's new multiple range test.

Table 2. Mean spot diameter, in micrometers (μm), deposited on water-sensitive cards attached to topsides and undersides of cotton leaves when sprayed with five different sprayers in 1995 and 1996 in a study in Georgia.

	1995		1996	
Sprayer	Topside	Underside	Topside	Underside
Air-assisted	189 c A y †	161 b A y	205 cd A y	178 ab A y
Drops	424 a A y	132 bc B z	334 a A z	187 ab B y
Electrostatic	128 d A y	114 c A y	159 d A y	142 b A y
Over-top	335 b A y	113 c B y	270 b A z	133 b B y
Shielded	320 b A y	283 a B y	249 bc A z	204 a A z
Mean	279 A y	161 B y	244 A z	169 B y
LSD ‡	39	39	49	49

† Values in columns followed by common lower-case letters (a–d) or values in rows followed by common upper case letters within years or lower case letters (y and z) between years are not different by Duncan's new multiple range test (P = 0.05).

‡ LSD (P = 0.05) for each year.

Table 3. Standard deviation of spot diameter, in micrometers (μm), deposited on water-sensitive cards attached to topsides and undersides of cotton leaves when sprayed with five different sprayers in 1995 and 1996 in a study in Georgia.

	1995		1996	
Sprayer	Topside	Underside	Topside	Underside
Air-assisted	198 c A y †	159 ab A y	261 cd A y	239 ab A y
Drops	497 a A y	96 bc B z	402 a A z	313 ab B y
Electrostatic	77 d A z	60 c A z	176 d A y	194 b A y
Over-top	211 c A y	62 c B y	236 b A y	140 b B y
Shielded	345 b A y	192 a B y	247 bc A z	233 a A y
Mean	27 A y	114 B z	267 A y	223 B y
LSD‡	73	73	99	99

† Values in columns followed by common lower-case letters (a–d) or values in rows followed by common upper-case letters within years of lower-case letters (y and z) between years are not different by Duncan's new multiple range test (P = 0.05).

‡ LSD (P = 0.05) for each year.

RESULTS AND DISCUSSION

Water-Sensitive Paper Method

Spot diameter on the leaf side was significant regardless of machine by leaf side interaction. The mean spot diameter on water-sensitive paper for sprayers combined was larger on the topsides than on the undersides of leaves for 1995 and 1996 (Table 2). Spot diameter and standard deviation of spot diameter for each of the five sprayers were larger on the topsides than on the undersides of leaves, and significantly larger for drops, over-top, and shielded sprayers in 1995 (Tables 2, 3).

Large spot diameters were associated with larger variations, as compared with smaller spot diameters. The air-assisted and electrostatic sprayers had more similar spot diameters on both sides of leaves than did other sprayers. This finding was attributed to the sprayer's ability to generate spray droplets that can swirl around leaves. In contrast, sprayers using hydraulic nozzles spray mostly large droplets directly onto the undersides of leaves. Droplets drifting and indirectly making contact with the leaf surface may have accounted for a large percentage of small spot diameters on the undersides of leaves.

The air-assisted, electrostatic sprayers or over-the-top sprayers are, therefore, not likely to deposit large droplets on the undersides of leaves. In 1996, the cotton plant canopy was less dense than in 1995, therefore, more large drops generally were found lower in the plant canopy and on the undersides of leaves in 1996 than in 1995 (Tables 2, 4).

Table 4. Mean spot diameter, in micrometers (μm), deposited on water-sensitive cards attached to cotton leaves from top and middle of the plant when sprayed with five different sprayers in 1995 and 1996 in studies in Georgia.

Sprayer	1995		1996	
	Top	Middle	Top	Middle
Air-assisted	155 b A y †	195 c A y	188 ab A y	196 bc A y
Drops	296 a A y	260 b A z	197 ab B z	324 a A y
Electrostatic	125 b A y	117 d A y	147 b A y	155 c A y
Over-top	243 a A y	205 c A y	223 a A y	180 c A y
Shielded	277 a B y	326 a A y	219 a A z	235 b A z
Mean	219 A y	221 A y	195A z	218 A y
LSD ‡	39	39	49	49

† Values in columns followed by common lower-case letters (a–d) or values in rows followed by common upper-case letters within years of lower-case letters (y and z) between years are not different by Duncan's new multiple range test ($P = 0.05$).

‡ LSD ($P = 0.05$) for each year.

Table 5. Standard deviation of spot diameter, in micrometers (μm), deposited on water-sensitive cards attached to cotton leaves from top and middle of plants when sprayed with five different sprayers in 1995 and 1996 in studies in Georgia.

Sprayer	1995		1996	
	Top	Middle	Top	Middle
Air-assisted	148 c A z †	208 a A y	273 ab A y	221 b A y
Drops	340 a A y	255 a B z	307 a A y	404 a A y
Electrostatic	78 c A z	60 b A z	185 b A y	187 b A y
Over-top	156 c A y	120 b A y	197 b A y	179 b A y
Shielded	245 b B y	289 a A y	246 ab A y	232 b A y
Mean	197 A y	185 A z	241 A z	247 A y
LSD ‡	73	73	99	99

† Values in columns followed by common lower-case letters (a–c) or values in rows followed by common upper-case letters within years of lower-case letters (y and z) between years are not different by Duncan's new multiple range test ($P = 0.05$).

‡ LSD ($P = 0.05$) for each year.

Table 6. Percent coverage of spots deposited on water-sensitive cards attached to topsides and undersides of cotton leaves when sprayed with five different sprayers in 1995 and 1996 in Georgia.

Sprayer	1995		1996	
	Topside	Underside	Topside	Underside
Air-assisted	8.2 b A y †	4.9 a A y	10.7 a A y	5.4 a B y
Drops	21.0 a A y	0.4 a B y	11.5 a A z	1.5 ab B y
Electrostatic	1.0 c A y	0.1 a A y	3.0 b A y	1.1 b A y
Over-top	5.7 bc A y	0.1 a B y	9.3 a A y	0.5 b B y
Shielded	20.7 a A y	2.4 a B y	9.8 a A z	1.9 ab B y
Mean	11.3A y	1.6 B y	8.9 A y	2.1 B y
LSD ‡	4.9	4.9	4.0	4.0

† Values in columns followed by common lower-case letters (a–c) or values in rows followed by common upper-case letters within years or lower-case letters (y and z) between years are not significantly different by Duncan's new multiple range test ($P = 0.05$).

‡ LSD ($P = 0.05$) for each year.

Table 7. Percent coverage of spots deposited on water-sensitive cards attached to cotton leaves in the top and middle of plants when sprayed with five different sprayers in 1995 and 1996 in Georgia.

Sprayer	1995		1996	
	Top	Middle	Top	Middle
Air-assisted	3.4 b A z †	9.7 a A y	8.2 a A y	8.0 a A y
Drops	13.3 a A y	8.2 a B y	8.0 a A z	4.9 ab A y
Electrostatic	1.0 b A y	0.1 b A y	3.4 a A y	0.6 b A y
Over-top	4.2 b A y	1.5 b B y	7.6 a A y	2.2 b B y
Shielded	10.7 a A y	12.4 a B y	6.4 a A y	5.3 ab A z
Mean	6.5 A y	6.4 A y	6.7 A y	4.2B z
LSD ‡	4.9	4.8	3.8	3.9

† Values in columns followed by common lower-case letters (a–c) or values in rows followed by common upper-case letters or lower-case letters (y and z) between years are not significantly different by Duncan's new multiple range test ($P = 0.05$).

‡ LSD ($P = 0.05$) for each year.

Plant canopy location (top or middle) was also important for spot diameter only because shielded sprayers deposited different spot diameters in the top than in the middle of the plant in 1995 (Table 4), probably because the nozzles were directed to the middle of the plants. The deviation in spot diameter by plant position was lower for smaller spots than for large spots (Table 5).

Percent coverage of spots on water-sensitive paper was significantly higher on the topsides than on the undersides of leaves for drops, over-top, and shielded sprayers and also numerically higher with all sprayers (Table 6).

The air-assisted sprayer produced better coverage on the undersides of leaves than other sprayers did and good coverage on the topsides in the top and middle of the plant. This result indicates an advantage for air-assisted sprayers for improved deposition in cotton, particularly for the undersides of leaves.

Coverage for all sprayers combined was best in the top of the plant and on the topsides of leaves. Also, coverage on the topsides of leaves in the middle of the plant was better than on the undersides of leaves throughout the plant canopy (Table 7). Coverage was generally poorer with the electrostatic sprayer system. However, because analysis of percent coverage and spot diameter are limited to measuring 71 μm spots or larger, this method may not detect a large percentage of small spots generated by the electrostatic sprayer, possibly accounting for some of the low percent coverage of the cards using the electrostatic sprayer. The electrostatic sprayer also had the lowest spray volume of all the sprayers. The amount of dye washed from the undersides of leaves sprayed with electrostatic system was as much as the quantity washed from the leaves using other application methods.

Leaf-Wash Method

The transmittance through washed solutions from leaves with known deposits of dye had a logarithmic relationship with amounts of dye deposited. Dye deposited on the leaf topsides in μg cm^{-2} = 3.6021 − 0.7833 [ln (Transmittance)], R^2 = 0.98, and dye deposit on the leaf undersides = 3.4865 − 0.7604 [log (Transmittance)], R^2 = 0.99, were used to calculate dye deposit from transmittance values of leaf-wash data. There was no significant difference by sprayer in dye washed from undersides of leaves (Table 8).

The over-top sprayer deposited the highest amount of dye on the topside of the leaf and the drops and the air-assisted sprayers deposited the least amount of dye. The over-top sprayer deposited more dye on the topsides than on the undersides of leaves. The drops sprayer deposited more dye on the undersides than the topsides of leaves and more in the top than in the middle of the plant. The drops sprayer directed the spray pattern toward the top of the plant and the undersides of leaves, indicating that hydraulic nozzles with directed spray did control the deposition location.

Table 8. Mean amount of dye deposited, in micrograms per square cm (μg cm^{-2}), for five sprayers on topsides and undersides of cotton leaves and top and middle of plants, evaluated by the leaf wash method, averaged over a period of 3 yr in Georgia.

	Leaf Side		Plant Position	
Sprayer	Topside	Underside	Top	Middle
Air-assist	0.135 b A †	0.157 a A	0.160 a A	0.132 a A
Over-top	0.214 a A	0.162 a B	0.207 a A	0.169 a A
Drops	0.117 b B	0.182 a A	0.180 a A	0.119 a B
Electrostatic	0.173 ab A	0.164 a A	0.219 a A	0.118 a B
Shielded	0.155 ab A	0.173 a A	0.161 a A	0.167 a A
LSD‡ by				
Sprayer	0.060	0.060	0.056	0.056
Location	0.049	0.049	0.039	0.039

† Values in columns followed by common lower-case letters or values in rows followed by common upper-case letters are not significantly different. Duncan's new multiple range test (P = 0.05) applied to transmittance data and transferred to dye values from calibration equations of known amounts of dye washed from leaves.

‡ LSD (P = 0.05) for sprayer or location.

Table 9. Mean net fluorescence area from a 12 m length of string for five sprayers at the top, middle, and bottom of cotton plants in 1994, 1995, and 1996 in Georgia.

	Mean Net Fluorescence Area		
Sprayer	Top	Middle	Bottom
		1994	
Air-assisted	136 650 a A †	34 886 a B	11 630 a C
Drops	34 339 bc A	9 354 b B	4 495 b B
Electrostatic	65 951 ab A	4 227 b B	4 016 b B
Over-top	43 151 bc A	3 779 b B	2 334 b B
Shielded	30 000 c A	8 971 b B	4 635 b B
Mean	62 018	12 243	5 422
		1995	
Air-assisted	37 010 a A	10 533 ab AB	6 273 a B
Drops	8 853 a A	4 744 abc A	1 164 c B
Electrostatic	15 710 a A	2 100 c B	1 284 bc B
Over-top	14 593 a A	2 609 bc B	1 579 b B
Shielded	10 973 a A	9 891 a A	9 043 a A
Mean	17 428	5 975	3 869
		1996	
Air-assisted	76 156 a A	36 550 a A	28 871 a A
Drops	11 970 b A	3 834 b AB	1 543 b B
Electrostatic	45 968 ab A	2 741 b B	808 b B
Over-top	15 011 b A	10 042 b B	364 c C
Shielded	27 271 ab A	3 188 b AB	2 717 b B
Mean	35 275	11 271	6 861

† Values of actual means in columns within years followed by common lower-case letters or values in rows followed by common upper-case letters are not significantly different. Duncan's new multiple range test (P = 0.05) applied to log transformed data and transferred to actual data (Steel and Torrie, 1960).

The electrostatic sprayer system provided greater coverage in the top of the plant canopy than in the bottom because the small droplets did not drift down to the middle of the plants, but instead were deposited mostly on the first available plant surface. The shielded sprayer deposited similar amounts of dye on the topsides and undersides of leaves and also to the top and middle of the plant canopy.

The hydraulic nozzles (five per row) of the shielded sprayer directed the spray about the same throughout the plant. The air-assisted sprayer also deposited the dye uniformly throughout the plant with turbulent air.

String Method

Each year the variance associated with the amount of total net fluorescence varied widely, suggesting that combining the data for the 3 yr would not yield meaningful results. We were not interested in year-to-year differences, but in whether the performance of machines were similar each year. Therefore, data were analyzed separately each year using actual values and by log transformation. Log transformed values (Steel and Torrie, 1960) gave improved mean separation by Duncan's new multiple range test and were used to separate the data (Table 9).

All sprayers in 1994 deposited a significantly greater amount of fluorescent dye in the top than in the middle and bottom of the plant canopy (Table 9). The air-assisted sprayer placed significantly less fluorescent dye at the bottom than the middle of the plant canopy. The air-assisted sprayer also placed significantly more fluorescent dye at all plant canopy positions than did the other sprayers tested, except the electrostatic sprayer system in the top of the plant canopy.

In 1995 all except the shielded sprayer placed significantly more fluorescent dye into the top than the bottom of the plant canopy. Air-assisted, drops, and shielded sprayers placed similar amounts of fluorescent dye into the top and middle of the canopy. The shielded sprayer also deposited similar amounts of fluorescent dye into the top, middle, and bottom of the plant canopy. The air-assisted sprayer deposited the most fluorescent dye into the top portion of the canopy, but not a significantly greater amount than other sprayers did. Of all the sprayers, the electrostatic sprayer deposited the least fluorescent dye into the middle of the canopy, but not significantly fewer than the drops and over-top sprayers. The drops sprayer deposited the least fluorescent dye in the bottom of the plant canopy, but not a significantly lower amount than the electrostatic sprayer did. The least fluorescent dye was recorded near the bottom of plants applied with electrostatic and drops sprayers.

In 1996, all sprayers except the air-assisted sprayer deposited a significantly greater amount of fluorescent dye into the top than into the bottom of the plant canopy (Table 9). The electrostatic and over-top sprayers also deposited more fluorescent dye than other sprayers into the middle of the canopy. The over-top sprayer deposited more fluorescent dye into the middle than the bottom of the plant canopy.

In the top of plants, the air-assisted sprayer deposited more fluorescent dye than all other sprayers did, but this amount was not significantly greater than that produced by the electrostatic and shielded sprayers. The air-assisted sprayer deposited significantly more fluorescent dye in the middle and bottom of the plant canopy than all other sprayers. The over-top sprayer deposited less fluorescent dye in the bottom of the plant canopy than all other sprayers did.

The air-assist sprayer with high air turbulence apparently forced the fluorescent dye down into the plant canopy and deposited more dye on the strings at the top, middle, and bottom of the canopy than the other sprayers did in all three years. All sprayers deposited more dye on strings in the top of the plant canopy than in the middle or bottom. The over-top sprayer was configured with hydraulic nozzles to spray mostly the top of plants, and results indicate effective deposition of dye in the top of plants. The shielded sprayer with hydraulic nozzles positioned down into the foliage sprayed dye into all parts of plants, with decreasing amounts of dye toward the bottom of plants. The electrostatic sprayer system uses air-assistance to force jets of air into plants; however, the small droplets generated by the system did not effectively penetrate down into the plant and attach to collector strings either year.

CONCLUSIONS

Spot diameters collected on water-sensitive paper from five sprayers in cotton plants were larger on the topsides than on the undersides of leaves. Variation in spot diameters coincided with the size of the spots, with large variations in the size of large spots and small variations in the size of small spots.

Sprayers with hydraulic nozzles had a higher percentage of spray materials directed onto the leaf surface as large droplets. Small droplets generally were deposited onto the undersides of leaves. Air-assisted and electrostatic sprayers produce turbulent air that deposited droplets of similar sizes on both sides of leaves. For all five sprayers, coverage was greater on the topsides than on undersides of leaves, with more in the top than in the bottom of plants. The air-assisted sprayer provided better coverage on the undersides of the leaves than other sprayers did, and it gave good coverage on the topsides of leaves.

Measurements taken with the leaf-wash method showed, as might be expected, that the hydraulic nozzles deposited most of their sprayed material where the nozzles were positioned and directed. Over-the-top sprayers, which are aimed mostly down, deposited their sprayed materials onto the top of leaves and mostly into the top of the plant. The drops sprayers, which apply from the top and the sides, deposited most of their spray materials on the top and sides of the upper part of the plant. The shielded drops sprayer, which had more nozzles that reached farther into the plant, deposited material throughout the top and middle of the plant canopy and had the further advantage of depositing material on the undersides of the plant's upper leaves. The air-assisted sprayer deposited material throughout the plant canopy and on both sides of leaves.

Total net fluorescence on collector strings varied between years and among the five sprayers. Net fluorescence generally decreased from top to bottom of the plant canopy for all three years. The air-assisted sprayer had higher net fluorescence than other sprayers throughout the plant canopy, indicating that turbulence from forced air carried the spray material into the plant canopy. Net fluorescence was also high in locations where hydraulic nozzles directed the spray material.

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