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CANOPY PENETRATION AND DEPOSITION OF BARRIER SPRAYS FROM ELECTROSTATIC AND CONVENTIONAL SPRAYERS[1]

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ABSTRACT. An experimental study was conducted to investigate the usefulness of electrostatic and conventional sprayers for barrier applications. Two conventional and three electrostatic sprayers were used in the study. Usefulness of the sprayers was rated based on penetration of spray into and deposition onto 2 sides of leaves on natural vegetation. Bifenthrin (Talstar™ adulticide) was applied at labeled rate, fluorescent dye was added to the tank mix as tracer, and all sprayers applied the dye and insecticide at the same rate. The results indicated that sprayers producing larger droplets produced significantly higher deposition on vegetation in barrier applications than the sprayers producing smaller droplets. Sprayers with higher air velocity at the nozzle discharge proved significantly better for barrier sprays than the sprayers with lower air velocity. Electrostatic sprayers did not show any improvement in deposition on vegetation or in penetration into vegetation over the conventional sprayers. There was no difference in deposition between truck-mounted and backpack sprayers.

KEY WORDS Barrier sprays, deposition, penetration, electrostatic, vector control

INTRODUCTION

Barrier treatments for mosquito control involve the application of insecticidal products onto localized areas of vegetation or natural/man-made surfaces where mosquitoes may rest during the day. The application technique is intended not to eliminate but to reduce the adult insect population. Barrier treatments have the potential to limit or prevent mosquitoes and other insects from moving into an area surrounded by that treatment. Perich et al. (1993) mentioned five conditions that need to be met for barrier spraying to be effective: 1) the mosquito species to be controlled must rest in a sylvatic habitat, fly into open urban area to bloodfeed, and return to the sylvatic to rest; 2) clear demarcation must exist between the sylvatic and the human dwelling zone; 3) breeding sites should not be inside the perimeter of the barrier zone; 4) the insecticide used must have long residuality; and 5) adult mosquitoes must contact the insecticide.

Barrier spraying in the 1960s along Thailand–Malaysia border helped control the spread of malaria (Huehne 1971). Perich et al. (1995) demonstrated in Guatemala that a single ground-level barrier spray application of insecticide provided significant suppression of the natural sand fly population and prevented sand flies (*Phlebotomus papatasi* Scopoli) from reaching the designated protected area for >80 days. Courshee (1990) discussed the use of barrier spraying as a means of controlling locusts (*Schistocera gregaria* Forskal). He narrates the purpose of barrier spraying as to limit insecticide application to a small proportion of the total area. This would enable application equipment to cover large areas in the given time using a fraction of the insecticide.

Given the potential benefits of barrier sprays on vegetation to control mosquitoes and other insects at reduced pesticide use and cost, the question arises which application system is suitable for barrier treatments. At this time, no standard method exists to evaluate residual sprays. Penetration of spray into the canopy and deposition on foliage (a possible resting place for mosquitoes and other insects) can be treated as foundations to effectiveness of any barrier treatment. Toxicity, longevity, and some other indicators would depend on deposition. It should be noted that the role of application equipment vanishes after the active ingredient is deposited on the target.

Spray penetration into and deposition on orchard tree canopies have been extensively studied (Salyani et al. 1988, Juste et al. 1990, Salyani and Whitney 1990, Hall et al. 1991, Koo et al. 2000, Farooq and Salyani 2002) using various air-assist sprayers for agricultural use. Spray penetration into canopies from aerial spraying has also been studied (Bouse 1969, Dix and Marchant 1984, Potter 1984, Brown et al. 2005).

Use of electrostatic sprayers has been studied for agricultural spraying (Kirk et al. 2001, Kang et al. 2004). For public health pest management, the use of aerosol-range droplets makes their control difficult during dispersion because of their suscep-

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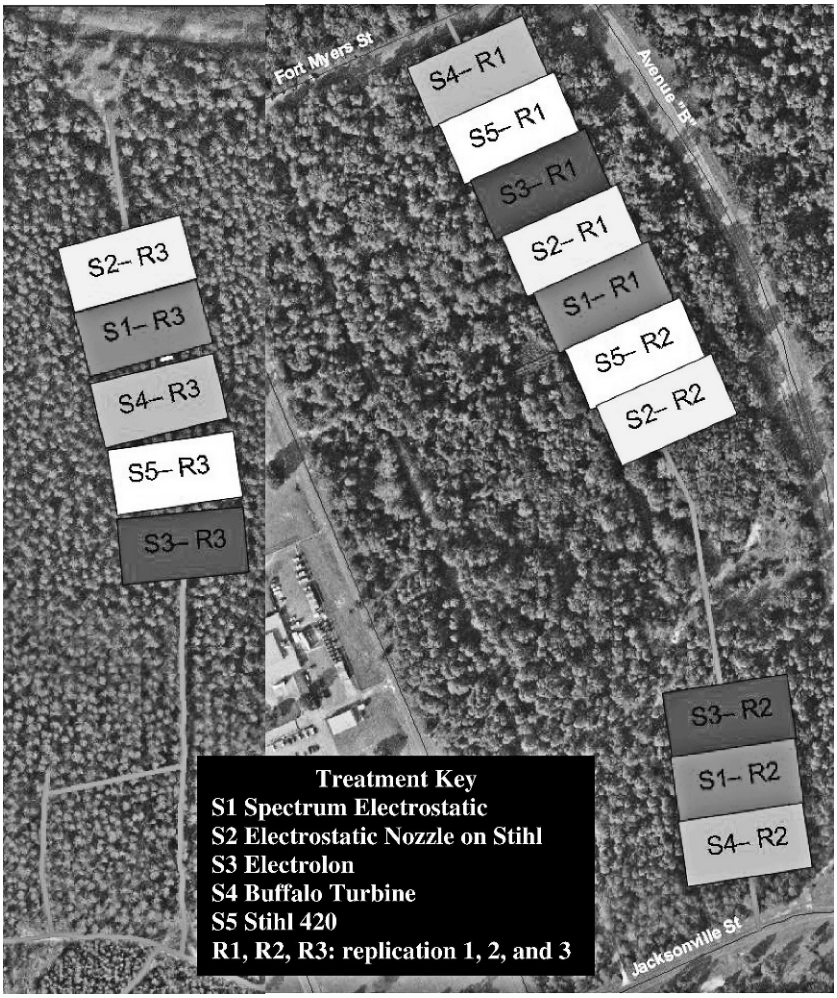

Fig. 1. Field layout.

tibility to atmospheric wind and turbulence. For barrier treatment to be effective, these droplets should also deposit on the underside of the foliage, the favorite site for mosquitoes to rest. Whitmore et al. (2001) compared electrically charged and conventional sprays for control of house flies (*Musca domestica* Linnaeus) and mosquitoes in the laboratory. The charged spray increased knock-down rate but did not affect mortality.

This study was aimed at investigating the effectiveness of barrier sprays from electrostatic and conventional sprayers through measurement of penetration into and deposition onto natural vegetation.

MATERIALS AND METHODS

The study was conducted on natural understory vegetation in a forest stand at Camp Blanding Joint Training Center, Starke, FL (29°59′N, 81°57′W). Two test sites were selected based on the canopy similarity and the availability of the required area. One site was used for 2 replicates while the other was used for the 3rd replicate (Fig. 1). Each spray plot in a treatment was 60 m long on an abandoned road and consisted of canopy on both sides of the road. All treatments within a replication were assigned randomly. Four sampling locations were selected in each plot, 2 on each side of the road and 10–20 m apart and at least 15 m from each edge. Five sprayers were replicated 3 times, making a total of 15 plots.

Sprayers

Two conventional and 3 electrostatic sprayers were used in the study. One sprayer in each category was truck/trailer mounted and the rest were backpack sprayers. The details of these sprayers are as below.

Buffalo Turbine mist sprayer (Model CSM2; Buffalo Turbine, Springville, NY) is a truck/

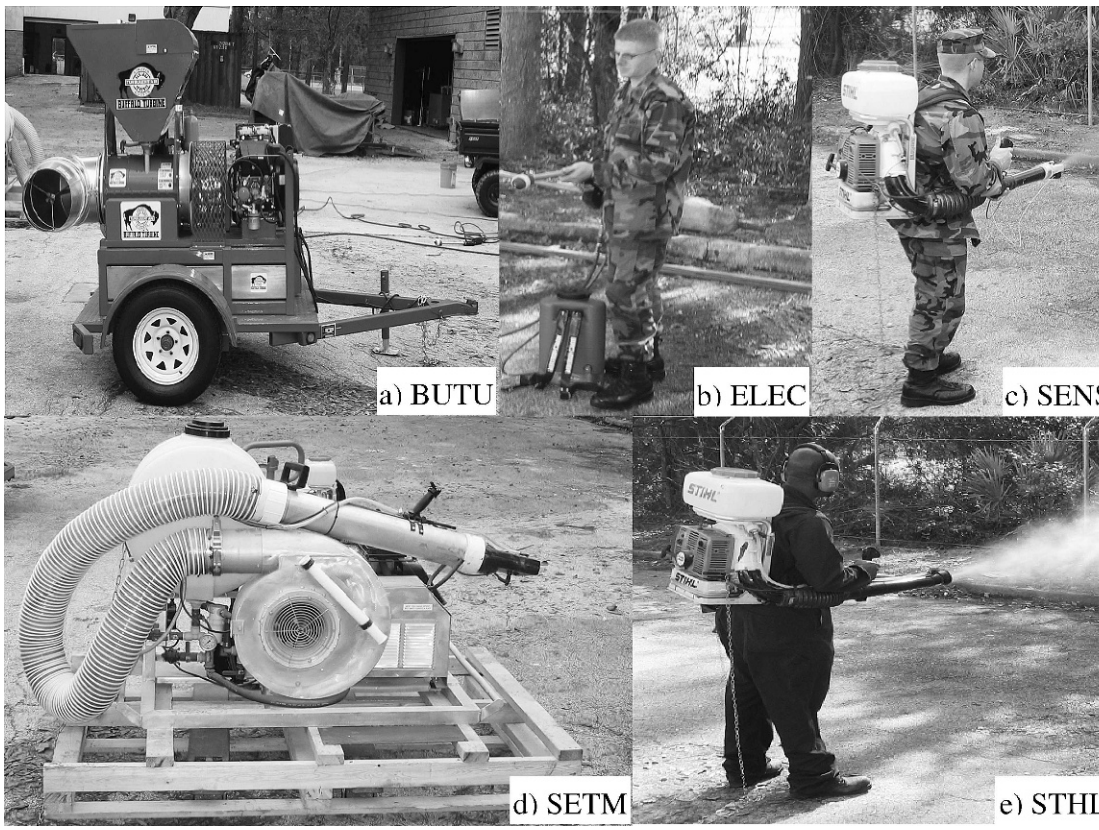

Fig. 2. Sprayers used in the study. a. BUTU, Buffalo Turbine; b. ELEC, Electrolon; c. SENS, Spectrum Electrostatic Nozzle on Stihl; d. SETM, Spectrum Electrostatic Truck Mounted; e. STHL, Stihl.

trailer-mounted unit (BUTU; Fig. 2a). It is powered by a 13.4-kW Lombardini diesel engine. The spray mist is created by a blower capable of an airflow of up to 283 m^3/min at a speed of 280 km/h. Four Teejet 8502 nozzles (Spraying Systems, Co, Wheaton, IL) in a cluster are placed at the center of the airstream that discharge along the airflow. The sprayer can generate a flow rate up to 37.9 liters/min at 2,758 kPa. The sprayer has a tank capacity of 190 liters.

Electrolon BP-2.5™ (Electrostatic Spraying Systems, Watkinsville, GA) is a backpack electrostatic mist blower (ELEC; Fig. 2b) that utilizes pressurized air from an auxiliary source with minimum supply of 0.23 m^3/min at 414 kPa. The sprayer uses an air-assistance induction-charge nozzle. The liquid to be applied is fed from the tank by gravity and is then siphoned to the handgun by movement of the pressurized air being forced out of the nozzle. The force of the pressurized air shatters the liquid at the nozzle to form the spray mist. The spray droplets are negatively charged using 2 9-V rechargeable batteries. This sprayer has a net weight of 4.1 kg. The ELEC has a tank capacity of 15 liters and a flow rate of approximately 194 ml/min.

The Stihl (Model SR 420; Andreas Stihl, Waiblingen, Germany) is a mist blower (STHL; Fig. 2e) powered by a 2.5-kW single-cylinder 2-cycle Stihl engine. The mist blower has the capability to produce an airflow rate of 17.7 m^3/min and an air velocity of 288 km/h. The sprayer uses an air-shear atomization head with screens to alter the spray release pattern. The flow rate can be set from a control knob placed near the head, which has 6 metering nozzle settings to adjust the flow rate. The flow rate ranges from 0.14 to 3.0 liters/min. The sprayer has a pesticide tank capacity of 14 liters. The bystander noise level for the sprayer is 75 dB and its net weight is 11 kg.

Spectrum Electrostatic Nozzle on Stihl SR 420 (SENS; Fig. 2c) is a modification of the backpack sprayer to an electrostatic sprayer. The conventional head on the STHL was replaced by Spectrum 3010 (Spectrum Electrostatic Sprayers, Houston, TX) nozzle. The nozzle is based on the same principle as the one used for Spectrum 4010.

Spectrum 4010 (Spectrum Electrostatic Sprayers, Houston, TX) is a truck-mounted electrostatic mist sprayer powered by a 10.4-kW, 1-cylinder 4-cycle Kohler engine (SETM; Fig. 2d). The sprayer is equipped with an air-shear electrostatic atom-

Table 1. Application parameters and tank mixtures.

Sprayer[1]	Flow rate (liters/min)	Travel speed (km/h)	Insecticide (ml/liter)	Dye (g/liter)	Sprayer air velocity (m/s) 61 cm away
BUTU	4.67	8.0	2.11	1.91	30.5
ELEC	0.20	3.2	19.70	17.77	0.7
SENS	0.84	3.2	4.69	4.23	29.3
SETM	6.75	8.0	1.46	1.32	31.0
STHL	2.77	3.2	1.42	1.28	30.3

[1] BUTU, Buffalo Turbine; ELEC, Electrolon; SENS, Spectrum Electrostatic Nozzle on Stihl; SETM, Spectrum Electrostatic Truck Mounted; STHL, Stihl.

ization nozzle mounted at the end of a flexible duct. Charging of the droplets is by conduction and it uses high voltages. This mist sprayer has the capability to produce an air velocity of 306 km/h. The sprayer has a net weight of 122.5 kg. The sprayer has a tank capacity of 114 liters and can deliver a flow rate up to 26.5 liters/min.

Spray characteristics

Prior to the tests, each sprayer was calibrated to determine the flow rate. The droplet size spectrum for each sprayer was measured with the Army Insecticide Measuring System (AIMS) (Model DCIII; KLD Labs, Inc., Huntington, NY) while spraying water. The AIMS utilizes a hot-wire probe as sensor that is cooled by droplets (Mahler 1985). The resulting electronic signal is converted to the droplet size. For droplet size measurement, the probe was held directly in front of the nozzle and perpendicular to the spray direction. The appropriate sprayer air velocity for the AIMS is between 5 and 7 m/sec. The instrument was set to measure approximately 1,000 droplets. The system software, in addition to many other parameters, computed mass median diam (volume median diam [$D_{V0.5}$]), Sauter mean diam, $D_{V0.1}$ and $D_{V0.9}$. Data were used to calculate percentage of volume in droplets <50 μm. The measurements were replicated 3 times.

Spray material

Talstar™ (bifenthrin 7.9%; FMC Corporation, Philadelphia, PA) was applied at labeled rates of 21.8 ml/300 m of treated row. Caracid Brilliant Flavine FFS fluorescent dye (Carolina Color and Chemical Co., Charlotte, NC) was added to the tank mix to serve as tracers for the deposition studies. As the sprayers used in the study had different flow rates and travel speeds, the concentration of insecticide and dye in the tank mix was varied so that each sprayer applied the same amount of dye and insecticide per 300 m of treated row. Tank samples from each of the sprayer tanks were collected at the end of the treatments to check the actual dye concentration in the spray mixture. The flow rate, and insecticide and dye concentrations for each spray tank mix are presented in Table 1.

Weather conditions

Weather conditions during spray applications are summarized in Table 2. The average wind speed, temperature, and relative humidity are presented, along with the range of conditions for applications using the 5 sprayers. For the trial, the wind speed ranged from 0.0 to 4.0 km/h, temperature from 27.2 to 32.3°C, and relative humidity from 49% to 73%. As shown in Table 2, there was not much variation in temperature and relative humidity during applications with the different sprayers.

Sampling

Four sampling lines (A, B, C, and D) were selected in each spray plot, 2 on each side of the road. The 2 lines on each side were selected in the middle of the row 10–20 m apart from each other (Fig. 3). The sampling lines were at least 15 m from edge of the spray plot. Along each sampling line, leaf samples were collected at 8 locations consisting of 2 heights (1 and 2 m) above ground and 4 distances (0, 1, 3, and 5 m) into the canopy.

Table 2. Summary of weather conditions during applications.

Sprayer[1]	Wind speed (range) (km/h)	Temperature (range) (°C)	Relative humidity (range) (%)
BUTU	1.2 (0.0–2.4)	29.7 (28.2–31.1)	59 (50–69)
ELEC	1.9 (1.5–2.4)	29.5 (28.3–30.8)	60 (49–71)
SENS	0.7 (0.0–1.5)	30.1 (28.3–32.0)	61 (53–69)
SETM	3.9 (3.9–4.0)	29.7 (28.0–31.4)	61 (49–73)
STHL	2.7 (0.8–3.7)	29.9 (27.2–32.3)	63 (49–72)

[1] BUTU, Buffalo Turbine; ELEC, Electrolon; SENS, Spectrum Electrostatic Nozzle on Stihl; SETM, Spectrum Electrostatic Truck Mounted; STHL, Stihl.

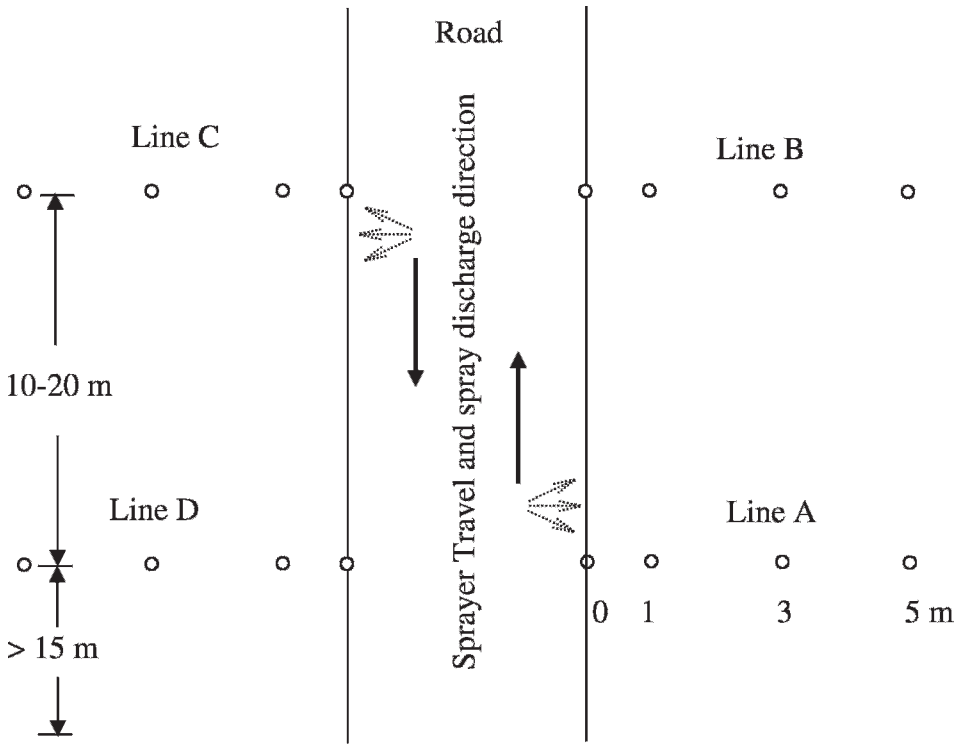

Fig. 3. Overview of sampling plots showing sampling lines and canopy depths.

Samples were collected between 10 and 40 min after completion of the spray in each plot.

At each sampling location, 2 leaves were collected and washed, the top and bottom separately, with 3 ml of methanol, using a handheld dual-side leaf washer (Carlton 1996). The dye concentration in the samples was measured with spectrofluorophotometer (Model RF5000U; Shimadzu, Kyoto, Japan) and related to deposition of insecticide based on tank sample concentrations.

RESULTS

Spray characteristics

The droplet size data from AIMS (Table 3) indicate that the ELEC sprayer resulted in the finest droplet size spectra, producing $D_{V0.5}$ of 49.7 μm, resulting in 51% volume in droplets <50 μm. The BUTU produced the largest droplets with $D_{V0.5}$ of 204.7 μm and only 2.3% of volume contained in droplets <50 μm. The BUTU produced significantly larger $D_{V0.5}$ than other sprayers except SETM. The STHL produced significantly smaller and larger $D_{V0.5}$ than BUTU and ELEC, respectively. The ELEC produced statistically smaller $D_{V0.5}$ than all sprayers except SENS. The comparison for $D_{V0.1}$ and $D_{V0.9}$ were, in general but with some exceptions, similar to $D_{V0.5}$. The ELEC produced significantly higher percentage of the volume in droplets <50 μm compared with all other sprayers.

Deposition

Effect of sprayers: The overall mean deposition of AI from all the sprayers ranged from 8.8 to

Table 3. Flow rate and droplet size characteristics of sprayers.

Sprayer[1]	Flow rate (liter/min)	$Dv_{0.1}$ (μm ± SD)[2]	$Dv_{0.5}$ (μm ± SD)	$Dv_{0.9}$ (μm ± SD)	% Vol <50 μm[3]
BUTU	4.67	97.0 ± 28.1 a	204.7 ± 56.9 a	375.5 ± 98.7 ab	2.3 ± 2.1 b
ELEC	0.20	12.9 ± 3.9 d	49.7 ± 18.8 d	117.9 ± 36.7 d	50.7 ± 13.0 a
SENS	0.84	53.3 ± 6.9 c	135.4 ± 10.0 cd	216.0 ± 44.2 cd	8.7 ± 2.6 b
SETM	6.75	80.7 ± 4.1 ab	186.3 ± 4.7 ab	414.7 ± 110.1 a	4.2 ± 1.1 b
STHL	2.77	63.3 ± 14.8 bc	162.7 ± 32.6 bc	285.9 ± 126.8 bc	7.0 ± 2.9 b

[1] BUTU, Buffalo Turbine; ELEC, Electrolon; SENS, Spectrum Electrostatic Nozzle on Stihl; SETM, Spectrum Electrostatic Truck Mounted; STHL, Stihl; Means with the same letter in a column are not significantly different.

[2] Means within each column with different letters were significantly different ($P < 0.05$). $Dv_{0.5}$, volume median diameter, $Dv_{0.1}$ and $Dv_{0.9}$, Sauter mean diameter.

[3] % Vol <50 μm = Percent of spray volume contained in spray droplets <50 μm in diameter.

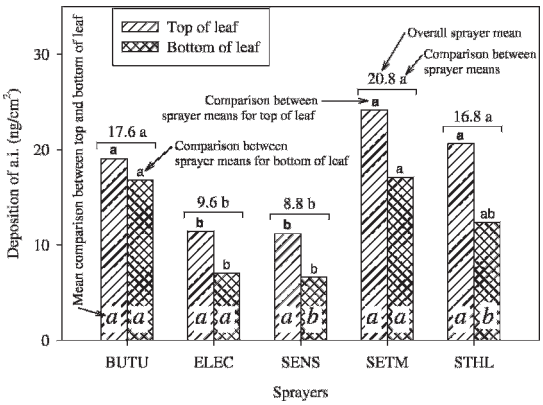

Fig. 4. Comparison of mean deposition from different sprayers. BUTU, Buffalo Turbine; ELEC, Electrolon; SENS, Spectrum Electrostatic Nozzle on Stihl; SETM, Spectrum Electrostatic Truck Mounted; STHL, Stihl. Means with same letters are not significantly different.

20.8 ng/cm^2 of sample surface (Fig. 4). The mean deposition from BUTU, SETM, and STHL was significantly higher than the other 2 backpack sprayers. However, the deposition from these 3 sprayers was not significantly different from each other. At the same time, the difference in deposition from SENS and ELEC was not significant, either. The mean deposition from these sprayers on top and bottom sides of the leaf showed the same trend as the overall mean deposition, except that the deposition on bottom of the leaf from STHL was not significantly different from SENS and ELET.

Figure 5 shows mean deposition from the different sprayers at 1.0- and 2.0-m heights above ground. At 1.0-m height, the SETM resulted in the highest deposition but it was not significantly higher than the deposition from STHL. The SENS resulted in the lowest deposition but significantly lower than the deposition from SETM and STHL only. At this height, the depositions from BUTU, SETM, and STHL were not significantly different at both the top and bottom of the leaf, while the depositions from ELEC and SENS were not different. At 2.0-m height, the BUTU provided the highest mean deposition but was not significantly different from SETM and STHL. At this height, the ELEC resulted in the lowest deposition but the difference between ELEC and SENS was not significant. At this height, the comparison between depositions on top and bottom side of the leaves from all sprayers showed similar trend as the average deposition. The exception to the trend was the deposition from STHL on bottom of the leaves that was significantly lower than deposition from BUTU only.

In general, the deposition decreased with increasing canopy depth. Figure 6 shows deposition from different sprayers at various depths. At the canopy edge (depth = 0), the SETM resulted in the significantly highest deposition. At 1.0-m canopy depth, the STHL produced the highest deposition but the difference from the BUTU and SETM was not significant. The ELEC resulted in the lowest deposition at this canopy depth. Figure 6 also shows the least relative difference in deposition between sprayers. At 3.0-m canopy depth, the BUTU had the highest deposition. At this depth, ELEC, SENS, and SETM sprayers had significantly lower deposition compared with the BUTU. At 5.0-m depth, the BUTU had the highest deposition among the sprayers.

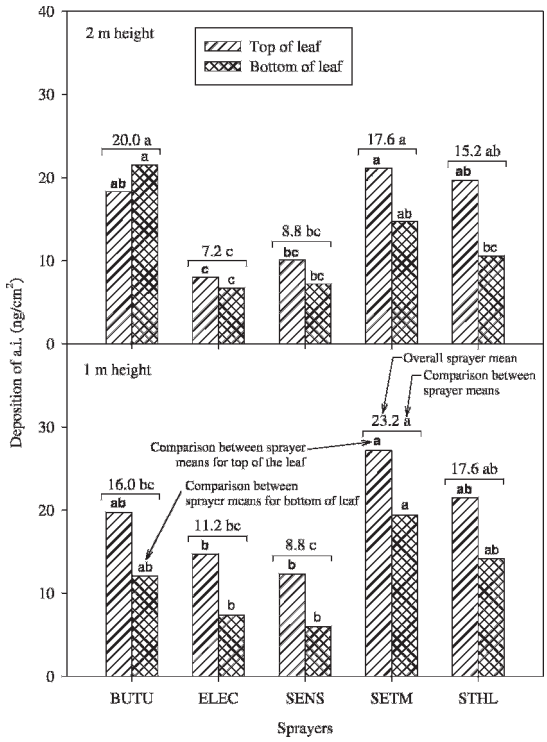

Fig. 5. Comparison of mean deposition from different sprayers at 2 canopy heights. BUTU, Buffalo Turbine; ELEC, Electrolon; SENS, Spectrum Electrostatic Nozzle on Stihl; SETM, Spectrum Electrostatic Truck Mounted; STHL, Stihl. Means with same letters are not significantly different.

Leaf side: On average, all the sprayers resulted in higher deposition on top side of the leaf compared to the bottom side (Fig. 4). However, the difference was only significant in the case of SENS and STHL sprayers. The least difference between deposition on top and bottom side of the leaf was recorded from BUTU. When looked at separately for 2 heights above ground, all the sprayers resulted in numerically higher deposition on the top side than on the bottom side except BUTU at 2.0-m height (Fig. 5). At this height, the deposition from BUTU on bottom of the leaves

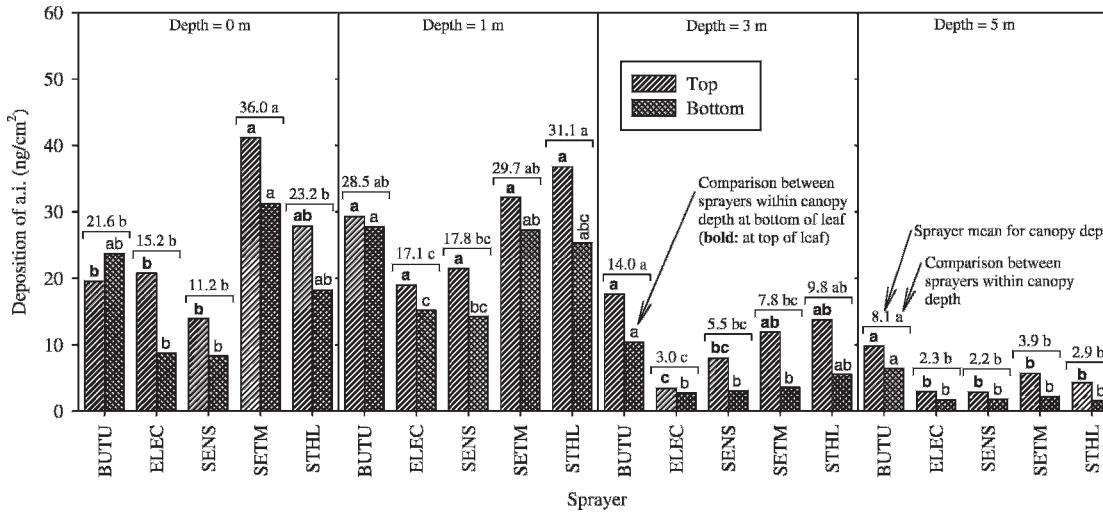

Fig. 6. Deposition from different sprayers at various canopy depths. BUTU, Buffalo Turbine; ELEC, Electrolon; SENS, Spectrum Electrostatic Nozzle on Stihl; SETM, Spectrum Electrostatic Truck Mounted; STHL, Stihl. Means with same letters are not significantly different.

was higher than the deposition on the top of the leaves. The difference in deposition on top and bottom of the leaf at both heights was not significant except for BUTU at 1.0-m height where the deposition on top of the leaves was higher than the deposition on bottom of the leaves.

As shown in Fig. 6, the comparison in deposition at various canopy depths indicated that deposition on top of the leaf was higher than the deposition on bottom of the leaf, from all sprayers at all canopy depths except from BUTU at the canopy edge. At 3.0-m canopy depth, the deposition from SENS, SETM, and STHL sprayers on top of the leaf was significantly higher than the deposition on bottom of the leaf.

Height above ground: All the sprayers resulted in higher deposition at 1.0-m height than the deposition at 2.0-m height except BUTU. However, the difference was not significant in any case. At both top and bottom of the leaf, the difference in mean deposition between heights was not significant for all sprayers except BUTU. The BUTU sprayer resulted in significantly higher deposition on the bottom of the leaf at 2.0-m height than the deposition at 1.0-m height.

Spray penetration: The spray deposition from all the sprayers decreased with increasing distance from the sprayer, i.e., the canopy depth. This characteristic of the spray deposition indicates the extent of spray penetration in to the canopy. Figure 7 shows change in mean deposition from different sprayers with increasing canopy depth from 0 to 5 m. The results show that the SETM had peak mean deposition at the canopy edge while all the other sprayers had their peak mean depositions at 1.0-m canopy depth. The SETM and STHL had the highest rate of reduction in deposition with the increasing canopy depth. The BUTU sprayer had the most uniform deposition throughout the canopy depth investigated. From SETM, ELEC, and STHL sprayers, the deposition stayed higher up to 1-m depth and then decreased significantly. The difference in deposition was not significant between 0- and 1-m depths as well as between 3- and 5-m depths. The deposition from SENS was highest at 1-m depth and significantly reduced away from the peak. The BUTU sprayer produced higher deposition at 1 m than at the canopy edge. The deposition at both these depths was significantly higher than the deposition at 3- and 5-m depths. However, the deposition at the last 2 depths was similar.

Figure 8 shows spray penetration at 2 canopy heights using different sprayers. At 1-m height, the SETM sprayer shows a rapid decrease in

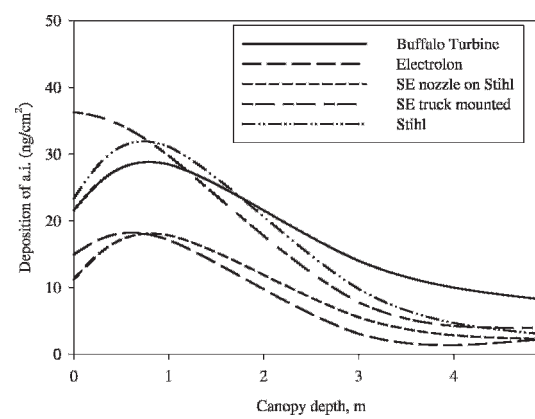

Fig. 7. Penetration (mean deposition at canopy depths) of spray into canopy. SE, Spectrum Electrostatic.

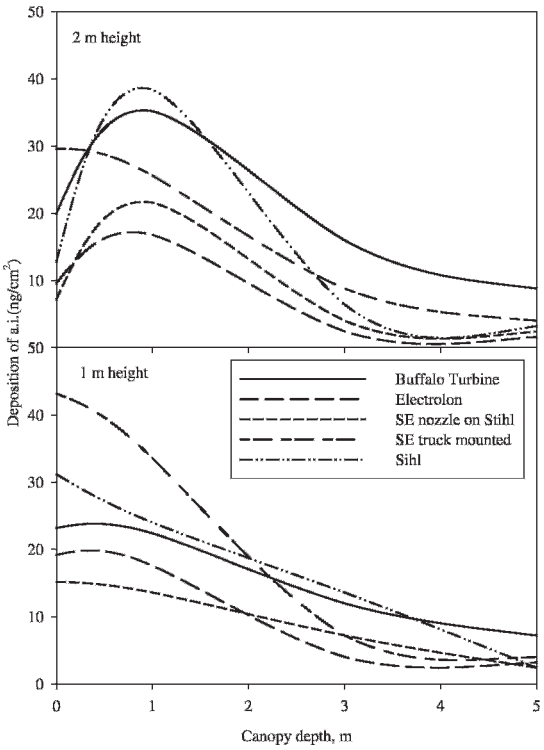

Fig. 8. Spray penetration at 2 canopy heights. SE, Spectrum Electrostatic.

deposition with increasing canopy depth while the BUTU showed the lowest rate of decrease followed by the STHL sprayer. This means the BUTU and STHL resulted in better penetration than did the SETM sprayer. It should be noted that the 3 sprayers did have difference in mean deposition at 1.0-m height (Fig. 5). The ELEC and SENS sprayers had good penetration but their overall deposition was much less than the BUTU, SETM, and STHL sprayers. At 2-m height, the BUTU and SETM sprayers resulted in better penetration compared with the other three sprayers. At 2-m height, the STHL deposited larger part of its spray at 1-m depth and there was little penetration beyond the 3-m canopy depth.

DISCUSSION

For barrier spraying, the coverage of the target vegetation is an important characteristic. The higher the coverage, the higher the chances are for the insects to acquire the lethal dose during their contact with the vegetation. The reported data indicate that the larger droplets are suited for barrier sprays. The smaller droplets, having their ability to float around, were able to escape deposition on vegetation. It is suspected that many of these droplets even escaped the measurement depth of 5 m. That explains why the lower levels of deposition were recorded in the front and rear zones of the canopy at the same time while using ELEC sprayer. The other important factor was the airspeed out of the spray head. Airspeed assists in spray penetration as well as deposition. The same-sized droplets have better chances of deposition in the presence of higher airspeed. In same level of airspeed, larger droplets have better chance of deposition than the smaller droplets. This might partially explain why the SENS performed more poorly than the STHL, even though the airspeeds were not much different (Table 1). The results indicated that deposition was not increased significantly when an electrostatic charge was applied to the spray droplet for either the truck-mounted sprayers or the backpack systems.

Among the 5 sprayers, the BUTU provided the better spray penetration as well as deposition, specifically at the 2-m canopy height. The STHL followed BUTU but only at 1-m canopy height. However, this sprayer being a handheld can be directed towards the target on demand. The SETM provided better deposition up to 1-m canopy depth (the near canopy) but had poor penetration. It would be a better choice for narrow band and not when penetration is the requirement.

Analysis of the results and the discussion presented leads us to conclude the following: Sprayers producing larger droplets proved significantly better than the sprayers producing smaller droplets for deposition on vegetation in barrier applications. Sprayers with higher air velocity at the nozzle discharge have proven significantly better than the sprayers with lower air velocity. Electrostatic sprayers have not shown any improvement in deposition on vegetation over the conventional sprayers. There was no difference in deposition between truck-mounted and backpack sprayers. However, the truck-mounted should be preferred over backpack for larger areas.

Among the sprayers evaluated, BUTU would be better if spray penetration as well as deposition is required specifically at upper parts of the canopy. The STHL backpack would be more appropriate if deposition within 1 m of the canopy height is desirable. The SETM would be a better choice if the required barrier depth is between 1 and 2 m into the canopy. It should be noted that these recommendations are based only on deposition and penetration.

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REFERENCES CITED

Bouse LF. 1969. Aerial spray penetration through foliage canopies. *Trans ASAE* 12:86–89.

Brown JR, Reynolds WH, Palmisano C, Taylor V. 2005. Aerial optimization and canopy penetration study of Dibrom 14 concentrate. *J Am Mosq Control Assoc* 21:106–113.

Carlton JB. 1996. *Dual side plant leaf washer and immersion cell* [Internet]. United States patent US 5503005 [accessed March 14, 2008]. Available from: http://www.freepatentsonline.com/5503005.html.

Cilek JE, Hallmon CF. 2006. Residual effectiveness of pyrethroid-treated foliage against adult *Aedes albopictus* and *Culex quinquefasciatus* in screened field cages. *J Am Mosq Control Assoc* 22:725–731.

Courshee RJ. 1990. Desert locusts and their control. *Int Pest Control* 32:16–18.

Dix AJ, Marchant JA. 1984. A mathematical model of the transport and deposition of charged spray drops. *J Agric Eng Res* 30:91–100.

Farooq M, Salyani M. 2002. Spray penetration into the citrus tree canopy from two air-carrier sprayers. *Trans ASABE* 45:1287–1293.

Hall FR, Cooper JA, Ferree DC. 1991. Orchard geometry and pesticide placement. In: *Air-assisted spraying in crop protection.* Monograph 46. Surrey, United Kingdom: British Crop Protection Council. p 171–176.

Huehne WH. 1971. Barrier spraying at the Kelantan side of the Thai–Malaysia border. *J Trop Med Hyg* 74:106–109.

Juste F, Sanches S, Ibanez R, Val L, Garcia C. 1990. Measurement of spray deposition and efficiency of pesticide application in citrus orchards. *J Agric Eng Res* 46:187–196.

Kang TG, Lee DH, Lee CS, Kim SH, Lee GI, Choi WK, No SY. 2004. Spray and depositional characteristics of electrostatic nozzles for orchard sprayers. St. Joseph, MI: American Society of Agricultural Engineers (ASAE). ASAE Paper number 041005.

Kirk IW, Hoffmann WC, Carlton JB. 2001. Aerial electrostatic spray system performance. *Trans ASAE* 44:1089–1092.

Koo YM, Salyani M, Whitney JD. 2000. Spray variable effects on abscission of orange fruit for mechanical harvesting. *Trans ASAE* 43:1067–1073.

Mahler DS. 1985. Measuring droplet size using hot-wire instrumentation. *Proc Annu Meet NJ Mosq Control Assoc* 72:112–121.

Perich MJ, Hoch AL, Rizzo N, Rowton ED. 1995. Insecticide barrier spraying for the control of sand fly vectors of cutaneous leishmaniasis in rural Guatemala. *Am J Trop Med Hyg* 52:485–488.

Perich MJ, Tidwell MA, Dobson SE, Sardelis MR, Zaglul A, Williams DC. 1993. Barrier spraying to control the malaria vector *Anopheles albimanus*: laboratory and field evaluation in the Dominican Republic. *Med Vet Entomol* 7:363–368.

Potter HS. 1984. Results of canopy spray penetration studies with fixed-wing aircraft. *Agric Aviat* 11:15, 18.

Salyani M, Fox RD. 1999. Evaluation of spray quality by oil- and water-sensitive papers. *Trans ASAE* 42:37–43.

Salyani M, McCoy CW, Hedden SL. 1988. Spray volume effects on deposition and citrus rust mite control. In: *Pesticide formulations and application systems—ASTM STP 980*. West Conshohocken, PA: American Society of Testing and Measurements (ASTM). p 254–263.

Salyani M, Whitney JD. 1990. Ground speed effect on spray deposition inside citrus trees. *Trans ASAE* 33:361–366.

Whitmore LF, Hughes JF, Harrison N, Abela M, Rourke PO. 2001. Enhanced efficiency of electrostatically charged insecticide aerosols. *Pest Manag Sci* 57:432–436.