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A COMPARISON OF TWO ULTRA-LOW–VOLUME SPRAY NOZZLE SYSTEMS BY USING A MULTIPLE SWATH SCENARIO FOR THE AERIAL APPLICATION OF FENTHION AGAINST ADULT MOSQUITOES

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ABSTRACT. Two hydraulic spray nozzle systems, a flat fan and a high-pressure hollow cone, were used for ultra-low–volume application of the mosquito adulticide fenthion under a multiple swath scheme. Eight swaths at 322-m intervals were applied from a height of 91 m to simulate operational conditions. Deposition, effects on nontarget organisms (fiddler crabs), aerial flux, and mosquito (*Ochlerotatus taeniorhynchus*) mortality were monitored for 8,230 m downwind, including the area under all 8 swaths. The flat-fan nozzle system deposited 88 times the amount of fenthion deposited by the high-pressure system in a lightly vegetated zone directly beneath the application area (0–2,134 m). Further downwind (2,286–4,420 m) in the 2nd semiopen urban zone, 10.5 times more chemical was deposited with the flat-fan nozzles than with the high-pressure nozzles, and in the 3rd highly vegetated zone (4,572–8,230 m), 25 times more was deposited compared with high-pressure nozzles. The corresponding nontarget mortalities with the flat-fan nozzle were 80, 12, and 17% at 2,438, 3,658, and 4,572 m, respectively. No treatment-induced mortality was observed with high-pressure nozzles. Similar amounts of fenthion residue were recovered from yarn samples for both nozzle systems, with the exception of the zone directly under the flight paths, where the flat-fan system deposited 2.5 times the amount recovered with the high-pressure system. Mosquito mortality was similar between the 2 nozzle types except in the farthest zone, where the average mortalities for the high-pressure system and the flat-fan system were 73.4 and 34.8%, respectively. Regression analysis of the mosquito mortality and yarn samples showed that the high-pressure hollow-cone application could control mosquitoes with half the amount of chemical compared to flat-fan nozzles.

KEY WORDS Ultra-low–volume aerial spray, high pressure, droplet size, ground deposition, nontarget organisms

INTRODUCTION

The optimum droplet size of aerosols used against adult mosquitoes has been well established in the laboratory and for ground-based applications (Latta et al. 1947, Haile et al. 1982). Yet in aerial mosquito control programs, application equipment that produces drops well beyond the optimum range of 5–25 μm has been the standard. Mosquito adulticide equipment was adapted from agriculture where the aim was to ensure deposition and minimize drift. However, the converse is true for mosquito control, and as a consequence, the greater atomization of aerial insecticidal sprays has been a longstanding goal.

This report documents the continuation of a study to compare 2 spray nozzle systems for the ultra-low–volume aerial application of insecticides for adult mosquito control. The initial goal of the research was to minimize wasteful insecticide deposition at ground level, which would reduce environmental contamination, while ensuring the ability to control adult mosquitoes. In the 1st part of the study, a single-swath application of fenthion was applied by using 2 different systems, a flat-fan nozzle system and a high-pressure hollow-cone system (Dukes et al. 2004). In that study, a substantial reduction was found in ground deposit, as measured by gas chromatography (GC), with the high-pressure system compared to the flat-fan system. Moreover, spray deposition from flat-fan nozzles resulted in a cumulative fiddler crab mortality of 80%, whereas no deaths were recorded with the high-pressure system. Fenthion applied by the flat-fan system resulted in 15% of its volume in droplets <30 μm, but applications of the same insecticide via a high-pressure hollow-cone nozzle resulted in >75% of the volume in droplets <30 μm. Although the high-pressure system had slightly better efficacy, as assayed by caged mosquitoes, neither system produced good control because use of only 1 swath produced unrealistic application rates. Therefore, a set of trials that used operational-type multiple swaths was initiated to determine if control efficacy could be increased to more operationally acceptable levels.

MATERIALS AND METHODS

Study site: A site was selected south of Naples, FL, that was often targeted for adult mosquito control by the Collier Mosquito Control District (CMDC). The site was oriented southeast–northwest and extended from SE of Fiddler Creek Golf

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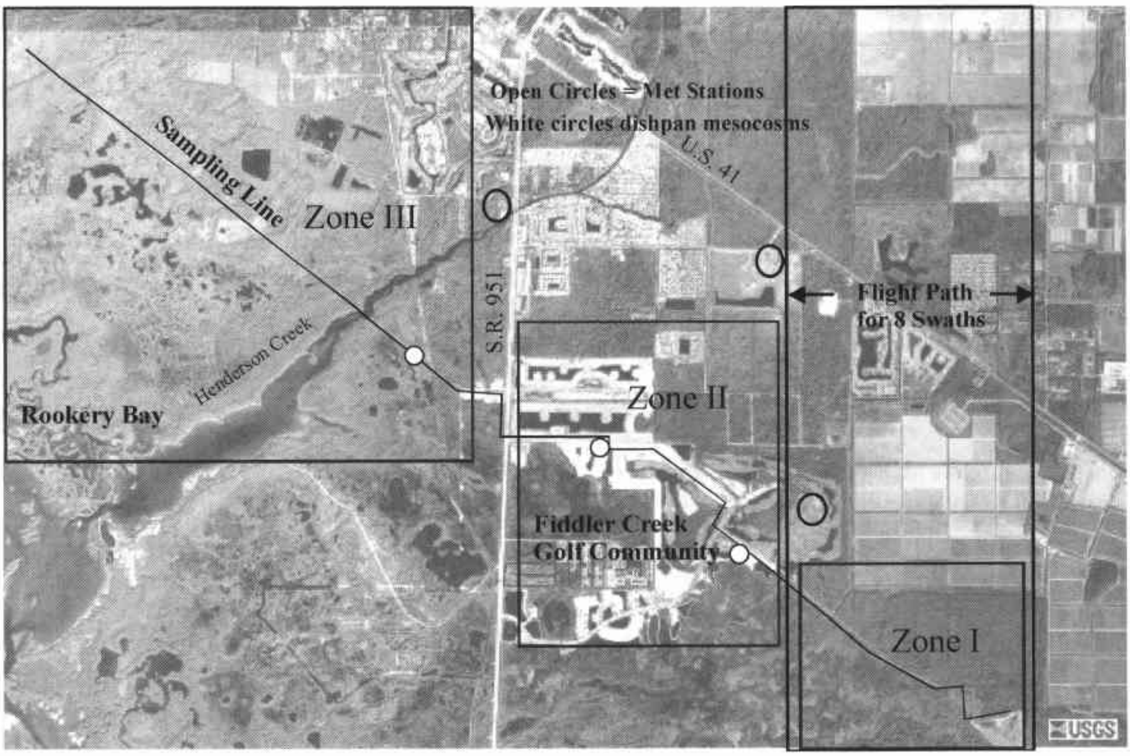

Fig. 1. Aerial map and schematic of site location.

Club and Community across Highway (Hwy) 951 and Henderson Creek to the northwest just outside of Rookery Bay Wildlife Sanctuary. The length of the potential drift area was 8.23 km as measured with a global positioning system (GPS) (Fig. 1). The area southeast of the golf club consisted of moderately dense vegetation ranging from about 2 to 10 m in height. The area from the edge of the golf club to Hwy 951 consisted of a semiopen urban development with a few stands of large pine trees. West of Hwy 951 to the end of the sample line was a very densely vegetated habitat with undergrowth of 5–10 m and many stands of 15- to 20-m pine trees. The area bordering Henderson Creek had extremely dense vegetation. These 3 habitats will be referred to as zone I (southeast of golf club, moderate vegetation), zone II (golf club area, semiopen urban), and zone III (west of Hwy 951, dense vegetation).

Application equipment: Fenthion application was conducted by the CMCD by using a DC-3 airplane equipped with a GPS. The insecticide was applied every 322 m for a total of 8 swaths starting at 2,286 m downwind of the beginning of the study area and moving upwind at an altitude of 91.4 m and was discharged at an air speed of 240 kph for both systems.

The 1st spray system tested high-pressure hollow-cone nozzles (Sprayer Systems Co.® nozzle code 1/8 M1SS; Wheaton, IL) operated at 20,684 kPa (3,000 psi) that were positioned on the tail boom pointing straight back. The 2nd system used conventional flat-fan nozzles (TeeJet® nozzle code 8002SS; Wheaton, IL), with 414 kPa (60 psi) of liquid pressure and at a nozzle angle of 45° forward, or into the wind. The spray pump was calibrated to deliver 35 ml/ha (0.48 oz/acre) for both systems. The flat-fan nozzle system generated aerosol droplets within a 79- to 94-μm volume mean diameter (VMD) range compared to a 14-μm VMD for the high-pressure system (Malvern laser data, unpublished data).

Meteorological monitoring: Three weather stations that used Campbell Scientific CR10X data loggers (Campbell Scientific Instruments, Logan, UT) were positioned downwind (Fig. 1). One weather station was located at the Fiddler Creek Golf Club close to the beginning of the semiopen urban area (zone I) and near where the 1st swath was placed. Another station was located at Manatee Middle School (Fig. 1), about 2 km north of the golf club. The 3rd station was located at the Rookery Bay Wildlife Sanctuary Headquarters, about 1.5 km north of the beginning of the heavy vegetation zone (Fig. 1) just west of Hwy 951. Each weather station consisted of a 10-m mast with weather monitors (propeller and wind vane) at 2 and 10 m; temperature sensors positioned at 1.5, 4.3, and 7.9 m; and a humidity sensor at 4.3 m. The three-axis anemometer was incorporated at 5.5 m into the weather station

Table 1. Meteorological variables for multiple swath treatments.

Nozzle	Trial	Spray time (a.m.)	Temperature (°C) 1.5 m	Temperature (°C) 7.9 m	Relative humidity (%)	10-m wind speed (m/sec)	10-m wind direction (compass °)	Direction SD (compass °)
High pressure	1	1:25	23.6	23.6	95.8	1.4	75.9	5.2
	2	1:20	24	23.9	96.9	2.4	79	6.1
	3	1:10	24.1	24.1	96.2	1.5	101.6	12.1
Flat fan	1	12:55	21.1	21.4	93.5	1.2	67.0	17.2
	2	12:45	18.2	18.7	95.1	<1.1	56.4[1]	9.3
	3	12:55	19.1	19.7	94.4	1.1[2]	92.4	85.1[3]

[1] Direction shown is for 1st 2 hours.

[2] Wind speed and direction shown are 1st 3.5 h.

[3] High standard deviation in direction reflects change within 1st 20 min after spraying started.

at the golf club. The anemometer measures the east–west (U), north–south (V), and vertical (W) orthogonal wind vectors, along 2 horizontal and 1 vertical axes (Campbell Scientific Instruments). A barometric pressure sensor (Campbell Scientific Instruments) at ground level also was incorporated into the weather station located at Manatee Middle School. Weather data were collected at a sampling rate of 1 Hz at the golf club station and 0.5 Hz at the other 2 weather stations. Meteorological measurements are given here as nightly averages (Table 1).

Mosquito bioassays: Caged mosquitoes were used to determine the efficacy of the fenthion aerial application and assay drift by using the methods of Riley et al. (1989). Approximately 25 adult female *Ochlerotatus taeniorhynchus* (Say) aged 6–8 days were placed in each cylindrical cage (14-cm diameter × 3.5-cm height with a 14 × 18 mesh size). Cotton pads, moistened with sugar water, were placed between all cages before and after testing. Cages were hung on stakes at a height of 1.5 m every 305 m (27 stations with 2 cages per stations). Eight mosquito cages, used as controls, were placed several kilometers upwind of the spray line. Approximately 5 h after the spray application, cages were picked up and mosquitoes were transferred to clean cages (Rathburn et al. 1969). The mosquitoes were counted at 12–14 h after treatment to determine percent mortality. Control cages were handled in the same manner as treatment cages.

Fiddler crab bioassays: Cages of fiddler crabs (*Uca pugilator* (Bose)) were used to assay nontarget effects of fenthion deposition (Zhong et al. 2003). Crabs were collected from a pristine area outside the pesticide application zone. Twenty-four hours before the scheduled spray time, 12 dish-pan mesocosms (30.5 × 40.5 cm) were prepared, with each containing 5 male and 5 female crabs. One inch of beach sand was placed in each dish-pan mesocosm, and the sand was wetted with 35‰ salt water. Mesocosms were covered with mesh cloth (12.7 × 12.7 mm) to prevent escape or predation. Dish-pan mesocosms were situated at 3 exposed locations at 2,438, 3,658, and 4,572 m down the transect line and 1 control at an unexposed upwind location. Crabs were picked up within the 1st hour after sunrise after the fenthion application. Percent mortality was recorded every 12 h up to 96 h after treatment; dead crabs were removed once they were counted.

Sampling insecticide: The aerosol flux was collected on a piece of acrylic, mohairlike, yarn (Lion Brand Yarn Co., New York, NY) measuring 6.7 m in length. The yarn was oriented vertically and attached in a zigzag pattern to the inside of a square 0.5 × 0.5-m polyvinyl chloride frame at a height of 2 m. Filter papers (24 cm in diameter, Whatman International Ltd., Maidstone, United Kingdom) were selected to collect ground deposits. Two filter papers were pinned side by side on a Styrofoam® board (40 × 80 cm) covered with aluminum foil. The yarn and filter paper samplers were located at 153-m intervals for the 1st 4.57 km; thereafter, west of Hwy 951, sampling stations were at 305-m intervals, in line with mosquito bioassays (total of 43 yarn and 43 filter papers). West of Henderson Creek, these were placed on a custom frame at a height of about 3 m and were attached to existing concrete utility towers. Residue samples were collected approximately 5 h after fenthion application to allow spray droplets to settle.

Insecticide analysis: Each yarn sample was removed from its frame and placed into a screw-top 40-ml Pyrex® culture tube. Filter papers were removed from the Styrofoam board, folded by using 2 pairs of forceps, and placed into separate screw-top 40-ml Pyrex culture tubes. Each tube was then filled with 30 ml of hexane for analysis. All samples were placed in a cooler with artificial ice and held at approximately 4°C. Quality control of residue recovery in field samples was conducted by spiking 50 μl of fenthion as a standard (1 mg/ml) onto filter paper at the time of aerial application. All field and spiked samples were transported to the John A. Mulrennan, Sr., Public Health Entomology Research and Education Center, Florida A&M University, Panama City, FL, for residue quantification.

Fenthion quantification was determined by a Varian 3400 gas chromatograph equipped with a thermionic specific detector and 8200 auto-sampler (Varian Analytical Instruments, Sugar Land, TX). Results were transferred to a personal computer

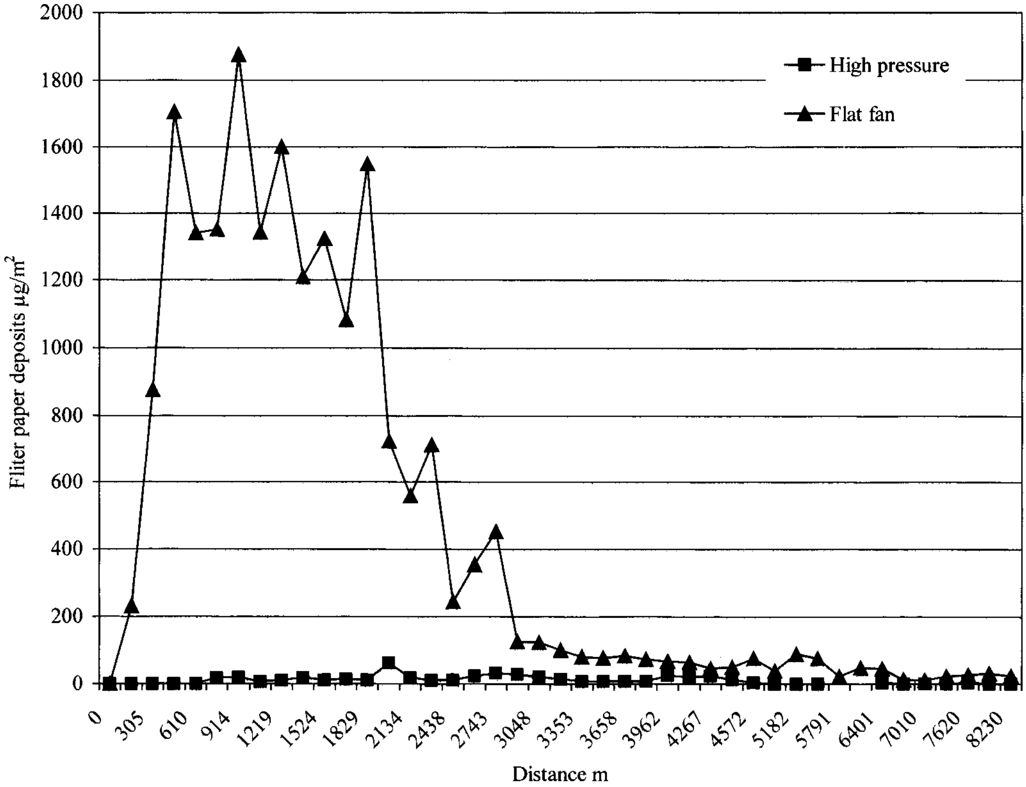

Fig. 2. Ground deposits of fenthion (µg/m²) recovered from filter papers for the high-pressure and flat-fan systems.

equipped with data-handling software for processing (Star Chromatograph Version 4.51, Varian Analytical Instruments). The injector was operated at 250°C in 10 to 1 split mode with the detector functioning at 300°C. A DB-5 capillary column (30 m × 0.25-mm inner diameter; film thickness 0.1 µm) bonded with fused silica also was used. The column oven starting temperature was 130°C with an increase at 15°C/min to 275°C, and holding for 3 min. Fenthion retention time was 5.6 min and the total analytical time was 10 min. A standard injection volume of 1 µl was used for all standards and samples. The fenthion standard calibration consisted of a 5-point calibration curve ranging from 0.1 µg/ml to 10 µg/ml with $R^2 \geq 0.995$. Continuous calibration (CC) at 2 µg/ml was conducted every 10 samples. The CC must pass the criteria of 100 ± 10% recovery each time; otherwise a new calibration curve must be generated. Laboratory and field spikes should pass the limit of 100 ± 20%. All blanks were clean of contaminants.

RESULTS AND DISCUSSION

The flat-fan system consistently deposited more fenthion on to the ground compared with the high-pressure system (88 times, 10.5 times, and 24.6 times in zones I, II, and III, respectively; Fig. 2). When ground deposit volumes were compared with mosquito mortality, no relationship was observed. This indicated that ground deposit volumes were not indicative of biological effect and thus cannot be used as an indicator of insecticidal effect. Conversely, Machado et al. (1969) showed that increased ground deposits resulted in decreased insecticide in the target zones. Ground deposition is a waste for mosquito control, and contaminates the environment so we concur that ground deposition is not desirable.

The fiddler crab bioassays were used as an indicator of potential environmental, nontarget effects. The flat-fan system was responsible for an average of 80, 12, and 17% mortality at 2,438, 3,658, and 4,572 m, respectively; no mortality was observed in the controls. Fenthion deposits from the high-pressure system caused less crab mortality than in the untreated controls (Table 2). Results showed that if more than 74 µg/m² is deposited on the ground, fiddler crab mortality will occur. Data on the quantity of chemical required to kill a specific nontarget organism are important because such data enable the use of artificial targets rather than the natural target for future fieldwork. If a set quantity of chemical can be shown to have a negative effect on a nontarget organism, then filter paper

Table 2. Fiddler crab mortality (Mort %) and range of residues (μg/m²) at each sample station (described by meters from first swath) for high-pressure and flat-fan nozzles (control corrected).

Distance (m)	High pressure Mort %	High pressure μg/m²	Flat fan Mort %	Flat fan μg/m²
2,438	0	0–27	80	212–270
3,658	0	0–13	12	76–95
4,572	0	0–11	17	74–79

samples alone can be used rather than risk killing the nontarget organism.

Figures 3 and 4 compare the recovered fenthion residue on yarns to the mosquito mortality for the flat-fan and high-pressure nozzles, respectively. The difference in residue recovered from yarn downwind between the 2 systems was small, with the flat fans on average collecting more spray, which is converse to the differences in mosquito mortality (Table 3). This also was found in the earlier study (Dukes et al. 2003). Marked differences in mosquito mortality could be seen between the 2 application systems in zone III, with 2.1 times greater mortality for the high-pressure system compared with the flat-fan system. However, the yarn only collected 1.3 times as much residue for the high-pressure as for the flat-fan applications. To have 2 times less mortality but yet a similar quantity of chemical present with the flat-fan system implies that the physical form that the insecticide takes is important. These results indicated that fewer droplets of optimum size for impingement upon mosquitoes were produced with the flat-fan system.

The quantity of pesticide present on the yarn samplers was compared directly to the mortality achieved with the 2 nozzle systems (Figs. 5 and 6). Regression analysis with these 2 parameters (logistical curve fitting with the logistic curve model: $y = A2 + (A1 - A2)/[1 + (x/x_0)^p]$, where A1 = initial y, A2 = final y, and p = power, shows a strong relationship between the quantity of aerosol recovered and mosquito mortality ($R^2 = 0.8$ for both systems). However, the shape of the curves was different. For the high-pressure system, the amount of insecticide required to kill 85, 80, and 50% of the mosquitoes was half that required with the flat-fan system.

This difference in the quantity of chemical required most likely is due to the size of the droplets produced. The high-pressure nozzles yielded a higher proportion of the spray in droplets optimal for impingement on mosquitoes, 7–22 μm in diameter (Mount et al. 1970c). In contrast, a large volume (87%) of the aerosol of the flat fans was in droplets larger than the optimal size for mosquito control.

The difference between the volume of fenthion and the resultant biological effect was due to lower collection efficiency for smaller droplets with the yarn, especially at low wind speeds. The quantity of droplets present with the high-pressure system

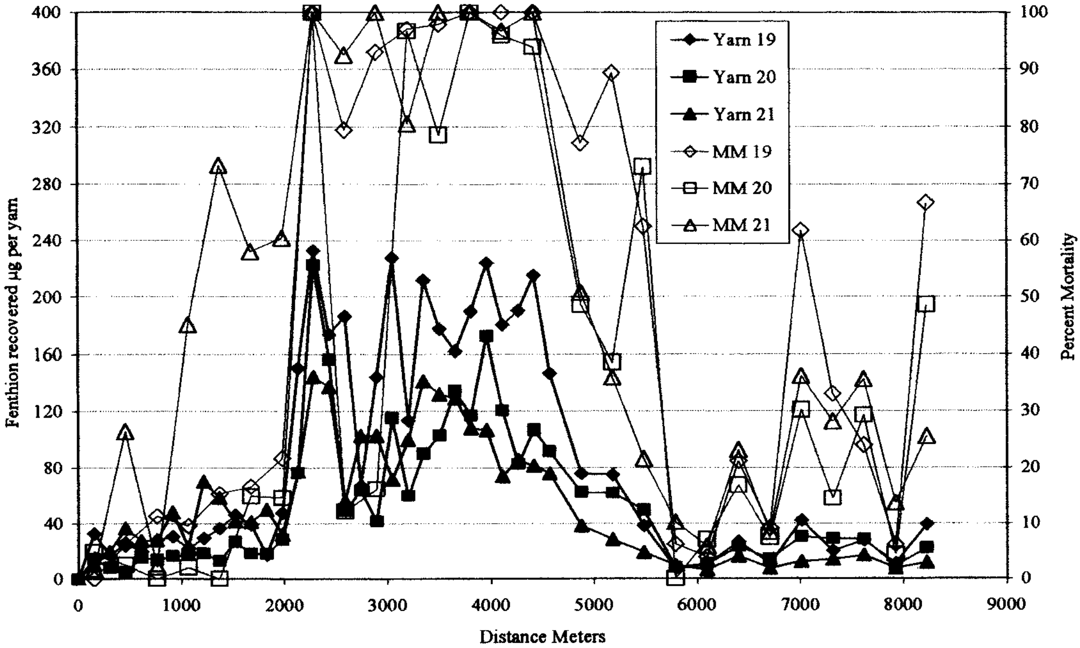

Fig. 3. Fenthion residue from yarn and percent adult mosquito mortality from the flat-fan nozzle applications May 19–21, 1999.

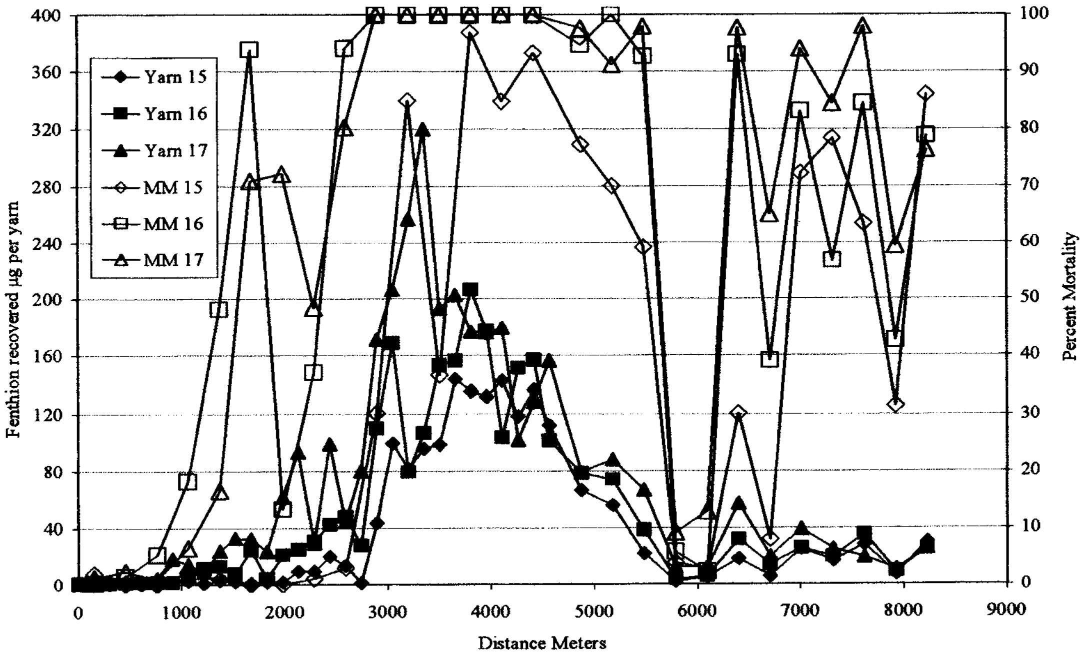

Fig. 4. Fenthion residue from yarn and percent adult mosquito mortality from the high-pressure hollow-cone nozzle applications September 15–17, 1998.

could be underestimated. As drop size decreases and wind speed drops, so too does the collection efficacy on yarn. By the time the aerosol reached zone III, a higher proportion of smaller droplets would be present because of sedimentation of the larger droplets. However, this would be relevant to both nozzle systems. In addition, the GC analysis is a volumetric measure, so loss of small droplets would hopefully only have a small volumetric impact. This still means that the high-pressure system produces kill with a smaller quantity of chemical, which can mean dose reduction with both economic and environmental ramifications.

Another very important point to make from the improved control in zone III and zone II is the offset in the pattern of control and the effective distance with the 2 spray systems. The primary target zone for insecticidal application has, in the past, been directly underneath the swaths. In these tests, control was not achieved underneath the swaths (zone I) with either system. This description of target zone is likely a vestige from the agricultural past of the machinery, where little to no offset occurs because of release height. This brings into question our methods of calibration and flight path design. Most professional applicators are aware of this but label information and calibration protocols are not. Mount et al. (1970a), found a similar offset effect in applications made at altitudes of 46 to more than 900 m. The best control was displaced several kilometers downwind, depending on application height.

The increased shift (offset) reflects the smaller overall droplet distribution of the optimally sized droplets produced by the high-pressure system. Droplet size is the primary factor that determines the drift distance of aerosols (Craig et al. 1998). Once those droplets are released they will accelerate downward under the force of gravity until that force is counterbalanced by aerodynamic drag; the fall then continues at terminal velocity. The most important factor affecting terminal velocity is droplet size. Droplets less than 30 µm in diameter will take several minutes to fall from a height of 3 m

Table 3. Average deposit per yarn for each zone and the associated standard deviation (SD) and coefficient of variation (CV %) for high-pressure and flat-fan nozzle.

	High pressure			Flat fan		
	Zone 1	Zone 2	Zone 3	Zone 1	Zone 2	Zone 3
Average	8.7	45.1	24.9	13.1	24.1	33.4
SD	9.0	22.4	7.1	7.8	16.6	15.7
CV%	102.7	49.8	28.3	59.4	69.2	46.9

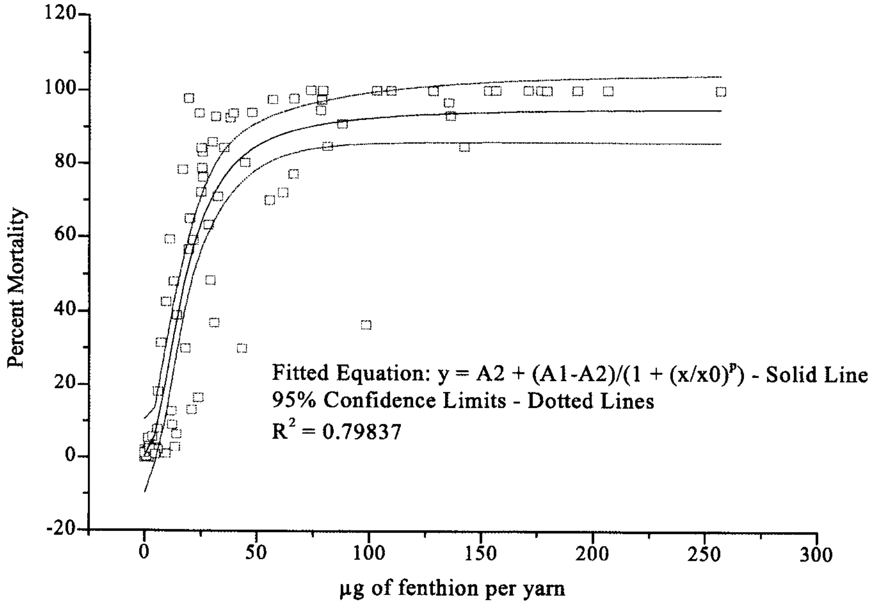

Fig. 5. Percent mortality of *Ochlerotatus taeniorhynchus* as a function of fenthion per yarn produced with the high-pressure nozzle (equation and confidence intervals were fitted by using Origin [Origin Lab Corp. Northampton, MA]).

in still air, whereas a 100-μm droplet would fall out in 11 sec. Thus, small droplets are exposed for longer periods of time to the influence of air movements (Matthews 1992).

This was demonstrated in zone III, where the average mosquito mortality was more than twice as high when using the high-pressure system as the flat-fan system, 73.4 and 34.8%, respectively (Fig. 4). Although both systems had close to adequate kill in zone II, or just beyond the application area, the high-pressure system continued to give almost the same level of mortality in zone III as in zone II. The mortality due to the flat-fan application dropped off significantly in zone III but the amount reaching the ground was far greater than under the high-pressure system and subsequently caused non-

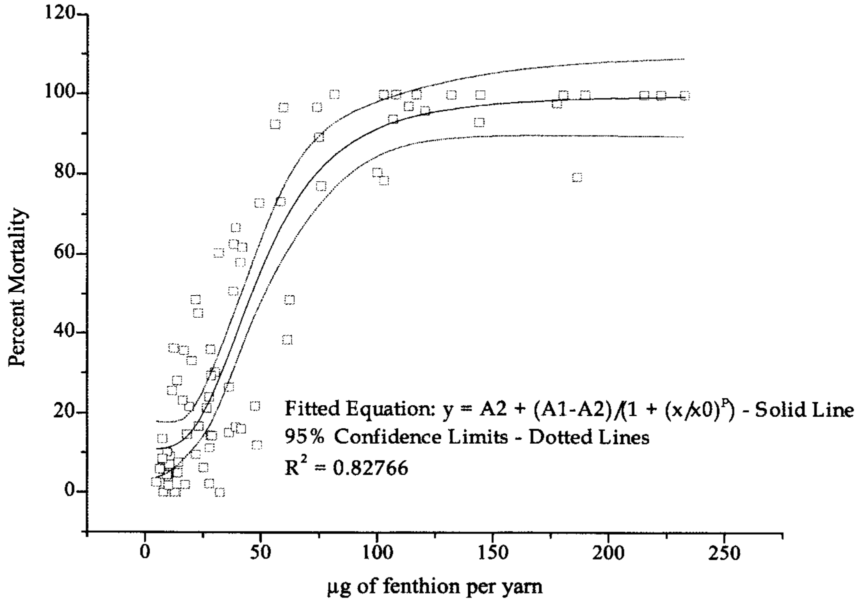

Fig. 6. Percent mortality of *Ochlerotatus taeniorhynchus* as a function of fenthion per yarn produced with the flat-fan nozzle (equation and confidence intervals were fitted by using Origin).

target mortality (17%) in that area. Machado et al. (1969) also found that switching to a smaller droplet VMD resulted in fewer drops per unit area on the ground while giving a higher level of control.

The driftable distance and level of ground deposition can be calculated theoretically with models. However, these models need validation by field trials such as this one. Duty time of the insecticide in the air can be most simply measured by using Stokes law, which calculates terminal velocity

$$V_t = \frac{gd^2\delta_d}{18\eta}$$

where V_t is the terminal velocity (m/sec), d is the diameter of the droplet (m), δ_d is the density of the droplet (kg/m^3), g is gravitational acceleration (m/sec^2), and η is the viscosity of air in newton seconds per square meter (Nsec/m^2) at 20°C (Matthews 1992).

Within 610 m of the 1st swath, the deposit for the flat-fan system had dropped from 712.6 μg/m^2 to 126.3 μg/m^2 or a greater than 5.5× reduction. By looking at the VMD for flat-fan nozzles 80 μm, this midrange droplet of fenthion would fall to the ground from our application height in about 388 sec, based on Stokes' law alone. Because deposition had decreased significantly by 610 m beyond the 1st swath, it is reasonable to assume that most of the droplets that large had fallen out by that distance. So calculating the necessary horizontal wind speed to produce that offset gives about 610 m/388 sec = 1.57 m/sec, which is consonant with reported wind speeds of an average of about 1.1 m/sec, assuming a logarithmic profile in wind speed with height (Stull 1988).

Deposition with the flat-fan system was reduced again by a large measure by 3,810 m beyond the 1st swath, or at 6,706 m. If the wind speed calculated above was used, this would be the distance it would take a 32-μm droplet of fenthion to fall out when using Stokes' law. Thus, if the flat-fan droplet distribution was below 32 μm beyond that point (6,706 m), then an acceptable level of control might have been possible (the highest was 42.8%) if the number of droplets passing through a unit area was high enough (Rathburn et al. 1987). However, because so much of the original volume was in droplets larger than 32 μm, little remained to keep the concentration high enough for adequate kill (Mount et al. 1970b). The high-pressure system in the area beyond 6,706 m still achieved 80% kill, which shows that even after the winnowing out of the larger fraction of droplets (Akesson et al. 1969, Taylor and Rathburn 1970) in an original distribution with a VMD of 14 μm, plenty of droplets in the optimum range still remained to give peak control of 80%.

Conclusion

Generally, the high-pressure system greatly reduced ground deposits of fenthion and maintained a good level of control for several kilometers. The flat-fan nozzle produced a spray cloud that preferentially deposited insecticide onto the ground and did not achieve a similar level of mosquito control as far downwind when compared to the high-pressure system. Examination of the data that were produced showed that fiddler crab mortality would occur if fenthion deposits were at or above 74 μg/m^2.

The droplet size spectrum was the important parameter, not the system producing it. The high-pressure system used in this study was a prototype; other systems also are being developed and tested that have a similar droplet spectrum. As such we are not necessarily promoting the use of the actual system used here, but rather the droplet size spectrum produced. Moreover, we encourage the movement away from relying on a single VMD measure to instead looking at the droplet spectrum (e.g., Dv_{10}, Dv_{50}, and Dv_{90}, where Dv_{10} and Dv_{90} are where 10% and 90% of the spray is in drops smaller than this size), and striving to keep the spray within the optimal range of droplet sizes. Accordingly, the system with a Dv_{10} of 3 μm, Dv_{50} of 14 μm, and Dv_{90} of 44 μm provided superior control and reduced ground contamination compared to the system with a Dv_{10} of 22 μm, Dv_{50} of 80 μm, and Dv_{90} of 225 μm.

In the future, studies of this type should include, where possible, a measurement of droplet size at target height to enable more assured conclusions about application effects; in other words, showing what droplet size was reaching the target. Moreover, an artificial target with more measurable errors would be desirable in comparison to yarn samplers, in particular, one that has a definable surface area, is independent of wind speed, and has a higher collection efficacy for the small drops at low wind speeds.

Optimization of equipment in terms of the droplet size spectrum is not only more environmentally attractive, but might lead to fiscal savings through such techniques as widening swath intervals, thereby saving on aircraft fuel (Mount et al. 1970b); and applying at higher altitudes, which extends the target area with the same number of treatment swaths.

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