Spray Drift of Pesticides Arising from Aerial Application in Cotton

Nicholas Woods,* Ian P. Craig, Gary Dorr, and Brian Young

ABSTRACT

This paper presents results from field studies carried out during the 1993–1998 Australian cotton (*Gossypium hirsutum* L.) seasons to monitor off-target droplet movement of endosulfan (6,7,8,9,10,10-hexachloro-1,5,5a,6,9,9a-hexahydro-6,9-methano-2,4,3-benzodioxathiepin 3-oxide) insecticide applied to a commercial cotton crop. Averaged over a wide range of conditions, off-target deposition 500 m downwind of the field boundary was approximately 2% of the field-applied rate with oil-based applications and 1% with water-based applications. Mean airborne drift values recorded 100 m downwind of a single flight line were a third as much with water-based application compared with oil-based application. Calculations using a Gaussian diffusion model and the U.S. Spray Drift Task Force AgDRIFT model produced downwind drift profiles that compared favorably with experimental data. Both models and data indicate that by adopting large droplet placement (LDP) application methods and incorporating crop buffer distances, spray drift can be effectively managed.

Agricultural aircraft are of great importance to the Australian cotton industry. Specialized aircraft are used to apply selected herbicides and fertilizers prior to planting, insecticides throughout the growing season, and defoliants prior to harvest. The use of agricultural aircraft has developed largely as a result of the greater speed, better timing, and efficiency of application offered by aerial distribution. Aircraft are able to apply agricultural products rapidly over large areas within narrow optimum application windows. When crop height and irrigated areas restrict the passage of wheeled vehicles, aircraft are able to place pesticides strategically on crops in response to economic thresholds, without contributing to soil compaction and breakdown.

There have been several previous studies that have addressed aircraft spray drift, for example Yates et al. (1978), Akesson and Yates (1974, p. 92–98), Riley and Wiesner (1989), Richardson et al. (1995), and the U.S. Spray Drift Task Force project (Spray Drift Task Force, 1997). Spray drift can pose a potential source of contamination to the environment, unless the application process is effectively managed. When pesticides are applied close to sensitive areas, management strategies are employed that can significantly reduce the off-target aerial movement of pesticides. This paper summarizes the work carried out from 1993 to 1998 to assess the aerial transport of pesticides on selected cotton properties and develop effective spray drift management strategies.

Two methods of endosulfan aerial application were studied: (i) ultra low volume (ULV) endosulfan (240 g/L oil-based application at 3.0 L/ha rates using Micronair AU5000 rotary cage nozzles [Micron Sprayers, Bromyard, UK]), and (ii) low volume (LV or emulsifiable concentrate [EC]) endosulfan (350 g/L water-based application with 2.1 L/ha in either 20 or 30 L/ha bulk rates using CP (CP Products, Tempe, AZ) or other hydraulic nozzles).

MATERIALS AND METHODS

Laser Droplet Sizing

Spray droplet size tests were conducted using a Malvern 2600 laser analyzer (Malvern Instruments, Malvern, UK) and a windtunnel. Tests were carried out with ULV and LV (EC) endosulfan formulations at windspeeds of 51 m/s (100 knots) and 67 m/s (130 knots) to simulate the airspeeds of slow piston–powered aircraft and fast turbine–powered aircraft, respectively. Details of the test procedure are described by Woods et al. (2000b).

Single-Flight-Line Drift Tests

Single-flight-line tests were carried out to determine the influence of nozzle type and droplet size on airborne drift profiles. To eliminate the effect of variable weather conditions with time, tests were carried out with two aircraft simultaneously. The aircraft were turbine powered (Air Tractor [Olney, TX] 502B) with similar airspeeds of approximately 60 m/s and flying heights of approximately 3 m. The first aircraft was equipped with Micronair AU5000 nozzles to apply endosulfan ULV as a standard and the second aircraft was equipped with a range of different hydraulic nozzles. Unbleached 1-mm-diameter cotton string was suspended vertically from 20-m-high trailer-mounted sampling masts. The masts were situated 100 m downwind from the single-flight-line path of each aircraft and were separated by approximately 1 km to avoid cross contamination. A fluorescent dye (Uvitex OB; Novartis Crop Protection, Basel, Switzerland) was added to the spray tank mix at a rate equivalent to approximately 15 g/ha. The string from the masts was cut into 2-m sections and the dye was extracted from 2-m sections of the string using 10 mL of isopropanol solvent. Dye concentration was measured using a Sequoia–Turner (Mountain View, CA) Model 450 fluorometer.

Full-Field Drift Tests

The off-target transport of droplets resulting from the commercial application of endosulfan was monitored during the 1993 to 1998 Australian cotton seasons (Woods et al., 1998a). In crop deposition characteristics were assessed by sampling leaves from top, mid, and low positions on the cotton plant. Ground deposition was assessed using 1-m-long chromatography paper–covered rulers placed perpendicular to and alternately half in and half out of the row. The leaf area index of the cotton canopy was assessed using the light squares method (Constable, 1986). Off-target transport of droplets was measured using an array of collection surfaces consisting of chromatography paper placed upon horizontal flat plates (usually at a 1-m height above ground), vertically orientated pipe cleaners, and cotton string suspended from 20-m-high towers

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Abbreviations: EC, emulsifiable concentrate; GDM, Gaussian diffusion model; LDP, large droplet placement; LV, low volume; ULV, ultra low volume; VMD, volume median diameter.

Table 1. Summary of aerial transport characteristics of endosulfan application.

Parameter	ULV application†	LV application‡
Nozzle type	AU5000 @ 4000 rpm	hydraulic CP @ 30°
Formulation	endosulfan ULV	endosulfan EC
Application rate (L/ha)	3	2.1
Application	applied as oil	in 30 L/ha water
Malvern laser data (VMD§) (μm)	67	182
Airborne drift @ 100 m (%)	18	6
Leaf coverage (full field) (%)	60	50
Ground deposit (full field) (%)	25	50
Fraction leaving field (500-m field) (%)	14	7
Depositing within 500 m (500-m field) (%)	7	5
Deposition at 200 m (% of applied rate)	5	2
Deposition at 500 m (% of applied rate)	2	1

† ULV, ultra low volume.
‡ LV, low volume.
§ VMD, volume median diameter.

(Woods et al., 2000a). Applications of both endosulfan ULV (applied at a rate of 3 L/ha using Micronair AU5000 equipment) and endosulfan EC (generally applied at a rate of 2.1 L/ha in 30 L/ha using CP hydraulic nozzles) were assessed (Table 1). An Environdata (Warwick, QLD, Australia) meteorological station was used to record wind speed (at 2 and 5 m), wind direction, temperature (at 2.5 and 10 m), relative humidity, solar radiation, and rainfall during each trial. Endosulfan residue samples were quantified using an ELISA immunoassay technique developed by CSIRO and the University of Sydney (Lee et al., 1997; Kennedy et al., 1998). In addition, some collection devices were analyzed by the NSW Agriculture Chemical Residue Laboratory using high performance gas chromotography (GC).

Computer Modeling

The Gaussian diffusion model (Bache and Sayer, 1975; Spillman, 1982), which assumes a single line source, and the U.S. Spray Drift Task Force AgDRIFT (Teske et al., 1997) model, which uses Lagrangian equations to compute a complex source dependant upon aircraft parameters, were used to provide benchmark comparisons against experimentally obtained spray drift data. The Gaussian diffusion model is based upon the following equation:

$$d = khq/(ix^2)\exp[-(h - vx/u)^2/2(i^2x^2)]$$

where d = deposit (m^3/m^2), k = constant (0.4), h = release height (4 m), q = line source (m^3/m), i = turbulence intensity, x = downwind distance (m), v = sedimentation velocity (m/s), and u = mean windspeed (m/s). A more detailed explanation of this model has been provided by Craig et al. (1998). Both Gaussian diffusion and AgDRIFT models have been successfully compared with spray drift data sets, by several researchers including Dorr (unpublished data, 1996) and Bird et al. (1996).

Parameters were entered into the models (Table 2) that represented the most typical conditions experienced during the field trial program. Droplet size data was incorporated from the laser diffraction studies. Computer modeling and mass balance mean figures were derived by normalizing data to correspond with spray application over a theoretical 500-m field source width. Some data points were corrected to account for variation in wind direction.

RESULTS

Laser Droplet Sizing

The relationship between endosulfan droplet volume median diameter (VMD) and Micronair AU5000 cage rotational speed, at airspeeds of 51 m/s (100 knots) and 67 m/s (130 knots), is illustrated in Fig. 1. The curves illustrate that cage RPM and airspeed were the most important factors governing droplet VMD, with formulation type and flow rate having less important effects. The graph shows that with Malvern laser droplet sizing equipment, droplet VMDs much above 180 μm (VMD) were not recorded with the Micronair rotary cage atomizer within its normal range of rotational speed.

Malvern laser droplet size data for the CP hydraulic nozzle are illustrated in Fig. 2. The chart relates to endosulfan EC applied at 20 L/ha through a CP nozzle with deflector settings of 30° (*coarse*) and 90° (*fine*); nozzle orifice sizes of 0.062, 0.078, 0.125, and 0.175 inches; and airspeeds of 51 and 67 m/s. The bars represent VMD or D[v,0.5] (i.e., 50% of the volume of the spray composed of droplets less than this size). The lines through the bars represent the D[v,0.9] to D[v,0.1] interval (i.e., the 90% to 10% spectral width of the spray). From the graph it can be deduced that airspeed is an important factor determining droplet size. The ef-

Table 2. Constants assumed in computer modeling (curves of Fig. 4 and 5).

Parameter	GDM†	AgDRIFT ULV‡	AgDRIFT LV§
Wind speed (m/s)	3	3 (1.3–4.8)¶	3 (1.5–6.5)¶
Temperature (°C)	N/A	29 (21–29)¶	29 (21–29)¶
Relative humidity (%)	N/A	45 (29–89)¶	45 (29–69)¶
Height (m)	3	3.05	3.05
Aircraft type	N/A	Piper Brave PA 36	Air Tractor 502b
Flying speed (m/s)	N/A	51	67
Nozzle	N/A	AU5000	CP coarse 30° def
Number of nozzles	N/A	8	29
Nozzle layout	N/A	as measured	as measured
Initial droplet size	Malvern data	Malvern data	Malvern data
Material	nonvolatile	oil	water
Swath width (m)	20	20	20
Field width (m)	500	500	500
Surface roughness	N/A	0.0075	0.0075
Turbulence intensity	0.1	N/A	N/A

† GDM, Gaussian diffusion model.
‡ ULV, ultra low volume.
§ LV, low volume.
¶ Range of field meteorological condition shown in brackets.

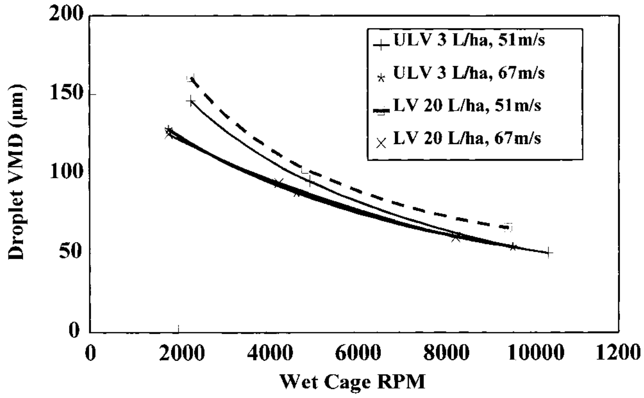

Fig. 1. **Droplet size (volume median diameter [VMD]) generated by a Micronair AU5000 applying two formulations of endosulfan (ultra low volume [ULV] and low volume [LV]) at two airspeeds (51 and 67 m/s). Measured with a Malvern 2600 Laser Droplet Analyser in a windtunnel.**

fect of increasing airstream velocity from 51 to 67 m/s was to decrease VMD from nearly 300 µm to less than 200 µm for the CP nozzle with a 30° deflector setting.

Single-Flight-Line Drift Tests

Simultaneous comparisons of the airborne drift from ULV and LV aircraft delivery systems are summarized in Fig. 3. The results were expressed as a percentage of the applied rate from the aircraft. This data demonstrates that the selection of large droplets using CP hydraulic nozzles with a 30° deflector plate (VMD values of about 250 µm) reduced the detected airborne fraction measured at 100 m downwind of release by a factor of two to three times compared with the AU5000 ULV application system.

Full-Field Drift Tests

Actual off-target deposition profiles obtained on paper-covered flat plates placed 1 m above the ground and downwind of the field during the monitoring of the commercial field trials are presented in Fig. 4 and 5. The data show the combined results from a number of

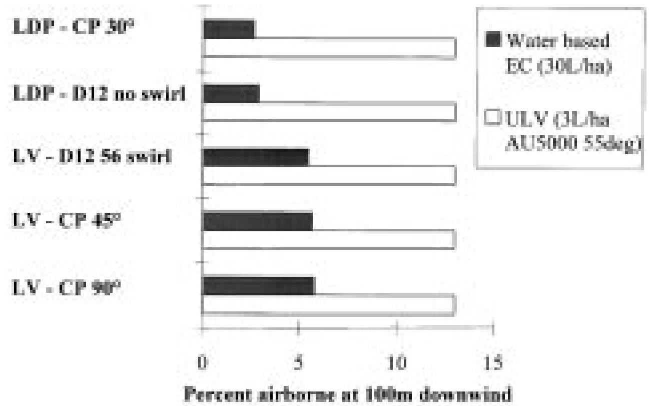

Fig. 3. **Airborne drift values measured using towers placed 100 m downwind of endosulfan low volume (LV) and large droplet placement (LDP) single-flight-line applications, normalized against simultaneous ultra low volume (ULV) applications.**

different trials carried out during the period 1993–1998. The data show the decline in deposit with distance from the edge of the sprayed area when ULV and LV techniques were used. Some data points were corrected to account for variation in wind direction. A high degree of variation in off-target deposition values was observed between the trials, which is indicative of the range of meteorological and operating conditions observed. With a coarse average taken across all trials, mean off-target deposition values (in g/m^2) at a downwind distance of 500 m fell to approximately 2 and 1% of the field-applied rate for ULV and LV applications, respectively. These values compare reasonably with figures of approximately 1 and 0.3% predicted by the Gaussian diffusion and AgDRIFT models for a 500-m-wide field source width with neutral conditions (Fig. 4 and 5). Agreement between the two computer models was generally good for downwind distances greater than 100 m.

Mass Balance

Normalizing mean figures to a 500-m-wide field (Fig. 6), deposition upon cotton leaves was approximately 60 and 50% for ULV and LV application, respectively.

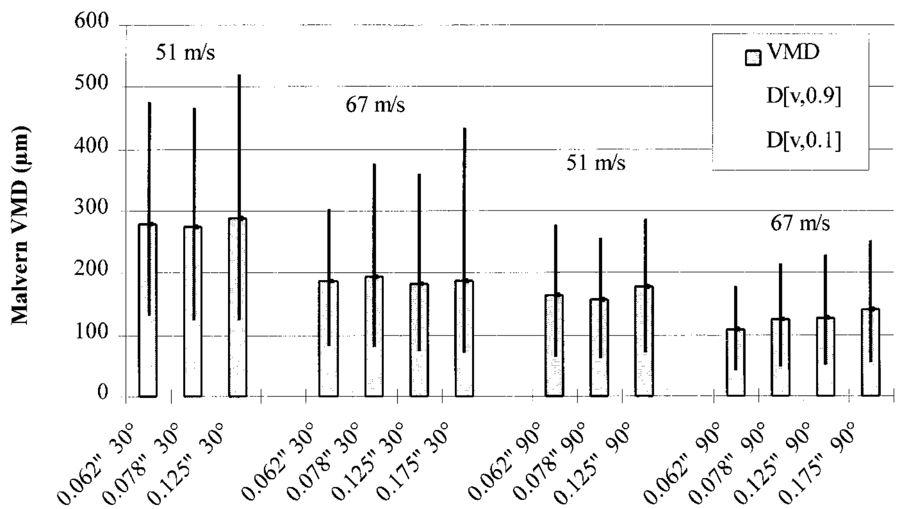

Fig. 2. **Malvern laser volume median diameter (VMD) values for the CP nozzle spraying endosulfan emulsifiable concentrate (EC) at 20 L/ha, measured at two airspeeds and two deflector angles to the airstream. Lines represent D[v,0.9] to D[v,0.1] interval (i.e., the width of the spectrum).**

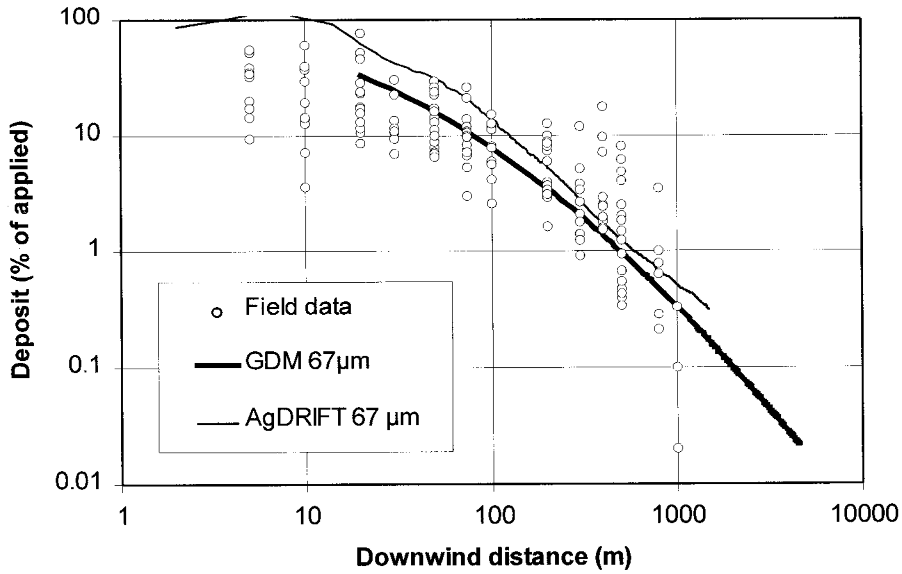

Fig. 4. Downwind deposition values obtained on horizontal flat plates for ultra low volume (ULV) application. Data compared against Gaussian diffusion (GDM) and AgDRIFT model outputs.

Ground deposition was notably higher at approximately 45% for the LV spray compared with 25% for the ULV spray. Of the total amount released per unit crosswind distance over a 500-m-wide field source width (in g/m), approximately 14% moved across the downwind edge of the field, with approximately half of this depositing within the first 500 m downwind. With LV application, this figure was approximately 7%, with most of this (5%) depositing within the first 500 m.

CONCLUSION

A comprehensive series of trials undertaken from 1993 to 1998 has helped to quantify the aerial transport of pesticides that occurs during normal commercial applications of endosulfan. Mean spray deposition upon cotton leaves crop surfaces was roughly equivalent for ULV and LV application, but losses to the air were higher with ULV applications, and losses to the ground were higher with LV applications. The high variation in data between trials was accounted for by the wide range of windspeed, temperature, humidity, atmospheric stability, and crop structure encountered.

Gaussian diffusion and AgDRIFT computer models (using droplet size data from laser difraction studies) have been successfully compared to the experimental data derived from this study. These models have proved useful in recommending spray drift buffer distances for implementation in spray drift management programs (Woods et al., 1998b; Dorr et al., 1998). The slight elevation of the AgDRIFT curve at mid-distance (Fig. 5) compared with the Gaussian diffusion model (GDM)

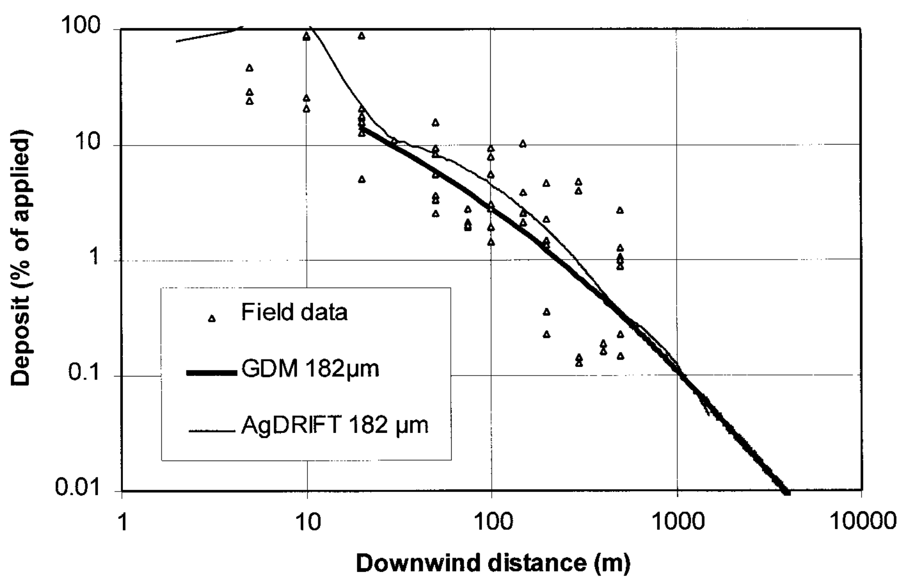

Fig. 5. Downwind deposition values obtained on horizontal flat plates for low volume (LV) application. Data compared against Gaussian diffusion (GDM) and AgDRIFT model outputs.

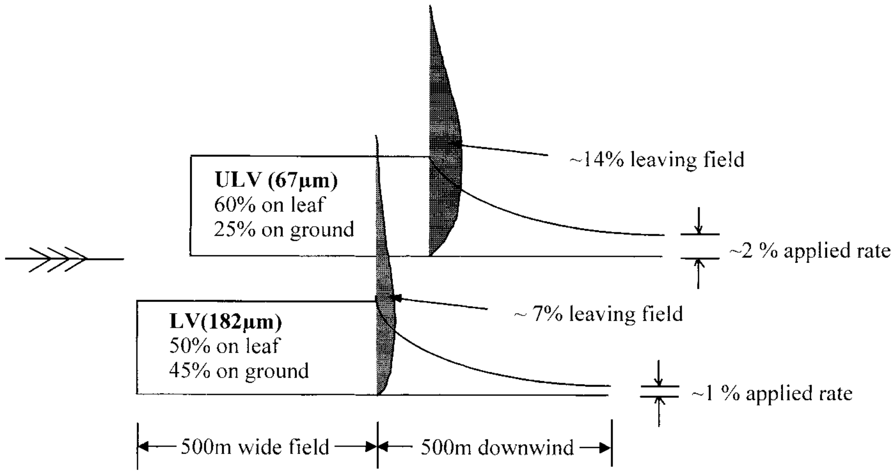

Fig. 6. Summary of transport characteristics for endosulfan insecticide, aerially applied in cotton.

curve for water-based spray drift may be due to the ability of the AgDRIFT model to predict the effect of droplet evaporation. There was, however, very good agreement between the models at distances greater than 500 m downwind. Some of the data was appreciably (up to 10 times) higher than levels predicted by the models. This may be because some of the trials were carried out in stable or dusk surface temperature inversion atmospheric conditions. Both the models assume a neutral atmosphere.

The selection of LDP water-based application techniques (i.e., VMD greater than 250 µm) reduced the detected airborne fraction by up to three times at 100 m downwind of a single flight line (Fig. 3). When larger droplets (VMD) are required, hydraulic nozzles should be used. However, higher volumes of carrier (up to 50 L/ha) may be required to ensure that droplet numbers per cm^2 on the leaf are sufficient for control of the insect pest. Compared with ULV application, efficacy may be reduced and losses to the ground may be increased. Future studies will be aimed at quantifying these effects.

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REFERENCES

Akesson, N.B., and W.E. Yates. 1974. The use of aircraft in agriculture. FAO Agric. Ser. 2, FAO Agric. Development Paper 94. FAO, Rome.

Bache, D.H., and W.J.D. Sayer. 1975. Transport of aerial spray. 1. A model of aerial dispersion. Agric. Meteorol. 15:257–271.

Bird, S., D.M. Esterly, and S.G. Perry. 1996. Atmospheric pollutants and trace gases: Off-target deposition of pesticides from agricultural spray applications. J. Environ. Qual. 25:1095–1104.

Constable, G.A. 1986. Growth and light receipt by mainstem cotton leaves in relation to plant density in the field. Agric. For. Meteorol. 37:279–292.

Craig, I.P., N. Woods, and G. Dorr. 1998. A simple guide to predicting aircraft spray drift. Crop Prot. 17:475–482.

Dorr, G., N. Woods, and I.P. Craig. 1998. Buffer zones for reducing drift from the application of pesticides. Paper no. 8. SEAg Int. Conf. on Eng. in Agric., Perth. Sept 1998. The Inst. of Eng. Australia, Barton, ACT, Australia.

Kennedy, I.R., N. Ahmad, H. Beasley, J. Chapman, J. Hobbs, B. Simpson, and N. Woods. 1998. Quality assurance in pesticide sampling and analysis. LWRRDC Occasional Paper No 14/98. Land & Water Resour. Res. & Development Corp., Canberra, Australia.

Lee, N., H. Beasley, S. Kimber, M. Silburn, N. Woods, J. Skerritt, and I. Kennedy. 1997. Application of immuno-assay to studies of the environmental fate of endosulfan. J. Food Agric. Chem. 45: 4147–4155.

Richardson, B., J.W. Ray, K.J. Miller, A.L. Vanner, and N.A. Davenhill. 1995. Evaluation of FSCBG—An aerial application simulation model. Appl. Eng. Agric. 11:485–494.

Riley, C.M., and C.J. Wiesner. 1989. Off-target deposition and drift of aerially applied agricultural sprays. Pestic. Sci. 26:159–166.

Spillman, J.J. 1982. A rapid method of calculating the downwind distribution from aerial atomisers. EPPO Bull. 13:425–431 and College of Aeronautics Memo no. 8224. Cranfield Inst. of Technol., Bedford, UK.

Spray Drift Task Force. 1997. A summary of aerial application studies. Spray Drift Task Force, c/o Stewart Agric. Res. Services, Macon, MO.

Teske, E.M., S. Bird, D. Easterly, S. Ray, and S. Perry. 1997. A users guide for AgDRIFT 1.0: A tiered approach for the assessment of spray drift of pesticides. CDI Tech. Note no. 95-10. Prepared on behalf of the Spray Drift Task Force, c/o Stewart Agric. Res. Services, Macon, MO.

Woods, N., I.P. Craig, and G.J. Dorr. 1998a. Aerial transport: Spray application & drift. p. 19–22. *In* Minimising the impact of pesticides on the riverine environment: Key findings from research with the cotton industry. LWRRDC Occasional Papers 23/98, 4. Land & Water Resour. Res. & Development Corp., Canberra, Australia.

Woods, N., I.P. Craig, and G.J. Dorr. 2000a. Measuring and assessing spray drift arising from the aerial application of pesticides in cotton. Paper no. 001026. ASAE meeting, Milwaukee, WI. 9–12 July 2000. Am. Soc. Agric. Eng., St. Joseph, MI.

Woods, N., G.J. Dorr, and I.P. Craig. 1998b. Practices for minimising spray drift and dust. p. 89–93. *In* Minimising the impact of pesticides on the riverine environment: Key findings from research with the cotton industry. LWRRDC Occasional Papers 23/98, 17. Land & Water Resour. Res. & Development Corp., Canberra, Australia.

Woods, N., G.J. Dorr, and I.P. Craig. 2000b. Droplet size analysis of aircraft nozzle systems applying oil and water based formulations of endosulfan insecticide. p. 372–377. *In* Proc. 8th Int. Conf. on Liquid Atomisation and Spray Systems, Pasadena, CA. 16–20 July 2000. Inst. of Liquid Atomisation and Spray Systems, Irvine, CA.

Yates, W.E., N.B. Akesson, and D.E. Bayer. 1978. Drift of glyphosate sprays applied with aerial and ground equipment. Weed Sci. 26: 597–604.