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SID 5 Research Project Final Report

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Project identification

1. Defra Project code: PS 2020

2. Project title: Identifying methods of controlling spray drift when using increased boom heights

3. Contractor organisation(s):
Silsoe Spray Applications Unit
(Part of The Arable Group)
Building 42, Wrest Park
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BEDFORD
Beds. MK45 4HP

4. Total Defra project costs (agreed fixed price): £ 74,887

5. Project: start date .... 1st September 2008

end date .... 31st December 2009

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Executive Summary

7. The executive summary must not exceed 2 sides in total of A4 and should be understandable to the intelligent non-scientist. It should cover the main objectives, methods and findings of the research, together with any other significant events and options for new work.

The study aimed to define the extent to which increases in spray drift associated with the operation of boom sprayers with booms substantially above the optimum height for both spray volume distribution at the crop/target height and drift control could be mitigated by using nozzles with reduced spray fan angles and/or changes to the forward speed of the sprayer.

Experiments were conducted with "03" flat fan nozzles and examples of both conventional and air-induction designs were obtained having nominal spray fan angles of 65^o, 80^o and 110^o. Measurements of the physical characteristics of the sprays (droplet size and velocity distributions and spray fan angles) were made at a distance of 350 mm below the nozzle for all designs and fan angles operating at pressures of 2.0, 3.0 and 4.0 bar. Measurements were also made close to the nozzle outlet orifice so as to generate input data required for a simulation model to predict airborne spray and sedimenting drift profiles. Results from the droplet size measurements showed the expected trends for both the conventional and air-induction nozzle designs with reducing spray fan angles increasing droplet sizes and reducing pressures also increasing droplet sizes.

Wind tunnel measurements of airborne spray profiles from both moving and static booms supporting conventional nozzles with the three spray fan angles showed that for a given boom height, reducing the spray fan angle reduced the quantity of airborne spray liquid downwind of the boom. Measurements with the static and moving booms gave results that were in good relative agreement with the use of a 65^o nozzle compared with a 110^o conventional design reducing the volume of airborne spray by up to 70% at nozzle heights of between 850 and 900 mm. Measurements with the air-induction nozzles mounted on a static boom in the wind tunnel also demonstrated that reducing the spray fan angle reduced the volume of airborne spray downwind of the boom with reductions in the range 35% to 46% for a change in spray fan angle from 110^o to 65^o and operating with boom heights of 900 and 1100 mm.

Field experiments measured airborne spray profiles at 5.0 and 10.0 m downwind of a single spray track that was traversed by a 24.0 m boom sprayer at speeds of 10.0 and 12.0 km/h when fitted with 65^o, 80^o and 110^o fan angled nozzles. Ground deposits at distances up to 10.0 m from the edge of the sprayed swath were also measured. Results at boom heights of 900 and 1100 mm were in good relative agreement with the wind tunnel studies but at 700 mm, the results in the first field trial did not show the expected trends with higher levels of airborne spray from the nozzles with the narrower spray fan angles. Results from a second series of field trials at a boom height of 700 mm gave results that were in closer agreement with those from the wind tunnel study. Field trial results typically showed that airborne spray profiles could be reduced by up to 75% by using a 65^o rather than 110^o nozzle although the results were variable and not all of the variability could be explained by variations in wind speeds at the time of the different measurements.

A computer simulation model was used to interpolate and extrapolate the results from the field experiments. While reasonably good agreement was found in some cases between model predictions of ground deposits and measured values, the agreement between measured and predicted airborne spray profiles at the two downwind distances was generally poor. This lack of agreement between measured and predicted airborne spray profiles for the different nozzle conditions and boom heights limited the ability to use the model to interpolate and extrapolate the field data although using a relative approach and relating predictions to the 110^o nozzle at 500 mm height did enable the observed trends to be smoothed but with limited confidence.

It was concluded that using nozzles with spray fan angles of less than 110^o could play an important role in reducing the risk of drift when boom heights above the optimum for spray volume distribution pattern and drift risk must be used. Air-induction nozzles can give drift reductions that are of at least as large as those achieved by reducing spray fan angles and often larger such that any strategy for managing drift from high booms is likely to use a combination of air-induction nozzles and reduced spray fan angles when treating targets where the use of a fine/medium spray quality is not critical for efficacy. Although at a given boom height the use of both air- induction nozzles and nozzles with smaller spray fan angles reduced the amount of drift, the results from the study showed that at boom heights of 900 mm and above, the use of 65^o air-induction nozzles would not give a drift profile that could be used to support a claim for a LERAP Low Drift three-star rating but that a two-star rating would be achievable at a boom height of 900 mm.

Further work is required:

- to quantify the magnitude of drift reductions that can be achieved in a wider range of operating conditions with different nozzle designs, boom heights and operating pressures;

- examine the drift performance of machines fitted with rate controllers and operating with different nozzle designs over a range of forward speeds;

- to improve the simulation model of drift from boom sprayers so as to enable results from field trials to be interpolated and extrapolated with confidence.

8. As a guide this report should be no longer than 20 sides of A4. This report is to provide Defra with details of the outputs of the research project for internal purposes; to meet the terms of the contract; and to allow Defra to publish details of the outputs to meet Environmental Information Regulation or Freedom of Information obligations. This short report to Defra does not preclude contractors from also seeking to publish a full, formal scientific report/paper in an appropriate scientific or other journal/publication. Indeed, Defra actively encourages such publications as part of the contract terms. The report to Defra should include:
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   - details of methods used and the results obtained, including statistical analysis (if appropriate);
   - a discussion of the results and their reliability;
   - the main implications of the findings;
   - possible future work; and
   - any action resulting from the research (e.g. IP, Knowledge Transfer).

1. Introduction

A number of studies relating to the risk of drift from agricultural crop sprayers have identified boom height as one of the most important variables that must be controlled if the risk of drift is to be minimised. Timeliness is a key feature influencing the efficacy of plant protection products and this is related to sprayer work rate and the range of conditions in which a machine can operate. For a boom sprayer, work rate is a function of spraying speed, boom width, application volume and filling/loading time. The trends towards the use of wider booms and higher spraying speeds to achieve higher work rates can make operations with boom heights of 500 mm or lower difficult to achieve. Boom suspension design and the use of automated boom height control systems can improve the opportunities for operating machines with boom heights at or below the threshold value for good drift control of 500 mm. However there are likely to be conditions, particularly involving undulating terrain, when maintaining the correct boom height for spray drift control is very difficult. This project set out to identify strategies that could be used to minimise the risk of drift when boom heights of greater than those associated with good drift control have to be used for operational reasons.

Spray angle is an important variable in determining the boom height at which a uniform volume distribution pattern will be achieved at crop canopy level. Spray angles of 110^o to 120^o have become an adopted standard within the industry enabling boom heights of less than 500 mm to be used to give a uniform volume distribution pattern. Results from computer simulation studies reported by Hobson *et al.*, (1993) have indicated that, if boom heights of less than 500 mm can be used with 110^o flat fan nozzles then this is a better option for drift control than using a narrower 80^o spray angle and boom heights of 500 mm or more. However, using 110^o nozzles at boom heights of more than 500 mm gives substantial increases in the risk of drift (Byron and Hamey, 2008; Miller *et al.*, 2008).

For boom sprayers operating over arable field conditions, the risk of drift can also be reduced by:

- Selecting an appropriate nozzle type: air-induction nozzles have been officially recognised as being able to deliver drift reductions of more than 75% of that from a reference conventional flat fan nozzle operating at a defined height and pressure and so achieve LERAP Low Drift three-star ratings;
- Reducing forward speed - a sprayer fitted with a “rate controller” in which the pressure at the nozzle will be reduced at lower speeds (and vice versa) so as to maintain a constant application rate may reduce the drift risk at a lower forward speed due to a reduced pressure at the nozzle and/or a change in the air flow around the spray with a reduced tendency to detrain small droplets that would then drift.

2. Objectives of the work

A. To assess the extent to which the increase in spray drift associated with operating spray booms above the optimum height can be mitigated by:

(a) selecting nozzles with an appropriate spray fan angle; and/or

(b) reducing forward speed and operating pressure as would be implemented in a conventional spray rate control system.

B. To define relationships between spray fan angle, boom height forward speed, nozzle pressure and the risk of drift from different nozzle designs integrated into a decision tree that will enable drift to be controlled when operating conditions require a boom height above the optimum to be used.

3. Experimental methods and results obtained

3.1 *Nozzles used in the study*

It was recognised that changes to the spray angle of a nozzle could have important implications for spray drift management at boom heights above the optimum when using 110^o flat fan nozzles because:

- reducing the spray fan angle with conventional flat fan nozzle designs generally results in an increase in the droplet sizes generated;
- there is likely to be less disturbance of the air flow around a spray fan with sprays having lower fan angles and therefore a reduced level of detrainment of small droplets from the spray structure.

However, the use of nozzles with spray fan angles of less than 110^o must involve operation at increased boom heights if the requirements for a uniform volume distribution are to be met. Most agricultural nozzles are now made with a colour-coded plastic body (although the orifice can be formed in plastic, stainless steel or ceramic) and have a spray angle of 110^o with 80^o versions also being available. Other spray fan angles are also available particularly for the US market but such nozzles are formed completely in stainless steel or brass. Nozzle catalogues for international use give operating data for spray fan angles of 110^o, 80^o and 65^o and so for this study conventional 110^o and 80^o flat fan nozzles with plastic orifices were used together with a 65^o design from a US-based manufacturer.

Measurements of the droplet size distribution were made using an optical imaging pulsed laser system (the Oxford Lasers Ltd “Visisizer”) at a distance of 350 mm below the nozzle tip. A representative sample of the whole spray was obtained by mounting the nozzle on a computer-controlled x-y transporter system that was programmed to traverse the spray produced in a raster pattern. Conditions at the nozzle, including pressure, liquid and air temperatures were monitored with transducers mounted close to the operating nozzle. The results obtained from an initial series with five “03” size nozzles of each spray angle spraying water only at a pressure of 3.0 bar are summarised in Table 1 below.

Table 1. Measured droplet sizes and velocities when spraying water at a pressure of 3.0 bar with conventional nozzle designs

Nozzle angle, °	Volume Median Diameter, µm		% volume <100 µm		Mean liquid velocity, m/s		Estimated fan angle, °	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
65	330.7	5.4	2.89	0.13	11.95	0.15	70	0.8
80	268.8	4.8	5.58	0.30	9.54	0.18	77	0.7
110	248.9	4.2	6.61	0.54	7.24	0.12	103	2.9

Discussions with representatives of a company supplying agricultural nozzles internationally and that have both 110^o and 80^o flat fan air-induction in their range indicated that they would make a sample of 65^o flat fan air-induction nozzles for experimental purposes. A second series of droplet size and velocity distribution measurements was therefore made that included nominal spray fan angles of 65^o, 80^o and 110^o in both conventional and air-induction agricultural nozzle designs and which also examined the effects of varying nozzle pressure. The results are summarised in Tables 2(a) and 2(b) below, as the mean values of three replicated measurements.

Table 2(a) Measured droplet sizes from "03" sized agricultural nozzles of both conventional and air-induction design having nominal spray fan angles of 65°, 80° and 110°, spraying water.

Nozzle type	Nominal spray fan angle, °	Pressure, bar	Volume Median Diameter, µm		% Spray volume <100 µm		Estimated spray fan angle, °	
			Mean	S.D.	Mean	S.D.	Mean	S.D.
Conventional flat fan	110	2.0	281.9	2.21	4.0	0.27	97	2.0
		3.0	259.9	3.76	5.7	0.19	100	0.6
		4.0	244.1	3.21	7.3	0.27	103	1.2
Conventional flat fan	80	2.0	306.6	5.74	3.4	0.06	73	0.6
		3.0	272.2	5.17	4.9	0.32	76	0.6
		4.0	258.9	4.57	6.1	0.16	79	0.6
Conventional flat fan	65	2.0	352.8	7.80	2.2	0.12	64	0.6
		3.0	338.0	11.63	3.0	0.67	68	0.6
		4.0	317.0	7.46	4.2	0.78	68	1.2
Air-induction flat fan	110	2.0	715.6	22.75	0.1	0.03	96	2.3
		3.0	585.5	29.17	0.2	0.02	104	1.7
		4.0	552.9	27.99	0.3	0.09	109	1.2
Air-induction flat fan	80	2.0	780.4	21.78	0.1	0.01	68	2.9
		3.0	690.1	8.60	0.2	0.02	77	2.0
		4.0	592.5	40.20	0.3	0.02	79	2.1
Air-induction flat fan	65	2.0	863.9	6.26	0.1	0.02	59	0..6
		3.0	717.6	6.03	0.1	0.01	66	2.1
		4.0	625.9	43.39	0.3	0.02	70	1.7

The results in Tables 1, 2(a) and 2(b) show many of the expected trends, namely:

- wider spray fan angles from nozzles of a given size and operating pressure produced a finer spray with a lower volume median diameter and an increased percentage of spray volume in droplets <100 µm in diameter: the results in Table 2(a) confirmed that this was the case with both conventional and air-induction nozzle designs;

- air-induction nozzle designs gave a much larger droplet size than the conventional design and these results confirm the basis for the drift reducing characteristic of such designs: the data in Table 2(a) show that for the examples used in this study the air-induction nozzles gave mean droplet sizes (as V.M.D.) that were between 112 and 125% larger than for the conventional nozzle whereas changing from 110° to 65° fan angle increased droplet size by some 30%: it is recognised that the risk of drift is a function of variables other than the droplet size distribution (e.g. droplet velocity; porosity of the spray fan to a cross flow of air (Miller, 1993) but that droplet size does provide a first order indication of drift risk particularly for sprays with directly comparable geometries;

- the vertical component of droplet velocity reported in Table 2(b) as a mean liquid velocity increased with decreasing spray fan angles and was higher for the conventional than for the air-induction nozzles: the velocity of droplets in the 40-60 µm size range was used as an indicator of the vertical component of the entrained air velocity which again was greater for conventional rather than air-induction nozzles;

- increasing the operating pressure for both nozzle types and all spray fan angles reduced the mean droplet sizes produced and increased the velocity of the droplets.

The estimated spray fan angles were obtained using the droplet size analyser to detect the edges of the spray fan in terms of measurable airborne droplets at a recorded position and show that at a pressure of 3.0 bar, measured angles for the 110° and 80° nozzles were less than the nominal whereas for the 65° nozzle the spray fan angle was greater than the nominal value. Differences between the spray fan angles, particularly for the 80° and 65° were less than originally planned.

Table 2(b) Measured droplet velocities from "03" sized agricultural nozzles of both conventional and air-induction design having nominal spray fan angles of 65°, 80° and 110°, spraying water.

Nozzle type	Nominal spray fan angle, °	Pressure, bar	Mean liquid velocity, m/s		Mean velocity of droplets 40-60 µm in diameter	
			Mean	S.D.	Mean	S.D.
Conventional flat fan	110	2.0	6.17	0.07	2.24	0.05
		3.0	7.16	0.07	2.47	0.07
		4.0	8.15	0.11	2.82	0.05
Conventional flat fan	80	2.0	8.09	0.08	2.87	0.04
		3.0	9.28	0.21	3.15	0.04
		4.0	10.45	0.06	3.39	0.06
Conventional flat fan	65	2.0	9.94	0.19	2.64	0.04
		3.0	11.78	0.29	2.72	0.06
		4.0	13.24	0.23	2.94	0.04
Air-induction flat fan	110	2.0	5.34	0.26	0.96	0.04
		3.0	5.71	0.11	1.19	0.03
		4.0	6.40	0.07	1.37	0.08
Air-induction flat fan	80	2.0	6.49	0.15	0.99	0.07
		3.0	7.41	0.03	1.22	0.08
		4.0	7.99	0.33	1.44	0.04
Air-induction flat fan	65	2.0	7.07	0.06	1.02	0.06
		3.0	7.89	0.12	1.11	0.02
		4.0	8.73	0.13	1.35	0.07

Different commercial designs of air-induction nozzle are known to have different characteristics particularly in relation to the droplet size distribution generated (Butler Ellis *et al.*, 2008; HGCA Nozzle Guide 2010). The 110° flat fan air-induction nozzle used in the study was representative of a nozzle design giving a mid-range droplet size distribution with the 80° and 65° designed using similar criteria.

Measurements reported in Tables 2(a) and 2(b) were made over a range of pressures because many sprayers will have automatic control systems that adjust pressure in response to variations in forward speed so as to deliver a constant applied dose over a range of speeds. Reducing spraying speed may be an appropriate drift management strategy and if used in conjunction with a "rate controller" would also involve operation at lower pressures at the nozzle.

3.2 *Wind tunnel experiments*

3.2.1 *With a moving boom*

A two-nozzle boom was mounted on a transporter system that was arranged so that the boom could be accelerated and decelerated in "side pods" outside of the main working section of the pesticides wind tunnel on the Silsoe site. The transporter was controlled such that the boom moved across the tunnel section at a speed of 10.0 km/h (2.78 m/s) with a uniform wind speed down the tunnel of 2.0 m/s (7.2 km/h) measured with an ultrasonic anemometer mounted at a height of 1.0 m above the floor of the tunnel. Measurements were made of the airborne spray profiles downwind of the moving boom using vertical arrays of passive polyethylene sampling line collectors of 1.98 mm diameter with a vertical spacing of 100 mm and positioned 2.0 and 5.0 m downwind of the end nozzle on the boom. The nozzles sprayed a solution of a tracer dye ("Green S" – Honeywill and Stein) at a nominal concentration of 0.1% and "Tween 20" (Croda Europe Ltd) also nominally at 0.1%. Deposits collected on the passive sampling lines were recovered into 10 ml of de-ionised water and quantified by colorimetry calibrated with samples of original spray liquid taken from the nozzles. Short artificial turf was placed on the floor of the tunnel immediately below the boom to minimise any splash and each measurement run involved a total of three passes of the boom across the working section of the tunnel

Measurements were made with three nozzle types; all "03" size flat fan designs operating at 3.0 bar pressure but with spray fan angles of 65^o, 80^o and 110^o as described in Section 2.1 above. Measurements were made with boom heights measured to the nozzle orifice of 350, 500, 700 and 850 mm. It was recognised that at the lowest boom height (350 mm), only the 110^o fan angle nozzles would give an approximately uniform volume distribution pattern, at 500 mm height this could potentially be achieved by both 110^o and 80^o nozzles and at 700 mm by all three nozzle angles used. It should be recognised that the lowest height settings used were less than those recommended in some commercial nozzle catalogues. All measurements were replicated three times.

Total measured collector deposits for the three nozzles sampling to a height of 0.6 m and at a distance of 5.0 m downwind (Figure 1) show the expected trends, namely:

- an increase in deposits with increasing boom heights for all nozzle spray angles – note that since the output from all of the nozzles was equal, the measured deposits are directly proportional to the dose of chemical that is airborne at the sampling distance: the increase in deposit with nozzle height for the 110^o degree spray fan angle is in line with results from previous studies (Miller *et al.*, 2008; Byron and Hamey, 2008);

- reduced deposits with reducing spray fan angles such that with a boom height of 850 mm and a 65^o spray fan angle deposits were approximately equal to those from 110^o spray fan angle nozzle operating with a boom height of 500 mm;

- relatively small error bars (except for the 80^o fan angle nozzle at a height of 850 mm) indicating that results from the wind tunnel experiments are relatively repeatable.

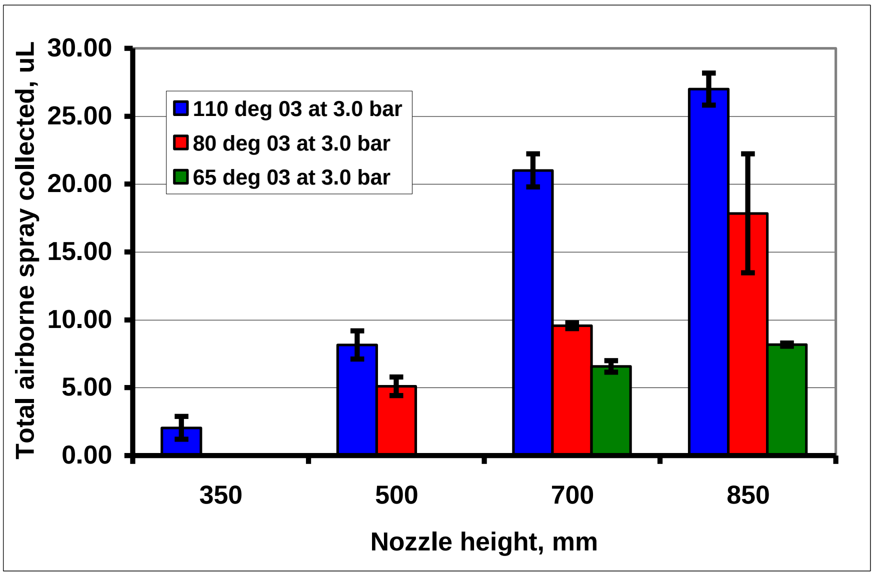

Figure 1 **Measured total collector line deposits 5.0 m downwind of a moving two-nozzle boom in a wind speed of 2.0 m/s: Error bars show ± one standard deviation.**

To provide results that can be compared across different experiments the results have been normalised such that the deposits for the 110^o nozzle operating at a height of 500 mm represent a value of 100%. Relative deposits measured at downwind distances of 5.0 and 2.0 m respectively are plotted in Figures 2 and 3, and show very consistent trends at the two downwind measuring distances. For the 110^o fan angle nozzle increasing the height from 500 to 850 mm increased the volume of airborne spray downwind of the boom by a factor of approximately 3.5 and using an 80^o fan angle nozzle for boom heights above 500 mm reduces the risk of drift by a factor of almost two.

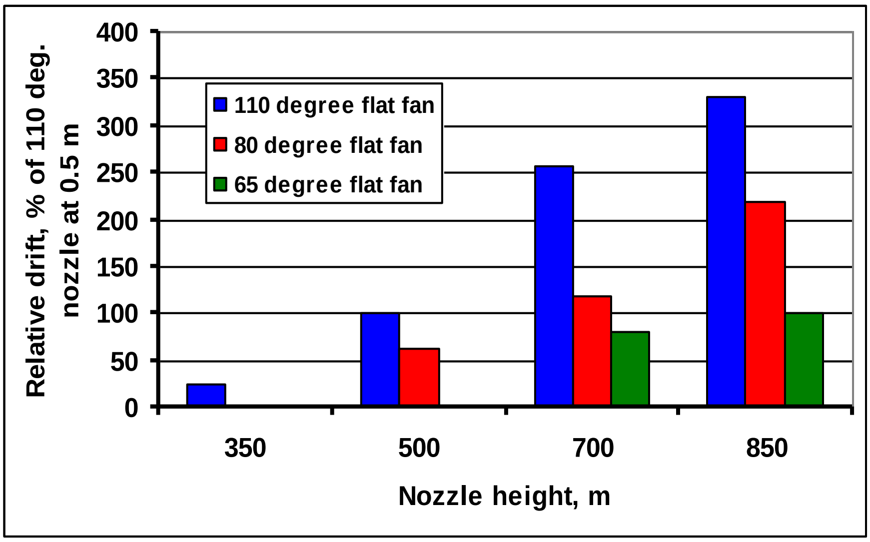

Figure 2 **Measured total collector line deposits measured 5.0 m downwind of a moving boom and expressed as a percentage of the deposits for a 110^o "03" nozzle operating at 3.0 bar pressure at a height of 500 mm.**

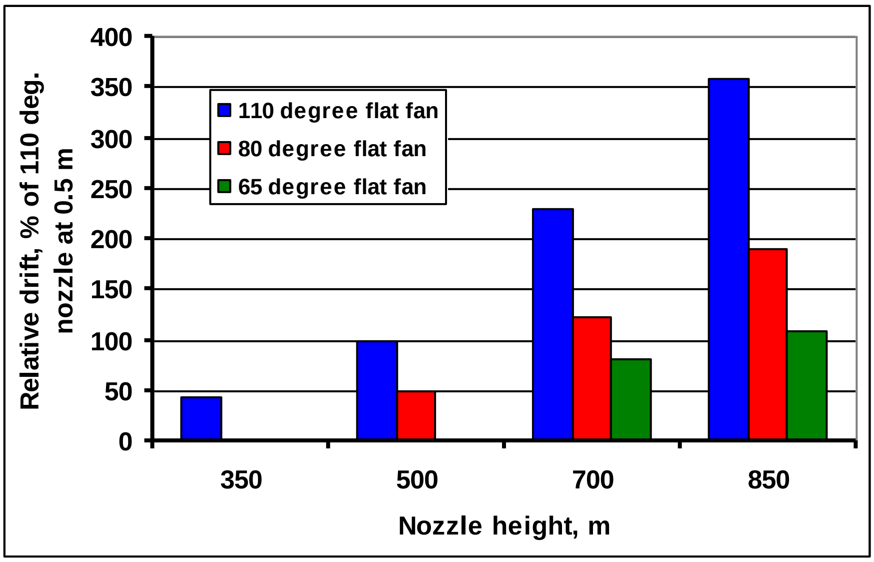

Figure 3 **Measured total collector line deposits measured 2.0 m downwind of a moving boom and expressed as a percentage of the deposit for a 110^o "03" nozzle operating at 3.0 bar pressure at a height of 500 mm.**

3.2.2 *With a static boom*

A boom with five nozzles spaced at 0.5 m was supported statically across the working section of the wind tunnel with provision to adjust the height above the floor of the tunnel. Experimental measurements were again made spraying a solution of a tracer dye (0.1% "Green S" and 0.1% "Tween 20") into a uniform wind speed down the tunnel of 2.0 m/s measured with an ultrasonic anemometer mounted in the centre of the tunnel section. The liquid supply to the nozzles was controlled by a solenoid valve connected to an electronic timer so that spray could be delivered for controlled time periods of 10 or 20 s depending on the nozzle types fitted. Measurements of the airborne spray downwind of the boom were made with a vertical array of passive line collectors (as described in 3.2.1 above) positioned 5.0 m downwind from the nozzles and extending across the full width of the tunnel.

Results plotted in Figure 4 show trends that are very similar to those obtained with the moving boom (Figure 1) but with higher volumes of spray liquid collected in line with the increased volume of spray liquid released into the tunnel. As with the moving boom, increasing nozzle height increased the quantity of spray collected as expected and reducing spray fan angle reduced airborne spray volumes collected downwind. With a nozzle height of 0.9 m, airborne spray volumes from the 65^o angle spray was just less than that from the 110^o nozzle operating at a height of 500 mm. Results expressed as a percentage of airborne spray volume collected from the

110° nozzle operating at a height of 500 mm (Figure 5) enable direct comparisons to be made with the results from nozzles mounted on a moving boom (Figures 2 and 3) and with field data – see Section 3.3 below.

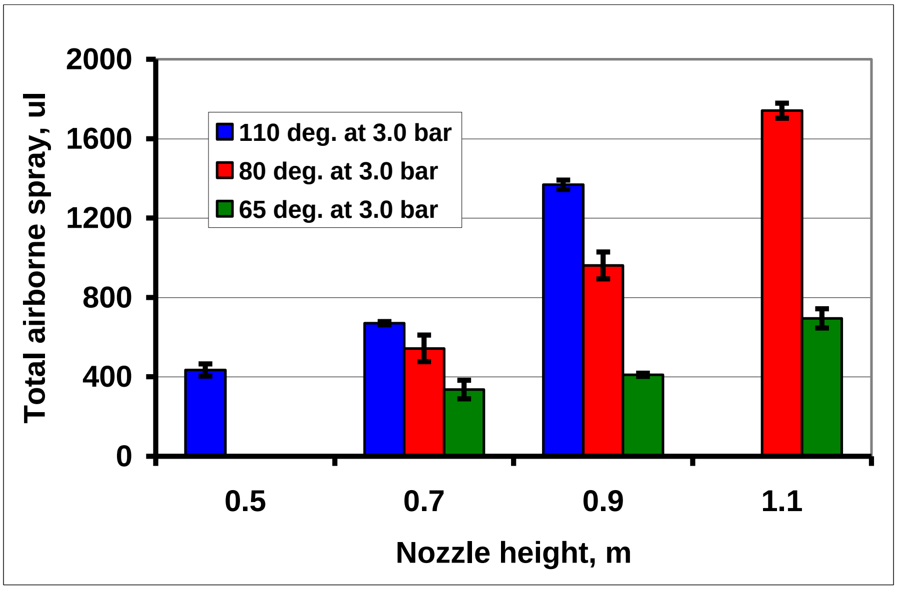

Figure 4 Measured total collector line deposits 5.0 m downwind of a static five nozzle boom operating in a wind speed of 2.0 m/s: Error bars show ± one standard deviation.

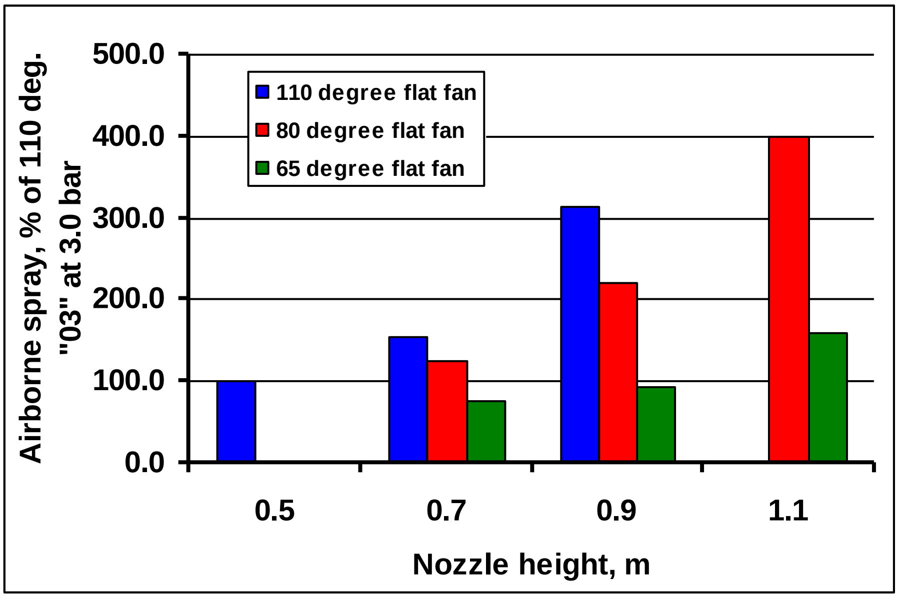

Figure 5 Measured total collector line deposits measured 5.0 m downwind of a static five nozzle boom operating in a wind speed of 2.0 m/s: results expressed as a percentage of those measured with an “03” 110° flat fan nozzle operating at 3.0 bar pressure and a height of 500 mm.

An additional series of measurements were made with the static five nozzle boom examining the airborne spray volumes downwind of a boom fitted with air-induction nozzles. The results, summarised in Table 3, show that at a boom height of 1100 mm, the 110° fan angle air-induction nozzle gave greater volumes of airborne spray than the conventional 110° fan angle nozzle operating at a height of 500 mm, but that reducing the spray fan angle to 65° reduced the volume of airborne spray by up to 45%. This reduction due to the change in spray fan angle was less than that recorded with conventional nozzles (Figures 2, 3 and 5) and may reflect the lower levels of spray volume detrained when using air-induction nozzles.

The spray volumes measured for the conventional 110° fan angled nozzle at a height of 500 mm in this second series (Table 3) were lower than in the initial series (Figure 1) and this variation has been observed between other series of wind tunnel experiments. The variability in the results was less for the air-induction nozzles (see standard deviation figures in Table 3) probably because a longer spraying period (20 s) was used with these nozzles compared to 10 s with the conventional nozzles where the risk of saturating parts of the sampling line limited the duration of the spray.

Table 3. Measured airborne spray volumes (in µl) 5.0 m downwind of a static boom fitted with air-induction nozzles.

	Nozzle				
	Conventional 110^{o} flat fan	**Air-induction 110^{o} flat fan**		**Air-induction 65^{o} flat fan**	
Boom height, mm	**500**	**900**	**1100**	**900**	**1100**
Measured total airborne spray volume 5.0 m downwind.					
Mean	223.4	155.4	251.0	110.8	136.2
Standard Deviation	19.9	8.1	8.4	11.2	1.1
Measured airborne spray volume as a percentage of that from the 110^{o} nozzle at a height of 500 mm	100	69.6	112.4	45.1	61.0

3.3 *Field measurements of drift*

A field trial (Trial 1) was conducted using a commercial design of 24 m wide self-propelled boom sprayer operating over a cut grass surface approximately 50 mm tall. A solution of a tracer dye (“Green S” – Honeywill and Stein at nominally 0.2%) and “Tween 20” (Croda Europe Ltd) at nominally 0.1% was sprayed. All measurements were made with the sprayer travelling at 12.0 km/h and a nozzle pressure of 3.0 bar and with the sprayer making four passes (two in each direction) of a measurement array positioned downwind of the spray track that was arranged to be at right angles to the mean wind direction. Measurements were made with 110^{o}, 80^{o} and 65^{o} nozzles and with nozzle heights of 500 mm (110^{o} fan angle only), 700 mm (all fan angles), 900 mm (all fan angles) and 1100 mm (80^{o} and 65^{o} fan angles only). Wind speed and direction was recorded during each measurement run using an ultrasonic anemometer mounted at a height of 2.0 m and positioned upwind of the spray track.

The downwind monitoring array comprised:

(a) two sampling frames positioned at 5.0 and 10.0 m downwind from the edge of the sprayed swath (measured from the position of the outer nozzle on the boom) with each frame supporting 20 passive polyethylene sampling lines, each 1.98 mm in diameter and with a vertical spacing on the frame of 100 mm;

(b) wooden laths 500 mm long and 50 mm wide supporting chromatography paper that was 50 mm wide and with laths positioned at 1.0, 2.0, 3.0, 5.0 and 10.0 m downwind of the edge of the sprayed swath and with two laths at each measurement distance.

(c) three wooden laths as in (b) above but positioned within the sprayed swath and removed after the first pass of the sprayer.

On completion of a measurement run, all collecting surfaces were placed in individual labelled polythene bags, placed in black polythene bags and transported to the laboratory for analysis. Tracer dye deposits were recovered into measured volumes of de-ionised water and quantified by colourimetry calibrated with samples of the original spray liquid taken from the nozzle at the time of application.

Measured total airborne deposits at distances of 5.0 m (Figure 6) and 10.0 m (Figure 7) show some of the expected trends but with some anomalies. Results obtained with nozzle heights of both 900 and 1100 mm give relative magnitudes of airborne spray that are consistent with expectation and in agreement with the results from the wind tunnel experiments. However results at the boom height of 700 mm do not show the expected trends with values for the 80° and 65° fan angle nozzle being higher than expected in relation to the values for the 110° nozzle – this may be that the values for the 110° fan angle nozzle at this height are unexpectedly low. There was some variation in the mean wind speed during the day as can be seen in Table 4. However, the variation in wind speeds observed during the experiment do not account for the unexpected trends in the results obtained and applying a simplified correction to account for the wind speed variation did not resolve the relatively high values for the lower spray angles observed at a nozzle height of 700 mm.

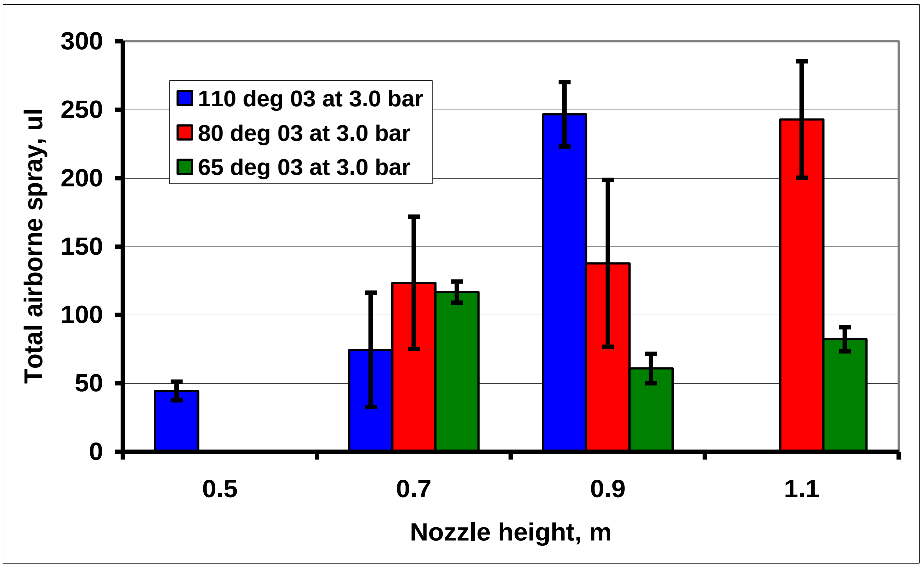

Figure 6 Measured total line deposits 5.0 m downwind of the edge of the spray swath in field conditions in field trial 1.

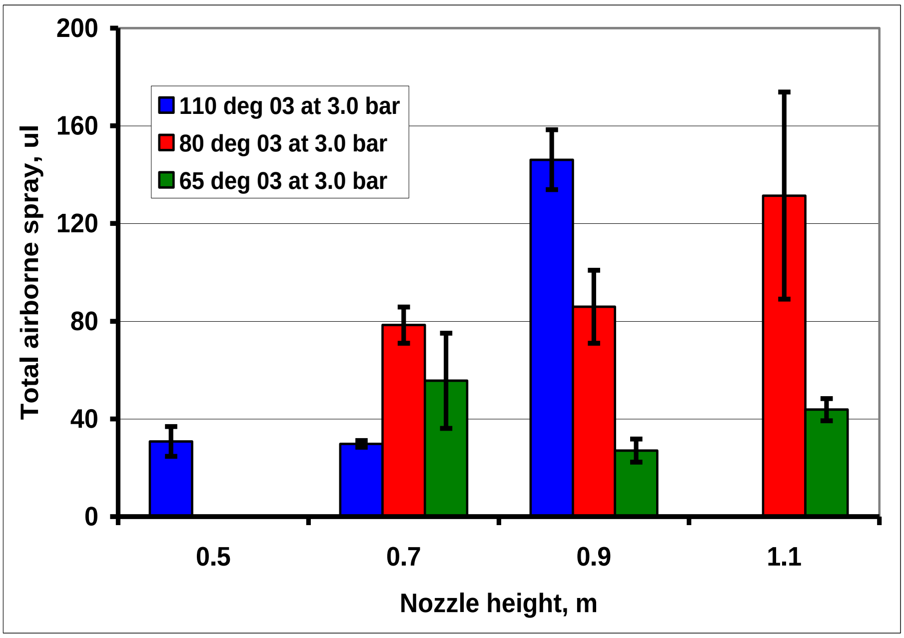

Figure 7 Measured total line deposits 10.0 m downwind of the edge of the spray swath in field conditions in field trial 1.

Table 4 Mean wind speeds in field trial 1

Run No.	Nozzle Angle, °	Boom Height, mm	Mean Wind Speed, m/s
1	110	500	2.12
2	110	700	2.53
3	110	900	2.91
4	80	700	2.86
5	80	900	2.66
6	80	1100	4.13
7	65	700	4.90
8	65	900	4.45
9	65	1100	4.45

Measured ground deposits in field trial 1, plotted in Figure 8 also show some of the expected trends with the lowest levels of deposition recorded at the lowest nozzle heights with all spray fan angles and with the highest deposits at the largest nozzle heights (1100 mm) for the 110° and 80° nozzles. At distances of between 3.0 and 5.0 m downwind, deposits from the 65° nozzle at all heights were similar to those from the 110° nozzle at 500 mm height.

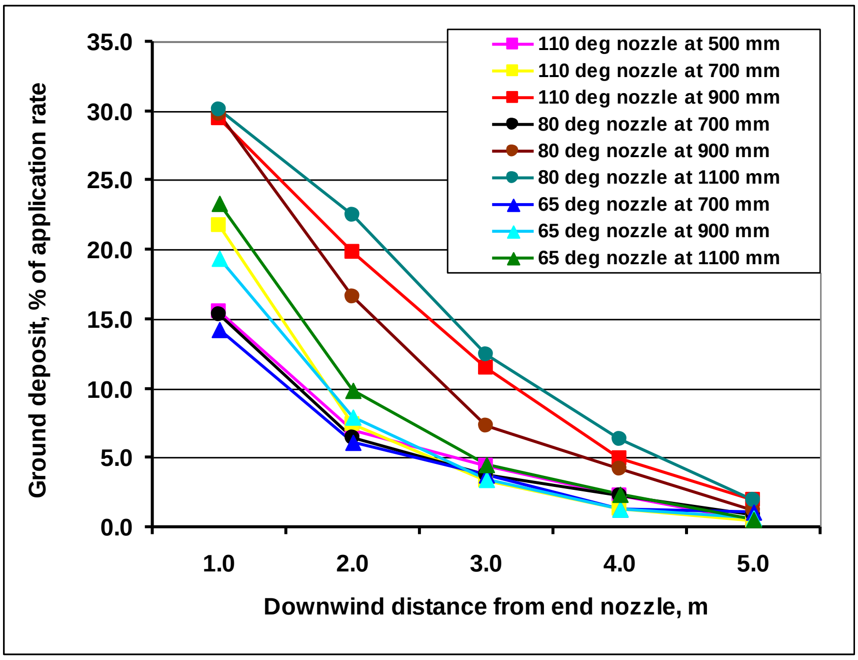

Figure 8 **Measured ground deposits up to 5.0 m downwind of the edge of the spray swath in field conditions in field trial 1.**

A second series of field experiments examined the performance of the three different spray angles at a nozzle height of 700 mm using a comparable methodology to that used in the first series of experiments and the results are summarised in Table 5 below. Results show the expected trends, namely:

- airborne spray volumes decreasing with reducing spray fan angle;
- close relative agreement between spray volumes measured at 5.0 and 10.0 m downwind of the spray track;
- ground deposits that reduced rapidly with increasing distance from the edge of the spray track and with substantially lower values for the 65° nozzle compared with the 110° fan angle nozzle as expected.

Table 5 Summary of results from the second field trial.

	Nozzle fan angle		
	110^o	**80^o**	**65^o**
Total airborne spray, µL			
at 5.0 m	189.72 ± 53.42	119.09 ± 25.37	56.58 ± 2.29
at 10.0 m	101.54 ± 24.50	80.41 ± 9.40	36.40 ± 5.29
Ground deposits, L/ha			
at 1.0 m downwind	286.80	220.10	125.43
at 2.0 m downwind	154.74	110.60	42.78
at 3.0 m downwind	80.02	56.40	37.47
at 5.0 m downwind	40.31	31.12	17.78
at 10.0 m downwind	12.92	12.28	5.42

4. Use of a computer simulation model to interpolate and extrapolate the experimental results

A computer simulation model (Butler Ellis and Miller, 2010) was used to interpolate the results obtained from the two series of field experiments. Input data for the model relating to droplet size and velocity distributions was obtained using the Oxford Lasers Ltd “Visisizer” instrument as described in Butler Ellis and Miller (2010) and which also produced mean droplet size statistics further from the nozzle as detailed in Section 3.1 of this report. The spray fan porosity parameters required by the model were taken as values for the 110^o design as given in published literature and the measured meteorological conditions for each run were used to run the model and predict the downwind dispersion of the spray and to give:

- airborne spray profiles at 5.0 and 10.0 m downwind of the sprayed swath; and
- ground deposits to 10.0 m downwind of the sprayed swath.

While ground deposits were predicted that were in reasonable agreement with measured values (see Figure 9), the predicted airborne spray profiles differed substantially from those that were measured with levels of agreement that were considerably less than those previously for the 110^o nozzle operating at a height of 500 mm (Butler Ellis and Miller). However the relative trends based on normalising deposits to those measured for the 110^o nozzle at a height of 0.5 m do show the expected trends (Figure 10) and reasonable agreement with the combined results from the field experiments (Figure 11).

The results plotted in Figure 10 confirm that reductions in spray fan angle for nozzles will reduce the risk of drift at a given boom height but that the values for the 65^o spray fan angle nozzle at all heights (0.7 m, 0.9 m and 1.1 m) were greater than for the 110^o nozzle at a height of 0.5 m. The trends plotted in Figure 10 are consistent with expectation with levels of airborne spray consistently reducing as spray angle was reduced. It was originally intended to use the model to explore possible combinations of nozzle design and spray fan angle that would give a good performance at a given boom height in relation to both the risk of drift and the spray volume distribution below the boom. However, the scope for conducting this part of the study was limited by the lack of agreement between predicted and measured airborne spray profiles. Previous work had shown reasonable agreement between measured and predicted airborne and sedimenting spray profiles (Butler Ellis and Miller, 2010) and the lack of agreement found in this work indicates that there are factors that are not adequately described in the model and that further work is needed particularly relating to the prediction of airborne profiles.

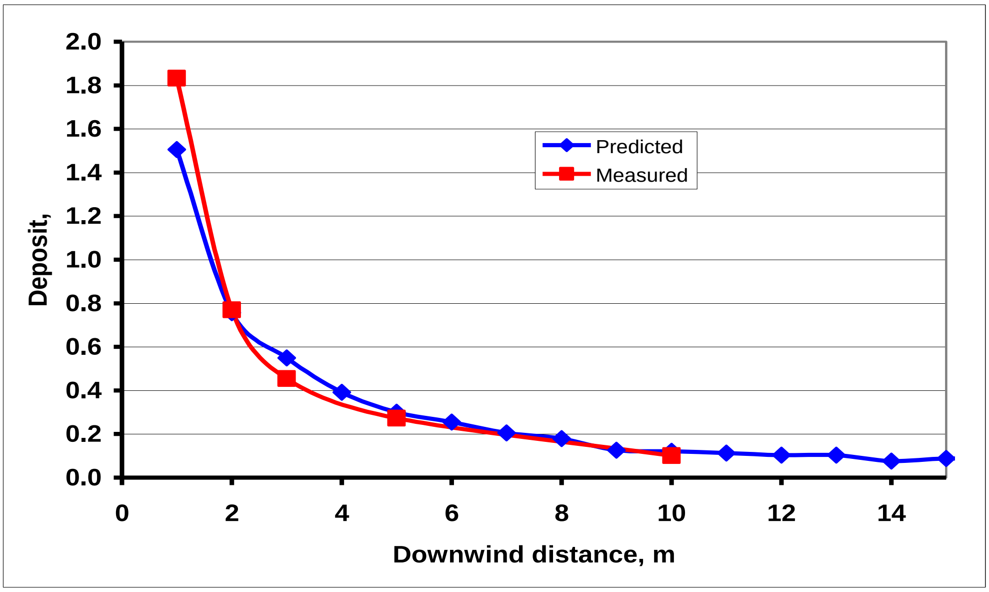

Figure 9 Comparison of measured and predicted ground deposits for the 80° nozzle operating at 0.7 m height in field trial 1.

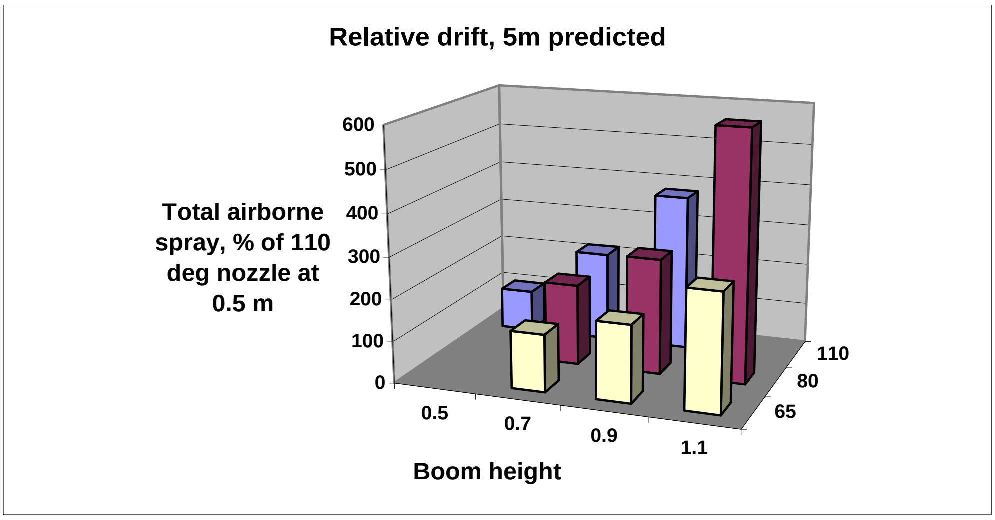

Figure 10 Relative predictions of total airborne spray volumes 5.0 m downwind of the treated swath – both field trials combined.

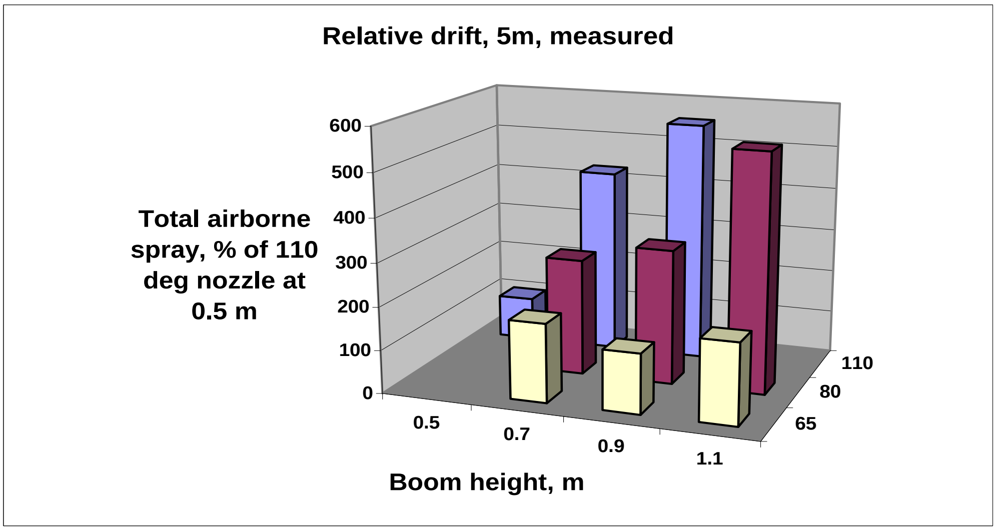

Figure 11 Relative measured values of total airborne spray volumes 5.0 m downwind of the treated swath – both field trials combined.

5. Discussion and conclusions

Results from this study have confirmed the expectation that for a given boom height, the risk of drift can be reduced by reducing the spray fan angle of the nozzle. However, if a uniform spray volume distribution pattern is to be maintained at the crop/target height then smaller spray fan angles will need to use booms at increased heights. Reducing spray fan angles is therefore only an option for drift control if boom heights of 650 mm or greater are to be used.

Reducing the spray fan angle probably reduces the risk of drift by a combination of:

- increasing the mean droplet size and reducing the proportion of spray in small droplets for a given size and design of nozzle;
- reducing the interactions between the spray fan and the cross-flow of air due for example to the forward motion of the sprayer;
- reducing the horizontal component of droplet trajectories at the edge of a spray pattern.

Comparing the results obtained in this study with those reported elsewhere (e.g. Miller *et al*., 2008) indicates that the drift reductions obtained by varying spray fan angle tend to be less than those achieved by using comparable air-induction nozzles although there is a wide range of air-induction nozzle performance depending on which commercial nozzle design is used. If boom heights of greater than the optimum for 110^o nozzles have to be used for operational reasons, then the first step towards implementing a drift control strategy should be to select an air-induction design, (see Figure 12). Such a nozzle selection will deliver a drift reduction based on increasing the droplet size and for some target systems this could have important implications for efficacy such that the use of such a nozzle would not be appropriate (Butler Ellis *et al*., 2008). If a fine/medium spray quality is needed for efficacy, then the options for controlling drift are to keep the boom as low as possible and reduce forward speed. The use of nozzles with a smaller spray fan angle could be appropriate and reduce the risk of drift providing that the spray quality generated by the nozzle is consistent with target requirements for efficacy.

Previous studies examining the effects of forward speed studies the effects due to the air flow around the boom/spray and the possible effects due to changing pressure separately, (Miller and Smith, 1997). At a constant pressure, increasing speed increased the risk of drift particularly in low wind speed conditions. Reducing nozzle pressure from 4.0 to 2.0 bar had a relatively small effect on drift with changes in the droplet size distribution being off-set by changes to the droplet velocity profiles. However, such relationships are likely to be dependant on nozzle size and design and further work is necessary to examine the relationship between drift risk and forward speed for sprayers operating with rate controllers. The results presented in Tables 2(a) and 2(b) showed that for the conventional nozzle designs, reducing the pressure from 3.0 to 2.0 bar increased the mean droplet size (as V.M.D.) by between 4.0 and 12.6% whereas for the air-induction nozzle design the increase was in the range 13.1 to 22.2%. It is therefore likely that varying forward speed with sprayers fitted with a rate controller and operating with air-induction nozzles will give a larger reduction in drift risk as speed is reduced than the same machine fitted with conventional nozzles. However, where droplet size is important for efficacy considerations, then conventional nozzles will need to be used and the magnitude of drift reductions that can be achieved when working with a spray rate controller needs to be verified in field experiments.

The results from experiments with air-induction nozzles having spray fan angles of 65^o and 110^o indicated that the use of the narrower spray fan angle would reduce the risk of drift by between 35.2 and 45.7% at nozzle heights of 900 and 1100 mm. This reduction is less than for the conventional nozzle where reductions were in the order of 70%. While using a narrow angled (65^o) air-induction flat fan nozzle will give substantial drift reductions when compared with other nozzle configurations operating at the same height, it is unlikely that this would give a drift profile that would enable a LERAP Low Drift three-star rating to be achieved at boom heights of 900 mm or greater (see Table 3), although a two-star rating at heights up to 900 mm would be achievable.

The UK market for agricultural spray nozzles is currently strongly dominated by 110^o flat fan nozzles although some 80^o versions are also available. There is now a wide selection of air-induction nozzle designs with a range of performance characteristics but again most of these nozzles are available as 110^o flat fan versions. For the work described in this report, 65^o fan angled versions of both the conventional and air-induction nozzles were obtained, the air-induction nozzle being purpose-made for the project work. For strategies based on using nozzles with smaller spray fan angles to be commercially effective, such nozzles would need to be more widely available and supported by manufacturing companies and distribution networks.

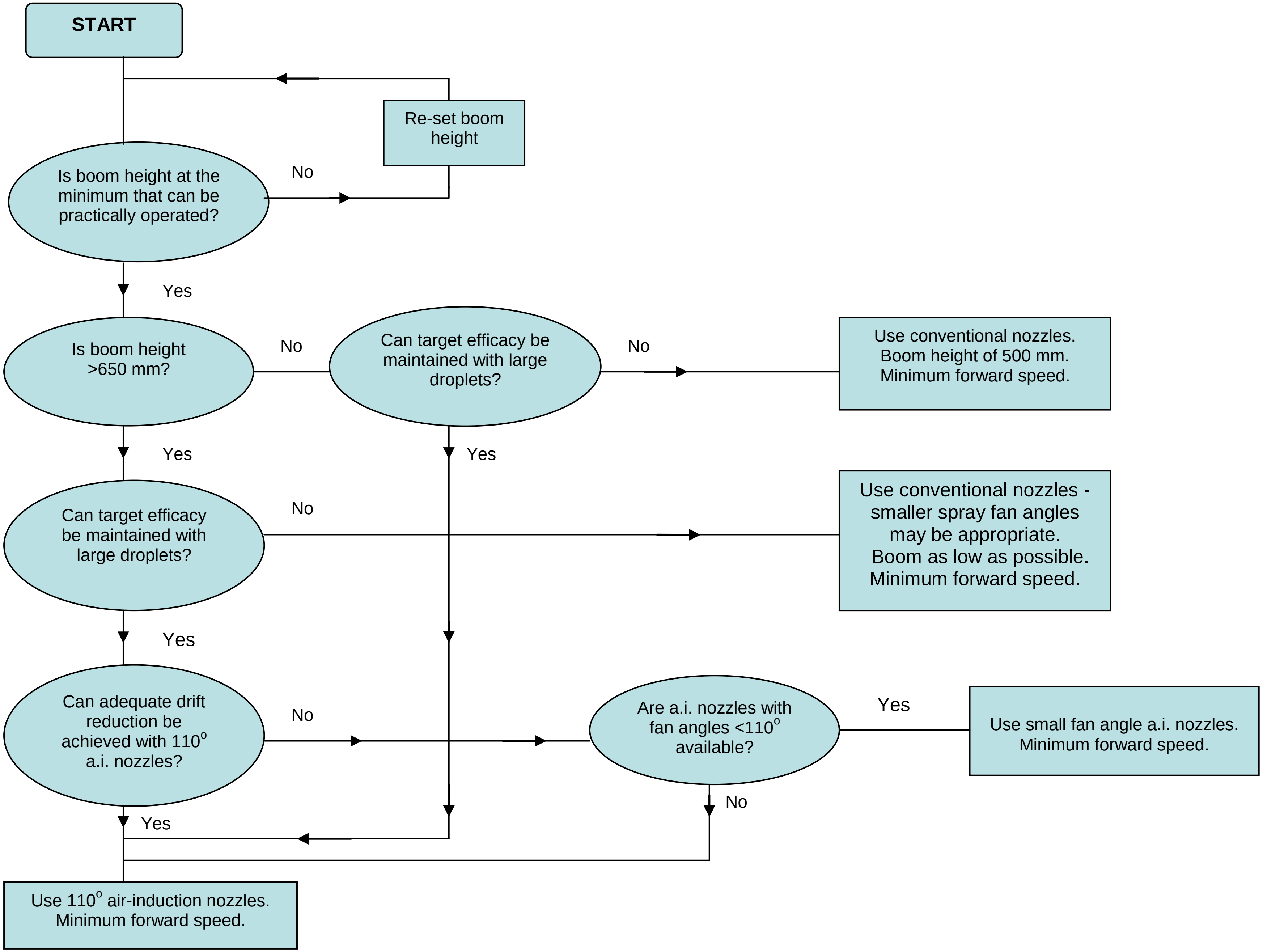

Figure 12 Decision tree for reducing drift with boom height above the optimum.

References to published material

9. This section should be used to record links (hypertext links where possible) or references to other published material generated by, or relating to this project.

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