SESSION 5B

HERBICIDE APPLICATION TECHNOLOGY

Chairman and Session Organiser	Mr D A Webb *IACR-Long Ashton, Bristol, UK*
Papers	5B-1 to 5B-6

Factors influencing the risk of drift into field boundaries

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ABSTRACT

Drift from boom sprayers operating over arable crops is a function of factors relating to the operating conditions, nozzle characteristics and, to a lesser extent, features of the boom and vehicle system. Drift can be related to the percentage of spray volume in small droplets and also spray structure and droplet velocities. For new designs, such as pre-orifice and air induction nozzles, variations in drift with operating variables such as size and pressure may be different to those for conventional nozzle designs. For all nozzle types, height is a critical parameter influencing drift. The use of established vegetative strips at field boundaries can give levels of drift in the order of 50 % less than those for cut stubble over a distance of 3 m into the strip.

INTRODUCTION

An important factor influencing the efficacy of plant protection products is the timeliness of application and this in turn is directly related to work rate. For a boom sprayer operating over arable crops, work rate can be increased by using higher forward speeds, reduced spray volume rates (with smaller nozzles and finer sprays) and wider booms (with a tendency for larger boom heights). All of these factors can lead to an increase in the risk of spray drift and therefore the need to control drift is an important factor relating to the optimised use of boom spraying systems. Many recent developments of both boom sprayers and nozzle systems have therefore been specifically aimed at delivering spray drift control.

The need to control drift has components relating to minimising direct contamination of human by-standers, to controlling deposition on to non-target organisms, particularly at the field boundary where the need to maintain high levels of bio-diversity is important, and to controlling the contamination of surface waters. With certain formulations, the use of buffer or no-spray zones adjacent to surface waters is used as part of the conditions of approval so as to minimise the potential for contamination due to drift (Tooby, 1997). Until early in 1999 such buffer zones, once specified, were fixed and were independent of conditions or application methods. The introduction of the Local Environment Risk Assessment for Pesticides (LERAP) Scheme (Anon, 1999) in April 1999 made provision for some reductions in the width of the buffer zone depending upon a number of factors. These included the dose rate being applied, the characteristics of the water course and the use of engineering controls to minimise the risk of drift. A component of such engineering controls defines LERAP – Low drift star ratings for both nozzles and sprayers that can be demonstrated to give defined levels of drift reduction when compared with a conventional boom arrangement operating with a reference nozzle condition. The reference nozzle is a 110° flat fan design operating at a pressure of 3.0 bar to give a flow rate of 1.2 litre/min as a medium quality spray.

There is then a need to be able to define the performance of boom spraying systems with respect to the risk of drift. Standardised protocols have now been published relating to the field measurement of drift from boom sprayers both as draft international standards and as part of the procedures for obtaining LERAP – Low drift status in the UK. A number of methodologies have been developed for assessing the risk of drift from different nozzle systems operating on a boom sprayer based on wind tunnel approaches (e.g. Walklate *et al*., 1998; Herbst & Helck, 1998) and the development of the international (BCPC) spray classification scheme will also include a component relating to the risk of drift (Southcombe *et al*., 1997). Computer simulation approaches have also been developed to predict the levels of drift from different spraying operations. These have been based on plume dispersal models, droplet trajectory calculations including the region close to the nozzle orifice (Miller, 1993) and statistical analyses to relate the physical characteristics of the spray liquid to the small droplet component of a spray and hence the risk of drift.

The risk of drift from boom sprayers operating over arable crops is a function of the performance of the nozzles mounted on the boom, features of the machine and boom on which the nozzles are mounted, the weather conditions at the time of spraying, the structural features of the crop and of the field boundary. This paper examines research results relating to each of these factors, except weather conditions and indicates how such research results can be used to control drift without compromising spray deposition and efficacy.

NOZZLE FACTORS

The effects of droplet size

It is well established that the droplet size distribution within a spray is a major factor influencing drift and that the percentage of spray volume in droplet sizes below a defined threshold (commonly taken as around 100 µm) is a good indicator of the risk of drift. Miller (1988) used a computer model to show that the potential for droplets in the spray from conventional nozzles to drift increased steeply for droplet sizes less than 75 µm in diameter. Results from both field and wind tunnel studies have also shown that the droplet size distribution in a spray is an important indicator of the risk of the drift for a given nozzle design. For example, field measurements with a tractor boom sprayer fitted with conventional flat fan nozzles delivering circa 100 litres/ha as a fine spray gave approximately twice the drift of that from a similar arrangement operating to deliver approximately 200 litres/ha as a medium quality spray, (Rutherford & Miller, 1993). The development of a wider range of nozzle types has meant that it is now necessary to consider factors in addition to the droplet size distribution when quantifying the risk of drift from nozzles mounted on boom sprayers.

The effects of droplet velocity

The velocity of droplets leaving a nozzle has components relating to both the speed and direction of travel. Variation in the spray fan angle from flat fan nozzles is one way in which droplet directions (trajectories) can be changed. Hobson *et al.* (1993) used a computer model to relate data describing the droplet size distribution and trajectory angles for conventional flat fan 80 and 110° nozzle to drift and concluded that, if the nozzle height was adjusted appropriately, then the drift for the 110° fan angle was less than for the 80° case. This result indicates that nozzle height effects are likely to dominate over the combined effects of the reduced droplet size and wider trajectory angles with the 110° nozzle and emphasises the importance of maintaining the nozzle at the correct working height if drift is to be minimised (see also later in this paper). The effect of droplet velocity can also explain the levels of drift measured from a wide angle hollow cone nozzle operating to produce a medium quality spray at approximately 100 litres/ha that, in a field study, gave drift volumes that were 14% above those from a flat fan nozzle operating to give a fine spray at the same volume application rate, (Rutherford & Miller, 1993).

The use of a pre-orifice in a flat fan nozzle design has been developed as one method of giving drift control by creating a coarser spray quality. Measurements of the droplet velocity profiles from such nozzles show that droplets from this nozzle design travel more slowly than from a conventional flat fan design operating at the same pressures and flow rates. This means that the level of drift reduction achieved by the pre-orifice design is less than would have been predicted only by considering the percentage of spray volume in small droplet sizes. This effect has been confirmed in measurements with a range of sizes of a given pre-orifice nozzle design where the level of drift reduction over the equivalent conventional design as assessed in wind tunnel tests was, on average, 12% less than expected.

Increasing the spray liquid pressure with most nozzle designs increases the velocity of droplets leaving the region of spray formation but also results in a finer spray. The balance between these two factors varies depending upon nozzle design, pressure level and external factors that may influence spray formation. Studies in a wind tunnel examining the effect of forward speed on drift from conventional flat fan nozzles (Miller & Smith, 1997) showed that the risk of drift tended to increase as pressure increased from 2.0 to 3.0 bar but then remained approximately constant as the pressure was increased to 4.0 bar. Results from recent wind tunnel tests with a range of nozzle types has shown similar trends. The risk of drift has tended to increase with initial increases in pressure as the effect of making a finer spray dominates. Further increases in pressure do not result in increasing drift and may, with some designs, result in a decrease in drift at high pressure due to the dominance of the droplet velocity effect. While these effects are reproducible in wind tunnel conditions with static nozzles, further research is required to understand the mechanisms involved and to examine the extent that these will relate to operation on a moving boom under field conditions.

One nozzle design in which the effect of pressure has been seen to initially increase and then reduce drift in wind tunnel tests is the air-induction design. Such nozzles have been shown to give large drift reductions when compared with conventional flat fan designs operating under comparable conditions and the generation of droplets with "air-inclusions" may mean that such drift reductions are achieved while relatively high levels of retention are maintained for many target surfaces. While data relating to both the drift and retention characteristics of this nozzle design are still being collected, it is important to note:

- that different commercial designs of this nozzle type have a wide range of performance characteristics in relation to the droplet size distribution and drift reduction that can be achieved; and

- that the performance of a range of sizes of an air-induction nozzle may not follow the same performance trends as for conventional nozzles – at least one commercial nozzle range of this design gives smaller droplet sizes with increasing nozzle size (flow rate) and hence the advantage of using the design to control drift is greatest at the smaller nozzle sizes, (Miller, 1998).

The effects of spray and droplet structure

Results from a number of wind tunnel studies examining the behaviour of sprays in an airflow have shown that the way that air moves close to a spray is an important factor influencing both the level and pattern of airborne spray drift. For flat fan sprays operating with the fan at right angles to the direction of the airflow (so representing the forward travel of a boom sprayer) and in relatively low wind speed conditions, the air tends to flow round the spray. Small droplets are detrained from the edge of the spray structure and are carried downwind in two vortices that are generated at the sides of the spray structure (Miller, 1993). At higher wind speeds, air tends to break through the spray structure detraining droplets from the main part of the spray. Work by Miller *et al.*, (1995) and Ghosh *et al.*, (1996) showed that the main determinant of the airflow spray behaviour was the ratio of the velocities of the entrained and cross air speeds, with larger output nozzles having higher entrained air velocities. The airflow around a flat fan spray is also influenced by the presence of adjacent nozzles on a boom. The restriction to air movements by a row of nozzles tends to accelerate the airflow into the gaps between nozzles and hence increase the total quantity of drift from each nozzle (Miller, *et al.*, 1995). The presence of adjacent nozzles also changes the shape of the vortices that tend to be smaller but more clearly defined from a boom arrangement of nozzles. The effect of nozzle spacing along a boom on drift has recently been examined experimentally (Murphy *et al.*, 1999) with results showing only a small dependence of drift on nozzle spacing. For 110° flat fan nozzles, the maximum drift volumes were measured with a spacing of 50 cm.

In twin-fluid nozzle designs, more of the liquid break-up to form a spray occurs within the nozzle body and hence the emerging spray is more porous and less of an obstruction to an approaching airflow. This leads to less air flowing around the spray structure and has been shown to be a major factor leading to the low levels of drift from this nozzle design (Young, 1991; Miller, 1993). It was also thought that the spray formation mechanisms with the air-induction nozzle designs were similar to those from twin-fluid nozzle systems. Recent studies however, have shown that many combinations of air-induction nozzle design and spray liquid specification do give spray break-up via a liquid sheet and hence the drift reductions achieved with this nozzle design are likely to result as a function of the reduction in the percentage of spray volume that is in small droplet sizes. Droplets in the spray from both twin-fluid nozzles and air-induction designs have “air-inclusions” in droplets with a diameter typically greater than 100 µm. These have the effect of reducing the effective mass of larger droplets within the spray, of reducing velocities and potentially increasing the risk of drift. However, the fact that large drift reductions in comparison with conventional flat fan nozzle designs has been achieved indicates that the larger droplets are of such a size not to be at risk of drift even though the density has been reduced.

SPRAYER FACTORS

The effects of boom structure

Given that the airflow around a spray structure is an important factor influencing drift, it is conceivable that the combined effect of spray and boom structure may also be important. Results from an experimental study (Murphy *et al.*, 1999) using boom structures with sections varying in depth from 100 to 300 mm in a wind tunnel showed that, although drift risk increased when using the deeper section boom, the magnitude of the increase was much smaller than would arise from changes in nozzle characteristics representative of a change in one nozzle classification category with conventional flat fan nozzles. Drift from boom sprayers was therefore shown to be dominated by the performance of the nozzle. This has important implications for the approach taken as part of the LERAP – Low drift status assessments where nozzles tested in a wind tunnel to achieve a given star rating can then be installed on a conventional boom arrangement and confer the same star rating to the whole sprayer. As spray volume rates decline, vehicle speeds increase and the size of crop spraying units gets larger, then it is possible that aerodynamic effects of both boom and spray vehicle structure will become more important in terms of both the risk of drift and spray deposition patterns. Further work is therefore required to define such effects.

The effects of boom height

The main function of the boom is to support the nozzles at the appropriate height above the target. Work on boom suspension systems has aimed at developing linkages that isolated the boom structure from the high frequency rolling and yawing movements of the spray vehicle but transmit the low frequency movements so that the boom followed the mean ground profile, and nozzles were kept at the correct height. Most commercial crop sprayers with boom widths above 10 m wide now incorporate a passive boom suspension system. However there is relatively little recent data to show the effects of nozzle height on the risk of spray drift.

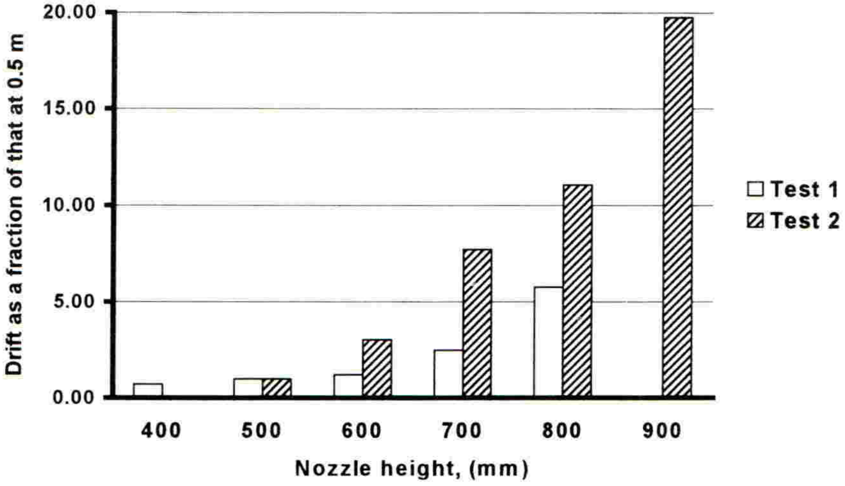

Figure 1. The effect of boom height on drift from flat fan nozzles.

The data in Figure 1 was obtained from two separate wind tunnel studies in which a single static nozzle was mounted in an air stream in the tunnel. Airborne spray was then collected 2.0 m downwind of the nozzle on an array of horizontal 1.98 mm diameter polyethylene tubing supported across the width of the tunnel at a vertical spacing of 100 mm. A tracer dye was sprayed in both cases which was then recovered from the sampling lines by washing each line in a known volume of water and quantifying the volume of recovered spray liquid captured on the lines using spectrophotometry (Test 1) or fluorimetry (Test 2) calibrated with samples of the spray liquid taken at the nozzle. Test 1 used a 110° flat fan nozzle operating at a pressure of 3.0 bar to produce a fine spray while Test 2 used a nozzle at the same pressure and fan angle to give a medium quality spray at a flow rate of 1.2 litres/min. In both cases, increasing nozzle height gave a steep increase in the total volume of airborne spray downwind of the nozzle particularly at the larger boom heights. The results therefore again emphasises the importance of nozzle height control in respect of minimising drift.

STRUCTURAL FEATURES OF THE FIELD BOUNDARY

Relatively little research work has addressed the effects of the structure of a field boundary on the deposition of drifting spray into the boundary. Modelling studies in the Netherlands, Germany and Canada have assumed a given structure for ditches when calculating the contamination of surface water due to drift deposition but the form of the ditch and vegetation on banks is not specifically included in such models. Some work has been conducted to examine spray drift collected on different plant species growing in field boundaries (Haughton *et al.*, 1998) and the results have shown lower levels of deposit in wider buffer strips. A collaborative research project funded by the Ministry of Agriculture Fisheries and Food is also now examining the effect of different plant structures in the area adjacent to a field boundary on the deposition of drift within and beyond the boundary area. There is the potential to manage such areas to give plant structures that will maximise bio-diversity while giving increased protection of surface water from contamination due to spray drift.

A series of measurements have been made in both wind tunnel and field conditions to assess the effects of spray characteristics, plant density and structure on spray drift deposition to the boundary zone. An initial series of experiments used a wind tunnel arrangement in which a small boom supporting a single F110/1.2/3.0 flat fan nozzle 350 mm above an established wheat crop 0.75 m tall was mounted on an electrically driven transporter such that it could be moved across the air flow at a speed of 2.0 m/s. The air speed down the tunnel, measured at nozzle height, had a mean value also of 2.0 m/s. The downwind zone from the edge of the sprayed swath comprised tray grown plants of either a typical cereal stubble cut at a height of 200 mm or an established grass/wild flower mixture selected to enhance bio-diversity at the field margin while having a structure that could intercept and filter airborne spray drift. Airborne spray profiles were measured at distances of 1.0, 2.0, 3.0 and 4.0 m into the downwind zone using an array of 1.98 mm diameter polyethylene line collectors supported on a frame 0.5 m wide and 1.0 m high. Experiments sprayed a solution of a coloured tracer dye ("Green S" – Merck Chemicals) and a 0.1% of a non-ionic surfactant in a series of multiple passes in both directions over the target crop to build up averaged drift deposits that could be quantified by spectrophotometry.

The results (Figure 2) show that when the drift profiles from within the grass/wild flower sward are compared with those measured over the stubble surface, there are reductions in the volume of airborne spray of up to 60% with the largest reductions at heights of 0.1 to 0.3m. These heights also correspond to the positions of the highest levels of airborne spray volume (Miller & Lane, 1999). At heights above the top of both the crop and grass/wild flower sward, there was some increase in airborne spray volumes over that measured with the stubble although it should be noted that the levels of airborne spray at these heights were very much lower than at the lower heights. The results therefore show that a grass/wild flower strip up to 3.0 m wide can act as an effective filter of airborne spray drift typically reducing airborne spray volumes by approximately 50%. Further research is now in progress to examine the effects of plant density and sward characteristics on the drift retention in the zone adjacent to a field boundary.

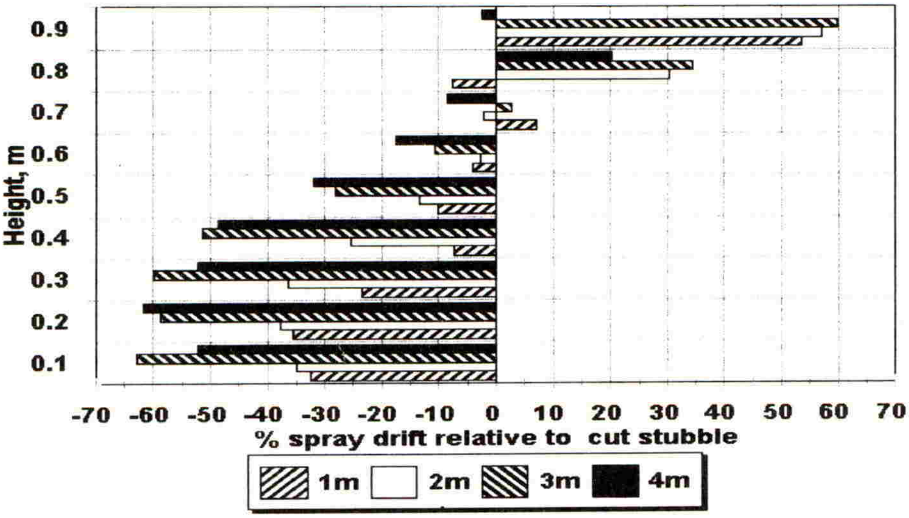

Figure 2. Airborne drift into a field boundary established with a wild flower/grass mixture as a percentage of that for a cut stubble.

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An appraisal of nozzles and sprayers abilities to meet regulatory demands for reduced airborne drift and downwind fallout from arable crop spraying

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ABSTRACT

Until recently, the emphasis in agrochemical spray drift studies was on the airborne component, but legislation now concentrates on downwind fallout. This paper describes measurements of both components in a wind-tunnel and in the field. The effect of spray quality dominated that of operating pressure and wind speed for conventional nozzles, while drift-reducing pre-orifice and air-inducing nozzles reduced drift losses by more than 75 % at equivalent outputs. Drift reduction *via* nozzle design alone may be associated with coarser sprays than BCPC Coarse, raising deposition and efficacy questions. In contrast, air assistance allows the use of the spray quality given on the agrochemical label while still reducing drift. Air assistance improved all nozzles' performance further; for example, with drift-reducing nozzles fallout was up to 95 % reduced compared to a conventional F110/1.6/3.0 nozzle without air assistance.

INTRODUCTION

The common aim in many European countries is to reduce the amount of pesticide entering the environment through drift outside the treatment area. Manufacturers have responded to this desire by developing sprayers and nozzles that reduce such wastage. However, until recently there was little - if any - regulatory recognition of the value of these drift-reducing systems, nor were there protocols enabling reliable comparative data to be produced against recognised standards. This situation has now changed in Northern Europe, where there exists both incentive and means to meet stringent demands in reducing drift-based pollution. Traditionally, nozzles are selected to meet agrochemical label recommendations, weather conditions, crop and safety restraints, prompting a specified water volume rate, spray quality and spraying speed, sometimes specifying the nozzle type too. Water volumes up to 300 litres/ha are applied with BCPC Fine, Medium or Coarse sprays (Doble *et al.*, 1985) at speeds of 6 to 12 km/h. No labels, as yet, advise the use of Very Coarse spray quality. This decision-making process, which is a crude, but careful, balance between the optimum method to meet biological and warranty expectations and that possible for a given spray window, is now further complicated by the need to select systems that meet statutory drift requirements. Most previous drift studies consider airborne drift rather than fallout, describing the interaction of spray quality, forward speed and air assistance with wind speed and crop structure (e.g. Andersen & Taylor, 1997). This paper considers both airborne drift and fallout, offering a manufacturer's view of methods for reducing drift losses and considering the opportunities and benefits for industry and the user that may arise from their use. Much of the data was generated for the Dutch Board for the Authorisation of Pesticides who want strict limits on surface water contamination i.e. 90 % reduction in fallout by 2000 (MYCPP, 1991). Values from the same field tests may also be appropriate for the UK LERAP data package.

MATERIALS AND METHODS

In all tests Very Fine, Fine, Medium and Coarse sprays were generated by F110/0.47,0.91,1.59 and 2.94/3.0 (Hardi 411010, 411014, 411020 and 411030) nozzles respectively at their rated pressures (BCPC nozzle code; Doble *et al.*, 1985). Pre-orifice [low drift] and air induction nozzles are as specified in the text. The spray solution was water with non-ionic surfactant at 0.1% v.v. unless otherwise specified.

Windtunnel studies were conducted in the Silsoe Research Institute facility. Nozzles were mounted 500 mm above the fallout collecting lines or plates whilst drift impacted on 2 mm wide lines; all deposits being measured by standard fluorometric methods (Walklate et al 2000). Field studies at HAUC used two field sprayers with 12 m booms, one conventional and one with air assistance (Hardi LX and Twin). Fallout was measured at either 2.25 to 3.25 m - the Dutch standardised system (Huijsmans *et al.*, 1997) or 1 to 2 m, 2 to 3 m, 3 to 4 m and 4 to 5 m (UK LERAP) from the end of the downwind swath. Drift was collected 5 metres downwind on pipe cleaners up to 5 m above the target and fallout at target height. F110 03 nozzles gave a sufficiently reliable drift benchmark for no others to be needed. Replicated data from five tests are combined.

WINDTUNNEL STUDIES

The windtunnel offered more controlled conditions than field tests, showing differences more clearly and reproducibly, as well as being an easier working environment. Airborne drift and fallout were markedly affected by spray quality with Fine producing twice that for Medium and more than four times that for Coarse (Table 1). The relationship between airborne drift and fallout was not constant; while both increased as spray quality became finer, fallout increased less rapidly. It is also conceivable that a very fine spray, or one with unusual structure (e.g. charged or more buoyant droplets) could reduce fallout but increase airborne drift, thus increasing a pollution hazard. Changing the operating pressure for nozzles used to apply Very Fine, Fine and Medium sprays influenced fallout volumes downwind (Table 2) although the magnitude of this change was less than that due to changing the nozzle size (i.e. spray quality) so that pressure changes are a less significant method of reducing drift than others considered here. As expected, higher wind speeds increased fallout from conventional nozzles (Table 3).

Nozzles with pre-orifice restrictors coarsen the spray, but in so doing reduce both droplet velocity and the intensity of air entrained in the spray. Airborne drift and fallout were lower than for equivalent output conventional nozzles; for example, with a Fine spray the pre-orifice nozzle [S411014LD] reduces airborne drift 2 m downwind by 53 % in a 2 m/s wind and by 57 % in a 5 m/s wind. Practically, for example, pre-orifice nozzles are of value in sugar beet spraying with phenmedipham. This should be applied as a Fine spray for maximum biological effect, but still has some effect as a coarser spray, so when wind speeds rise pre-orifice nozzles avoid the need for recalibration or, worse, changing the spray liquid concentration.

Table 1. The effect of spray quality on airborne drift and fallout in a 4 m/s wind

Spray Quality	Airborne Drift (% emission) [2 m downwind]	Fallout (% emission) [2 to 3 m downwind]	Drift : Fallout ratio
Very Fine	22.9	11.2	2.04
Fine	10.2	6.3	1.62
Medium	4.7	3.4	1.38
Coarse	2.0	1.6	1.25

Table 2. The effect of pressure and spray quality on fallout in a 3 m/s wind

Pressure (bar)	Fallout (% emission) [2 to 3 m downwind]		
	Very Fine	Fine	Medium
1	5.55	2.43	0.86
2	8.15	3.78	1.55
3	8.55	3.92	1.87
4	6.54	4.25	2.58

Table 3. The effect of wind speed and spray quality on fallout

Wind Speed (m/s)	Fallout (% emission) [2 to 3 m downwind]		
	Very fine	Fine	Medium
2	8.89	4.40	0.80
3	7.55	4.07	2.00
4	9.09	5.58	2.50

Air-induction [AI] nozzles currently offer, perhaps, the greatest scope for reduction of airborne drift and fallout by the nozzle alone; here fallout was reduced by at least 75 % and gave a flatter distance profile than F110 03 (Table 4). However, the sprays are Very or Extra Coarse and may apply contrasting distribution patterns to those from traditional nozzles. There is evidence that, while deposition may be adequate for many conditions (Cooper & Taylor, 1999), there are circumstances where their use may reduce biological efficacy (Jensen, 1999); independent guidance advises against their use on certain targets (Powell *et al.*, 1999). More biological data is urgently needed, particularly for field-type conditions and to consider the scope for using adjuvants that will enhance the deposition and activity of large droplets. A surfactant is considered necessary for the formation of air inclusions within the larger droplets, but had little effect on airborne drift. For example, drift for water was 9.9 % that of a Fine spray with AI 02 and 14.7 % with AI 04, while the addition of 0.1 % surfactant (Agral; Zeneca, UK) only increased these values to 10.6 and 15.2 % respectively. Overlaying fallout patterns from different nozzles indicated that spraying with the swath edge just 1 m from a water course may, with some air-induction nozzles, not cause more contamination than the restrictive 5 m No Spray Zone for conventional nozzles.

Air-induction nozzles are primarily intended for use in higher wind speeds than their conventional equivalents without increasing fallout. This was observed (Table 5); for example, AI 03 in 8 m/s wind gave 83 % less fallout than F110 03 in 4 m/s wind.

Table 4. Fallout from F110 03 and air-induction nozzles in a 2 m/s wind

Nozzle	Fallout (μl per l/min emission) at downwind distance (m)						% change
	1	2	3	4	5	6	
F110 03	463	130	65	35	25	20	0
AI 015	40	20	10	10	10	10	- 86
AI 02	39	23	15	8	8	8	- 86
AI 03	26	16	5	5	5	5	- 91
AI 04	39	19	8	8	4	4	- 88

Table 5. Fallout from air-induction nozzles in varying wind speeds

Nozzle	Wind speed (m/s)	Fallout (μl per l/min emission) at downwind distance (m)						% change
		1	2	3	4	5	6	
F110 03	4	955	492	307	181	146	141	0
F110 03	6	774	804	497	231	317	266	+ 30
AI 03	6	100	30	120	30	18	15	- 86
AI 03	8	125	100	55	65	15	5	- 83

FIELD STUDIES

Using data from previous windtunnel and field tests which had the same nozzle, pressure and spray solution a Relative Driftability Index (RDI) was calculated. RDIs for windtunnel and field tests were in reasonable agreement (as were the windtunnel and field studies reported here). For conventional nozzles, RDIs (with a Very Fine spray being 1) for Fine and Medium sprays in the windtunnel were 2.12 and 4.1, with the respective values in the field being 1.84 and 4.38. However, field studies of sprayer performance which demand absolute fallout volumes, should remain the basis for serious commercial drift reduction claims.

Spraying without air assistance at 7.2 km/h forward speed over short mown grass with conventional, pre-orifice and air induction nozzles gave similar fallout results to the windtunnel (Table 6). The equivalent output F110 04LD reduced fallout by 36 % compared to F110 04, while air-induction nozzles gave even lower fallout with a maximum reduction of 86 %. The fallout profile 1 to 5 m downwind was flatter for air induction nozzles than F110 03, though naturally still highest nearest the swath end (Table 7). Further, these values indicate that air induction nozzles deposited less than 0.5 % of the total emission between 1 and 5 m downwind. Border nozzles were needed to reach the target of 90 % fallout reduction over "flat" surfaces (e.g. short mown grass) (Table 7). Their use also becomes critical if direct spraying of a zone more than 1 m away from the edge of a crop is to be avoided (Van de Zande *et al.*, 1995).

Table 6. Fallout at 2.25 to 3.25 m downwind with different nozzles

Nozzle	Pressure (bar)	Wind speed (m/s)	Fallout (% emission)
F110 04	3	3.89	0.84
F110 04LD	3	3.97	0.54
F110 08	1.5	4.87	0.39
AI 02	3	3.75	0.30
AI 03	3	4.17	0.12
AI 04	3	4.32	0.18

Table 7. Fallout decay profiles from nozzles without air assistance [Mean of 5 occasions]

	Nozzle	Fallout (% emission)					% change
		1 to 2	2 to 3	3 to 4	4 to 5	total	
Short mown grass	FF03	0.715	0.388	0.304	0.214	1.621	0
	AI03	0.065	0.068	0.030	0.029	0.192	- 88
	AI03 + Border	0.072	0.034	0.024	0.018	0.148	- 90
	AI04	0.091	0.073	0.047	0.030	0.241	- 85
	AI04 + Border	0.051	0.035	0.023	0.015	0.124	- 92
Taller crop	AI03	0.155	0.021	0.013	0.011	0.200	n/a
	AI03 + Border	0.049	0.015	0.009	0.006	0.079	n/a
	AI04	0.337	0.027	0.020	0.013	0.397	n/a
	AI04 + Border	0.045	0.020	0.013	0.011	0.089	n/a

Air assistance reduced fallout 1 to 5 m downwind from F110 03 over short mown grass by 44 %, and improved the drift reducing capability of air-induction nozzles (with and without Border nozzles) despite the very flat surface, giving a maximum reduction of 97 % (Table 8) - a result in agreement with that cited by Koster *et al.* (1999).

Table 8. Fallout 1 to 5 m downwind with or without air assistance [Mean of 5 occasions]

Nozzle	Air Assistance	Fallout (% emission)	% change
FF03	off	0.477	0
FF03	on	0.263	- 45
AI03	on	0.018	- 96
AI03 + Border	on	0.016	- 97
AI04	on	0.026	- 95
AI04 + Border	on	0.016	- 97

DISCUSSION

As the data in this paper show, manufacturers have produced equipment that reduces airborne drift and fallout with varying degrees of success. A simple nozzle change can meet many drift reducing requirements, but deposition on the target surface may be compromised; this fundamental side-effect could reduce product efficacy and may force the operator away from agrochemical label recommendations. However, user surveys (May, 1997) suggest that this may be offset by the value of spraying at the optimum time (correct spray timing, perhaps, being under-rated). If this is true, and agrochemical manufacturers re-asses their spray quality advice so that the use of air-inclusion nozzles is supported, then the advance that is sought for wind speeds restrictive to conventional practice can be made with confidence. It is vital that the efficacy of products specifying a Fine spray is tested with air-inclusion nozzles since these would give the largest drift pollution reductions.

Air assistance on sprayers also reduces airborne drift and fallout, but without the problem of changing spray quality and water volumes from approved label recommendations so that, for example, Fine sprays can be used without compromising drift reduction. Equally, air assistance also further reduces the drift from drift-reducing and Border nozzles, so that the ultimate goal of protecting sensitive areas downwind (such as water courses) to a degree never possible before is within commercial reach. Is there is even the possibility that plant protection products that are currently not eligible for reduced Buffer Zone use might be eligible when applied with such spraying techniques?

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Herbicide performance with low volume low-drift and air-inclusion nozzles

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ABSTRACT

The efficacy of herbicides applied to small, difficult to wet dicotyledon and monocotyledon weeds was compared for standard flat fan nozzles, low-drift nozzles and air-inclusion nozzles. A range of doses was applied in order to generate dose-response curves and quantify differences between nozzle types. In general, the efficacy obtained when controlling with low-volume low-drift nozzles was comparable to the efficacy with standard flat fan nozzles. However, with low volume air-inclusion nozzles, herbicide efficacy was significantly reduced, and a 25 - 40 % increase in herbicide dose was required in order to obtain the same efficacy as with the standard flat fan nozzle. The influence of spray solution properties and application volume on herbicide efficacy when using different nozzles is also illustrated.

INTRODUCTION

Focus on agricultural pesticide use has caused increased interest in drift-reducing application techniques. Different types of drift-reducing nozzles, such as low-drift and air-inclusion nozzles, have been introduced; spray drift control with these nozzles is superior to standard flat fan nozzles due to their coarser atomization. In general, however, smaller droplets are considered biologically more effective than larger droplets for pesticide application (e.g. herbicides; Knoche, 1994). From an agronomic as well as from an environmental point of view, it is important that the biological efficacy of pesticides applied with alternative nozzle types is maintained. It is, therefore, necessary to find and define the areas where drift-reducing nozzles can replace traditional flat fan nozzles and maintain biological efficacy, since an efficient application method allows the pesticide dose to be reduced to a minimum. This can be achieved with Decision Support Systems that adjust the normal recommended dose according to the field specific conditions at the time of application.

When the pesticide dose is adjusted according to the prevailing conditions in the field, it is important to know how the choice of application technique influences the final biological efficacy, since this may require further adjustment to the dose. Many investigations into the influence of the application technique have shown little or no difference between the techniques (Nordbo *et al.*, 1995; Giese, 1998). However, this is not necessarily because the application technique does not influence the biological efficacy; it is often a result of the choice of an inappropriate experimental method. Commonly, the pesticide dose chosen was so high that full biological control was achieved with all treatments (e.g. Cawood *et al.*, 1995) which prevents differentiation between techniques. Another problem often encountered in field experiments is the heterogeneity in the distribution and development of the pest.

In this paper, the test method chosen has been used previously to quantify the effects of different factors on the efficacy of herbicides (Kudsk & Streibig, 1993) and the dose required with different flat fan nozzles to control dicotyledon weeds in peas (Jensen & Kirknel, 1994). The biological efficacy of low volume low-drift and air-inclusion nozzles applying herbicides was compared to that of standard flat fan nozzles. Experiments with varied application volume have been combined with a comparison of the efficacy of herbicides with different manufacturers' low-drift and air-inclusion nozzles.

MATERIALS AND METHODS

The field experiments involved the use of plots containing a "model" weed planted as a single species. This method was chosen because crop species normally develop more evenly than weeds, so that it was possible to achieve much greater uniformity between plots than would have been possible with "true" weeds. Uniformity was important in order to maximize statistical differences between treatments. Oilseed rape (*Brassica napus* cv. *Ceres*) and ryegrass (*Lolium perenne* cv. *Borvi*), which both have diffcult to wet foliage, represented, respectively, a horizontal habit dicotyledon and a small vertical habit monocotyledon model weed. Plots used in the experiments were 2.5 x 3.0 m. Seeding rates used were 12 kg/ha for oilseed rape and 18 kg/ha for ryegrass.

All treatments were applied using a self-propelled plot sprayer and a forward speed of 6 km/h unless otherwise stated. The nozzles used, and their approximate classification according to the BCPC classification, (Southcombe *et al.*, 1997) are given in table 1. In general, the FF14 nozzle (F110/0.83/2.5), which corresponds to F110/02, was used as the reference nozzle.

Table 1. Details of the nozzles used for herbicide application

Type	Nozzle	Code	Pressure (bar)	Output (litres/min)	Spray quality	Application (litres/ha)
Conventional	S4110-14 *	FF14	2.5	0.83	Fine	166
Conventional	S4110-30 *	FF30	2.5	2.68	Coarse	536
Low-drift	SD015 **	SD015	2.5	0.55	Medium	110
Low-drift	SD03 **	SD03	2.5	1.10	Medium/Coarse	220
Low-drift	SL4110-10 *	SL10	2.5	0.48	Fine/Medium	96
Low-drift	SL4110-12 *	SL12	2.5	0.67	Medium	134
Low-drift	AD120-015 ***	AD015	2.5	0.54	Medium	108
Low-drift	TT11001-VP ****	TT01	3	0.39	Fine/Medium	78
Low-drift	TT11002-VP ****	TT02	3	0.79	Medium	158
Air-inclusion	ID120-015 ***	ID015/5	5	0.76	Coarse	152
		ID015/7	7	0.90	Medium/Coarse	180
Air-inclusion	DB015F120 **	DB015/3	3	0.60	Coarse	120
		DB015/5	5	0.78	Medium/Coarse	156
Air-inclusion	DB02F120 **	DB02	3	0.80	Coarse	160
Air-inclusion	AI110015-VS ****	AI015	5	0.76	Very coarse	152

* Hardi, ** Lurmark, *** Lechler, **** Spraying Systems Teejet

The effect of the different treatments was monitored using a non-destructive method which measured plant canopy reflectance in the red and near-infrared, and converted these measurements to vegetation indices. A vegetation index indicates the photosynthetic size of a plant canopy. A close correlation between plant biomass and vegetation indices was found by Jensen & Christensen (1993), so that the use of vegetation indices offers an alternative method for evaluating herbicide efficacy in single species plots. Vegetation indices range from approximately 1.3 on bare soil, increasing linearly with biomass for the range of values recorded in these experiments. The vegetation index is converted to a relative vegetation index (RVI), with the biomass in a control plot set to be equal to an RVI of 100. Thus, the lower the RVI the greater the plant kill and herbicide efficacy. The general design of the experiments used 4 - 6 doses of a herbicide to give a sufficiently wide dose range. Haloxyfop (Gallant, Dow AgroScience, Denmark) was used on *L. perenne*, while phenmedipham (Herbasan, KVK Agro, Denmark) and tribenuron-methyl (Express, Du Pont, Denmark) were used on *B. napus*. The surfactant used was a non-ionic linear alcohol polyethoxylate (Lissapol Bio, Zeneca, Denmark).

The dose response curve for a nozzle was fitted to an established model which quantifies differences in biological performance. A randomized complete block design included four replicates per treatment. Data were analysed with the "parallel line assay" technique which was described by Kudsk & Streibig (1993) and by Streibig *et al.* (1993) and used by Jensen & Kirknel (1994) to evaluate differences between three flat fan nozzles. A log-transformation was used to stabilize the variance before the vegetation index data were fitted to the models. Initially, two models were used. The extended model fitted the dose response data to a symmetrical sigmoid curve, which is seen when plant response (U), in this case the vegetation index, is plotted against the logarithm of the herbicide dose (z). This curve can be described by the logistic four-parameter model suggested by Finney (1979):

$$U = (D - C)/(1 + \exp\{-2[a + b^{*}\log(z)]\}) + C, \quad b<0 \qquad (1)$$

where D denotes the upper limit at zero dosage, C denotes the lower limit at very large dosage, *a* denotes the horizontal location of the dose-response curve and *b* is proportional to the slope of the curve around ED_{50} (=antilog$\{-a/b\}$). Dose-response curves for the different nozzles were fitted simultaneously to Equation (1) with common D and C parameters and individual *a* and *b* parameters. The simpler model:

$$U = (D - C)/(1 + \exp\{-2[a + b^{*}\log(Rz)]\}) + C, \quad b<0 \qquad (2)$$

where R is the relative potency (the ratio of the doses for a reference nozzle and a test nozzle that give the same effect), allowed the dose-response curves obtained for different nozzles to share *a* and *b* parameters, i.e. parallel dose-response curves were assumed. In general, no significant improvement was found using the extended model (Equation (1)) and the simpler model (Equation (2)) was used throughout.

A relative potency above 1 means that the biological effect with a test nozzle is superior to the chosen reference, whereas the opposite is true if the relative potency is below 1. For a test nozzle, the fraction 1/R is the factor by which the herbicide dose rate must be multiplied to obtain the same efficacy as for the reference nozzle.

RESULTS

As a further illustration of the analytical method, consider the results of an experiment where ryegrass (*L perenne*) was controlled with haloxyfop (with and without surfactant) sprayed at *ca.* 160 litres/ha from a flat fan and an air-inclusion nozzle (Figure 1). It can be seen that, in the case without surfactant, the efficacy of the FF14 nozzle was superior to the ID015 nozzle at some of the dose levels; but it is difficult to estimate directly from this graph how much the dose has to be increased with the ID015 nozzle in order to achieve the same efficacy as for the FF14 nozzle. However, when the data is fitted to the model with parallel dose response curves (Figure 2), then the difference in dose required for the ID015 nozzle to achieve the same efficacy as the FF14 nozzle can be described by the relative potency no matter which efficacy level is desired. The relative potencies for haloxyfop with and without surfactant (Table 2) show that surfactant addition enhanced biological efficacy for all nozzles, and the ID015 nozzle caused a loss of efficacy compared to the FF14 nozzle spraying the same solution.
Since the relative potency for the ID015 nozzle at 5 bar was 0.83, the herbicide dose would need to be increased by 20 % for the ID015 nozzle to achieve the same level of control as the FF14 nozzle.

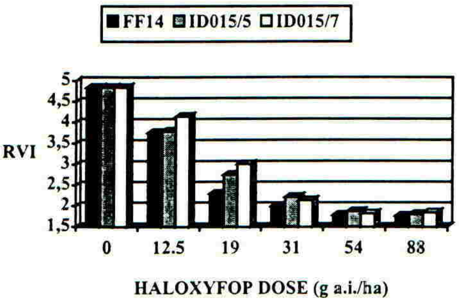

Figure 1. Control of *L. perenne* with haloxyfop using standard and air-inclusion nozzles

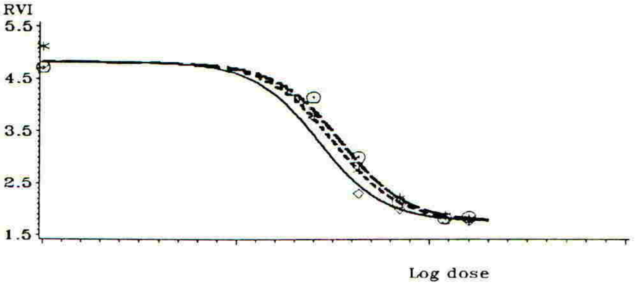

Figure 2. Estimated dose-response curve and observed values of vegetation index (RVI) for control of Lolium perenne with haloxyfop.
Hardi S4110-14 flat fan ▬▬◊, Lechler ID120-015, 5 bar ▬ ▬ ◎, Lechler ID120-015, 7 bar ▪▪▪▪*.

Table 2. Relative potency of standard and air-inclusion nozzles for control of *L. perenne* with haloxyfop with and without surfactant

	Relative Potency		
	FF14	ID015/5	ID015/7
No surfactant	1	0.83 *	0.76 *
0.1 % surfactant	1.63	1.13 *	1.16 *

* significant difference ($P = 0.05$) from FF14

Control of *B. napus* at the cotyledon stage was investigated in two separate trials using phenmedipham at 6 dose rates with air-inclusion nozzles spraying *ca.* 150 litres/ha. The efficacy data obtained with the different dose rates was fitted to the model (Equation 2) and the relative potencies calculated relative to the FF14 nozzle (Table 3). In general, the recommended operating pressure for air-inclusion nozzles is 5 bar, but for the DBxxx nozzles it is 3 bar. In these tests the DB015 nozzle was used at both 3 and 5 bar, and it can be seen that its efficacy was increased significantly by increasing the pressure to 5 bar. Increasing the pressure to 5 bar decreases droplet size. However, it also seemed that 3 bar was too low a pressure to maintain stable droplet formation and spray pattern, an aspect which probably also explains the differences between trial 1 and trial 2 for the DB015 nozzle.

Table 3. Control of *B. napus* (cotyledon) with phenmedipham using various nozzles

	Relative Potency	
	Trial 1	Trial 2
FF14	1.00	1.00
ID015	0.65	0.67
DB015/3	0.31 *	0.56 *
DB015/5	0.57 *	0.83
DB02	0.66	0.66
AI015	0.63	0.72

* significant difference ($P = 0.05$) between air inclusion nozzles

Control of *B. napus* at the cotyledon stage was also investigated in another set of trials using phenmedipham at 6 dose rates with low-drift nozzles spraying *ca.* 80 - 150 litres/ha. Efficacy with these nozzle was in general close to that of the FF14 reference nozzle. In general, the results from the two trials were similar, except for the TT01 nozzle (Table 4).

To clarify these results with the TT01 nozzle, and also with the SL10 nozzle which gave reduced efficacy in both trials, a further test was conducted. In this test *L. perenne* was controlled with haloxyfop with or without surfactant. Again, the SL10 nozzle significantly reduced efficacy both with and without surfactant (Table 5), confirming the previous results (Table 4). The TT01 nozzle, on the other hand, gave a significant improvement in efficacy compared to the FF14 nozzle with or without surfactant (Table 5), suggesting that the reduced efficacy observed previously (Table 4 - trial 1) was an anomalous result.

Table 4. Control of *B. napus* (cotyledon) with phenmedipham using various nozzles

	Relative Potency	
	Trial 1	Trial 2
FF14	1.00	1.00
SL10	0.88 *	0.88 *
SL12	0.96	1.00
AD015	0.90	1.00
TT01	0.70 *	0.96
TT02	0.88 *	0.96

* significant difference (*P = 0.05*) from FF14 for low-drift nozzle

Table 5. Control of *L. perenne* with haloxyfop using various nozzles with and without surfactant

	Relative Potency		
	FF14	SL10	TT01
No surfactant	1.00	0.91 *	1.23 *
0.1% surfactant	1.04	0.84 *	1.23 *

* significant difference (*P = 0.05*) from FF14

The influence of surfactant was also investigated in another experiment. *B. napus* at the 2-4 leaf stage was controlled with tribenuron-methyl with and without surfactant using Fine, Medium and Coarse sprays. Surfactant is recommended for use with tribenuron-methyl for all common applications. Applied without surfactant, efficacy was significantly lower with the Coarse and the Medium sprays than with the Fine spray (Table 6). With surfactant, efficacy with the Medium spray was at the same level as the Fine spray, with the Coarse spray still giving reduced efficacy.

Table 6. Effect of surfactant on control of *B. napus* (2 - 4 leaf) with tribenuron-methyl using Fine, Medium and Coarse sprays

	Relative Potency		
	Fine FF14	Medium SD015	Coarse FF30
No surfactant	1.00	0.72 *	0.72 *
0.01 % surfactant	1.04	1.05	0.88

* significant difference (*P = 0.05*) from FF14

The last issue investigated was the effect of application volume on herbicide performance, in this case *B. napus* at the cotyledon stage controlled with phenmedipham. Three different application volumes were achieved by using three forward speeds (6, 3 and 1.5 km/h) to give normal, x2 and x4 application volumes. Herbicide concentration was varied at different speeds to maintain the required doses. For the two nozzles with coarser sprays there was a significant difference in efficacy for different application volumes (Table 7), with decreasing efficacy when application volume was increased. This may be due to the reduced herbicide concentration in the spray, or because of increased runoff at higher application volumes. With the Medium spray there was no effect of application volume on herbicide efficacy, while the Fine spray gave decreased efficacy at the highest application volume.

Table 7. Effect of application volume on control of *B. napus* (cotyledon) with phenmedipham using various nozzles

	Relative Potency			
	Fine FF14	Medium SD015	Medium/Coarse SD03	Coarse FF30
Normal application volume	1.00	0.95	0.89	0.84
2 * Normal application volume	0.93	0.92	0.83	0.64 *
4 * Normal application volume	0.84 *	0.94	0.70 *	0.51 *

* significant difference ($P = 0.05$) from Normal

DISCUSSION

When a new application technique is introduced it is important to document not only the physical behaviour (droplet size etc.), but also the biological performance of pesticides applied with this technique. There has been a strong focus on drift-reducing techniques for some years, and it is vitally important that the biological efficacy of pesticides applied with the different drift-reducing application techniques is maintained. A reduction in efficacy requires an increased pesticide dose, which again increases total drift volumes, losses in the field and expenditure on inputs to crop production. These experiments represented a severe test of the application technique; i.e. control of small weeds with leaves which are difficult to wet. If the tested drift-reducing nozzles achieved the same efficacy as the normal recommended standard nozzle for these difficult applications then they would be considered suitable to replace standard flat fan nozzles more generally. The variable herbicide dose test method applied here makes it possible to quantify differences in efficacy and to describe how much the herbicide dose has to be changed for an alternative application technique to obtain the same efficacy as a reference technique. Parallel dose-response curves were assumed, and the deviation from these were small. (Alternatively, a comparison based on a specific efficacy level (e.g. Enfält *et al.*, 1997) could be used.)

When a coarser spray is used at the same, or even at a lower application volume, droplet numbers hitting the target are reduced. This has often been used as an argument against the use of low-drift nozzles for weed control with foliar acting herbicides. However there exists very little evidence about the influence of droplet number density on biological efficacy. The results described here did not support the theory that lower droplet numbers reduce efficacy at practical application rates (*ca.* 110 - 170 l/ha) since the low-drift nozzle (SD015, Medium spray) gave similar efficacy at normal and x4 application volumes. Whether this is true for coarser low-drift and air-inclusion nozzles is another question worthy of investigation.

The physical properties of the applied pesticide solution strongly influences the retention of spray on the target - as was shown in tests where surfactant addition gave enhanced efficacy - and this factor is probably as important as droplet coverage when considering biological efficacy. This means that the efficacy of alternative application techniques should be evaluated on a number of different representative targets.

In summary, the biological performance of the low-drift nozzles in experiments with control of oilseed rape at the cotyledon stage with phenmedipham, and of ryegrass with haloxyfop, was comparable to the standard flat fan nozzle. In contrast, herbicide efficacy with the air-inclusion nozzles tested was strongly reduced compared to the standard flat fan nozzles; the applied dose would have to be raised by 25 - 40 % to achieve the same efficacy as the reference flat fan nozzle. The conclusion that must be drawn is that the air-inclusion nozzles tested have some limitations when spraying small, difficult to wet weeds with herbicides. Further work is needed to clarify where and when air-inclusion nozzles can be used without reducing pesticide efficacy.

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The distribution and retention of sprays on contrasting targets using air-inducing and conventional nozzles at two wind speeds

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ABSTRACT

The magnitude and variability of spray deposits on artificial targets, when applied by conventional and air-inducing nozzles in the absence of wind are not significantly different. However, in wind speeds up to 4 m/s, deposits from conventional nozzles may be enhanced on vertical surfaces, but diminished on those which are horizontal. In contrast, air-inducing nozzles generate spray that can more effectively maintain the volume captured in both target planes and the uniformity of dispersion under adverse wind conditions.

INTRODUCTION

The hydraulic nozzle has been the dominant method of applying pesticides throughout the past century. The spray pattern has been honed to produce the desired distribution of spray droplets over the swath. The need to operate with greater field efficiency in recent years has encouraged the move to lower application volumes, which with conventional hydraulic nozzles resulted in a trend towards smaller droplets being used. While this has many advantages with respect to coverage and retention (Taylor & Shaw 1983) - suiting the requirements of contact products - it has been questioned by environmentalists concerned with the resulting drift levels. These concerns range from the effects on non-target species in the crop margins (Haughton *et al.*, 1998) to contamination of the operator (Cooper, 1994). Large droplets which drift less readily may give lower biological efficacy than smaller droplets under perfect conditions (Enfalt *et al.*, 1997) because of reduced retention on the plant. Research also suggests that traditional higher volume coarser spray nozzles do not necessarily give a linear increase in retention as application volume increases.

Industry has responded to this pressure with the development of equipment designed to combat drift. One simple and cost effective approach modifies the hydraulic nozzle to give a coarser droplet spectrum at low flow rates. Adapted from the standard flat fan nozzle, an orifice plate restricts the flow, so reducing the effective operating pressure and producing the low-drift pre-orifice nozzle. Alternatively, by making the restrictor plate a venturi, air is drawn into the liquid stream to form a coarser spray with droplets containing air bubbles. The merits of such air-inducing nozzles are described by Bouse *et al.* (1976) and Cecil (1997). However, trading droplet size for drift reduction has drawn into question the coverage and magnitude of spray deposits from such nozzles. This paper considers how wind speed affects these deposits on contrasting target surfaces when spraying at 100 and 200 litres/ha.

MATERIALS AND METHODS

Fifteen different types of nozzle belonging to three generic groups were used in the study (Table 1) to spray a fluorescent tracer over two contrasting artificial and one plant target. The nozzles were grouped into two flow rates, 0.6 and 1.2 litres/min (100 and 200 litres/ha). They were then further grouped according to their type and size, i.e. flat fan, low-drift and air-inducing 015, 02 and 03. Three like nozzles were mounted 0.5 m apart on a boom, which traversed the 2 x 1.5 x 6 m wind tunnel at Silsoe Research Institute, Bedfordshire at 2 m/s in wind speeds of 0 and 4 m/s. The spray liquid was a solution of 0.01 % (${}^{w}/_{v}$ aqueous) fluorescein sodium and 0.1 % (${}^{v}/_{v}$) non-ionic surfactant (Agral, Zeneca, UK) in tap water. Spray pressure was maintained by a high capacity centrifugal pump and was monitored by an electronic pressure transducer. Flow rate was determined by collecting and weighing the liquid from the central nozzle before each treatment. Spray solution samples were taken to give standard dilutions and quantify the magnitude of the deposits.

Table 1. Nozzle description and operating characteristics.

Nozzle	Type	Pressure (bar)	Flow (litres/min)	Spray Quality
4110-12 *	flat fan	2.5	0.6	Fine
Low-drift 12 *	pre-orifice	2.5	0.6	Medium/Coarse
Injet 015 *	air-inducing	3.0	0.6	Very Coarse
Driftbeta 015 **	air-inducing	3.0	0.6	Very Coarse
Bubblejet 015 ***	air-inducing	3.0	0.6	Very Coarse
Injet 02 *	air-inducing	2.0	0.6	Very Coarse
Driftbeta 02 **	air-inducing	2.0	0.6	Very Coarse
Bubblejet 02 ***	air-inducing	2.0	0.6	Very Coarse
AI 02 ****	air-inducing	2.0	0.6	Very Coarse
4110-18 *	flat fan	2.5	1.2	Medium
Low-drift 18 *	pre-orifice	2.5	1.2	Coarse
Injet 03 *	air-inducing	3.0	1.2	Very Coarse
Driftbeta 03 **	air-inducing	3.0	1.2	Very Coarse
Bubblejet 03 ***	air-inducing	3.0	1.2	Very Coarse
AI 03 ****	air-inducing	3.0	1.2	Very Coarse

* Hardi, ** Lurmark, *** Billericay Farm Services, **** Spraying Systems Teejet

Artificial targets were set on wooden boards and consisted of 20 mm diameter filter paper discs set horizontally 25 mm above the windtunnel base and 150 mm long, 5 mm wide plastic coated horticultural ribbon wire ties set vertically from the windtunnel base. Each board consisted of two rows of five of each target type, with two replications for each treatment. The nozzle was set at 540 mm above the tunnel base to allow a complete spray pattern formation to develop. Boards containing target arrays were placed both upwind and downwind of the sample boards. Targets were collected individually into plastic vials and spray deposits washed into a solution 0.1 % ($^v/_v$) non-ionic surfactant (Agral, Zeneca, UK) and 0.2 % ($^v/_v$) 1M NaOH in tap water. The tracer concentration in each sample was measured with a luminescence spectrometer (Perkin Elmer LS2).

Winter wheat (*Triticum aestivum* cv Brigadier) at Zadoks growth stage 69 (GS 69) was used to examine the retention of the spray on a plant surface. The crop had been grown outdoors in a soil based compost in plastic trays measuring 320 mm x 260 mm x 150 mm deep and trays for test selected to be similar with an average 32 ears per tray. The boom height was set at 450 mm above the ear or 500 mm above the flag leaf. Availability of plant material limited each treatment to three trays, with trays placed both upwind and downwind of the measured tray to combat edge and eddy effects. Each tray for measurement was cut at ground level, the spray deposits were washed off and tracer measured as described earlier. All samples were stored in the dark prior to analysis. Deposit data was normalised as μlitres/target/(100 litres/ha) and a three way ANOVA carried out on the data to determine the significance of differences between nozzle groups when compared to the flat fan application. The spray deposits on the wheat plants was normalised to μlitres/tray/(100 litres/ha).

RESULTS AND DISCUSSION

The spray deposit data is presented for each target type in turn. Figure 1 shows the average deposit per target and the standard error for each nozzle group at two wind speeds for vertical targets. Nozzles are grouped by flow rate into a 100 litres/ha group (Figure 1a) and 200 litres/ha group (Figure 1b) The spray deposit data for the horizontal targets shown similarly for the 100 litres/ha and 200 litres/ha nozzle groups in Figures 2a and 2b respectively. The data for spray retention on wheat plants is displayed in Figure 3a for 100 litres/ha and Figure 3b for 200 litres/ha applications. The spray deposit values are normalised to μlitres/tray/(100 litres/ha). Differences in levels of significance for each flow rate group as compared to the flat fan for contrasting targets and wind speeds are shown in Table 2.

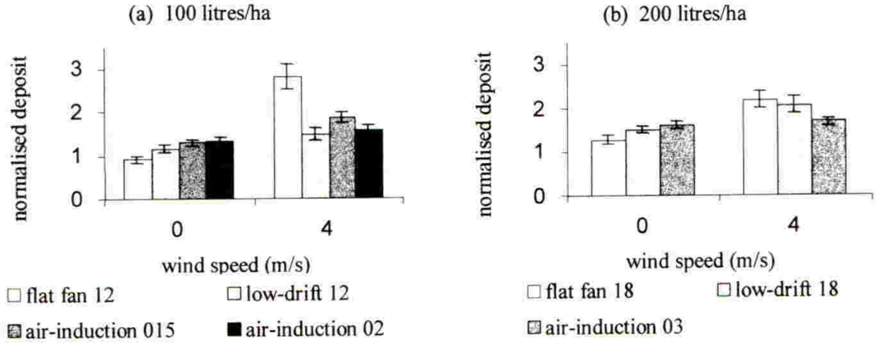

Figure 1. Spray deposits on vertical targets (a) 100 litres/ha group (b) 200 litres/ha group.

On vertical targets in still air conditions (Figures 1a & 1b) the low-drift and air-induction nozzles gave higher deposits than the flat fan within both flow groups, although these differences were not significant (Table 2). However, the difference for one nozzle in the air-induction 02 group was significant at the 5 % level. In a 4 m/s cross-wind (Figures1a & 1b) the flat fan nozzle gave higher deposits than the other nozzles, with the differences all being significant except for the high volume low-drift nozzle.

In still air the Injet and Driftbeta nozzles gave higher deposition values which could be due to a wider spray angle increasing the proportion of their output with some horizontal motion. The lowest deposition of the group was the Bubblejet. When a cross wind is experienced then the smaller and more drift prone droplets of the flat fan are more strongly entrained and take on a greater horizontal vector than larger droplets: indeed at 100 litres/ha (0.6 litres/min) the droplets from the flat fan nozzle are particularly prone to drift and exhibit the highest deposits. Although a proportion of the drift is captured, there is the inherent risk of a larger overall percentage of the spray volume leaving the target area. This effect is less pronounced with the Medium spray quality of the 200 litres/ha (1.2 litres/min) application. Low-drift nozzles also gain from diversion of their trajectories because, although the droplets are larger by virtue of the lower operating pressure their velocity and hence, droplet momentum is correspondingly reduced. Air-induction nozzles producing a smaller droplet size than their peers, such as the Bubblejet and Driftbeta also benefited in a cross-wind.

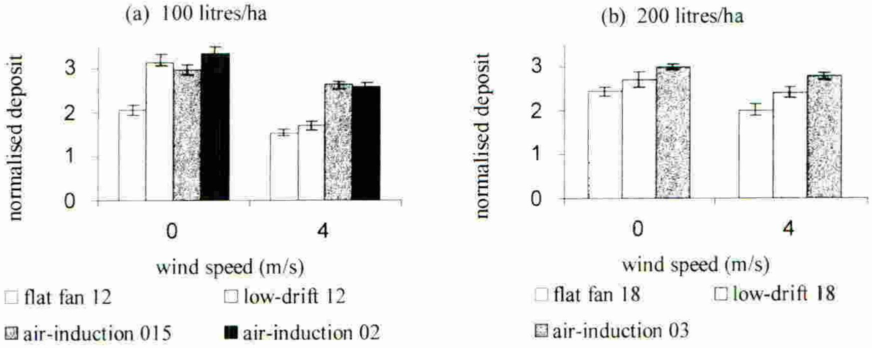

Figure 2. Spray deposits on horizontal targets (a) 100 litres/ha group (b) 200 litres/ha group.

On horizontal targets in still air conditions (Figures 2a & 2b), there were no significance between deposits within both flow groups (Table 2). However, at wind speeds of 4 m/s (Figures 2a & 2b) it was seen that flat fan and low drift nozzles suffered reduced deposits for both 100 and 200 litres/ha (0.6 and 1.2 litres/min) flow groups. The air-induction nozzles appeared to maintain their deposits for both flow groups, also giving significantly higher deposits than the other nozzles (Table 2).

In still air with an absorbent target, little, if any, differences in deposition would be expected, however, the Injet and AI nozzles gave higher deposits. When a cross-wind is present, the resulting diversion of the smaller and slower droplets to a more horizontal trajectory now means that the droplets approach the horizontal target edge on with a smaller projected area to hit. They may also drift out of the target area. The air-inducing nozzles appear to maintain their downward trajectory more strongly and drift away less.

Biological targets, which in reality are the destination for chemical applications are rarely mono-planar, as the winter wheat used in this study demonstrates. While the stems are predominantly vertical targets, the mature leaves presented a curved surface with a greater horizontal component.

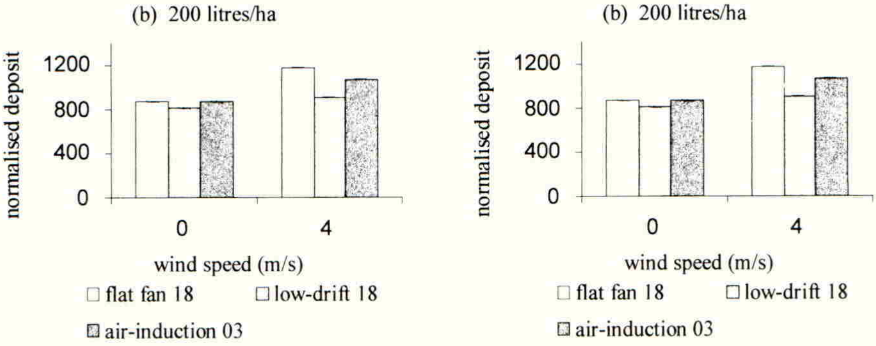

Figure 3. Spray deposits on winter wheat GS 69 (a) 100 litres/ha group (b) 200 litres/ha group.

The low flow group result in still air (Figure 3a) was possibly due to the wider spray angle exhibited by the air-inducing nozzles gaining better coverage of the vertical stems or the ability of the bubble filled droplets being retained more effectively The effect is shown with greater significance under a cross-wind of 4 m/s. The proportion of vertical and horizontal targets within the crop canopy has enabled the Fine spray application to maintain its capture even though the site of the deposits may have been traded. When larger 200 litres/ha application volumes were used (Figure 3b) this may have tended to dominate and mask any of differences. Again it should be noted that a mature cereal crop is a relatively dense and wettable target.

Table 2. Deposition performance for different targets and wind speeds.

Nozzle type	Vertical Wire Tie		Horizontal 20 mm Disc		Wheat	
	wind 0 m/s	Wind 4 m/s	wind 0 m/s	wind 4 m/s	wind 0 m/s	Wind 4 m/s
Flat fan12	-	-	-	-	-	-
Low-drift12	ns	***	ns	*	ns	ns
Air-inducing 015	ns	**	ns	***	**	**
Air-inducing 02	ns	***	ns	***	**	**
Flat fan18	-	-	-	-	-	-
Low-drift 18	ns	ns	ns	ns	ns	ns
Air-inducing 03	ns	*	ns	**	ns	ns

*** significant at 0.1% level, ** significant at 1% level, * significant at 5% level, ns not significant.

CONCLUSION

The way in which a particular droplet size is captured by a plant target is all-important when considering if the applied chemical is to be effective. Droplets produced from hydraulic nozzles vary in size and velocity giving rise to a wide range of momentum and kinetic energy. The prevailing atmospheric conditions absorb this energy with the potential to divert the droplet from its intended path and target. As a consequence the loading of spray deposits is seen to vary on contrasting targets. Droplets are likely to impinge on a vertical target only if there is some horizontal component to their trajectory. In the case of horizontal targets natural sedimentation of the spray droplets will effect a capture of all but the smallest of droplets.

Studying the data from the artificial targets it is concluded that air-induction nozzles are more able to maintain deposits on both vertical and horizontal surfaces, whereas, the flat fan and low drift (to a lesser extent) are affected as wind speeds increase to 4 m/s. It should be noted that while the horizontal targets used were wettable, the vertical targets were less so, but may still give superior retention over strongly water-repellent plant surfaces (e.g. young cereals, grasses etc.). Results from a mature cereal crop appeared to follow a similar trend.

In conclusion, for the operator who wants to ensure the success of an application, particularly when dose rates are cut or when timing and other application parameters are not optimal, such information as reported here may assist in nozzle choice. If the deposits and their siting secured from a poor choice do not achieve particular thresholds as a result of the differences reported here, the effects are likely to be witnessed as poor efficacy of chemical products in the field.

ACKNOWLEDGMENTS

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Guidelines on nozzle selection for conventional sprayers

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ABSTRACT

Nozzle selection aims to maintain the balance between biological efficacy, human and environmental safety with particular respect to spray drift. This paper reports the development of a guide, for use in cereal crops, which aims to assist farmers in their selection of nozzle type for use on conventional boom sprayers. The guide summarises nozzle type recommendations based on the information that was available in early 1999 from a review of relevant literature and consultations with representatives of independent research organizations, nozzle manufacturers and agrochemical companies, both in the UK and in Europe. As further information becomes available, particularly on the classification and efficacy of air-induction nozzles, the guide will need to be updated.

INTRODUCTION

Pressure to control spray drift has resulted in the development of a number of nozzles for use with conventional boom sprayers. Nozzle selection for any given target must maintain the balance between biological efficacy, human and environmental safety with particular respect to spray drift. The spray quality classification developed by the British Crop Protection Council (BCPC) (Doble *et al.*, 1985) uses information on droplet sizes to define five spray quality classes from Very Fine to Very Coarse. This system provides a useful basis for nozzle selection and is now being further developed to include a direct assessment of the risk of spray drift (Southcombe *et al.*, 1997). However, it does not yet have a basis for classifying sprays that include air within the droplets, although this is the subject of on-going research.

Spray drift is a function of droplet size, droplet velocity and spray structure (Miller, 1993), and recent research has shown that the risk of drift from boom sprayers is primarily a function of nozzle characteristics (Murphy *et al.*, 1999). The use of a pre-orifice in a conventional flat fan nozzle design has been shown to increase droplet size and hence reduce drift. Air-induction nozzle designs that use a Venturi arrangement in a modified nozzle body (Cecil, 1997) to create relatively coarse sprays whose droplets contain air inclusions have also been developed to offer lower drift than equivalent conventional nozzles.

Drift control can also be achieved by modification of the complete sprayer, although such systems are beyond the scope of the current guide. Air assistance (the addition of an airbag to the boom) allows the user to follow agrochemical label recommendations and reduce drift (Taylor & Anderson, 1997). Air can also be used as part of the spray generation process, for example in twin-fluid and air-shear nozzles. The twin-fluid nozzle can operate with a range of spray characteristics and volume application rates from a fixed nozzle geometry, and reduces spray drift at low volumes when compared to conventional flat fan nozzle designs (Miller *et al.*, 1991). Sprays produced by twin fluid nozzles give droplets within the spray that have air inclusions (Rutherford *et al.*, 1989).

The effect of nozzle type on biological efficacy is complex, depending on many inter-related variables such as droplet size, droplet speed, application volume, pesticide concentration, sprayer forward speed etc.. The use of large droplets, particularly when they are fast-moving, can lead to reduced levels of retention on the target. However, the presence of air inclusions may modify the behaviour of large droplets on contact with the surface of the target and maintain retention levels (Rutherford *et al.*, 1989).

This paper reports the development of a guide for use in cereal crops, which aims to help farmers select nozzles for use in conjunction with conventional boom sprayers. The main information in the guide is presented as a chart of different nozzle types and spray targets with indications of nozzle selection based on achieving the highest levels of biological efficacy with acceptable levels of spray drift.

METHOD

The guide was produced following a review of relevant literature (Rutherford *et al.*, 1989; Rutherford & Miller, 1993; Csorba *et al.*, 1995; Cawood *et al.*, 1995). Due to the paucity of published information, particularly relating to the biological efficacy of air-induction nozzles, a wide survey of unpublished information was also incorporated in the guide. This information was obtained from consultations and interviews with representatives of independent research organisations, nozzle manufacturers and agrochemical companies in the UK and Europe.

The measures of performance upon which the guide was based were the biological efficacy and level of spray drift in cereal crops when operating a conventional boom sprayer at 150 litres/ha with any given nozzles. Performance of a given nozzle type is dependent upon nozzle size and operating pressure so, for the purposes of this guide, "typical" BCPC spray qualities for the different nozzle types were used (Southcombe *et al.*, 1997). The reference for comparing spray drift levels was a BCPC F110/1.2/3 nozzle (Fine/Medium spray).

RESULTS

The chart

The main output was presented as a single chart, here split into two for ease of presentation (Tables 1a & 1b). Although it is known that the spray characteristics produced by different designs of air-induction nozzle are very different, all nozzles of this design were considered in a single category. This approach was taken pending the further development of a classification system that will discriminate between the performance of different designs of this nozzle type.

Biological efficacy

In the guide, there were additional comments relating to biological efficacy. These, as printed, were:

- Precise nozzle classification and pesticide modes of action are not always simple. Where the mode of action spans two classifications, such as both foliar and soil-applied, select the nozzle that provides the better spray coverage i.e. the finer quality spray. Similarly, select the nozzle which satisfies the most demanding requirements of the components used in a tank mix.
- Check with your adviser if it is intended to use a coarse quality spray in volumes less than 150 litres/ha and less than 100 litres/ha for medium quality sprays.
- Use a fine to medium quality spray for foliar-applied herbicides where the target is small - broad-leaved weeds up to 15 mm across or some grass weeds up to 2 fully expanded leaves - in an open crop canopy.
- Crop size is important; use a fine to medium quality spray for foliar-applied insecticides and fungicides when the crop has less than 3 leaves. When crop groundcover is above 50 % use more than 150 litres/ha and avoid a fine quality spray in order to control weeds shaded by the crop, or to control insects and diseases in the lower part of the crop.
- Some herbicides, such as glyphosate, provide higher levels of control in lower volumes.
- Lower volumes than those recommended on the label can be used provided:
  - the label volume is not a condition of approval
  - the approved concentration is not increased for pesticides which require personal protection equipment when the pesticide product is diluted to the minimum volume on the label for that dose or for pesticides labelled *toxic*, *very toxic*, *corrosive* or *risk of serious damage to eyes*
  - the approved concentration is not increased by more than tenfold for other pesticides

The guide also included a comment that pesticide labels should always be read prior to nozzle choice and any specific label advice on application of the product should be followed.

Drift risk assessment

No account was taken of factors such as forward speed, air assistance or boom structure on the risk of drift. These factors are obviously significant when considering the choice of nozzle type and size for an application at a given volume.

Drift assessments were based on interpolation of available data from both field and windtunnel tests.

DISCUSSION

The guide summarised the recommendations for nozzle type choice when spraying onto different targets, based on information available in early 1999. Further information is becoming available, particularly on the biological efficacy of air-induction nozzles, and the guide will need to be updated to take this into account. Recent data (Cooper & Taylor, 1999; Jensen, 1999) suggest that these nozzles can be as effective as conventional designs for some, but not all, targets, and that there is a wide range of spray characteristics for different designs within this nozzle type. The development of a classification system that includes such nozzles will enable better resolution of the linkage between spray characteristics and biological efficacy. It is also known that the properties of the spray liquid influence spray characteristics (Miller *et al.*, 1995; Butler Ellis *et al.*, 1997). Recent data suggest that the spray characteristics from air-induction nozzles are more strongly dependent upon spray liquid properties than other nozzles, and this may further influence future assessments in the guide. Research in this subject is continuing at a number of centres.

Table 1a. Nozzle selection chart as incorporated in the guide – conventional nozzles

(✓) acceptable spray quality for use in tank mixes
✓ acceptable spray quality
✓✓ preferred nozzle choice - minimises drift without compromising efficacy although alternative nozzles may be required in order to reduce further spray drift into vulnerable areas

	Conventional				
	Hollow cone		**Flat Fan**		
BCPC Spray Quality [a]	Fine	Medium	Fine	Medium	Coarse
Likely drift potential [b]	high	high	high	medium	low
Herbicides					
Soil-applied				(✓)	✓
Foliar-applied - grass/translocated			✓	✓✓	
Foliar-applied - broad-leaved/translocated				✓✓	
Foliar-applied - broad-leaved/contact (e.g. ioxynil)				✓✓	
Foliar-applied - non-selective (e.g. glyphosate)				✓✓	✓
Fungicides (foliar-applied)					
GS 13-32			✓	✓✓	
GS 33-49		✓	✓	✓✓	
GS 50 +		✓	✓✓	✓	
Insecticides (foliar-applied)					
Autumn spray			✓	✓✓	
Ear spray	✓	✓	✓✓	✓	

[a] BCPC Boom Sprayers Handbook (Anon., 1991)

[b] Compared to a conventional flat fan nozzle BCPC F110/1.2/3

In March 1999 the new scheme for Local Environmental Risk Assessments for Pesticides (LERAPs) was introduced (Anon., 1999). This implemented new procedures for assessing buffer zone requirements next to watercourses for pesticide products applied with a boom sprayer. Under LERAP, the width of the buffer zone is dependent on the pesticide product and dose applied, the size of the watercourse and the spray equipment being used. This scheme also introduced the 'LERAP – Low Drift' star rating for spray equipment with a particular ability to reduce spray drift. The guide presented in the paper was developed independently of the LERAP scheme and may have to be updated to take the star ratings of nozzles into account in the future.

Table 1b. Nozzle selection chart as incorporated in the guide – drift-reducing nozzles

(✓) acceptable spray quality for use in tank mixes
✓ acceptable spray quality
✓✓ preferred nozzle choice - minimises drift without compromising efficacy although alternative nozzles may be required in order to reduce further spray drift into vulnerable areas

	Low drift (pre-orifice)				Air Induction
	Flat Fan		**Deflector**		**Flat Fan**
BCPC Spray Quality [a]	Medium	Coarse	Medium	Coarse	not yet defined
Likely drift potential [b]	low	v. low	medium	low	v. low
Herbicides					
Soil-applied	(✓)	✓	(✓)	✓	✓✓
Foliar-applied - grass/translocated					
Foliar-applied - broad-leaved/translocated	✓		✓		✓
Foliar-applied - broad-leaved/contact (e.g. ioxynil)	✓		✓		✓
Foliar-applied - non-selective (e.g. glyphosate)	✓	✓	✓	✓	✓
Fungicides (foliar-applied)					
GS 13-32	✓				✓
GS 33-49	✓				✓
GS 50 +					
Insecticides (foliar-applied)					
Autumn spray					✓
Ear spray					✓

[a] BCPC Boom Sprayers Handbook (Anon., 1991)

[b] Compared to a conventional flat fan nozzle BCPC F110/1.2/3

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The development of twin-fluid nozzle for precision agriculture

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ABSTRACT

Spray information and lateral distribution data are presented for two configurations of a twin-fluid nozzle arrangement designed to give a wide range of delivery rates with a given droplet size distribution. The droplet size measurements showed that a similar size range was produced over a wide range of liquid flows; 425 to 1790 ml/min/nozzle for one nozzle design and 320 to 1780 for the other. Air volume requirements were mostly less than 10 litres/min per nozzle or at least 50 % less than for competitive commercial twin fluid nozzle designs. Surprisingly, liquid flow was found to increase virtually linearly with increasing pressure. The latter effect and the low air requirement are suggested to result from the effects of the Venturi insert. Lateral spray distribution was found to have a coefficient of variation of less than 10% for most of the flow rates tested. A high level of air entrainment in the droplets was also noted when a non-ionic surfactant was used. It is concluded that the nozzle design has an important role when operating boom sprayers over wide speed ranges or for patch spraying applications.

INTRODUCTION

For efficient spraying, it is necessary to deliver a defined dose with a very similar droplet size range over a defined treated area. This need presents a considerable challenge as sprayer speeds increase to attain faster work rates and patch spraying becomes more widely adopted to reduce the environmental burden. To achieve the objective application rates have to be varied. The term Turn Down Ratio (TDR= lowest flow rate – highest flow rate ÷ lowest flow rate) has been used to reflect changes in application volume rate while maintaining a similar droplet size range. For example, to reconcile sprayer speed changes, a TDR of up to 3.0 is necessary (Combellack & Miller, 1998) and where patch spraying is practiced, a TDR of up to 4.0 is required (Paice *et al.*, 1996). A TDR of 3.0 can be obtained with hydraulic nozzles on multiple booms (Paice *et al.*, 1996; Combellack & Miller, 1998), 2.5 with some twin-fluid nozzles if air and liquid pressures are varied simultaneously (Young, 1991; Combellack & Miller, 1998), up to 5.0 with another type of twin-fluid nozzle operating at a constant air pressure (Miller & Combellack, 1997) or 3.0 by using intermittent flow through hydraulic nozzles controlled by fast acting solenoids (Paice *et al.*, 1996). Each of these systems presents different challenges. Multiple booms require more elaborate plumbing and a computerised programme to determine which of the two booms or if both are to be used (Paice *et al.*, 1995). Also multiple booms are typically unable to maintain a very similar droplet size range as the nozzle size on one boom is usually larger than for the other(s). With such a set up not only is the droplet size variable, but the flow rate range which can be accommodated is limited if the liquid pressure range is restricted to between 2 and 4 bar to minimize variations in droplet size range. A computer programme is required with the two commercialised twin fluid nozzles (Airtech™ and Airjet™) so as to simultaneously vary liquid and air volumes to maintain a similar droplet size range. The latter nozzles are limited to a maximum liquid flow rate of around one litre/min, which is too low for faster spraying and restricts their TDR to around 2.5 (Combellack & Miller, 1988). Further, both nozzles require up to 30 litres/min of air per nozzle to effect droplet generation over their recommended operating range. Another twin fluid nozzle (Malan, in Miller & Combellack, 1997) produced a similar droplet size range, with VMDs around 400 µm, for a liquid flow rate range of 0.25 to 1.5 litres/min. This nozzle, therefore, had a TDR of 6.0 when both air and liquid pressures were varied but required up to 28 litres/min of air (Miller & Combellack, 1997). Obviating the need for a computer to simultaneously vary liquid and air pressures may be advantageous as it may reduce complication, arguably increase reliability and probably reduce costs. The Malan nozzle did produce a similar droplet size range for a three-fold change in liquid flow at constant air pressure, but the droplets were large (VMDs over 500 µm) (Miller & Combellack, 1997). The twin fluid nozzle described in this paper generates droplets over a wide range of liquid flow rates and uses lower air volumes working on a different principle to other twin fluid nozzles.

NOZZLE DESIGN

The design of the nozzles used is based on a removable insert that has a primary liquid entry orifice that is smaller than the secondary air/liquid orifice. The two orifices are separated by an annular chamber such that the area of the chamber is greater than the area of either of the orifices. This creates a Venturi effect and draws, or helps draw in, air though cross-drilled ports into the chamber. The air substantially atomises the liquid at this point and the droplets so formed then pass along the main conduit and are distributed by a nozzle tip. For the nozzles described in this paper, an anvil tip has been used. The atomisation is dependent on liquid flow, the liquid physical characteristics, and the pressure of both air and liquid. The results from two nozzles are presented, one with a low volume tip (nominally 250 to 1250 ml/min) which gives an "even spray" pattern (LVES) and the other with a medium volume tip (nominally 400 to 1750 ml/min) with a wider spray angle designed for broad acre spraying (MVBA).

An efficient Venturi effect, a function of the ratio of the primary liquid and secondary air/liquid orifices, is essential if this nozzle type is to operate efficiently. Therefore when testing, the ratio of the primary to secondary orifices were varied such that this area ratio was in the range 1.2 to 4.0. Maximum efficiency for a given liquid orifice size was obtained by varying the secondary orifice size and measuring the vacuum pressure as well as the volume of air induced using a variable flow air meter.

NOZZLE PERFORMANCE

Droplet size distributions

Results of a typical test for an MVBA insert are presented as Table 1. The nozzle configuration for these measurements used an insert with a 1.2 mm liquid inlet orifice, four

1.5 mm air entry ports and a 1.9 mm air/liquid outlet orifice with an MVBA anvil nozzle tip. After determining the most efficient Venturi arrangement, compressed air was applied via a side entry on the nozzle body to the cross-drilled ports. Liquid and air flow were then varied and measured using a Platon Model GTF 2CHD air flow meter and balance attached to a computer to measure weight loss and hence liquid flow rate. The measurements presented in Table 1 show that this set-up provided a very effective Venturi, and that a significant volume of air was induced without the aid of a compressor; thus, this design could be used as an efficient "air induction" nozzle.

Table 1. Air and liquid flow rates for an MVBA anvil nozzle tip

Liquid pressure kPa	Liquid volume ml/min	Vacuum kPa	Liquid volume ml/min	Air volume ml/min
100	770	-31.5	750	300
200	1180	-69	1070	500
300	1380	-98	1300	700
400	1550	-98	1510	900
500	1700	-98	1700	1100
600	1850	-98	1830	1300

Droplet size range was measured using Silsoe Research Institute's Particle Measuring Systems droplet spectra analyser. The nozzle was operated 350 mm above the laser beam with a full double plane scan at 50 mm/s used for the LVES tip (Table 2) and a half double plane scan at 40 mm/sec used for the MVBA tip (Table3).

Table 2. Spray generation data for LVES nozzle with surfactant at 0.1 % v/v

Air pressure kpa	Air volume litres/min	Liquid pressure kPa	Liquid volume ml/min	Droplet Data				
				DV 0.1	DV 0.5	DV 0.9	Span	Liquid velocity m/s
100	8.0	112	321	232.5	435.6	600.7	0.54	2.51
	5.5	154	590	238.5	417.4	689.7	1.08	3.47
	4.8	224	890	220.2	386.3	627.1	1.05	3.42
	4.8	330	1211	200.3	358.3	549.2	0.97	3.84
	4.8	458	1509	190.0	348.1	574.5	1.10	4.63
	4.8	600	1784	175.6	327.3	546.3	1.13	4.95
200	11.5	206	302	206.0	322.9	488.8	0.88	1.63
	10.5	238	500	216.6	394.0	639.0	1.07	2.70
	8.5	260	623	206.8	372.3	612.7	1.09	2.89
	6.0	333	916	203.2	356.9	571.0	1.03	3.36
	5.7	443	1240	197.7	345.7	517.8	0.93	3.47
	5.5	604	1610	182.4	325.9	521.9	1.04	3.71

100 kPa air pressure :- DV 0.5 mean = 378.8 ± 10% = 340.9 to 416.7

200 kPa air pressure :- DV 0.5 mean = 352.9 ± 10% = 317.6 to 388.2

The data for the LVES nozzle (Table 2) show that at 100 kPa air pressure, the VMD gradually declined as liquid pressure increased for 320 to 1780 ml/min. The liquid velocity increased with liquid flow even though the droplet size declined. Spray span (DV01. – DV0.9 ÷ DV0.5) was low for all flow rates. Air volume input declined rapidly, but then, surprisingly, remained constant. Liquid pressure increase was virtually linearly related to increasing liquid flow. One exception to the trend in lower VMD with increasing liquid flow for the 200 kPa air pressure was at 300 ml/min. The lower VMD for this flow rate reflects the increased air volume used. VMDs were, predictably, reduced for 200 kPa compared to 100 kPa air pressure, and also led to a reduction in liquid velocity. Air volume input was slightly higher at the higher air pressure as expected. The data were generated using a non-ionic surfactant (Agral, Zeneca, UK) at 0.1 % v/v, and this gave large volumes of air trapped in the droplets and the spray appeared very "foamy". This effect means that the volume of liquid in the droplets was not as high as that measured by the PMS. From other data, and observations of droplets captured in oil over silicone mixture, at least 30 % of the droplet volume was air.

Table 3. Spray generation data for MVBA nozzle with water

Air pressure (bar)	Air volume (litres/min)	Liquid pressure (bar)	Liquid volume (ml/min)	Droplet information				
				DV 0.1	DV 0.5	DV 0.9	Span	Liquid velocity m/s
100	10	137	563	251.4	459.1	761.3	1.11	2.40
	6.5	200	971	231.9	443.8	691.3	1.04	2.76
	5.3	300	1107	243.4	427.3	663.7	0.98	3.50
	3.5	450	1486	244.2	438.4	660.5	0.95	3.20
	3.5	600	1779	228.5	411.9	655.7	1.04	3.64
200	17	225	425	207.6	348.8	600.6	1.13	1.97
	11	300	793	218.7	366.9	551.5	0.91	2.14
	10	324	883	220	379.6	601.5	1.01	2.61
	8	450	1253	215.9	376.0	589.7	0.99	2.93
	7	600	1580	202.6	347.6	503.4	0.87	3.00

100 air pressure DV 0.5 mean = 436.1 ± 10% = 392.5 to 479.7
200 air pressure DV 0.5 mean = 363.8 ± 10% = 327.4 to 400.2

The data for the MVBA nozzle using water (Table 3) show that at both 100 and 200 kPa air pressures the VMD remained very similar over the range of liquid flow rates tested. Predictably, the VMDs were substantially reduced at 200 kPa compared to 100 kPa air pressure. There was a small increase in liquid velocity with liquid flow at both air pressures, but velocities were generally lower with the higher air pressure, reflecting the smaller droplet size range. Spray span was low for all flow rates at both air pressures. The air volume requirement declined rapidly, but then remained fairly constant. Liquid pressure increase was virtually linearly related to increasing liquid flow. The air volume requirement was predictably slightly higher at the higher air pressure.

Lateral spray distribution

Because the MVBA nozzles give a very wide spray pattern (1.7 to 2.5 m when operated at a spraying height of 500 mm), lateral spray distribution had to be assessed using four nozzles and collecting and weighing the liquid from the 75 mm channels beneath the middle two nozzles. The same set up was also used for the LVES nozzles. The results using tap water are presented as coefficient of variation (Tables 4 and 5).

Table 4. Lateral spray distribution - LVES nozzle (as coefficient of variation)

Air Pressure	Liquid flow rate, ml/min/nozzle			
100 kPa	250	500	750	1000
CV %→	31.3	7.0	9.7	6.4
200 kPa	650	750	875	1000
CV %→	6.2	4.2	5.3	4.9

Table 5. Lateral spray distribution - MVBA nozzle (as coefficient of variation)

Air Pressure	Liquid flow rate, ml/min/nozzle			
100 kPa	350	500	750	1000
CV %→	3.0	7.6	2.8	2.7
200 kPa	500	750	1000	1400
CV %→	6.4	5.6	2.9	3.6

Both the LVES and MVBA nozzles gave very low CVs over most of their liquid flow rate range. With the LVES nozzle, the CV varied dramatically when liquid flow fell below 500 ml/min/nozzle. This is because the distribution pattern from a single nozzle is similar to that from an even spray tip, and its spray sheet angle falls below 80°. The MVBA nozzle tip was designed to produce a wider (140 to 160°) spray pattern to enable it to produce low CVs over a wider range of flow rates (Table 4). Further, with the MVBA nozzle the CVs were typically under 10 % even when the boom height was 350 mm (data not presented).

DISCUSSION OF RESULTS

It has been found that if air is delivered to a point where an efficient Venturi is created by the liquid then air volume requirements are greatly reduced and liquid flow through its orifice does not follow the normal square function with pressure. It was seen (Table 2) that there was a 5.5 fold change in liquid flow for a 5.4 fold change in liquid pressure, i.e. from 112 to 600 kPa. Comparing data from the LVES and MVBA nozzles (Tables 2 and 3) it can be deduced that this relationship varies with air pressure and the efficiency of the Venturi. Even so, the effect enables large changes in liquid flow rate over a relatively small change in liquid pressure and can, therefore, be used as the basis for a large TDR. The other important aspect of the performance of this nozzle is the very small air volume required to effect droplet generation, typically 5 to 8 litres/min per nozzle. This is some 50 % less than that for other commercialised twin fluid nozzles.

The droplet size data for this nozzle showed there to be little change over a wide range of liquid flows, particularly with the MVBA nozzle. It is recognised, however, that the TDR implies that the droplet size range remains the same over the flow rate range: this is neither entirely practical nor achievable. There appears to have been no limit set on the acceptable variability in the droplet spectra for the TDR. We therefore suggest that for the TDR to be meaningful, the average VMD over the nominated flow rate range should be no greater than ± 10 %. Using this definition, it can be seen that with the LVES tip (Table 2) the TDR was around 2.7 at 100 and 5.3 at 200 kPa air pressure when using surfactant, and with the MVBA tip the TDR was 3.15 at 100 kPa and 3.7 at 200 kPa air pressure when using water. Both tips, therefore, generated a reasonable TDR.

The MVBA nozzles gave even lateral distributions over the recommended liquid low rate range and, from data not presented, could be operated satisfactorily at 350 mm boom height. While the LVES nozzles gave good CVs over most of their flow rate range, CVs increased rapidly at flow rates less than 500 ml/min due to the spray sheet angle becoming less than 80°; thus, they did not give CVs under 10 % at 350 mm boom height.

The droplet size range for the LVES and MVBA tips cannot be directly compared as surfactant at 0.1 % v/v was the test solution for the former and water was the test solution for the latter. Surfactant aided in the induction of a large volume of air in droplets generated by the LVES and MVBA nozzles. Therefore, the VMDs appeared somewhat larger when surfactant was used than would be the case with water alone, or with some oil-based adjuvants (Combellack *et al.*, 1996). The droplet spectra data showed that both nozzles gave a very low span, which indicates that their droplet size ranges were relatively narrow. Further, liquid velocity was low and, from data not presented, large droplets moved relatively slowly compared to those from hydraulic nozzles. This would suggest that droplet capture would be improved, as reflection would be reduced, as has been noted before (Miller and Combellack 1997). It is also speculated that droplet capture would be improved by the MVBA design as droplet trajectory would arrive at a target from multiple angles.

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