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Spray behaviour and efficacy of herbicides and fungicides applied to wheat at reduced volumes

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Abstract

Timing is a key component of maximising the efficacy of pesticide sprays and therefore of reducing inputs relating to the production of arable crops. Timeliness is a function of work rate and the ability to make applications in as wide a range of conditions as possible. For a boom sprayer, work rate is mainly a function of spraying speed, boom width and application volume, particularly as filling the sprayer takes quite a long time. Studies have shown that reducing volumes from 200 to 100 L/ha can typically increase work rates by 30%. However, reduced volume applications may mean reduced efficacy and, with conventional nozzle systems, increased drift. While drift control has been addressed by application methods, such as nozzle design and the use of air assistance, questions relating to efficacy remain, particularly when using drift reducing application systems. This project aimed to identify acceptable limits for reducing application volumes and provide information to assist users in determining application methods appropriate for use with reduced application volumes.

Studies to characterise the delivery systems that can be used to make low volume applications used laboratory and field experiments to examine deposits on artificial vertical and horizontal target surfaces. The results showed that coverage on both target types was a function of application volume rather than delivery system. Reducing volumes increased the variability in deposits with all delivery systems and some systems increased the deposit on vertical targets as volumes were reduced. Large droplets from air induction nozzles gave greater variability in target deposits at all application volumes.

Field trials applying a T2 fungicide to winter wheat showed no significant differences between different application systems. Disease control and yield were better at 50 and 100 L/ha than at 25 and 200 L/ha, although differences at the higher volumes were not statistically significant. There was some indication that high forward speeds and low application volumes may reduce efficacy.

Results from herbicide trials conducted over a total of four growing seasons showed no effects due to volume, nozzle type or spray angle in the first two years of the study. In the second two years there was some indication of reduced efficacy at the lowest application volumes of 37 and 73 L/ha.

The results of the work strongly suggest that application volumes can be reduced from 200 L/ha without increasing the risk of drift by appropriate choice of application method. None of the field trials conducted showed a loss of efficacy at 100 L/ha, although care is needed when extrapolating the results to a wider range of products, formulations, tank mixes and application conditions.

Summary

Timeliness in respect to the application of crop protection chemicals is of key importance because:

(i) achieving the correct timing of applications enables efficacy to be maximised and therefore inputs to be minimised;

(ii) the number of spraying occasions defined in relation to crop condition, weather conditions, particularly wind speed and rain and trafficability are limited;

(iii) capital and operating costs of application machinery need to be spread over larger areas so as to reduce costs per hectare.

Achieving high work rates is therefore a critical component in the planning of application strategies. For boom sprayers operating over arable crops, work rates are mainly a function of forward speed while spraying, boom width and application volume. Application volume is important because of the time taken to load and fill the sprayer, particularly when this is done at a dedicated loading site away from the field. A reduction in application volume from 200 to 100 L/ha can typically increase overall work rates by some 30%.

Reductions in application volumes have conventionally been limited by the risks of increasing drift with hydraulic pressure nozzles and by concerns relating to product efficacy. The risk of drift has been addressed over the past two decades by the development of application systems based on:

- the generation of relatively large droplets and reducing the percentage of spray volume in smaller droplet sizes, typically less than 100 µm in diameter – the pre-orifice nozzles and spinning discs are examples of such systems;

- producing very large droplets but with air inclusions within the droplets so that the spray is not deflected by wind but that droplets are retained on target surfaces;

- using air assistance to increase the velocity of small droplets and establish an air flow into the crop canopy that minimises the risk of drift even with relatively fine sprays: this approach also gives the potential to adjust deposition patterns within the crop canopy.

A substantial number of studies have recently examined spray drift and the drift reducing characteristics of different application systems but less research work has been directed at examining

the effect on efficacy of operating application systems, including those designed to reduce spray drift, at reduced application volumes. Previous work in the 1970's and 1980's examined the performance of spinning disc (CDA) application systems, often operating at reduced application volumes. The project work reported here sought to examine the performance of a wider range of application systems, particularly those designed to reduce drift, when operating at application volumes substantially less than 200 L/ha.

The approach to the project work consisted of two main elements, namely:

(a) a study of spray deposition characteristics on a range of artificial and natural targets in both field and laboratory conditions; and

(b) an examination of product efficacy for two main application scenarios where it was thought that application volume may be a critical parameter – i.e. the treatment of small targets such as the application of herbicides to grass weeds in the autumn and the spring application of a (T2) fungicide where target coverage may be important.

The results of laboratory studies examining deposits on different artificial collector systems showed little difference in mean levels obtained with the different application systems. This was as expected since the target collectors were relatively good collectors of spray. There was a difference in the variability of measured deposits with the large droplet air induction nozzle giving higher values for the coefficient of variation on both vertical and horizontal targets (with values up to 91%) while values from other systems used did not exceed 50%. The surface coverage of the artificial targets was mainly a function of application volume with smaller differences due to the application system used. The highest levels of coverage were achieved with conventional flat fan nozzle systems.

Measurements of spray deposits on tray-grown ryegrass plants treated in the laboratory showed that deposit levels were largely independent of application volume but that the variability in deposit was influenced by both application volume and the method of application.

The results from the laboratory studies therefore indicated that there were potentially two aspects of using low volumes that may cause problems with product efficacy, namely:

- that lower volumes resulted in reduced coverage; and
- systems applying low volumes in large droplets gave high levels of variability at the target surface (as measured by coefficient of variation) and this may have implications for product efficacy.

Reducing application volumes tended to increase target deposits particularly on some vertical targets, and the variability in deposits from all application systems tended to increase with reducing application volumes.

Measurements of spray deposits on ryegrass plants in field conditions also showed no relationship with application volume. Wind conditions at the time of application were shown to be a factor influencing deposition on such small targets.

Field trials applying herbicide to ryegrass plants in 2003 and 2004 showed no effects on the level of control due to application volume, nozzle type or nozzle angle. The data from the 2005 trial did not show the same trends with an apparent reduction in control being observed at the lower water volumes. This may however have been due to:

- delayed treatment in this season such that the weeds were much larger at the time of treatment; and

- a moderate level of control being achieved with no consistent dose response.

The 2005 trial was therefore repeated in 2006 and again showed no statistically significant effects on the level of control with application volume, although more surviving heads were recorded at the lowest application volume and particularly at the lower herbicide dose.

Field experiments applying a T2 fungicide in 2002 and 2003 measured low levels of disease in all plots and hence low disease pressure on the treatments. Results showed no effect due to application volume or nozzle type at volumes down to 25 L/ha. There was some indication that treatments using large droplets and/or coarse sprays performed less well than those fine sprays with the large droplet air induction nozzle performing less well compared with other systems at a range of application volumes and doses. Small droplet air induction nozzles performed similarly to conventional flat fan nozzles.

For the 2005 T2 fungicide trial disease pressure was higher. Disease control on leaf 2 was better at 100 and 50 L/ha than at 200 L/ha, and for the flag leaf was better at 100 and 50 L/ha than at 25 L/ha. The 25 L/ha treatment yielded less well than the 50 and 100 L/ha treatments. There was no effect of nozzle type on either disease control or crop yield.

It is concluded that for many products and targets there are substantial timeliness advantages from making applications in volumes of between 75 and 150 L/ha and the evidence from the trial results presented in this report shows that this can be achieved without a loss of efficacy. It is recognised that not all products/targets involve the same modes of action and therefore product manufacturers must be consulted before such applications are made routinely. The use of application systems such as the air induction nozzle would enable the use of such low volumes while also delivering reductions in drift risk when compared with the use of conventional flat fan nozzles.

1. Introduction

Timeliness of application is an important factor in the control of pests, disease and weeds and is therefore fundamental to optimising pesticide inputs. Decreasing water volumes is an important component in achieving good timeliness and reducing water volumes below 200 L/ha is one of the most useful methods of increasing work rates. The results from a computer simulation of sprayer operation in a typical arable situation (see Figure 1) illustrate the advantages that can be achieved by using low application volumes.

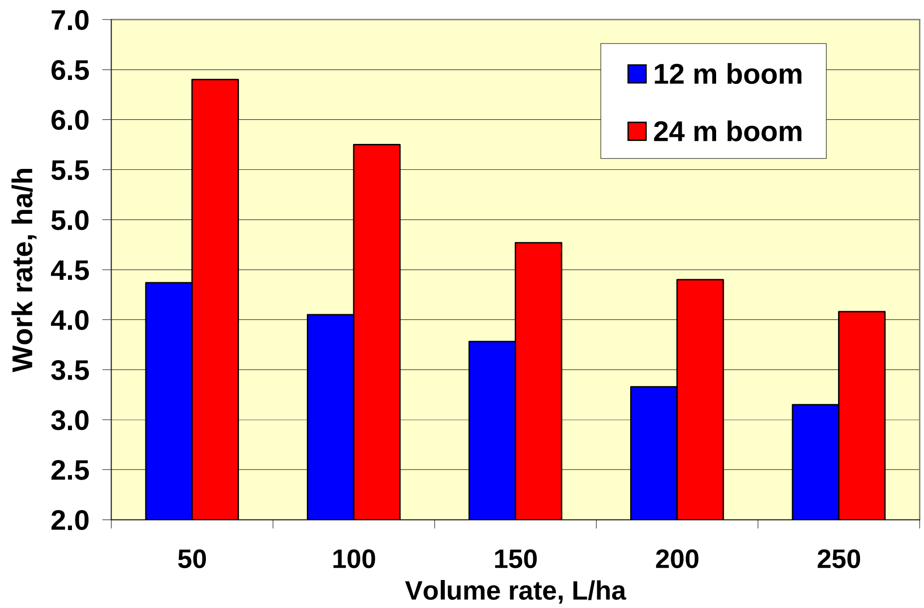

Figure 1. The effect of application volume on overall sprayer work rates.

In practice, there are two limiting factors preventing volumes from being reduced. Firstly, with conventional hydraulic nozzles, spray drift will increase as volumes are reduced. For operation at a given spraying speed, the application volume can be reduced by fitting nozzles with a lower output that will generally give a smaller droplet size distribution that will be more prone to drift. Travelling faster with the same nozzles can also reduce application volume but results from research have shown that this will also increase the risk of drift (Miller and Smith, 1997). Secondly, there is insufficient published data from field trials supporting the use of low volumes. While spray drift can be overcome by developments in application techniques (Miller, 1999), there has been concern that some of these, and in particular low-drift techniques that use coarse sprays, might reduce the efficacy of the application. There is also concern that reduced volumes themselves might, in some circumstances, reduce efficacy because of the inability to achieve sufficient coverage with a dense crop canopy or transport of the active ingredient to the site of action (e.g. into the leaf axial).

Therefore it is possible that there are limits below which volumes cannot be reduced without compromising the quantity of pesticide retained and the distribution of deposits on the target. Since application techniques are known to influence the efficacy of some active ingredients, with perhaps droplet size being one of the most significant factors, these limits are likely to depend upon the application equipment and operating parameters. A potential conflict therefore exists between reducing application volumes and optimising efficacy.

It is clear that there are many variables that influence the efficacy of spray application so that evaluating the effect of reducing water volumes is not straightforward. The characteristics of the spray (determined by the spray generation equipment and operating parameters) are arguably the most important variables controlling how much is deposited on the target and how it is distributed. The properties of the spray liquid, which will be influenced by the tank mix of formulations, adjuvants and water volume, also modify the quantity and distribution of deposit (Holloway *et al*., 2000). The crop canopy (density, structure – see Miller *et al*., 2000 **-** and surface) and the target site are also important factors. There is a substantial amount of relevant literature, particularly relating to herbicides (e.g. Knoche, 1994), about the effect of application on pesticide performance. However, most studies have considered only one or two variables over a limited range, and cannot be extrapolated to different application methods, crops or pesticides because the underlying mechanisms are not understood. The aim of this work is to explore generic aspects of how sprays behave at low volumes, to begin to define the limits to which volume can safely be reduced in some common scenarios, and provide some information about appropriate application techniques.

This study was not specifically aimed at application systems that had been shown in other work to reduce the risk of drift in comparison with conventional flat fan nozzles although most of the methods that have been developed practically for low volume applications do also have drift-reducing characteristics. The development of the Local Environmental Risk Assessment for Pesticides (LERAP) scheme (Anon, 1999) gave a basis for assessing the drift reducing characteristics of different application systems with a "three star" system giving less than 25% of the drift of the reference system. This comparison is based on a 12.0 m wide boom sprayer operating with FF110/1.2/3.0 ("03" 110 degree flat fan) nozzles at a pressure of 3.0 bar and applies to stated boom heights, operating pressures and forward speeds for the star rated nozzle. Much of the data to support claims for LERAP star ratings has been generated in wind tunnel tests (see typical example in Figure 2) although with systems such as air assistance, data from full-scale field trials has been used.

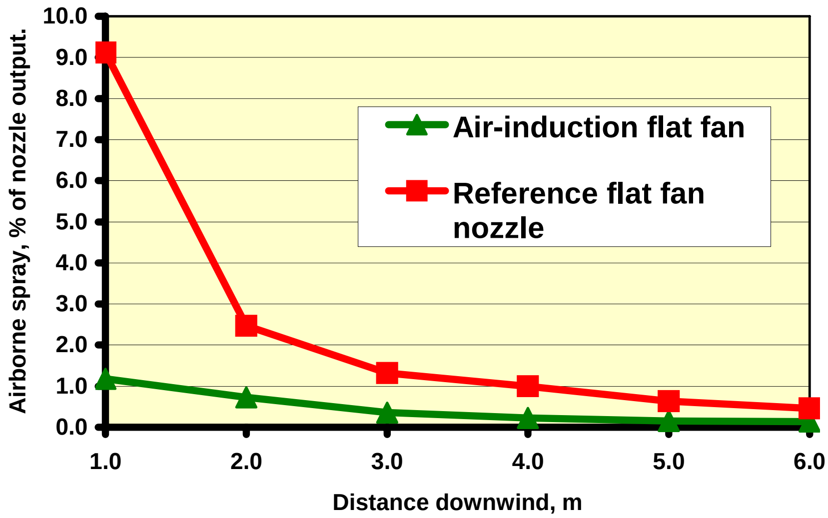

Figure 2. An example of horizontal airborne spray profiles measured in wind tunnel tests to support claims for a LERAP three star rating.

Two scenarios that may be inappropriate for low volume application have been considered in this work, namely:

(1) An established cereal crop canopy, such as for the spring application of fungicide, where coverage may be important; and

(2) Very small targets, such as autumn grass weed control, where a low number density of droplets may be inadequate.

Powell *et al.*, 2002 suggested that large air-included droplets may not provide adequate control with small grass weeds, and a common assertion is that there are insufficient droplet numbers. This is likely to be exaggerated at lower volumes, and therefore one of the hypotheses that we aimed to test was that, with some application systems, small targets may risk receiving an inadequate dose as volumes were reduced below 100 L/ha.

In the first part of the project, laboratory studies were undertaken to assess the characteristics of sprays that could potentially be used to deliver pesticides at low volumes. These assessments included as many application techniques as possible, and subsequently in the second part of the project a subset were selected to take into field trials which assessed, over three seasons, the consequences for efficacy.

The objectives of the project were:

- To determine how changing application techniques to reduce water volumes affects the characteristics of the spray delivered to the crop.

- To consider how the distribution of pesticide within crop canopies can be influenced by the interaction between application parameters, crop canopy characteristics and physical properties of the spray liquid.

- To consider the implications of (1) and (2) for biological efficacy.

- To provide scientifically based information to allow the acceptable limits to reducing water volumes to be determined.

2. Laboratory Experiments

The first phase of the project made laboratory assessments of the characteristics of sprays to determine how they are influenced by a range of techniques that can be used to reduce application volume.

The main scenario that was considered was the control of small weeds. Powell *et al.,* 2002 suggested that large air-included droplets may not provide adequate control with small grass weeds, and a common assertion is that there are insufficient droplet numbers. This is likely to be exaggerated at lower volumes, and therefore these assessments aimed to test the hypothesis that, with some application systems, small targets may risk receiving an inadequate dose as volumes are reduced below 100 L/ha.

Artificial targets were used for an initial set of experiments that enabled comparison between different spray generation systems without the complication of biological variability. However, the physics of spray retention is strongly influenced by the structure and surface characteristics of the target and so while artificial targets (which will retain spray droplets relatively easily) give a good indication of how particular structures intercept sprays, they do not represent complex surfaces that have low wettability. Therefore an additional set of experiments were conducted with plants, although still within the laboratory to allow control of environmental parameters.

The nature of the spray liquid is also crucial in determining the quantity of spray retained by a target plant. Holloway *et al.* (2000) showed that with high wettability targets (such as paper or plastic), spray liquid properties make little difference to retention. Therefore any tests of the effect of changing liquid properties (which occurs as volumes reduce because of the increasing concentration of formulation ingredients) have to be undertaken on plants, not artificial targets. A third set of experiments was undertaken to evaluate the potential effect of increasing concentration on quantity retained.

2.1 Materials and methods

2.1.1 Characterisation of sprays with artificial targets

Sprays have conventionally been characterised by measuring parameters such as droplet size distributions, droplet velocities and volume distribution patterns (Tuck *et al.*, 1997). The relationship between these parameters and deposit on a target plant is not straightforward. Therefore it was seen as appropriate to use parameters directly related to deposits to characterise each of the sprays under investigation, and to evaluate those deposits on artificial targets where there would be a high collection efficiency and no biological variability. Full details of the experiments undertaken were published in Butler Ellis *et al,* 2003. The application systems used in the evaluation are shown in Table 1.

Since the hypothesis to be tested was that small targets are vulnerable when applying low volumes, small artificial targets were used to characterise the spray. These consisted of plastic discs of diameter 15 mm, placed horizontally, and drinking straws of diameter 5 mm and length 50 mm, placed vertically. Pieces of chromatography paper were also placed horizontally and vertically to allow estimation of coverage (see Figure 3). Two experiments were conducted, one at Silsoe Research Institute, and one at Hardi International in Denmark, with slightly differing layouts. The application techniques evaluated at Silsoe Research Institute were conventional flat fan nozzles, air induction nozzles, twin fluid nozzles, spinning disc CDA, some of which were combined with increased forward speed as necessary. Air assisted spraying was evaluated in the laboratory at Hardi International. Volumes between 25 and 200 L/ha were investigated.

Table 1. Application systems used in laboratory tests.

Application type	Volume rate, L/ha	Nozzle	Liquid pressure, bar	Other info	Nozzle output, L/min	Forward speed, km/h
Conventional[1]	200	110^o 04	2.0		1.33	8.0
	100	110^o 02	2.0		0.67	8.0
	50	110^o 02	1.8		0.63	15.1
	25	110^o 01	1.8		0.32	15.1
Air Induction, small[2]	200	Bubblejet 03	3.5		1.33	8.0
	100	Bubblejet 015	4.0		0.67	8.0
	50	Bubblejet 015	3.8		0.63	15.1
	34	Bubblejet 015	1.8		0.43	15.1
Air Induction, Large	200	DriftBeta 04[1]	2.0		1.33	8.0
	100	Injet 02[3]	2.0		0.67	8.0
	50	Injet 02[3]	1.8		0.63	15.1
	36	DriftBeta 015[1]	1.8		0.45	15.1
Twin Fluid[4]	120	Airtec 40	3.79	2.41 bar air	0.8	8.0
	80	Airtec 35	2.76	1.72 bar air	0.53	8.0
	50	Airtec 40	3.1	2.07 bar air	0.63	15.1
	25	Airtec 35	2.14	1.72 bar air	0.315	15.1
CDA (Micromax)[5]	200	No restrictor	1.4	2000 rpm	2.67	8.0
	100	55 restrictor	2.55	3500 rpm	1.33	8.0
	50	37 restrictor	2.4	3500 rpm	0.67	8.0
	25	37 restrictor	1.25	5000 rpm	0.33	8.0
Air assistance[3,6]	200	110^o 04	2.0	No air	1.33	8.0
	100	110^o 02	2.0		0.67	8.0
	50	110^o 02	1.8		0.63	15.0
	25	110^o 01	1.8		0.31	15.0
	200	110^o 04	2.0	Vertical air	1.33	8.0
	100	110^o 02	2.0		0.67	8.0
	50	110^o 02	1.8		0.63	15.0
	25	110^o 01	1.8		0.31	15.0
	200	110^o 04	2.0	Angled air and nozzles	1.33	8.0
	100	110^o 02	2.0		0.67	8.0
	50	110^o 02	1.8		0.63	15.0
	25	110^o 01	1.8		0.31	15.0

[1]Hypro EU Ltd (Lurmark) [2] Billericay Farm Services Ltd [3] Hardi International [4] Cleanacres Machinery Ltd [5] Micron Sprayers Ltd [6] Conducted at Hardi International, Denmark with targets placed on a table below the track sprayer.

Figure 3. Sampling arrangement used at Silsoe Research Institute.

2.1.2. Evaluation of plant and spray liquid interactions

A set of similar experiments to those described above were conducted at Silsoe Research Institute using real plants. Trays of Italian ryegrass plants were grown outdoors and brought into the laboratory to spray at two growth stages: GS 11-15 and GS 20-30. The ryegrass was thinned out to a low density so that there was minimal interaction between plants (see Figure 4). The treatments applied, a subset of those used with the artificial targets, are given in Table 2. For each treatment, there were three replicate applications.

Figure 4. Trays of Italian ryegrass used for laboratory measurement of deposition on plants. Large plants (GS 20–30) are at the top, small plants (GS 11–15) at the bottom.

Table 2. Application systems used in laboratory tests on plants.

Application type	Volume rate, L/ha	Nozzle	Liquid pressure, bar	Other info	Nozzle output, L/min	Forward speed, km/h
Conventional[1]	200	110° 04	2.0		1.33	8.0
	50	110° 02	1.8		0.63	15.1
	25	110° 01	1.8		0.32	15.1
Air Induction, small[2]	50	Bubblejet 015	3.8		0.63	15.1
	34	Bubblejet 015	1.8		0.43	15.1
Air Induction,	50	Injet 02[3]	1.8		0.63	15.1
Large	36	DriftBeta 015[1]	1.8		0.45	15.1
Twin Fluid[4]	50	Airtec 40	3.1	2.07 bar air	0.63	15.1
	25	Airtec 35	2.14	1.72 bar air	0.315	15.1
CDA	50	37 restrictor	2.4	3500 rpm	0.67	8.0
(Micromax)[5]	25	37 restrictor	1.25	5000 rpm	0.33	8.0

[1] Hypro EU Ltd (Lurmark) [2] Billericay Farm Services Ltd [3] Hardi International [4] Cleanacres Machinery Ltd [5] Micron Sprayers.

Nine plants were sampled at random from each tray, following spraying, by cutting at soil level. The plant material was weighed and then washed off in de-ionised water. The quantity of spray liquid was then determined in the same way as the artificial targets. The quantity of spray liquid per gram of plant material was then calculated.

The original plan included a number of experiments to evaluate the effect of spray liquid properties – and in particular the effect of increasing the concentration of spray liquid components – on the deposit on plants in the laboratory. Health and safety considerations unfortunately required that the use of relatively high concentrations of chemicals in an enclosed space had to be kept to a minimum and therefore a very restricted set of experiments was conducted. Only one test spray liquid was used – a solution of Agral (Syngenta Crop Protection Ltd) at 0.5% - which could then be compared with the results from the previous experiments which included Agral at 0.1%. Only the large (GS 20–30) ryegrass plants were treated, and the treatments evaluated are the same as those given in Table 2, but excluding the CDA treatment.

A third set of experiments was undertaken to evaluate deposit on winter wheat at GS 65 using conventional flat fan nozzles and CDA. This aimed to provide data for the field trials, where the use of CDA at low volumes for the application of a T2 fungicide was evaluated. Full details of this are given in Butler Ellis *et al.*, 2004.

2.1.3 Visualisation of deposits and coverage

Experiments were conducted using a track sprayer fitted with a three-nozzle boom that was supplied from pressurised canisters. Lengths of chromatography paper were supported on boards and placed at ground level and across the sprayed swath. Applications of a tracer dye and non-ionic surfactant were then made using a range of nozzle types, sizes and forward speeds to give a range of application volumes with different droplet size distributions. Measurements of the droplet size distributions produced by each of the nozzle conditions were measured in the spray chamber at Silsoe Research Institute using standardised protocols (Tuck *et al*., 1997)

2.2 Results and discussion

2.2.1 Laboratory experiments – artificial targets

The mean levels of deposit on horizontal targets did not differ significantly either with volume or with application system. This was expected, since the chosen targets are good collectors and would be expected to collect all of the spray impacting them. The mean deposits on vertical targets were expected to differ, since the droplet trajectory is a crucial component in determining whether a droplet will contact a vertical surface. Those application systems that have a significant horizontal component (CDA, twin fluid, angled air assistance) would be expected to have higher levels of vertical deposit; fine sprays can take advantage of horizontal air movements to increase vertical deposits, and higher forward speeds also might increase vertical deposition. Figures 5 (UK) and 6 (Denmark) show the mean vertical deposits obtained for the different application systems.

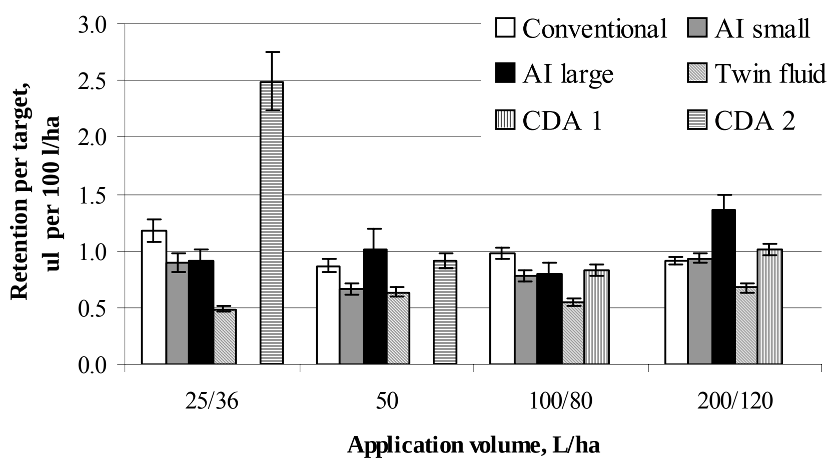

Figure 5. Deposit on vertical targets at Silsoe Research Institute, UK (error bars show SEM).

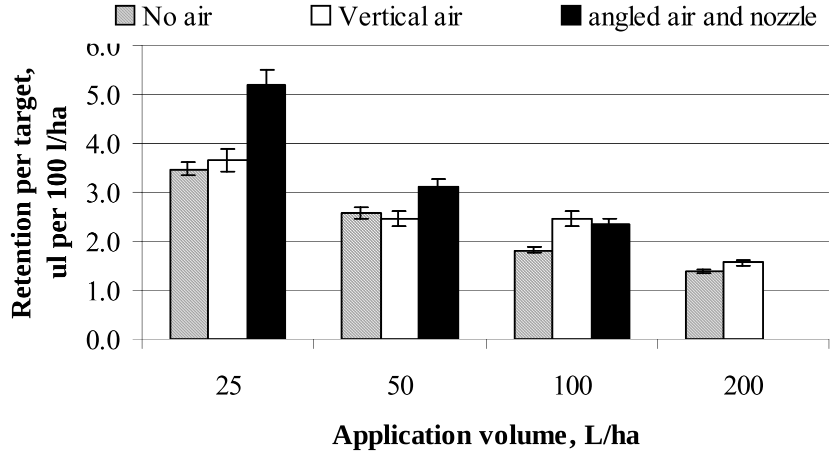

Figure 6. Deposit on vertical targets at Hardi International, Denmark (error bars show SEM).

There were problems with the CDA treatment in sampling over a representative swath, because its "nozzle spacing" of 1 m differs from the other systems tested, which had a nozzle spacing of 0.5 m. This was exacerbated by uneven patternation of the CDA system at low volumes. The first data set (CDA 1) used the same target spacing of 12.5 cm as the other systems, covering a width of 25 cm. This led to extremely high deposit values at the lowest two volumes that were not thought to be representative of the average. The measurements were then repeated at the two lowest volumes (CDA 2) with a target spacing of 25 cm, covering a width of 50 cm and lower average values were measured.

Differences between application systems are small, but significant in some cases, particularly at 25 L/ha, where the CDA treatment gave extremely high levels, which may have been due to high horizontal droplet velocities. The expected higher levels of deposit with conventional and twin fluid nozzles were not seen, nor with the increase of speed that occurred between 100 and 50 L/ha in the experiments conducted at Silsoe (Figure 5). There was therefore, little effect of reducing volume. However, at Hardi International, there was a noticeable increase in deposit with reducing volume (Figure 6). The angled treatment also showed higher levels of deposit, particularly at 25 L/ha, and there may be a forward speed effect since deposits were higher at 50 L/ha than 100 L/ha. The difference between the two experiments is likely to be as a result of different experimental layouts. In Denmark, there was less space and more blockage from the boom than in the laboratory at Silsoe, leading to more turbulence and potentially higher horizontal droplet trajectories. Neither situation is entirely representative of the situation in the field, which, with naturally occurring air currents, may be somewhere between the two. Deposition will also be different (probably much lower) on real plants with real spray liquids. The data shown indicate the likely differences between application systems and volume.

The hypothesis that small targets may risk receiving inadequate doses with some low volume treatments cannot be tested by looking solely at mean deposit levels. Table 3 shows the coefficients of variation for each of the replicate measurements for each treatment, and indicates the level of variability. The greatest values for each volume rate are shaded, and it can be seen that the large droplet air induction treatment is always the most variable.

Table 3. Coefficients of variation (CV), %, of the deposit per target, normalised to 100 L/ha, for different application systems and volumes.

Application type	CV horizontal targets				CV vertical targets			
Applic. vol, L/ha	200 or 120*	100 or 80*	50	25 or 36*	200 or 120*	100 or 80*	50	25 or 36*
Conventional	20.3	17.0	18.6	21.3	18.9	18.8	20.6	28.4
Air Induction, small	14.8	14.8	14.2	23*	19.8	33.4	32.1	49.0*
Air Induction, large	22.9	37.0	45.5	37*	55.8	70.5	91.0	56.9*
Twin fluid	18.5*	16.1*	16.3	22.5	30*	34.1*	29.6	28.5
CDA (Micromax)	19.4	21.9	38.8	24.9	24.7	29.2	33.4	37.6
Air assist, no air	7.0	8.4	11.5	10.0	16.5	16.5	20.8	17.5
Air assist, vertical	15.7	13.4	15.2	18.1	17.7	25.6	28.6	32.2
Air assistance, angled		13.4	10.2	16.8		16.4	24.7	28.0

It must be pointed out that the low pressures deliberately used to generate very large droplets were at or below the limit of manufacturers' recommendations and the results do not necessarily reflect normal practice. There are few other differences in the horizontal CVs. There is a tendency, although not strong, for the CV to increase with reducing volume, and this trend is more noticeable for vertical deposit CVs. These high CVs indicate that there may be some targets which receive less than an acceptable dose, leading to potential poorer performance. However, no treatments resulted in a zero deposit, even at the lowest volumes and with the largest droplets.

A second parameter that may influence efficacy is the surface coverage. It has been suggested that finer sprays associated with lower volumes when using conventional hydraulic nozzles give better levels of coverage. The percentage target area covered by droplets was estimated and examples are shown in Figures 7 and 8 to show the range. This data has not been normalised to 100 L/ha but shows the absolute coverage. There were some differences between application systems, with conventional sprays giving the best coverage on horizontal targets, and large AI droplets and vertical air assistance the worst.

There was much less coverage of vertical targets, with angled air assistance giving the highest, and CDA the lowest. The large droplet AI treatment was seen to give good coverage at low volumes because individual droplets ran down the target, leaving long tracks, and enhancing the spread. There is a clear volume effect, showing that coverage increases with volume despite the finer sprays used at some lower volumes. Again, these results only indicate how different application systems and volumes influence coverage. In practice surface properties of both plant and liquid will have a significant effect on droplet spreading.

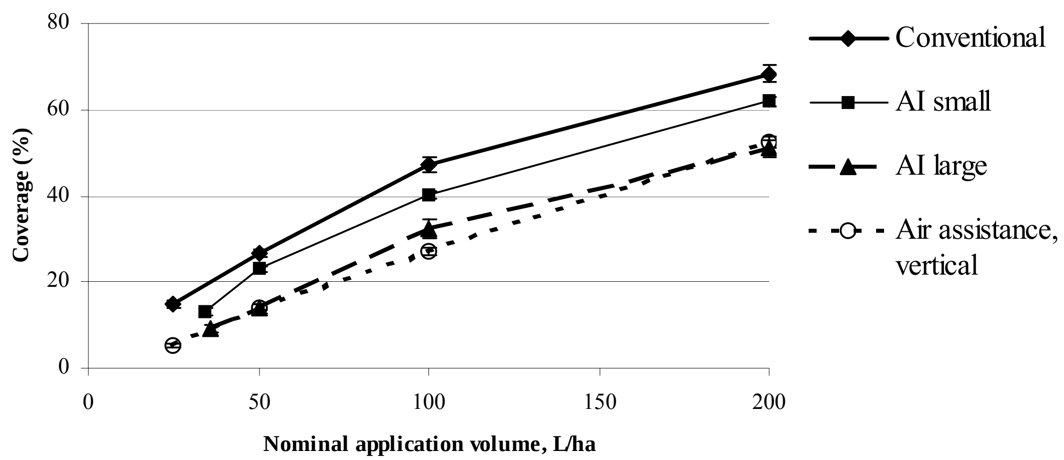

Figure 7. Coverage of horizontal targets (error bars show SEM).

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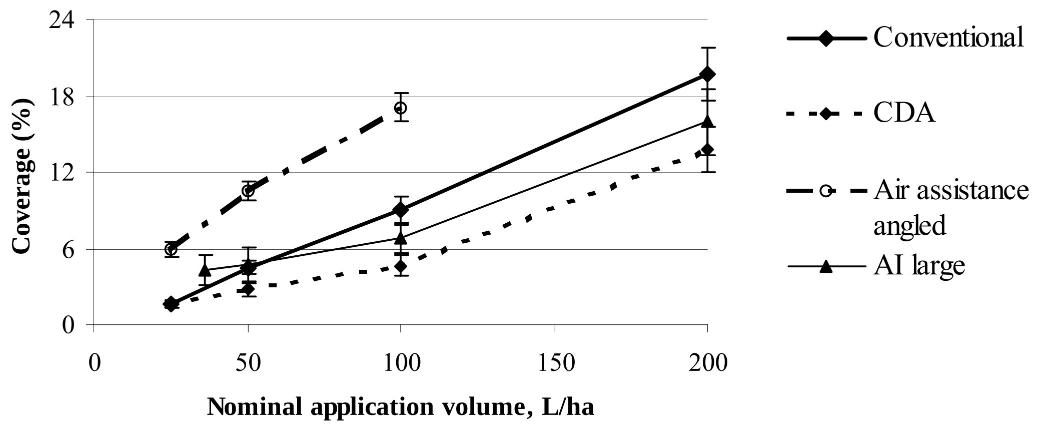


Figure 8. Coverage on vertical targets (error bars show SEM).

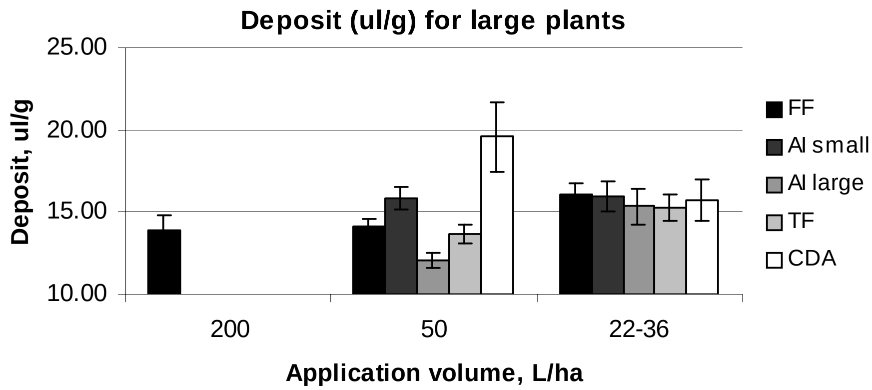
2.2.2 Laboratory experiments – tray-grown plants

2.2.2.1 Ryegrass

Figure 9 shows the deposit per gram of plant material on both large and small ryegrass plants, normalised to 100 L/ha application volume. None of the application equipment at volumes 22 – 36 L/ha produced deposits significantly different from that for a flat fan nozzle at 200 L/ha, although the large droplet air induction nozzle produced significantly lower deposits at 50 L/ha, with both sizes of plants. This was not supported by results from artificial targets.

The coefficients of variation (CV) of deposit for the ryegrass plants are shown in Table 4. The CVs are in general higher than those measured with artificial targets, not unexpectedly, since variations in plant structure will add to the variability. No single application system had consistently high or low CVs, although when averaged over two volumes and both plant sizes, the conventional flat fan was the lowest and CDA followed by large droplet air induction nozzle the highest. On average, CVs were higher for smaller plants and lower volumes.

There is, therefore, a strong suggestion that application volume will not have a strong effect on the quantity of spray liquid deposited on small grass weeds, but that both volume and application technique may increase the variability of the quantity deposited, potentially leading to poorer performance in the field.



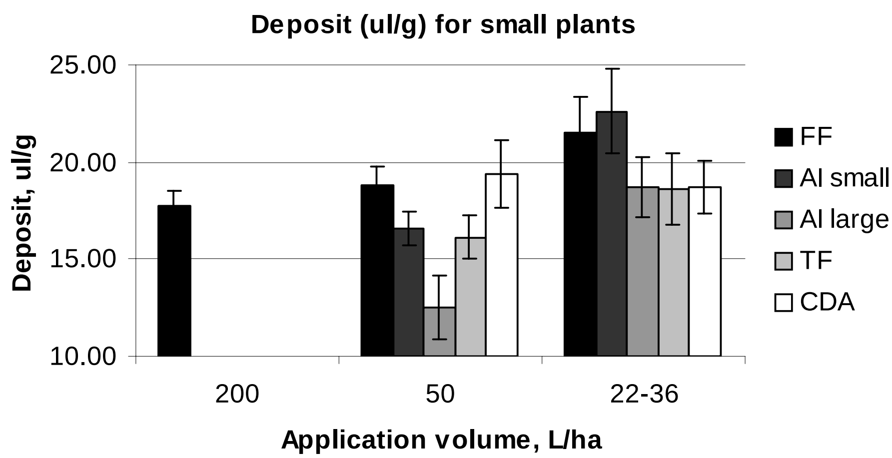


Figure 9. Deposit on large and small ryegrass plants, per gram of plant material, normalised to 100 L/ha volume.

Table 4. Coefficients of variation for deposit on ryegrass plants, obtained in laboratory experiments. The highest CV in each case is shaded.

Volume, L/ha	200		50		22-36		Mean
Plant size:	large	small	large	small	large	small	
Nozzle							
FF	34.3	21.1	19.0	26.5	21.9	44.3	**27.9**
AI small	-	-	23.1	28.1	28.9	50.7	**32.7**
AI large	-	-	19.5	68.5	36.8	42.6	**41.9**
TF	-	-	21.0	36.4	27.6	52.2	**34.3**
CDA	-	-	57.3	46.5	40.9	37.9	**45.6**
		mean	**28.0**	**41.2**	**31.2**	**45.5**	

The experiments that tested the effect of increased surfactant concentration showed no interaction with volume or equipment (Table 5) and therefore the effect of spray liquid was not considered further in the project.

Table 5. Comparison of deposits with low and high concentration of surfactant (Agral – Syngenta Crop Protection Ltd) evaluated at the lowest volume for each treatment on the large ryegrass plants.

Concentration	0.10%		0.50%	
	Mean deposit	sem	Mean deposit	sem
Flat fan	16.11	0.68	16.08	1.12
AI small	15.95	0.89	15.85	0.95
AI large	15.36	1.09	13.32	0.88
Twin Fluid	15.28	0.81	15.18	0.76

2.2.2.2 Wheat

Measurements of deposit achieved using flat fan conventional nozzles and CDA, on winter wheat under laboratory conditions are shown in Figure 10. From this graph it can be seen that the CDA had slightly higher deposit levels on leaves 2, 3 and 4 than either of the flat fan treatments. Although the deposit on the flag leaf was slightly lower, this was not significantly different. The implications for these data are discussed along side field trials results in Section 3.3.1.2.

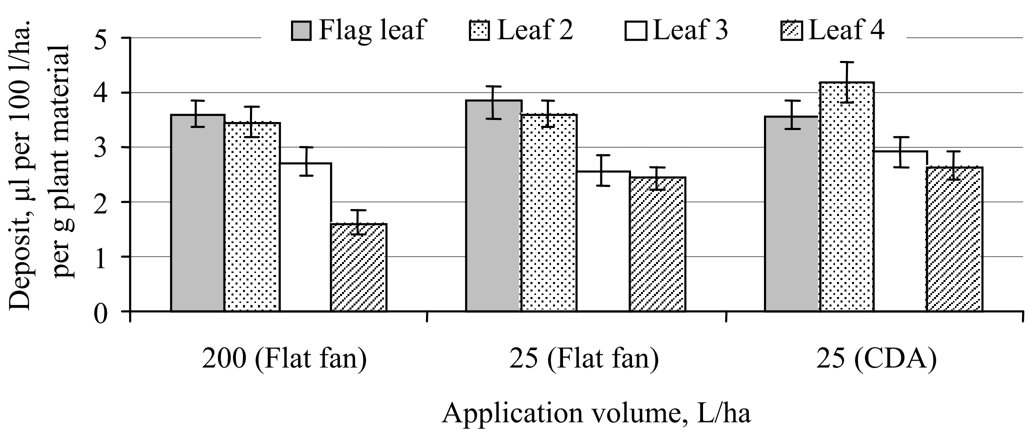


Figure 10. Effect of application method on deposition levels with flat fan nozzles and CDA (Laboratory trials). Error bars indicate sem.

2.2.3 Visualisation of deposits

Typical examples of the deposits and coverage achieved with different nozzle conditions are shown in Figures 11 and 12. The results demonstrate the expected trends with levels of coverage visually higher at the higher application volumes and the larger droplet sizes giving a more discrete form of target coverage. The differences in target coverage when using conventional and large droplet air induction nozzles are clearly visible when comparing the results in Figures 11 and 12.

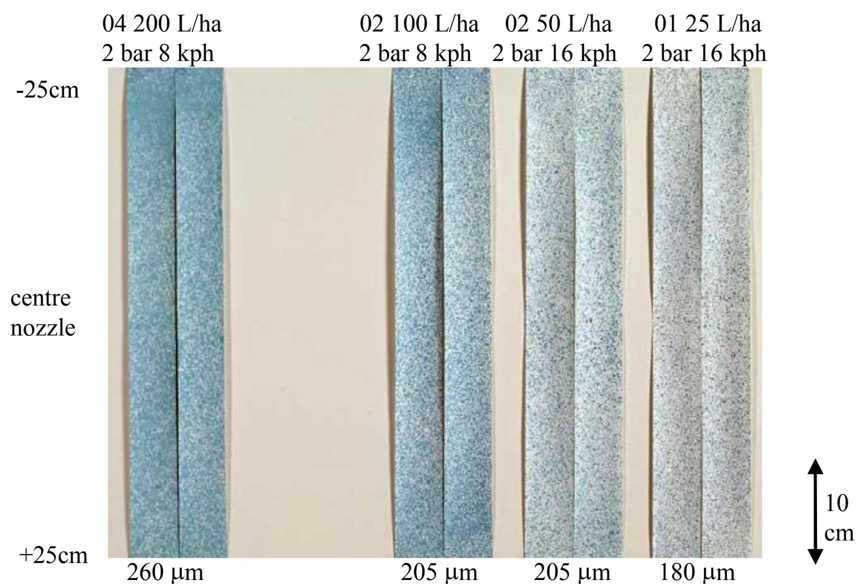


Figure 11. Deposits from conventional flat fan nozzles in the visualisation experiments.

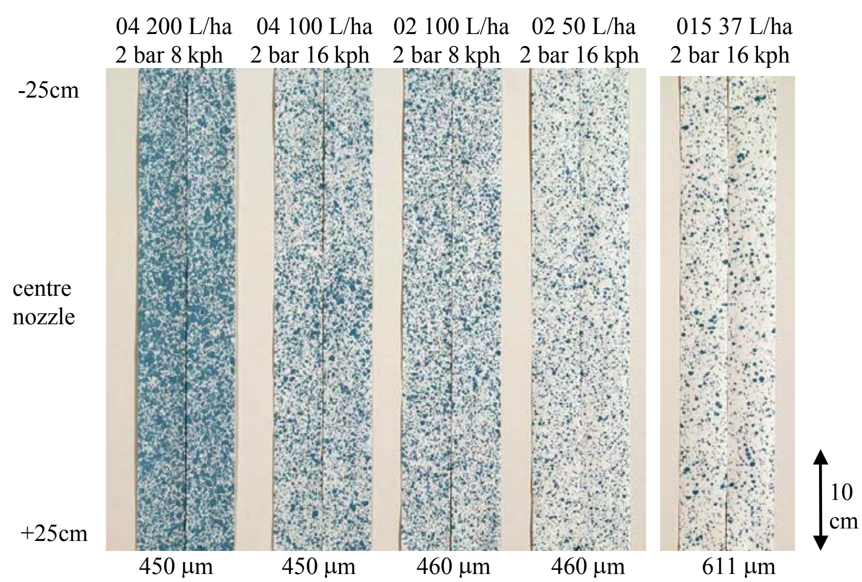


Figure 12. Deposits from flat fan air induction nozzles in the visualisation experiments.

2.3 Conclusions from laboratory experiments

The differences in the characteristics of sprays between application systems and volumes were small. The most notable findings were:

- Increased deposits on vertical targets with some systems at low volumes.
- Greater variability between target deposits for large droplets from air induction nozzles.
- Coverage was mostly affected by volume, not application system.

This suggests that, if there is a reduction in performance with reducing volume, it is not because of mean deposit levels, but may be because of greater variability or poorer coverage. The high variability with large AI droplets may be a factor in the poorer performance of these nozzles on small grass weeds, demonstrated by Powell *et* al. (2002). Any increase in performance with reduced volume could be because of increased concentration, or because of a direct link between deposit size or number and behaviour of the pesticide on the plant.

Thus laboratory measurements indicated that there were potentially two causes of problems when using volumes lower than the 100 – 200 L/ha that are most common practice:

- Lower volumes lead to lower coverage, and therefore an application where good coverage is required for good performance would be expected to be less effective at lower volumes;

- The largest droplet sprays had the highest coefficients of variation on small targets, and therefore it is possible that some small targets may have insufficient deposit to be effective, which may become most noticeable at lower volumes.

3. Field Trials – Part 1

In order to test whether the effects observed in the laboratory are also apparent in field conditions, two model systems were evaluated. These were a spring fungicide application to determine whether lower levels of coverage resulted in poorer performance at low volumes, and an autumn herbicide application to determine whether greater variability of deposit would result in poorer control at lower volumes with large droplet sprays.

A subset of the treatments evaluated in the laboratory was used, a conventional flat-fan treatment compared with an alternative (with some emphasis on systems that can control drift). The effect of angling nozzles was also investigated for the herbicide application, since purpose-designed angled nozzles for grass weed control are becoming commercially available and the previous laboratory measurements had suggested that backward-angled nozzles could improve deposits on small vertical targets, particularly with some nozzle designs and at low volumes. Some assessments were also made to evaluate deposits in the field.

3.1 Materials and methods

3.1.1 Spring fungicide trials

Field experiments were conducted at two sites (Site 1: Cambridgeshire, Site 2: Hampshire) over two consecutive winter wheat growing seasons, 2001/2002 and 2002/2003. In each season a range of application methods and application volumes were assessed with a T2 fungicide treatment, each treatment being replicated four times over the field area. No other fungicide treatments were applied to the plots (i.e. no T1 or T3 sprays). Disease was visually assessed and yields were measured using a plot combine harvester fitted with a weighing system. In the first year at Site 2, problems were encountered with the experimental procedure and as a consequence, both the dose of pesticide and the application volume were varied, whereas the dose should have remained constant. At Site 1 in Year 2, assessments of spray deposits were also made. Further details of the 2001/2 and 2002/3 trials were published in Butler Ellis *et a*l. (2004). Table 6 shows the treatments evaluated.

3.1.2 Autumn grass weed trials

Field trials were carried out in two successive seasons, 2002/03 and 2003/04 at two different sites in Dorset. In order to ensure a uniform, susceptible weed population, plots of winter wheat drilled in mid October were under-sown with Italian ryegrass at a rate of 6 kg/ha. This produced an average pre-treatment ryegrass population of about 180 plants/m^2 in 2002/03, but only 50 plants/m^2 in 2003/04 as a result of the drier autumn.

3.1.2.1 Efficacy trials

Eight spray treatments were applied with a Hardi Master MB800 to plots measuring 5.0 m wide and 20.0 m long, and replicated four times. An additional area was left untreated. The herbicide used was the foliar-acting product Tralkoxydim ("Grasp", Syngenta Crop Protection UK Ltd) at a rate of 0.7 L/ha, applied with the adjuvant "Output" (Syngenta Crop Protection UK Ltd) at a fixed dose of 0.36 L/ha. Application dates (and ryegrass growth stages) were 12/2/03 (GS 13-15) in 2002/03 and 15/12/03 (GS 12) in 2003/04. Treatments are shown in Table 7.

Table 6. Application systems and treatment details for the field trials conducted during 2001/2002 and 2002/2003 growing seasons.

Application type	Volume rate, L/ha	Nozzle	Liquid pressure, bar	Forward speed, km/h	Other info
2001/2002, Site 1, Variety: Claire, Fungicide Amistar, 0.5 L/ha (azoxystrobin) + Opus, 0.25 L/ha (epoxiconazole), Date applied: 27/05/02					
Flat fan	200	F110/1.6/3.0[1]	2.0	8	
Flat fan	100	F110/0.8/3.0[1]	2.0	8	
Flat fan	50	F110/0.8/3.0[1]	2.0	16	
Flat fan	25	F110/0.4/3.0[1]	2.0	16	
Twin fluid - medium	120	Airtec 40[2]	3.0	8	1.3 bar air
Twin fluid - fine	80	Airtec 35[2]	2.4	8	1.3 bar air
Twin fluid - fine	50	Airtec 40[2]	2.5	16	1.3 bar air
Twin fluid - fine	25	Airtec 35[2]	1.5	16	1.3 bar air
2001/2002, Site 2, Variety: Consort, Fungicide Amistar + Opus, Date applied: 31/05/02					
Flat fan	200	F110/1.6/3.0[1]	2.0	8	<u>200 L/ha</u>
Flat fan	100	F110/0.8/3.0[1]	2.0	8	0.94 L/ha Amistar
Flat fan	50	F110/0.8/3.0[1]	2.0	16	+
Air induction – large droplet	200	AI110/1.6/3.0[1]	2.0	8	0.94 L/ha Opus <u>100 L/ha</u>
Air induction – large droplet	100	AI110/0.8/3.0[3]	2.0	8	0.78 L/ha Amistar +
Air induction – large droplet	50	AI110/0.8/3.0[1]	2.0	16	0.78 L/ha Opus <u>50 L/ha</u>
					$0.65\ L/ha^{-1}$ Amistar + 0.65 L/ha Opus
2002/2003, Site 1, Variety: Consort, Fungicide Amistar, 0.6 L/ha + Opus, 0.3 L/ha + Helios 0.12 L/ha, Date applied: 25/05/03					
Untreated	0				
Flat fan	100	F110/0.8/3.0[1]	1.9	8	
Twin fluid - coarse	100	Airtec 35[2]	2.2	8	0.7 bar air
Twin fluid - coarse	50	Airtec 35[2]	2.1	8	0.7 bar air
Twin fluid - coarse	25	Airtec 35[2]	1.0	16	0.7 bar air
Twin fluid - fine	100	Airtec 35[2]	2.8	16	1.75 bar air
Twin fluid - fine	50	Airtec 35[2]	2.5	16	1.4 bar air
Twin fluid - fine	25	Airtec 35[2]	1.5	16	1.4 bar air
2002/2003, Site 2, Variety: Napier, Fungicide Comet, 0.3 L/ha (pyraclostrobin) + Opus, 0.4 L/ha, Date applied: 02/06/03					
Untreated	0				
Flat fan	100		2.0	8	
Flat fan	50		2.0	16	
Flat fan	25		2.0	16	
Air induction – small droplet	100	AI110/0.8/3.0[4]	2.0	8	

Application type	Volume rate, L/ha	Nozzle	Liquid pressure, bar	Forward speed, km/h	Other info
Air induction – small droplet	50	AI110/0.8/3.0[4]	2.0	16	
Air induction – small droplet	25	AI110/0.4/3.0[4]	2.0	16	
CDA	25	Spinning disc[5]	1.3	8	37 Restriction, disc speed 5000 rpm

[1]Hypro EU Ltd; [2] Cleanacres Machinery Ltd; [3] Hardi International; [4] Billericay Farm Services Ltd; [5] Micron Sprayers Ltd

Table 7. Treatments for herbicide trials.

Application volume, L/ha	Speed, km/h	Nozzle type/ size	Pressure, bar	Angle
164	8.0	FF/110/1.2/3.0 (03)	2.5	Vertical
164	8.0	Air induction, Drift Beta (03)	2.5	Vertical
73	8.0	FF/110/0.6/3.0 (015)	2.0	Vertical
73	8.0	Air induction, Drift Beta (015)	2.0	Vertical
37	16.0	FF/110/0.6/3.0 (015)	2.0	Vertical
37	16.0	Air induction, Drift Beta (015)	2.0	Vertical
73	8.0	FF/110/0.6/3.0(015)	2.0	30 degrees backwards
73	8.0	Air induction, Drift Beta (015)	2.0	30 degrees backwards

Control of ryegrass was evaluated 2 months after application, on 16/04/03 and 18/02/04 respectively. This was achieved by counting the number of weeds that had survived treatment in five 0.10 m^2 quadrats per plot. These had been marked and counted prior to application. The percentage control in each quadrat was then calculated and an average taken. Further assessments of the ryegrass population were carried out at 3 months after application and at heading, but these were considered less reliable due to the difficulty by that stage in differentiating plants that had emerged after the treatment application.

3.1.2.2 Deposit trial

The spray liquid used was 0.1% Agral (Syngenta Crop Protection UK Ltd) with 1.0 g/L “Green S” (Merck Chemicals) tracer dye. While there is likely to have been differences in spray liquid properties between this test liquid and the tank mix containing the herbicide and adjuvant, and this might lead to differences in retention on ryegrass plants, the earlier laboratory measurements of deposit on ryegrass suggest that any differences are likely to be small and the relative levels of spray deposit for different application techniques are expected to be similar. Applications were made with a 1000 litre, 12 m mounted air assisted sprayer but without the air assistance being used and the air bag tied down to the boom to minimise the disturbance to air flow around the boom. Wind speeds at a height of 2.0 m at the time of application were measured with a vane anemometer.

The same treatments that were used for the efficacy trials (Table 7) were evaluated, with three replicate plots per treatment. Following spraying, five samples of 10 plants were taken randomly from each plot and washed in de-ionised water. The washed-off solution was analysed by spectrophotometry and compared with a tank sample to determine the quantity of spray liquid retained.

In addition to the direct sampling of plants, 50 mm wide strips of chromatography paper were mounted on wooden lathes and laid in line with crop rows at the edge of each plot. These strips enabled spray deposits to be visualised for each plot treatment and strips from replicated plots were collected together and photographed to give a record of the treatments applied.

3.2 Results and discussion

3.2.1 Spring fungicide trials

3.2.1.1 Twin fluid nozzles vs conventional nozzles (Site 1)

Disease pressure was very low during both trials on Site 1. During the first year, levels of Septoria tritici assessed 42 days after application showed negligible levels present on the flag leaf, around 2 – 3% on leaf 2 and, over all treatments, an average of 34% on leaf 3. There were no significant differences between treatments. In the second year there was negligible disease on leaves 1 – 4. However, azoxystrobin can have a direct yield effect even when disease levels are very low. Figure 13 shows there is no effect of volume on yield with either conventional flat fan nozzles or twin fluid nozzles in Year 1. Although there were no significant differences between any of the treatments, Figure 13 clearly suggests that the twin fluid nozzle treatments tended to give a slightly higher yield than the flat fan nozzle conventional treatment at all volumes.

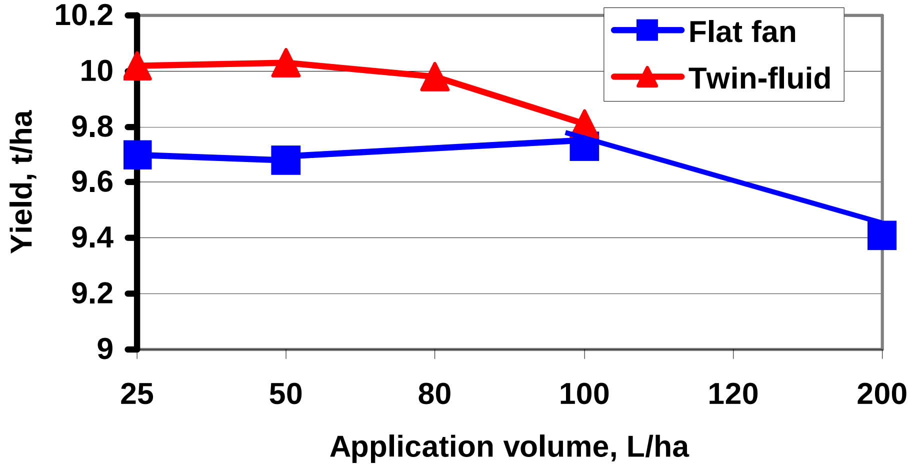


Figure 13. The effect of application volume on yield with flat fan conventional and twin fluid nozzles. (Site 1, Year 1). Least significant difference (LSD) = 1.2 t/ha.

In the second year, the experiment was modified to evaluate the difference between a coarse and a fine setting of twin fluid nozzles. The fine setting used in Year 1 would be expected to have drift levels similar to that of a conventional flat fan nozzle, whereas a drift reduction would be preferable. Once again there were no significant differences between any of the treatments. Nevertheless, there is a suggestion (Figure 14.) that the twin fluid nozzle treatments again gave higher yields than either the untreated or the conventional flat fan treatment. Moreover, the twin fluid nozzles set to give a fine spray application gave a slightly higher yield than when producing a coarse spray at all application volumes.

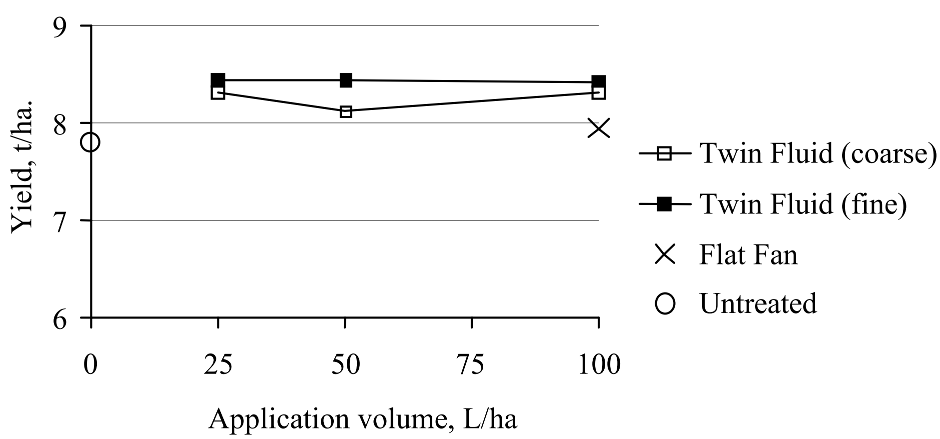


Figure 14. Effect of application volume on yield with flat fan conventional and twin fluid nozzles (Site 1, Year 2). LSD = 0.9 t/ha.

Measurements of deposit were also made in both years of the study. Results of the deposit distribution within the crop canopy made in Year 1 are given in Appendix I. These show relatively low deposit levels for the twin fluid nozzles operating at 120 L/ha and for the conventional nozzles operating at 25 L/ha. There was no definable correlation between measured deposits and levels of disease control.

Figure 15 shows the effect of volume and application method on deposit levels measured in the second year of the study. In this case there were significant differences (p = 0.016) with the twin fluid nozzles giving a fine spray having higher deposition levels compared with the twin fluid nozzles giving a coarse spray. This corresponds with the higher yields achieved with the fine twin fluid nozzle spray (Figure 14). However the flat fan conventional nozzle at 100 L/ha gave a higher deposit level than the twin fluid nozzles, which contradicts the findings of the yield data. Figure 15 shows a noticeable increase in deposit as volume reduced but this may be largely due to an increase in forward speed, from 8 to 16 km/h between the 100 and 50 L/ha treatments. There appears to be a poor relationship between the quantity of spray liquid retained and the efficacy of the treatment in terms of yield.

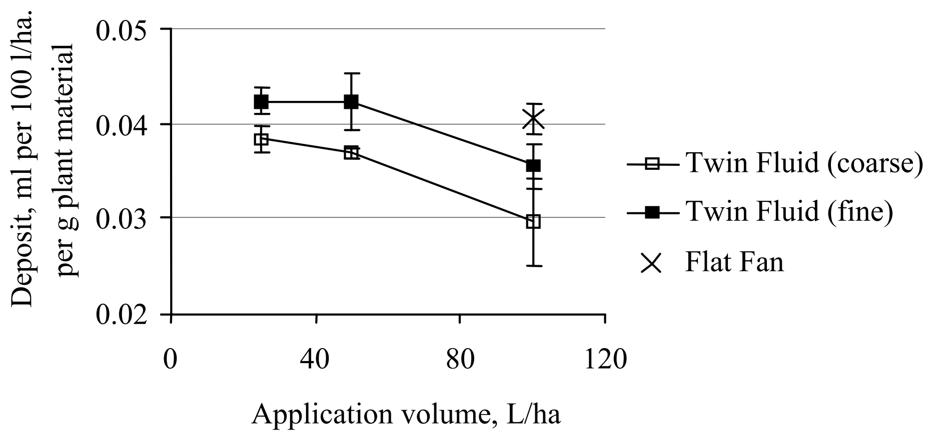


Figure 15. The effect of application volume on deposit with flat fan conventional and twin fluid nozzles. Error bars denote standard error of the mean (SEM). (Site 1, Year 2).

Results from these experiments suggest that differences in deposit did not result in meaningful differences in efficacy or yield. With little or no disease pressure and small variations in crop yield it is not possible to draw strong conclusions relating to treatment effects on efficacy.

3.2.1.2 Air induction nozzles vs conventional nozzles (Site 2)

Much higher levels of disease were observed at Site 2 than Site 1 (Figure 16). Although no significant difference in disease assessment between the treatments was observed, the disease levels were slightly higher for the air induction nozzles than for the conventional flat fan nozzles. However, higher yields were achieved for those plots treated with flat fan conventional nozzles than those treated with large-droplet air induction nozzles for all volumes and doses (Figure 17). These differences were significant at 100 and 50 L ha^{-1}. The changing dose with volume in the first year unfortunately meant that the effect of volume could not be deduced.

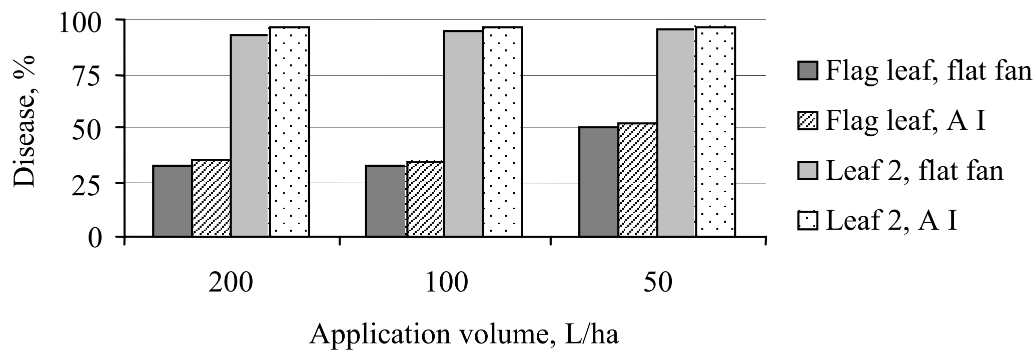


Figure 16. Effect of application volume and dose (see Table 1) on levels of Septoria tritici with flat fan and air induction nozzles (Site 2, Year 1). LSD flag leaf = 19.8%; LSD leaf 2 = 4.2%.

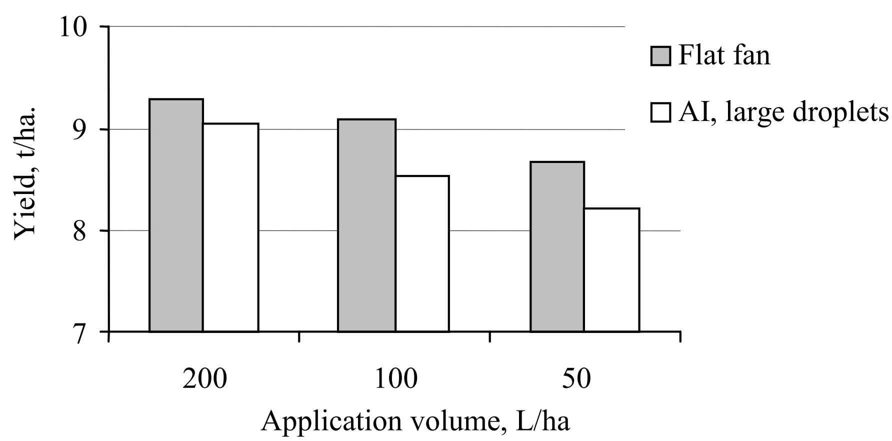


Figure 17. Effect of application volume and dose (see Table 1) on yield using flat fan and air induction nozzles (Site 2, Year 1). LSD = 0.33 t/ha.

The air induction nozzles used for this experiment produced droplets that are at the larger end of the air-included spectrum, and were deliberately used at relatively low pressures to make them larger still. The results do not therefore necessarily apply to the same nozzles used under different conditions, but are indicative of the effect of very large air included droplets. The lower yields and higher disease level with large-droplet air induction nozzles suggest that droplet size is potentially important in the efficacy of these fungicides. Since no deposit data was available, it is possible that this was because the air induction nozzles resulted in a lower deposit. Previous work (Robinson *et al.*, 2001) has suggested that the difference in deposit between conventional and air induction nozzles is small, and unlikely to account for the differences in yield seen here.

In the second year, a similar experiment was undertaken, comparing a conventional treatment with a smaller-droplet air induction nozzle. While this would not be expected to give as good drift control as the large-droplet sprays used in Year 1, it was hoped that this would give better performance with a substantially greater level of drift control than a conventional spray. An additional treatment, using a spinning disc (CDA) system, was also introduced at 25 L/ha, since this technique was specifically designed to deliver low volumes and had been shown to give good deposit characteristics in laboratory trials (Butler Ellis *et al.*, 2003).

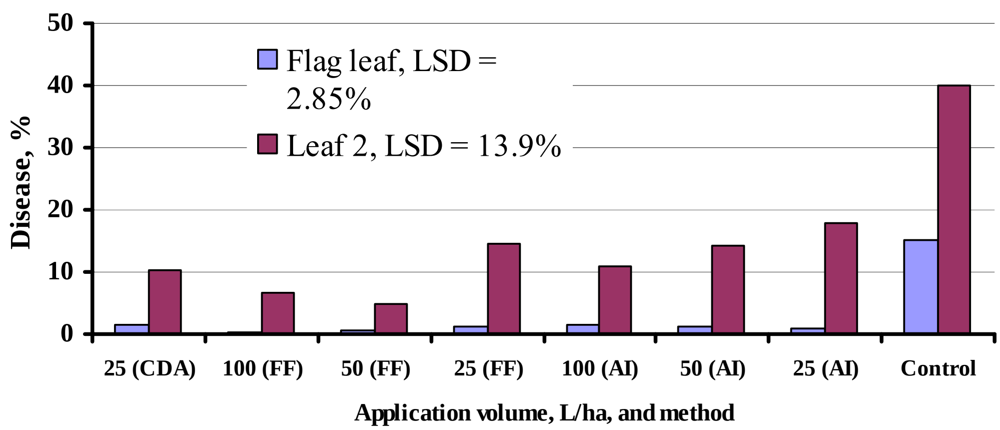


Figure 18. The effect of application volume on disease levels with flat fan (FF), CDA and air induction (AI) nozzles (Site 2, Year 2). LSD flag leaf = 3.1%; leaf 2 = 14.2% (CDA treatment excluded from the statistical analysis).

Disease levels in the second year (Figure 18) were lower than those in the first year. All treatments had similar levels of disease on the flag leaf (less than 2%) and leaf 2 (less than 18%) with the untreated plots having significantly higher levels of disease at 15% and 40% for the flag leaf and leaf 2 respectively. Generally this corresponds with the yield data (Figure 19) where most treatments gave similar yields. There was no effect of application volume on yield, and the performance of the small droplet air induction nozzles was equivalent to that of flat fan nozzles at all application volumes. The two trials, Year 1 and Year 2, indicated that there is an important difference in performance between large and small droplet air induction nozzles, as identified by Powell *et al.* (2002) with small grass weed control.

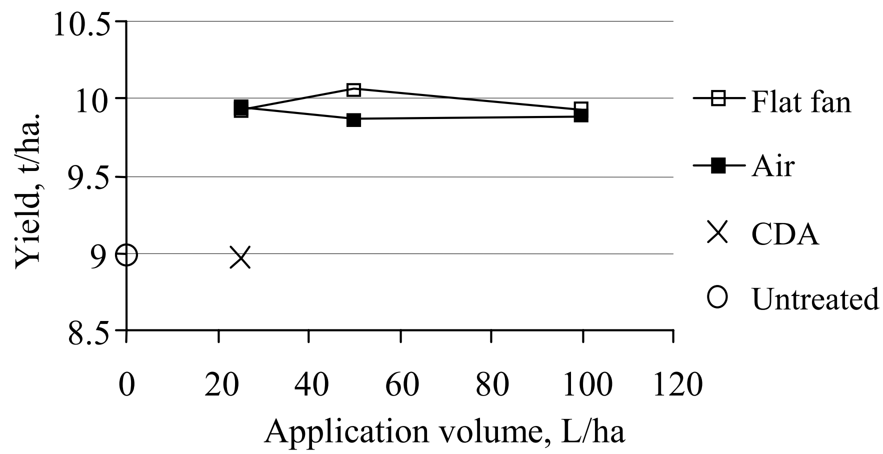


Figure 19. The effect of application volume on yield with flat fan conventional and air induction nozzles (Site 2, Year 2). LSD = 0.34 t/ha.

The untreated plot gave a significantly lower yield as expected. However the CDA also gave a significantly lower yield than the other treatments, which was not expected especially as the disease levels did not show significant differences from any of the other treatments. The laboratory measurements of deposit on wheat, reported in Section 2.2.2.2, indicated that the cause of this low yield was unlikely to be as a result of a reduction in the quantity deposited compared with conventional treatments.

The layout of the field experiments was such that all the CDA plots were together in one block. This was essential to avoid the potential contamination of adjacent plots with the CDA sprayer since the droplet trajectories are very wide with this system. Thus there may have been environmental effects that caused the low measured yields.

3.2.2 Autumn herbicide trials

3.2.2.1 Efficacy

Results for the two trials (Table 2) showed that there were no statistically significant differences in 2002/3, and only between the best (air induction nozzle at 73 L/ha) and the worst (flat fan at 73 L/ha angled backwards) in 2003/4. No trends in terms of application volume or application type were apparent.

Table 8. Percent weed control for the 2002 and 2003 trials, measured two months after application.

Application volume, L/ha	Speed, km/h	Nozzle type/ size	Angle	% Control 2002	% Control 2003
164	8.0	Flat fan	Vertical	70	89
164	8.0	Air induction	Vertical	80	92
73	8.0	Flat fan	Vertical	77	83
73	8.0	Air induction	Vertical	75	98
37	16.0	Flat fan	Vertical	69	95
37	16.0	Air induction	Vertical	65	97
73	8.0	Flat fan	30 degrees backwards	70	80
73	8.0	Air induction	30 degrees backwards	68	90
Least significant difference				23	16

Angling nozzles 30 degrees backwards also had no statistically significant effect on performance, although the angled treatments were consistently poorer than the vertical treatments. There is therefore no evidence to support the hypothesis that backward-angled nozzles improve control of small grass weeds.

3.2.2.2 Deposit trial

Measurements of the quantity of spray liquid deposited on ten ryegrass plants are shown in Figure 20. During application of the 73 L/ha angled treatments on two plots (one flat fan and one air induction), a gust of wind was measured of more than 3.5 m/s compared with mean speeds for most of the applications that were between 2.0 and 2.6 m/s. When the deposit data was analysed, it was apparent that this had an important effect on deposit and was therefore removed from the results shown in Figure 20. An analysis of variance of all data showed that there is a statistically significant interaction between gust and nozzle ($F(2,11) = 17.4$, $p<0.001$) and there were no other statistically significant treatment effects or interactions. The interpretation of this interaction may relate to the gust of wind having a greater effect on the spray from the flat fan nozzle compared with that from the air induction nozzle. In both cases, the deposition was increased but for the air induction nozzle, the response was

1.4 times greater whereas for the flat fan nozzle, the response was 2.6 times greater. Similarly, the difference between the flat fan and air induction nozzles was dependent on the wind speed – i.e. the flat fan nozzle produced deposits 1.6 times that of the air induction nozzle without the gust, but 2.8 times greater when there was a gust.

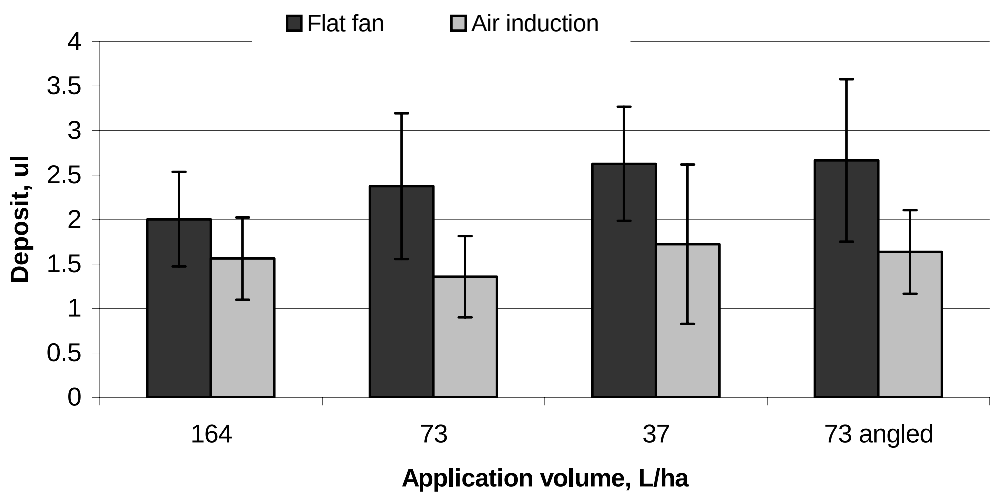


Figure 20. The effect of application volume and nozzle type on the deposit on 10 ryegrass plants.

Although there is an apparent increase in deposit as volume reduces with a flat fan nozzle, this was not statistically significant. This is consistent with laboratory results, (Butler Ellis *et al.*, 2003) where in two separate experiments, one showed no effect of reducing volume, and the other an increase in deposit. It was hypothesised that under more natural conditions, something between the two, i.e. a small volume effect might occur. This is due to the ability of a fine spray to take advantage of air currents that will provide horizontal trajectories and increase the probability of making contact with vertical targets. The spray from the air induction nozzle, since it is relatively unaffected by air currents (and hence controls drift) would not be deflected from its original trajectory, leading to lower deposit levels.

The variability of deposit on individual plants could not be determined because insufficient quantity retained on such small plants would lead to poor resolution. However, coefficients of variation for 10 plants (Table 9) showed that for flat fan nozzles there was again no volume effect while for air induction nozzles, there was a noticeably higher CV at 37 L/ha, suggesting that the lowest volume treatment with the air induction nozzle might result in poorer levels of control on some plants.

Despite this, results from the first two seasons showed no effect of either nozzle or volume. The mean wind speed during the deposit trial was around 2.2 m/s. It is possible that, in lower wind conditions, there would have been lower deposit levels from the flat fan nozzle and therefore much smaller differences. Previous laboratory measurements in still air showed no difference between conventional flat fan nozzles and air induction nozzles with artificial targets (Butler Ellis *et al.,* 2003). However, the laboratory measurements with ryegrass plants (Section 2.2.2.1), although not statistically significant, also suggested lower retention with an air induction nozzle producing very large droplets. It would be interesting to establish whether the deposit from an air induction nozzle used in "windy" conditions would be equivalent to the deposit from a flat fan nozzle used in "ideal" conditions.

Table 9. Coefficients of variation of deposit on ryegrass plants.

Application volume, L/ha	Flat fan	Air Induction
164	26.51	29.53
73	34.52	33.72
37	24.41	52.02
73 - angled	34.31	28.81
Mean	29.94	36.02

3.3 Conclusions from field trials – Part 1

There was no measured effect of application volume on the performance of azoxystrobin plus epoxiconazole or pyraclostrobin plus epoxiconazole with conventional sprays, twin fluid sprays or air included sprays at volumes down to 25 L/ha under low disease pressure.

There was a strong indication that droplet size may be an important factor in the performance of these fungicides, with coarse sprays performing less well than fine sprays. Large droplet air induction nozzles performed consistently poorly at a range of volumes and doses. Small droplet air induction nozzles were similar in performance to conventional flat fan nozzles but would give significantly better drift control, particularly at low volumes.

There was no effect of volume on the performance of the grass weed herbicide tralkoxydim on ryegrass, nor was there any effect of nozzle type, when comparing conventional flat fan nozzles with an air induction nozzle. Angling nozzles backwards at 30 degrees also had no effect on performance.

Measurements of deposit on ryegrass plants showed that there is a possibility of a difference in deposit between flat fan and air induction nozzles but this depends on the wind speed at the time of the experiment. Flat fan nozzles produce a fine spray that can be influenced by air movements that potentially increase the deposit on small vertical targets. The use of the flat fan nozzle resulted in deposits that were significantly higher than those from an air induction nozzle, and the difference increased as the wind strength increased. Spraying during "ideal" low wind speed conditions would be likely to reduce the difference between the two nozzle types.

Since no differences in control were observed in any of the field trials, it is likely that any differences in the quantity deposited on ryegrass plants were too small to have any effect.

4. Field Trials – Part 2

A further season of field trials were undertaken, with additional project funding, to provide greater reassurance of the results which, particularly in the case of the spring fungicide application where disease pressure was low in the second year, were not seen as sufficiently robust to provide advice to farmers. An additional objective was to begin to test the principle of lower volumes with a wider range of chemicals and pests. Therefore two further trials were undertaken to repeat the autumn herbicide application and the spring fungicide application, and a third separate trial was carried out by Syngenta Crop Protection (UK) Ltd to investigate a model system of their choice – autumn application of clodinafop-propargyl and trifluralin (Hawk) to control blackgrass. A summary of the results of this Syngenta trial is given in Appendix II.

4.1 Spring fungicide application

4.1.1 Materials and methods

The field experiment was conducted at a site in Hampshire in a crop of winter wheat (variety: Consort) that was drilled on 28 September 2003. A range of application methods and application volumes were assessed with a T2 fungicide treatment that was 0.3 L ha^{-1} of pyraclostrobin (as Comet) and 0.5 L ha^{-1} of expoxiconazole (as Opus) applied on 2 June 2004. Each treatment was replicated four times over the field area. No other fungicide treatments were applied to the plots (i.e. no T1 or T3 sprays). Treatments were applied with a Hardi Master MB800 sprayer to plots that were 5.0 m wide and 20.0 m long. Yields of each plot were measured using a plot combine harvester fitted with a weighing system and the disease on different crop leaves was visually assessed. Details of the treatments used are given in Table 10.

Table 10. Application systems and treatment details.

Application type	Volume rate, L/ha	Nozzle	Liquid pressure, bar	Forward speed, km/h
Untreated	0			
Flat fan	25	FF110/0.4/3.0[1]	2.0	16.0
Flat fan	50	FF110/0.8/3.0[1]	2.0	16.0
Flat fan	100	FF110/0.8/3.0[1]	2.0	8.0
Flat fan	100	FF110/1.2/3.0[1]	3.5	16.0
Flat fan	200	FF110/1.2/3.0[1]	3.5	8.0
Air induction – small droplet	25	AI110/0.4 /3.0[2]	2.0	16.0
Air induction – small droplet	50	AI110/0.8/3.0[2]	2.0	16.0
Air induction – small droplet	100	AI110/0.8/3.0[2]	2.0	8.0
Air induction - medium droplet	50	AI110/0.8/3.0[1]	3.5	16.0
Flat fan	25	TP110/0.2/3.0[4]	2.0	8.0
CDA	25	Spinning disc[3]	1.3	8.0

[1]Hypro EU Ltd; [2] Billericay Farm Services Ltd; [3] Micron Sprayers Ltd, [4] Spraying Systems industrial nozzle.

As in previous trials (Butler Ellis *et al*., 2004), application volumes were varied by using a combination of nozzle size and forward speed. The speed range of 8.0 to 16.0 km/h was selected as being representative of practical sprayer operation. The emphasis on the small droplet air included nozzle was because results from earlier work had suggested that such nozzles could achieve levels of performance that were comparable with that from conventional flat fan nozzles but with the ability to give an improved level of drift control. An additional treatment with a medium droplet AI nozzle was included in order to begin to probe at what droplet size performance becomes noticeably poorer. The droplet sizes of the air induction nozzles were known from previous droplet size measurement (Butler Ellis *et al.*, 2001).

The CDA spinning disc system was operated with a disc speed of 5000 rev/min with the disc fed via a 37 restrictor. Plots were laid out in a fully randomised trial design. However, it was recognised that the CDA spinning disc and the very fine flat fan nozzle treatments posed a significant drift risk that could lead to the contamination of neighbouring plots. These treatments were therefore not included in the randomised layout design but plots were laid out at the edge of the main trial area. It was also recognised that the use of the very small flat fan nozzle (TP110/0.2/3.0) was much too small for practical on-farm use but was included in the trial for comparison purposes. Such a nozzle size is not supplied as part of any agricultural nozzle range and was sourced for this work from an industrial nozzle catalogue.

4.1.2 Results

4.1.2.1 Disease control

The levels of disease control achieved are summarised in Table 11. Because of the layout of the trial, the results for the CDA and very fine nozzle applications have not been included in the main analysis although the results for these treatments are consistent with data from the fully randomised treatments.

Table 11. Disease results assessed 4 weeks after application.

Nozzle type	Speed, km/h	Volume, L/ha	% Septoria on flag leaf	% Septoria on leaf 2
Untreated	-	-	43.8	92.5
Flat fan	16.0	25	22.5	71.3
Flat fan	16.0	50	11.5	58.8
Flat fan	8.0	100	13.8	62.5
Flat fan	16.0	100	12.5	57.5
Flat fan	8.0	200	18.3	76.3
Small droplet AI	16.0	25	19.3	72.0
Small droplet AI	16.0	50	14.0	55.0
Small droplet AI	8.0	100	18.3	67.5
Medium droplet AI	16.0	50	13.3	59.6
		LSD	8.3	14.3
		P	0.0001	0.0004
Flat fan	8.0	25	13.3	67.5
CDA Spinning disc	8.0	25	18.8	76.3

The results show that the experiment was conducted with a high level of disease pressure (*Septoria tritici*) and that moderate control was achieved. For the flat fan treatments, control was good for application volumes between 50 and 100 L/ha but less good at both 25 and 200 L/ha. Comparing the 100 L/ha treatments at 8.0 and 16.0 km/h would suggest that forward speed was not a factor influencing performance. However, where performance had deteriorated at 25 L/ha there is some indication that forward speed as well as the reduced volume could account for the reduction in control. The performance of the small droplet air induction nozzles generally matched that of the conventional flat fan nozzles although there was some evidence of reduced performance at the 100 L/ha volume. The medium droplet size air induction nozzle gave levels of control at 50 L/ha that were comparable with the small droplet size nozzles but the yield was not as high as for small droplet size air induction nozzle applying the same volume. The spinning disc system at 25 L/ha also gave levels of control that were of the same order as for the conventional nozzles applying the same volume.

4.1.2.2 Grain yield measurements

Mean grain yield measurements from the plots (Table 12) show values that reflect the results from the disease assessments.

Table 12. Measured grain yield in the plot trial.

Nozzle type	Speed, km/h	Volume, L/ha	Yield, t/ha	Yield as % of control plot
Untreated	-	-	6.83	100
Flat fan	16.0	25	7.71	113
Flat fan	16.0	50	7.97	117
Flat fan	8.0	100	8.19	120
Flat fan	16.0	100	8.21	120
Flat fan	8.0	200	7.95	116
Small droplet AI	16.0	25	7.70	113
Small droplet AI	16.0	50	8.11	119
Small droplet AI	8.0	100	7.84	115
Medium droplet AI	16.0	50	7.94	116
		LSD	0.43	
		P	0.0001	
Flat fan	8.0	25	7.75	113
CDA Spinning disc	8.0	25	7.69	113

There was a good relationship between disease control and yield for both the mean disease assessments on leaves 1 and 2 (Figure 21) and for the assessment of disease levels on leaf 2 alone (Figure 22).

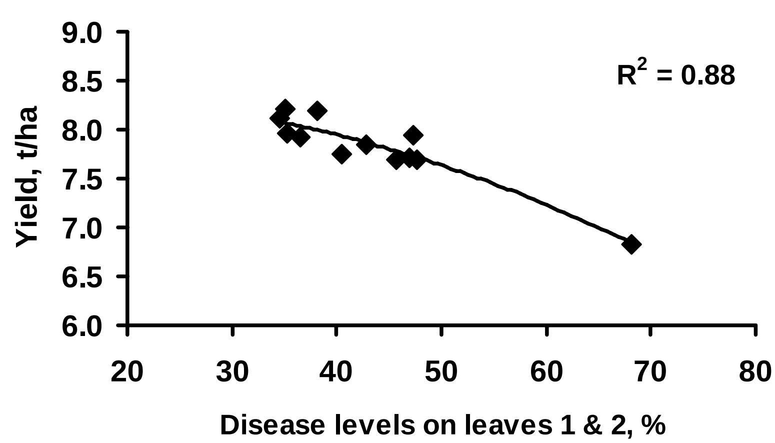


Figure 21. The relationship between yield and disease levels (% Septoria) as assessed on leaves 1 & 2

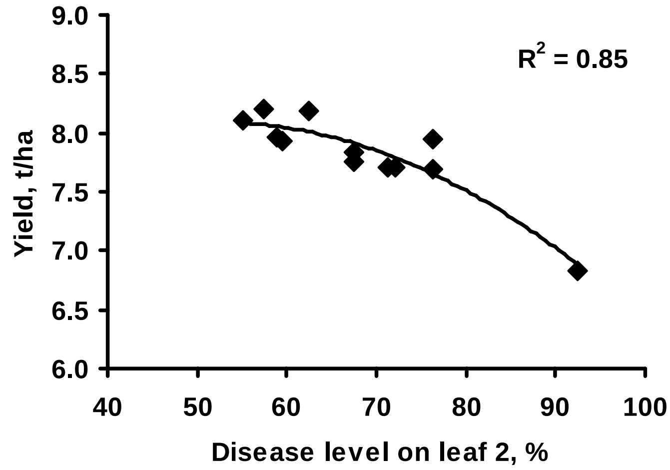


Figure 22. The relationship between yield and disease levels (% Septoria) as assessed on leaf 2 only.

The previous trials had also shown no statistically significant differences between application equipment or nozzle, although the CDA treatment had resulted in low yields despite good disease control. The lack of disease may have influenced the lack of a volume effect, however. The 2004/5 trial has shown that under higher disease pressure, the 100 L/ha treatments with flat fan nozzles gave significantly higher yields than at 25 L/ha and higher (but not statistically significantly so) than at 200 L/ha. There was no effect of forward speed with a flat fan nozzle (Figure 23), and although there is a suggestion that a faster forward speed might improve the performance of the small droplet AI nozzle (apparent in both disease control and yield), this was not significant.

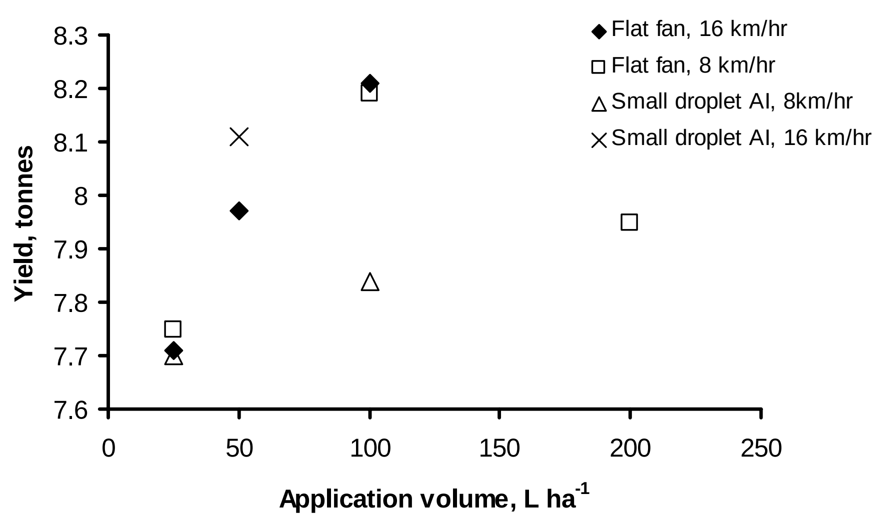


Figure 23. The effect of application volume, forward speed and nozzle type on yield

The poorer yield performance with a CDA system in the previous trial (Butler Ellis *et al.*, 2004) was not repeated in the recent trial, suggesting that CDA could be a satisfactory method of achieving low volumes, although more data is needed.

4.2 Autumn herbicide application – Grasp on ryegrass

4.2.1 Materials and methods

Italian ryegrass was undersown on 7/10/04 at 6 kg/ha in a crop of winter wheat, at a site in Dorset as in the previous two seasons. The ryegrass had a plant density of 160 plants/m^2. Because of adverse weather conditions, the herbicide was not applied until the following year, 10/3/05 when the ryegrass growth stage was 1-2 tillers. The ten herbicide treatments are shown in Table 13. Two different doses of tralkoxydim were used in order to ensure that levels of control were both low enough to identify any differences between treatments but at the same time provide information relevant to practical use. A single dose of the adjuvant “Output” of 0.36 L/ha was used for all treatments. The herbicide was applied with a Hardi Master MB800. Since backward angling had shown no effect in previous trials, all treatments in this trial used nozzles spraying vertically downwards.

Control was assessed in the same way as previous trials, 2 months after application.

Table 13. Treatments for the 2004/5 season herbicide field trial.

Dose (Grasp), L/ha	Application volume, L/ha	Speed, km/h	Nozzle type/ size	Pressure, bar
0.7	147	8.0	FF/110/1.2/3.0 (03)	2.0
0.7	73	8.0	FF/110/0.6/3.0 (015)	2.0
0.7	73	8.0	Air induction, Drift Beta (015)	2.0
0.7	37	16.0	FF/110/0.6/3.0 (015)	2.0
0.7	37	16.0	Air induction, Drift Beta (015)	2.0
0.35	147	8.0	FF/110/1.2/3.0 (03)	2.0
0.35	73	8.0	FF/110/0.6/3.0 (015)	2.0
0.35	73	8.0	Air induction, Drift Beta (015)	2.0
0.35	37	16.0	FF/110/0.6/3.0(015)	2.0
0.35	37	16.0	Air induction, Drift Beta (015)	2.0

4.2.2 Results and discussion

Control of ryegrass is shown in Table 14. Although there are some statistically significant differences, and an apparent trend of reduced performance with reducing volume, the results are not consistent with those from 2002/2003 and 2003/2004 (Figure 24). The results of this trial were complicated by a delayed treatment resulting in a larger weed size at the time of treatment. Although a moderate level of control was achieved, there was no consistent dose response that would have been expected. For the flat fan treatments in particular, levels of control achieved by the 0.35 L/ha dose were comparable with those at 0.7 L/ha. Plots were marked out in the autumn and detailed ryegrass population counts made in marked quadrats at that time. However, treatments were not applied until March because of weather conditions and it is possible that there was some further emergence of ryegrass between the counts being made and the treatments applied. This is considered unlikely but cannot be ruled out. There were also some inconsistencies in the assessments at one and two months after treatment. There was an increase in the level of control for some treatments, possibly due to a slow kill, whereas with others there was a reduction in control that could have been due to recovery of the weeds post treatment. It was not possible to determine if such effects were directly related to the applied treatments.

Table 14. Control of ryegrass 1 and 2 months after application.

				1 month after application		2 months after application	
Dose (Grasp), L/ha	Application volume, L/ha	Speed, km/h	Nozzle type/ size	Plants/m^2	% Control	Plants/m^2	% Control
0.7	147	8.0	FF/110/1.2/3.0 (03)	79	46	43	73
0.7	73	8.0	FF/110/0.6/3.0 (015)	85	44	107	39
0.7	73	8.0	Air induction Drift Beta (015)	103	43	76	56
0.7	37	16.0	FF/110/0.6/3.0 (015)	84	31	97	25
0.7	37	16.0	Air induction Drift Beta (015)	85	37	80	47
0.35	147	8.0	FF/110/1.2/3.0 (03)	95	42	109	37
0.35	73	8.0	FF/110/0.6/3.0 (015)	85	43	110	33
0.35	73	8.0	Air induction Drift Beta (015)	112	32	117	31
0.35	37	16.0	FF/110/0.6/3.0 (015)	92	37	104	35
0.35	37	16.0	Air induction Drift Beta (015)	99	35	128	24
LSD				No significant differences		47	23

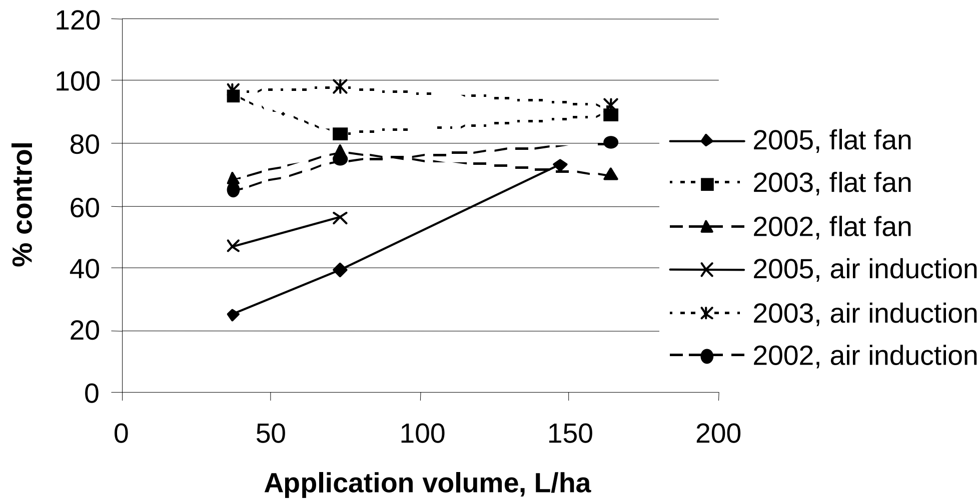


Figure 24. The effect of volume on control of ryegrass over three seasons with flat fan and air induction nozzles.

Because of the uncertainties associated with this trial and because the results did not then fit with the trends observed in the previous two seasons, it was decided that the trial had to be repeated in the 2005/06 season at the end of the project.

4.3 Repeat autumn herbicide trial 2005/06

4.3.1 Materials and methods

The trial was conducted to the same protocol and methods as used in the 2004/05 season described in 4.2.1 above. The ryegrass was established with a population of100 plants/m^2. The treatments defined in Table 13 were applied on 13/12/2005 when the weeds were at growth stage 12.

4.3.2 Results

The results for the repeated trial are summarised in Table 15.

Table 15. Control of ryegrass 2 months after application.

Dose (Grasp), L/ha	Application volume, L/ha	Speed, km/h	Nozzle type/ size	% Control (13/02/06)	Heads/m^2 (09/06/06)
0.7	147	8.0	FF/110/1.2/3.0 (03)	86	1.5
0.7	73	8.0	FF/110/0.6/3.0 (015)	83	1.6
0.7	73	8.0	Air induction Drift Beta (015)	84	3.5
0.7	37	16.0	FF/110/0.6/3.0 (015)	85	5.0
0.7	37	16.0	Air induction Drift Beta (015)	86	6.0
0.35	147	8.0	FF/110/1.2/3.0 (03)	92	6.5
0.35	73	8.0	FF/110/0.6/3.0 (015)	88	7.0
0.35	73	8.0	Air induction Drift Beta (015)	80	12.0
0.35	37	16.0	FF/110/0.6/3.0 (015)	88	19.0
0.35	37	16.0	Air induction Drift Beta (015)	77	20.0
	LSD	12	10.4		
	Prob.	NS	0.0058		

While the results show that there were no significant effects of application volume on the control of ryegrass the largest numbers of heads were counted in the lowest volume plots particularly when the lower dose of herbicide was used.

4.4 Conclusions from field trials – Part 2

The best fungicide performance occurred with application volumes within the range 50 to 100 L ha^{-1}. Small droplet air induction nozzles were similar in performance to conventional flat fan nozzles, but would give significantly better drift control, particularly at the lower volumes. There was no difference in performance between the ‘small’ and ‘medium’ droplet AI nozzles, which suggests that only at the largest droplet sizes do air induction nozzles give a significant reduction in fungicide performance.

200 L ha^{-1} gave significantly worse disease control than 100 L ha^{-1} with a flat fan nozzle. 25 L ha^{-1} gave significantly lower yields than 100 L ha^{-1} with a flat fan nozzle. There was no effect of forward speed in the range 8 – 16 km h^{-1} and no effect of nozzle type.

The results from the two herbicide trials suggest that performance is influenced by application particularly when operating at the lowest volume of 37 L/ha. Results from the trial conducted in 2004/05 gave poor levels of control overall and a comparison of results at 73 and 37 L/ha indicated a reduced level of control at the lower volume. This was also seen in the repeated trial. Here effects due to application volume were not statistically significant but the number of heads were the highest at the lowest volumes and lowest doses. There was no detectable effects due to nozzle type.

5. Conclusions

Investigations of the characteristics of sprays and deposits, both in the laboratory and in the field showed:

- More variability in the deposits with medium and large droplet air induction nozzles;
- Only a small increase in deposit with reducing volume for conventional flat fan nozzles that was not significant in the field;
- A large reduction in coverage as volumes reduce;
- Highest coverage with conventional flat fan nozzles and other equipment giving lower levels;
- Lower deposits in the field with an air induction nozzle that were not observed in laboratory results;
- Air flows in the environment can make a significant difference to deposits in the field – this may account for different results seen in the field and in the laboratory. The use of a wind tunnel for laboratory measurements of deposit, where a consistent low level of air flow can be achieved, may be appropriate in the future;
- Forward speed had an effect on deposit only on winter wheat and only in field experiments. The interactions between forward speed, environmental air flow and the structure of the crop may be important in determining deposits.

Investigations of the effect of low volumes on the performance of a T2 fungicide application showed that:

- Large droplet air induction nozzles performed poorly at all volumes;
- Small droplet air induction nozzles had equivalent performance to flat fan nozzles;
- There was no measurable effect of volume.

Investigations of the effect of low volumes on the performance of an autumn herbicide applied to Italian ryegrass showed that:

- There was no application volume or application technique effect in the trials conducted although the fact that high head counts were seen in the repeat trial with the lowest doses and lowest doses suggests that an application volume of 37 L/ha may be too low to be robust.

While there are some fundamental reasons why low volumes may result in poorer pesticide performance, none of these influenced the efficacy of the pesticides investigated in this work. The most important factor that was shown to be influenced by application volume was coverage. Large droplet air induction nozzles, used to control drift did not perform well with the T2 fungicide application, but this appeared to be true at all volumes. Therefore it seems likely that volumes can be successfully reduced alongside modest drift control in a number of scenarios. It is important to find out how far these results can be extrapolated to other scenarios.

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Appendix I

Spray distribution results

Appendix II

Results obtained by Syngenta Crop Protection (UK) Ltd in trials with autumn herbicide application.measured by Syngenta Crop Protection (UK) Ltd in Year 1 at Site 1.