HGCA

PROJECT REPORT 317

DEFINING THE SIZE OF TARGET FOR
AIR INDUCTION NOZZLES

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DEFINING THE SIZE OF TARGET FOR AIR INDUCTION NOZZLES

by

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1   Abstract

The use of air induction nozzles on boom sprayers applying sprays to arable crops has become an established way of achieving high levels of drift control. Such nozzles create a spray with relatively large sized droplets that have air inclusions within the droplets such that they behave differently from droplets created with conventional nozzles. Because the droplets are large there are fewer of them and there is then the potential for small targets such as weeds at early stages of growth to receive an inadequate dose or coverage to give good control. This study measured the droplet size distributions produced by a range of air induction nozzles operating with tank mixes typical of those used to treat both grass and broad-leaved weeds. Nozzles were then selected for use in pot and field trials that gave sprays with large, medium and small relative droplet size distributions for this type of nozzle.

Field trials were conducted over two seasons in which the level of control of both a grass (black-grass) and a broad-leaved weed species (common field-speedwell - second year only) were assessed when sprayed with the different air induction nozzles at a range of doses and timing of applications. The field studies were supported by experiments in which comparable treatments of foliar-acting herbicides were applied to outdoor grown pot plants of a range of target weed species at different stages of growth using the same air induction nozzles. Results from the pot studies were analysed in terms of ED_{90} doses for each weed/nozzle/growth stage combination and were used to support the interpretation of the field trial data.

Results of the work showed:
- air induction nozzles with the same specification but from different manufacturers/suppliers gave different droplet size distributions particularly when spraying water or water plus a surfactant;
- operation with typical tank mixes reduced the differences between droplet size distributions from different commercial versions of the same air induction nozzle specifications although there were still significant differences between different versions;
- air induction nozzles gave lower levels of efficacy when compared with applications from conventional nozzle designs with the greatest reductions in efficacy coming from applications with air induction nozzles producing the largest droplet size distributions: greater reductions in efficacy were generally observed in the pot experiments than in the field trials;
- for the grass weed target, the highest levels of efficacy were observed at the 2-3 leaf stage rather than at the one leaf stage;

It was concluded that air induction nozzles provide a good method of achieving drift control but with some risk to efficacy on small targets with foliar-acting herbicides. This risk can be reduced by using air induction nozzles that create a relatively small mean droplet size and by treating grass weed targets at the 2-3 leaf stage.

2   Summary

1.   Measurements of the droplet size distributions from six commercial designs of air indication nozzle spraying water and water plus a surfactant were made using three different measurement techniques. The results showed:

- good agreement between the measurement methods used;
- that, when cross-referenced with data from elsewhere, the following nozzles could be selected as being representative of different size distributions at the "02" nozzle size:
  - Billericay "BubbleJet" – representative of a relatively small droplet size distribution.
  - Hardi/Lechler "InJet" – representative of a medium droplet size distribution.
  - Sprays International "PneuJet" – representative of a large droplet size distribution.

2.   Measurements of the droplet size distribution from the three representative nozzles spraying a total of sixteen tank mix liquids typical of those used to treat both grass and broad-leaved weeds showed only small differences due to the constituents of the tank mix: the effects on droplet size distribution due to tank mix components were therefore much smaller than those due to nozzle design.

3.   Visualisations of the deposits from the three representative air induction nozzles showed that in practical conditions a very high percentage of weeds (effectively all) would intercept some spray when treated at 100 l/ha although the coverage and distribution on the target surface would be very different when using air induction nozzles.

4.   Pot experiments were conducted over two seasons in which both grass and broad-leaved weed species were sprayed with different foliar-acting formulations using the selected air induction nozzles and a conventional flat fan nozzle design: plants were raised sequentially such that at the time of treatment the only variable was the stage of growth: results were analysed to calculate an ED_{90} value for each application situation.

5   Results from the pot experiments over the two seasons in which rye-grass was treated with clodinafop-propargyl showed that the highest efficacy was obtained with the conventional flat fan nozzle: although differences between the results with the different air induction nozzles were not significant, there was a consistent trend for lower levels of efficacy when treatments were applied with nozzles giving a larger droplet size: directly comparable results were obtained when black-grass plants were treated with the same formulation in the second year of the project work.

6.   With grass weeds in the pot experiments, lower ED_{90} values (i.e. higher levels of efficacy) were found at growth stages between two and four leaf stages rather than at the one leaf stage for all the nozzles
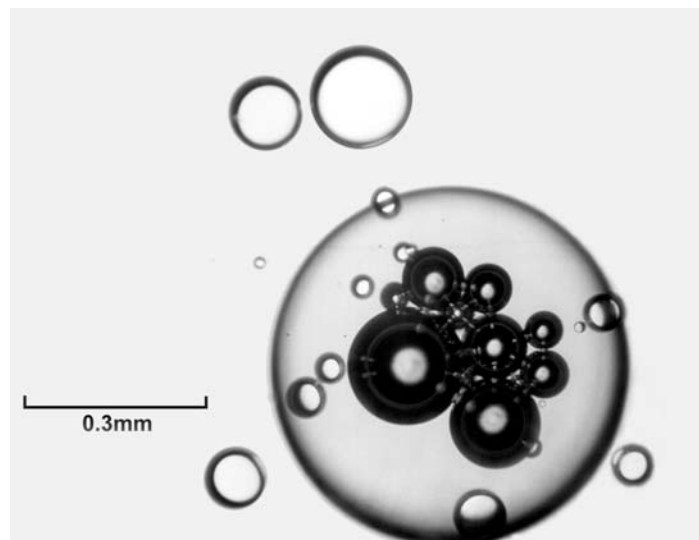
used: this was considered to relate to the small leaf area not being able to capture an adequate dose to give high levels of efficacy.

7. Pot experiments with broad-leaved weeds also gave the highest levels of efficacy with conventional flat fan nozzles and the same trends of reducing efficacy with applications from air induction nozzles with an increasing droplet size distribution: however, in the case of broad-leaved weeds, the highest levels of efficacy with all nozzle types was observed with treatments applied at the earliest stage of growth.

8. Field trials were also conducted over the two seasons treating both grass and broad-leaved weed species with foliar-acting formulations applied with the selected nozzles and a reference conventional flat fan nozzle treatment.

9. Results from the field trials with grass weeds gave results that were equivalent to those from the pot study although the reduction in efficacy with the air induction nozzles was less pronounced: efficacy generally declined with increasing droplet size for the air induction nozzles and the highest levels of efficacy for all nozzles was at the two to three leaf stage.

10. Using rape as the simulated broad-leaved weed in the first years field trial resulted in very high levels of control such that no treatment differences could be observed: in the second year with common field-speedwell as the target weed, there was again a trend towards higher levels of control with the conventional nozzle and evidence of declining efficacy with increasing droplet size with air induction nozzles: the highest levels of control for all nozzle types were observed with treatments applied at the earliest growth stage.

11. Results form this study indicate a need to provide the user with more information relating to air induction nozzle performance such that the correct balance between drift control and maintenance of efficacy can be determined: existing nozzle/spray classification systems and available user guides do not distinguish between the performance of different designs of air induction nozzle while results from this project work indicate that this would be useful: presentation of any such information must balance the increasing complexity in nozzle selection with systems that are easy to use.

12. For situations where grass weeds need to be treated with systems giving a high level of drift control, the use of an air induction nozzle generating a relatively small droplet size has been shown to give a reasonable compromise between high levels of efficacy and drift control.

3. Introduction

High levels of spray drift control when using boom sprayers can be achieved by fitting air induction nozzles. Studies have shown that such nozzles are capable of achieving drift reductions of more than 75% when compared with a reference F110/1.2/3.0 nozzle operating at a pressure of 3.0 bar (Butler Ellis *et al.*, 2001; Butler Ellis *et al.*, 2002, Miller and Lane, 1999). Drift reductions with these nozzles are achieved by creating a spray with a relatively large droplet size distribution but with the large droplets having air inclusions (Figure 3.1) within them that are likely to modify target retention and coverage characteristics of the spray. Measurements of the droplet size distribution from different commercial versions of these nozzles have shown a wide variation in mean size for the same nozzle specification (e.g. Piggott and Matthews, 1999). Research has also shown that for all nozzle types, performance is influenced by formulation (Miller and Butler Ellis, 2000) with the effects with air induction nozzles being different to those with conventional pressure nozzles (Butler Ellis and Tuck, 2000). Previous studies used sprays generated from liquids with a single adjuvant or formulation type while the work in this project has examined air induction nozzle performance when spraying tank mixes typical of many practical application conditions.

Figure 3.1. Air included droplets captured on an oil surface. HGCA-funded research has shown that this type of droplet structure is produced by twin-fluid and air induction nozzles

The presence in a spray of large droplets having air inclusions within them is likely to have implications for target coverage at the droplet scale that are difficult to quantify on real plant targets. There will be a reduced number of droplets such that, particularly at low volume application rates, there is the potential for small targets such as grass weeds at an early stage of growth to be missed and receive no chemical dose or inadequate coverage. When sprays do impact on a leaf surface, it is likely that the form of deposit with air

included droplets will be different from that of conventional droplets and this may also have implications for chemical uptake and efficacy.

The use of air induction nozzles in the UK has increased considerably since 1999 owing to the introduction of the LERAP (Local Environmental Risk Assessments for Pesticides) scheme. By minimising drift with the use of certain air induction nozzles classified within the LERAP scheme, farmers are able to reduce the width of buffer zones next to watercourses. However, little research has been carried out to evaluate the biological performance of air induction nozzles in the field. Cawood *et al*., (1995) demonstrated that higher deposition or spray retention on black-grass occurred when finer quality sprays were used i.e. when droplets were small. Research by Jensen, (1999) showed that herbicide efficacy could be reduced with low volume air induction nozzles, spraying larger droplets, when treating small targets. Robinson *et. al.* (2001) conducted field trials with air induction nozzles and found them to perform in ways comparable with medium quality sprays applied with conventional nozzles.

The research in this project set out to test the hypothesis:

> *There is a minimum size of target (such as a weed) below which the use of induction nozzles*
> *may provide inadequate biological control.*

The work also aimed at assessing:-

- the effect of realistic tank mixes typical of many application situations on the performance of air induction nozzles;
- whether differences between different commercial designs of air induction nozzle as determined by measurements of the droplet size distribution would have implications for product efficacy;
- the implications for farmers of using air induction nozzles for spray drift control when applying foliar-acting herbicides to control both broad-leaved and grass weeds – this to be based on results from a combination of field and outdoor pot experiments using nozzles and formulations selected after a review of the available literature and preliminary laboratory measurements.

The study was conducted over two cropping sessions with interim results from the first year of the work being reported by Powell *et. al*., (2002).

4 Materials and Methods

4.1 Measurement of droplet size distributions

Measurements of the droplet size distributions from a total of six commercial designs of air induction nozzle were made in the spray chamber at Silsoe Research Institute using the Oxford Lasers "Visi-sizer" instrument configured to measure droplets in the size range 50-2000 μm in diameter.

This instrument was chosen for the main part of the work because size measurements are made using images of individual droplets collected as "shadows" by a video camera that views an area within the spray that is illuminated by a pulsed laser. The image-based measurements would therefore be representative of the outer surfaces of air included droplets with a minimum risk of interference due to the internal structure of the droplets. There have been concerns that light scattering instruments for measuring droplet size distributions in sprays with air inclusions may give values that are influenced by this internal structure. However, recent experimental results suggest that this is likely to be an important feature only when formulations with very high levels of surfactant are to be sprayed (Combellack and Miller, 2001; Combellack *et al*., 2002).

To provide additional confidence that the measured relative droplet size distributions were consistent with data published elsewhere (e.g. Piggott and Matthews, 1999), measurements were also made with a Malvern Analyser and Particle Measuring Systems (PMS) instrument. The PMS instrument operates using the same image analysis principles as the Oxford Laser System but is an older unit. The nozzle sampling arrangements for the PMS were therefore directly comparable with those used for the Oxford Lasers System (see below). The Malvern Analyser is a light scattering instrument (Parkin, 1993) and in this case the nozzle was moved through the sampling laser with the spray fan at right angles to the laser. Such comparative measurements were made when spraying water and water and a surfactant only.

Nozzles were selected for the field and pot trials work on the basis of the results obtained and previous measurements (Butler Ellis *et al.*, 2002) with the aim of using nozzles that were representative of the full range of mean droplet sizes. All measurements were made with a nozzle size giving a nominal flow rate of 0.8 litres/min at a pressure of 3.0 bar. The nozzles, all F110/0.8/3.0, selected were:-

Nozzle A - Billericay "BubbleJet" – giving a relatively small droplet size
Nozzle B - Hardi "InJet" – giving a medium droplet size
Nozzle C - Sprays International "PneuJet" – giving a relatively large droplet size

Measurements of the droplet size distributions with all of the instrument systems were made with a single nozzle mounted on a computer-controlled transporter programmed to move the nozzle at 40 mm/s across a sampling grid 1.1 m square and 50 cm above the measurement laser such that the whole of the spray from the nozzle was sampled. Tank mixes were prepared from commercially available formulations mixed in stainless steel pressurised containers with the supply to the nozzle regulated by the control of air pressure.

Each supply tank was mounted on a platform scale system such that flow rate to the nozzle could be monitored by change in weight. The formulations used for this work were typical of those that might relate to the application of foliar-acting herbicides to control grass and broad-leaved weeds and are detailed in Tables 4.1 and 4.2 respectively. In addition to measurements with the defined tank mixes, data was also collected when spraying water only and 0.1% of a non-ionic surfactant (Agral-Zeneca Agrochemicals - now Syngenta Crop Protection Ltd).

4.2   Visual assessments of target coverage

To gain an appreciation of the difference in coverage that might be achieved by the use of air induction compared with conventional flat fan nozzles, a glossy white horizontal plastic surface was sprayed from a three nozzle boom mounted on a transporter in the laboratory at Silsoe Research Institute. To avoid saturation of the difficult to wet surface, F110/0.8/3.0 nozzles were used at a forward speed of 8.0 km/h to treat surfaces positioned 50 cm below the boom. A coloured tracer dye and a non-ionic surfactant were included in the spray liquid and the deposit distribution on the plastic surface was recorded photographically while the deposits were still wet.

Some visualisation of deposit distribution was also made by spraying into a tray grown cereal canopy at an early stage of growth (just before growth stage 30). For these visualisation experiments, a fluorescent tracer dye was used and deposits were viewed by illuminating the treated plant trays with an ultra-violet light source.

4.3   Controlled applications to outdoor grown pot plants

Plants of perennial rye-grass (*Lolium perenne* L.), black-grass (*Alopecurus myosuroides*), oilseed rape (*Brassica napus*), scentless mayweed (*Tripleurospermum inodorum*), and common poppy (*Papaver rhoeas*) were grown outdoors in 2 litre pots in a potting mixture (soil + sand + peat, 2:1:1 w/w) containing all necessary macro- and micro-nutrients at the Danish Institute of Agricultural Sciences in each of the two years over which the experiments ran. Pots were sown on three (2000) or four (2001) occasions and consequently plants at three or four different growth stages could be sprayed simultaneously.

Table 4.1 **Tank mixes and formulations representative of the application of foliar and soil-acting herbicides for grass weed control that were used for the measurements of droplet size distributions**

Tank mix number	Active ingredient (formulation)	Dose (incorporation rate into spray liquid)	Dose (effective application rate)
1	water only		
2	non-ionic surfactant	0.1%	100 ml/ha
3	clodinafop-propargyl (e.c.)	0.125%	125 ml/ha
	emulsifiable vegetable oil	2.5%	2.5 l/ha
4	clodinafop-propargyl (e.c.)	0.125%	125 ml/ha
	methylated vegetable oil	1.0%	1.0 l/ha
5	clodinafop-propargyl + trifluralin (e.c.)	2.5%	2.5 l/ha
	emulsifiable vegetable oil	2.5%	2.5 l/ha
6	clodinafop-propargyl + trifluralin (e.c.)	2.5%	2.5 l/ha
	cypermethrin (e.c.)	0.25%	250 ml/ha
	methylated vegetable oil	2.75%	2.75 l/ha
7	clodinafop-propargyl + trifluralin (e.c.)	2.5%	2.5 l/ha
	isoproturon (s.c.)	2.0%	2.0 l/ha
	methylated vegetable oil	4.5%	4.5 l/ha
8	clodinafop-propargyl + trifluralin (e.c.)	2.5%	2.5 l/ha
	isoproturon (s.c.)	2.0%	2.0 l/ha
	cypermethrin (e.c.)	0.25%	250 ml/ha
	methylated vegetable oil	4.75%	4.75 l/ha

Table 4.2 Tank mixes and formulations representative of the application of foliar-acting herbicides for broad-leaved weed control that were used for the measurement of droplet size distributions.

Tank mix number	Active ingredient (formulation)	Dose (incorporation rate into spray liquid)	Dose (effective application rate)
1	water only		
2	non-ionic surfactant	0.1%	100 ml/ha
3	bromoxynil + ioxynil (e.c.)	1.5%	1.5 l/ha
	cypermethrin (e.c.)	0.25%	250 ml/ha
4	bromoxynil + ioxynil (e.c.)	1.5%	1.5 l/ha
	mecoprop-P (soln.)	2.0%	2.0 l/ha
5	bromoxynil + ioxynil (e.c.)	1.5%	1.5 l/ha
	lambda-cyhalothrin (e.c.)	1.0%	1.0 l/ha
6	bromoxynil + ioxynil (e.c.)	1.5%	1.5 l/ha
	epoxiconazole (s.c.)	1.0%	1.0 l/ha
	chlorothalonil (s.c.)	1.0%	1.0 l/ha
7	bromoxynil + ioxynil (e.c.)*	1.5%	1.5 l/ha
	chlormequat (soln.)	2.5%	2.5 l/ha
	mecoprop-P (soln.)	2.0%	2.0 l/ha
8.	bromoxynil + ioxynil (e.c.)	1.5%	1.5 l/ha
	chlormequat (soln.)	2.5%	2.5 l/ha
	lambda-cyhalothrin (e.c.)	1.0%	1.0 l/ha

*- alternative commercial formulation used.

The pots were sub-irrigated automatically up to five times daily with deionised water. For the experiment with Hawk (clodinafop-propargyl + trifluralin), black-grass plants were grown in a glasshouse in 1 litre pots containing a sandy loam soil to ensure maximum residual activity of trifluralin. The pots were placed on an automatic gravimetrical watering table and sub-irrigated up to 3 times daily with a nutrient solution, however one and two days after application pots were watered on the top to maximise soil activity of trifluralin. The experimental design was a randomised block design with growth stages as blocks. The same three air induction nozzles as in Section 4.1 above (A-C) were examined together with a conventional flat fan nozzle (D). The nozzles were used at a pressure of 3.0 bar and a speed of 7.8 km h^{-1} resulting in the following volume rates (variation between experiments): 89.8-95.4, 105.5-113.4, 95.3-101.0 and 91.7-101.0 litres/ha respectively.

The plants were sprayed with six doses of clodinafop-propargyl in admixture with 2.5% Toil (a methylated vegetable oil adjuvant) (rye-grass and black-grass), clodinafop-propargyl + trifluralin in admixtures with 2.5% Toil (black-grass) or a bromoxynil + ioxynil and mecoprop-P tank mix (oilseed rape, scentless mayweed and common poppy). At the time of application, three pots of each growth stage were harvested and dry weights were recorded. Plants were harvested 37 days after treatment and dry weights were recorded. Relative dry weights were calculated as the increase in dry weight from spraying to harvest divided by the corresponding dry weight increase of the control plants and multiplied by 100. Using the dry weight increase as the response variable rather than dry weight makes it possible to compare the three growth stages.

The response of relative dry weight increase (control=100) (U) on dose (z) was assumed to be well described by the logistic model:

$$U_{ij} = \frac{X - Y}{1 + \exp[2b_i(\log(ED_{50(i)}) - \log(z_{ij}))]} + Y$$

where U_{ij} denotes the relative dry weight increase at jth dose at growth stage i ; X and Y denote the upper and lower limit of dry weight increases at zero and at infinite doses and were assumed to be the same for all dose response curves within an experiment. $ED_{50(i)}$ denotes the dose required to reduce dry weight increase half way between the upper and lower limit, X and Y, and b_i is proportional to the slope around $ED_{50(i)}$. The $ED_{50(i)}$ can be replaced by any ED_n parameter, e.g. ED_{90}:

$$U_{ij} = \frac{X - Y}{1 + \exp[2b_i(\log(ED_{90(i)}) + 1.099/b_i - \log(z_{ij}))]} + Y$$

Results for the experiments were therefore calculated in terms of an ED_{90} dose value.

Table 4.3 provides an overview of the experiments on outdoor grown pot plants

Table 4.3 Weed species used in the outdoor grown pot experiments

Weed	Years	Treatment (maximum dose)
Rye-grass (*Lolium perenne*)	1 and 2	clodinafop-propargyl (1.6 l/ha)
Black-grass (*Alopecurus myosuroides*)	2 only	clodinafop-propargyl (0.8 l/ha)
Black-grass (*Alopecurus myosuroides*)	2 only	clodinafop-propargyl + trifluralin (2.5 l/ha)
Oilseed rape (*Brassica napus*)	1 and 2	bromoxynil + ioxynil (1.5 l/ha) mecoprop-P (2.0 l/ha)
Scentless mayweed (*Tripleurospermum inodorum*)	1 and 2	bromoxynil + ioxynil (1.5 l/ha) mecoprop-P (2.0 l/ha)
Common poppy (*Papaver rhoeas*)	1 only	bromoxynil + ioxynil (1.5 l/ha) mecoprop-P (2.0 l/ha)

4.4   Field trials

4.4.1 Grass weeds

Field trials in winter wheat were carried out at Morley Research Centre over two seasons to confirm the results from the laboratory and outdoor pot experiments and to determine the minimum size of black-grass (*Alopecurus myosuroides*) for use of air induction nozzles without a reduction in herbicide efficacy.

In Year 1 (2001 harvest season) black-grass seeds were sown at a seed rate of 400 seeds/m^2 immediately prior to drilling a crop of winter wheat (cv. Napier). The same air induction nozzles (A-C) were selected as for the droplet size distribution measurements and the outdoor pot experiments along with a conventional flat fan nozzle (D). A tank mix of Hawk (clodinafop-propargyl + trifluralin) + Toil (a methylated vegetable oil) was applied to illustrate a 'worst case scenario' in terms of effects on droplet size and spray characteristics, as illustrated by results from Silsoe Research Institute, while also applying a treatment used commercially by farmers in the UK to control black-grass. This was applied at full and half label recommended dose, at two timings - 1 leaf and 2-3 leaf stages of the black-grass. The trial comprised a factorial design and treatments were applied using the nozzles at the same settings (pressure and forward speed) as used in the outdoor pot experiments and with nozzles at 50 cm spacing. Control of black-grass was measured by counting the number of black-grass panicles in ten 30 cm x 30 cm quadrats per plot.

The experiment was repeated in the second year in a crop of winter wheat (cv. Napier) and with black-grass seed sown at a rate of 500 seeds/m^2 with the aim of achieving higher weed plant populations. Spray

applications were the same as in Year 1 in respect of timings, herbicides applied and doses and control was again assessed by counting the number of black-grass panicles in ten 30 cm x 30 cm quadrats per plot.

4.4.2 Broad-leaved weeds

Similar experiments to those outlined in Section 4.4.1 were conducted in parallel at Morley Research Centre using broad-leaved weed species. In Year 1 of the project, oilseed rape (*Brassica napus*) was sown at a seed rate of 400 seeds/m^2 immediately prior to drilling the winter wheat (cv. Napier). A tank mix of Oxytril (bromoxynil + ioxynil) + Duplosan (mecoprop-P) was applied at the cotyledon and two true leaf growth stages at full (1.5 l/ha Oxytril + 2.0 l/ha Duplosan) and half dose. Control was assessed by counting surviving plants in ten 30 cm x 30 cm quadrats per plot.

Because the level of control achieved using oilseed rape as a simulated broad-leaved weed (see Section 3.6.) was so high, common field-speedwell (*Veronica persica*) was used as the target weed for experiments in the second year of the project. Plots were established that enabled four doses; full and half dose in one design and a quarter and eighth dose in a second, of the bromoxynil + ioxynil and mecoprop-P tank mix as used in the first years' field trial and the outdoor pot experiments in Denmark. The common field-speedwell was sown at a seed rate of 1000 seeds/m^2, again immediately prior to drilling the wheat crop (cv. Napier). Treatments were applied at two timings, cotyledon and the two true leaf stage and levels of control assessed by counting the number of surviving plants in ten 30 cm x 30 cm quadrats per plot.
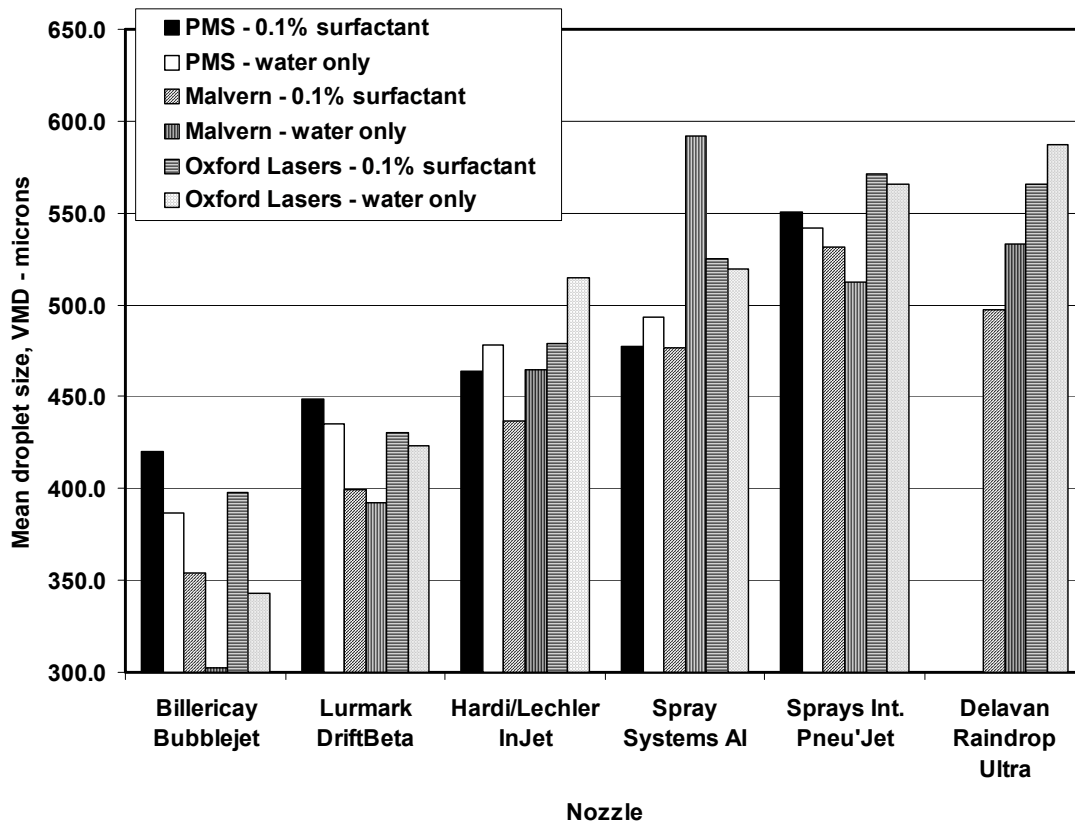
5   Results

5.1   Measured droplet size distributions

The measured droplet size distributions for the six commercial nozzle designs are summarised in Figure 5.1.1. The results show:
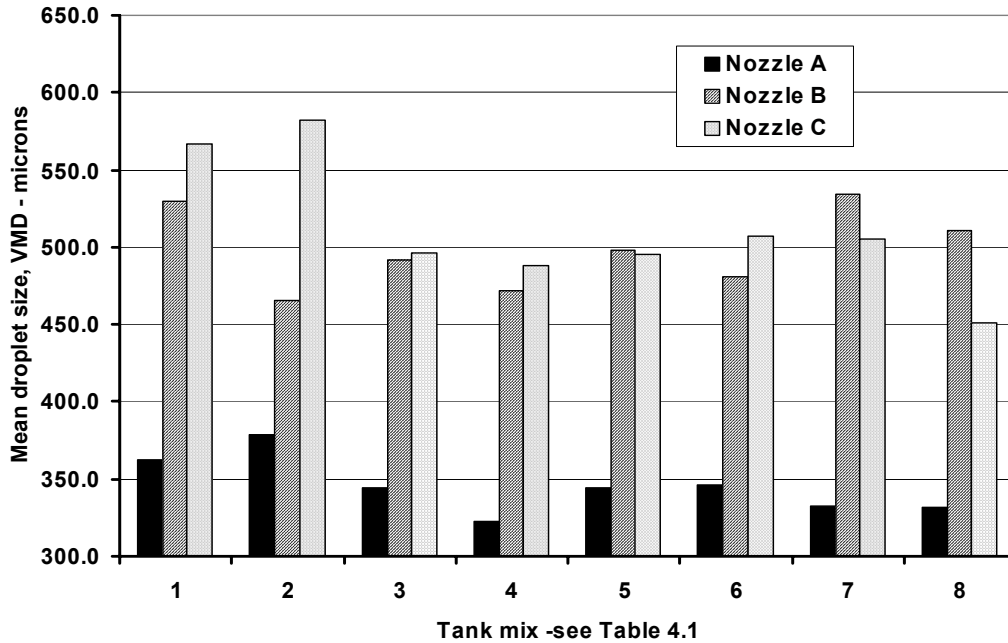
- a considerable variation in the mean droplet size from different commercial designs of the six nozzles and with a gradation that confirmed the selection of representative nozzles as follows:
  - Nozzle A - Billericay BubbleJet - representative of an air induction nozzle giving a relatively small droplet size distribution;
  - Nozzle B - Hardi/Lechler InJet - representative of a medium droplet size;
  - Nozzle C - Sprays International PneuJet - representative of a large droplet size.
- good agreement between the measurements made with the different systems with consistent mean size trends from each of the measuring systems;
- no consistent relationships between the measured size distributions when spraying water or water plus surfactant: for the Billericay BubbleJet the size was consistently larger when spraying surfactant as measured by all systems but this trend was not the same for all nozzle designs.

Figure 5.1.1. Mean measured droplet sizes (as Volume Median Diameter (VMD)) for six commercial designs of air induction nozzle ('02' size) spraying water and water plus a surfactant
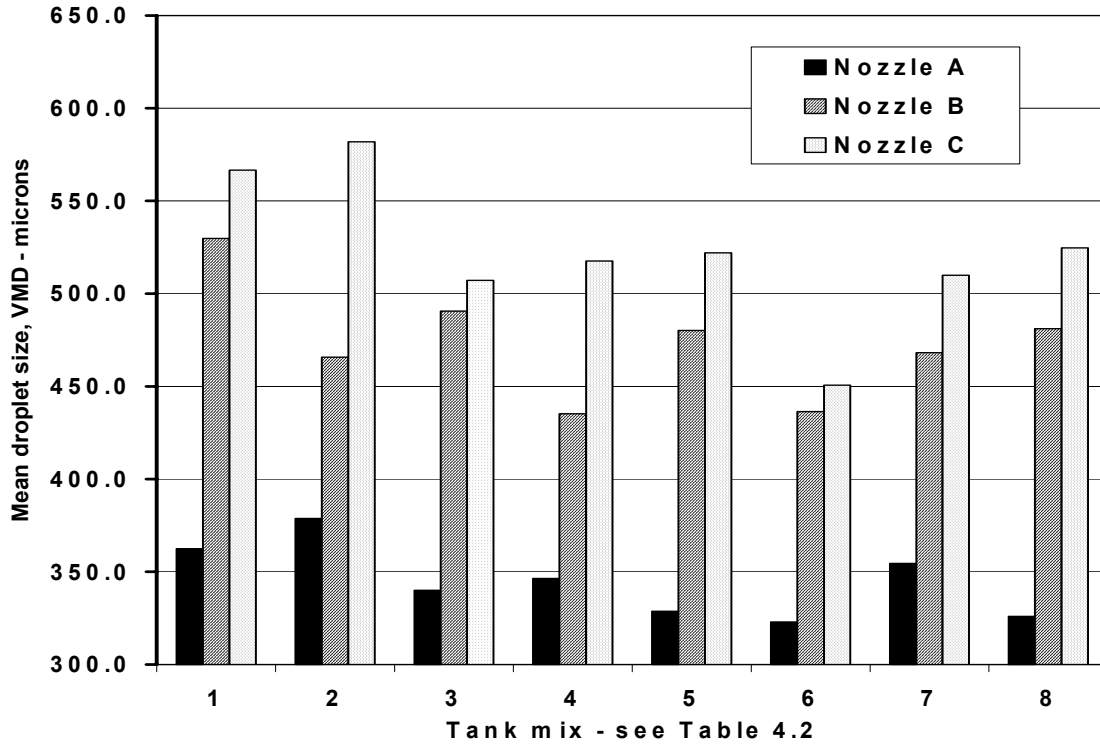

Mean droplet sizes as expressed by the volume median diameter (VMD) for the grass weed herbicide mixtures sprayed through the three selected nozzles are shown in Figure 5.1.2. Sizes when spraying the non-ionic surfactant give the expected range with VMD's of between 379 and 582 μm. When spraying water alone, mean sizes were reduced by some 15 μm for nozzles A and C but were higher for nozzle B. The result for nozzle B appears anomalous since it would be expected that the presence of a surfactant would increase the level of air included in the droplets. Droplet sizes when spraying all of the tank mixes were less than both the water and non-ionic surfactant cases and this is likely to be due to the presence of the oil emulsion in the spray liquid (Butler Ellis and Tuck, 2000). It is noticeable that the difference in droplet sizes from the two larger droplet size nozzles B and C is much less when spraying the tank mixes than with the non-ionic surfactant and water. The lack of differences in the measured sizes when spraying the different tank mixes indicates that selection of the specific nozzle will be more important than considerations relating to the detail of the tank mix.

Figure 5.1.2. Mean measured droplet sizes for the three different air induction nozzles operating with tank mixes relevant to the treatment of grass weeds in cereal crops – nozzles operating at 0.8 l/min

Similar results were found when measuring the droplet size distributions for the tank mixes relevant to the treatment of broad-leaved weeds, see Figure 5.1.3. Here the small droplet sizes measured with tank mix 6 are particularly noticeable but no obvious reason for this could be established. Mean droplet sizes for the tank mixtures obtained with nozzle C tended to be slightly larger than with the grass weed herbicide mixtures and more variable from both nozzles B and C than when spraying the tank mixtures used in Figure 5.1.2.
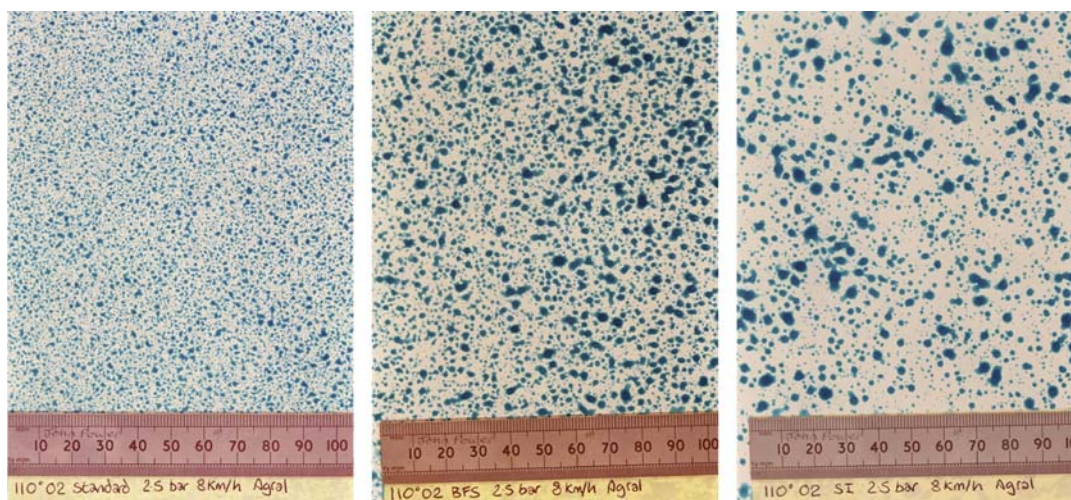
Figure 5.1.3. Mean measured droplet sizes for the three different air induction nozzles operating with tank mixes relevant to the treatment of broad-leaved weeds in cereal crops – nozzles operating at 0.8 l/min

5.2   Visualisation of deposit distribution

Examples of the spray deposits captured on horizontal difficult to wet targets are shown in Figure 5.2.1. It can be seen that the larger droplet size from the air induction nozzles may have implications for the distribution of deposits on target surfaces. The larger deposits from the air induction nozzles give increased areas between droplet deposits that could result in small targets getting very low or zero deposits.

Figure 5.2.1. Deposit distributions collected on horizontal surfaces for the conventional nozzle (left), air induction nozzle A (centre) and air induction nozzle C (right)
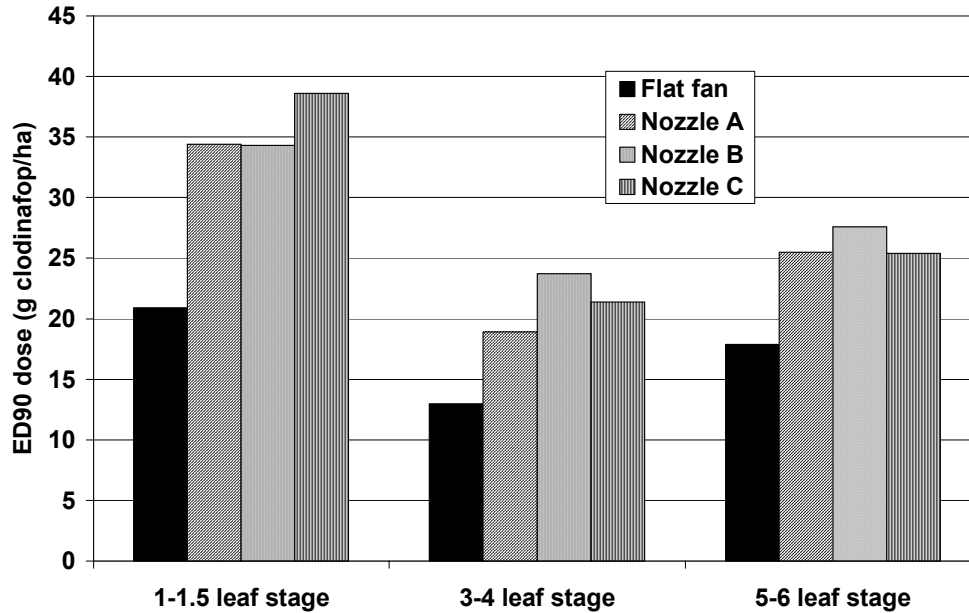

While gaps in the deposit distribution leading to low or no deposit on small targets may be a factor influencing the efficacy obtained with air induction nozzles, the form of the deposit may also be an important factor. Differences in coverage are likely to influence uptake and such effects are likely to be more important with small targets and when herbicide performance may be compromised by low doses and or poor conditions for efficacy.

5.3 Results obtained with the outdoor pot grown grass weed plants

The results obtained when clodinafop-propargyl was applied to rye-grass (*Lolium perenne*) showed some small dependence on stage of growth (Figures 5.3.1 and 5.3.2) with the greatest responses at the 3-4 leaf stage in Year 1 (Figure 5.3.1) and at the 2 and 3 leaf stage in Year 2 (Figure 5.3.2) . It is likely that the lower activity at the earlier growth stage is due to reduced spray retention on the smaller more erect plants.
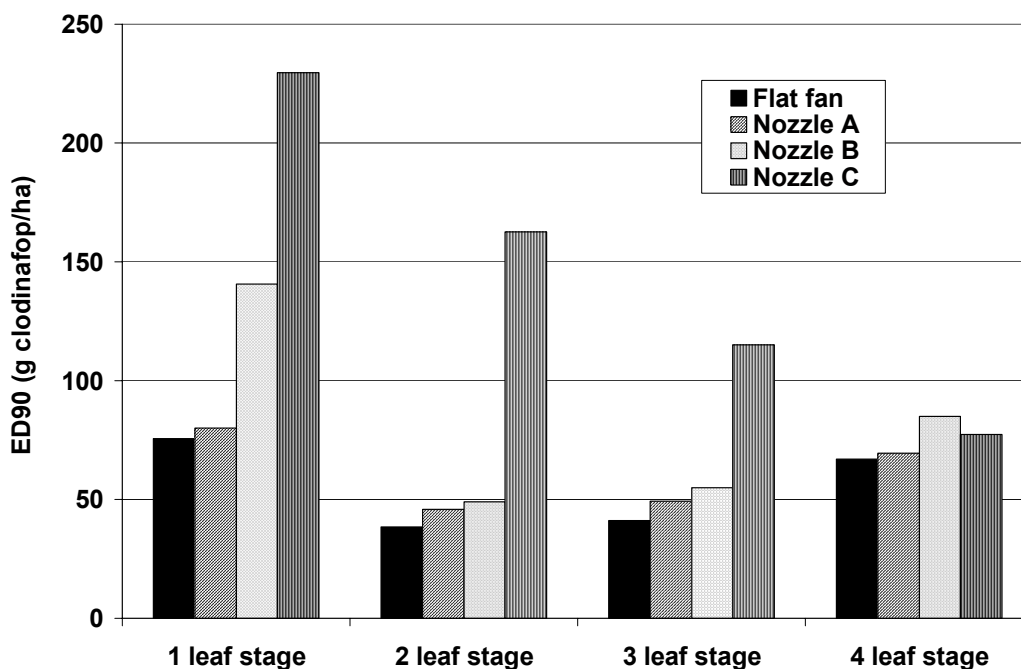
Figure 5.3.1. Calculated ED$_{90}$ doses of clodinafop-propargyl (g a.i./ha) on rye-grass (*Lolium perenne*) applied with different nozzles in Year 1 of the project

In Year 1 (Figure 5.3.1) the performance of the clodinafop-propargyl was significantly better when applied with the conventional flat nozzle than with the three air induction nozzles at all growth stages. In Year 2 (Figure 5.3.2) the conventional flat fan nozzle also gave the highest level of efficacy at all growth stages. There was a strong trend in the results from both years for the levels of efficacy to decline with increasing droplet size from the air induction nozzles.

The hypothesis that very small targets may be missed with air induction nozzles leading to lower overall performance of herbicides when applied through this type of nozzle at the early compared to later growth stages was not confirmed by these trials. If a minimum target size existed in these experiments it was at much later growth stage than anticipated. However, the reduced efficacy with the air induction nozzles was evidence that the form of the deposit based on the larger droplet sizes may have an adverse effect on product efficacy.

Figure 5.3.2. Calculated ED_{90} doses of clodinafop-propargyl (g a.i./ha) on rye-grass (*Lolium perenne*) applied with different nozzles in Year 2 of the project

There was a difference in the ED_{90} values calculated from the experimental results obtained in the two years of the work. This probably relates to seasonal effects influencing plant growth and herbicide response characteristics.

The results obtained when Hawk (clodinafop-propargyl + trifluralin) was applied to black-grass (*Alopecurus myosuroides*) in Year 2 of the project are shown in Figure 5.3.3. At the early growth stages, no differences were found between nozzles while the conventional flat nozzle was superior to the air induction nozzles at the later growth stages. It is reasonable to assume that the performance of a residual herbicide like trifluralin is only weakly influenced by nozzle type in contrast to a foliar-acting herbicide like clodinafop-propargyl. Trifluralin contributes significantly to the overall effect at the early growth stages whereas clodinafop-propargyl is the most active component at the later growth stages and this may explain the lack of differences between the nozzles observed at the earliest growth in this experiment.

The application of clodinafop-propargyl to black-grass (*Alopecurus myosuroides*) in year 1 of the project gave responses that were relatively similar to those obtained when the same chemical was applied to rye-grass (*Lolium perenne*) (Figures 5.3.1 and 5.3.2) but with the decline in efficacy with increasing droplet size from the air induction nozzles more pronounced (see Figure 5.3.4). The highest level of efficacy at all growth stages was obtained with the conventional flat fan nozzle. There was a clear relationship between

droplet size and efficacy in this experiment and hence the highest efficacy being measured with the conventional nozzle design.

Figure 5.3.3. **Calculated ED$_{90}$ doses of Hawk (clodinafop-propargyl + trifluralin) on black-grass (*Alopecurus myosuroides)* applied with different nozzles in Year 2 of the project**
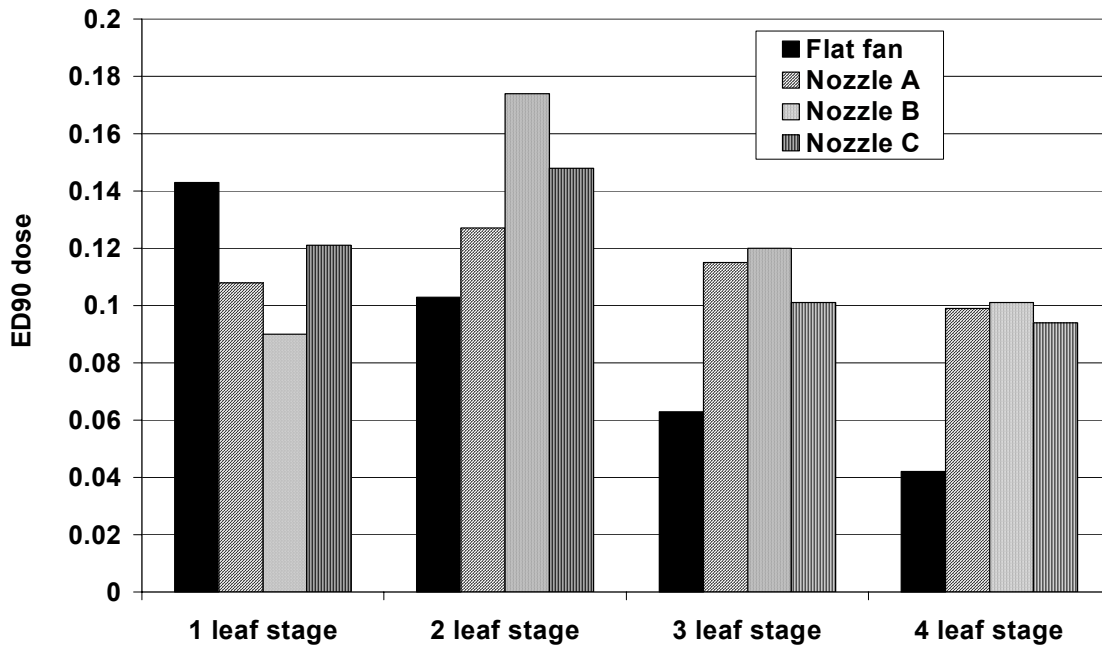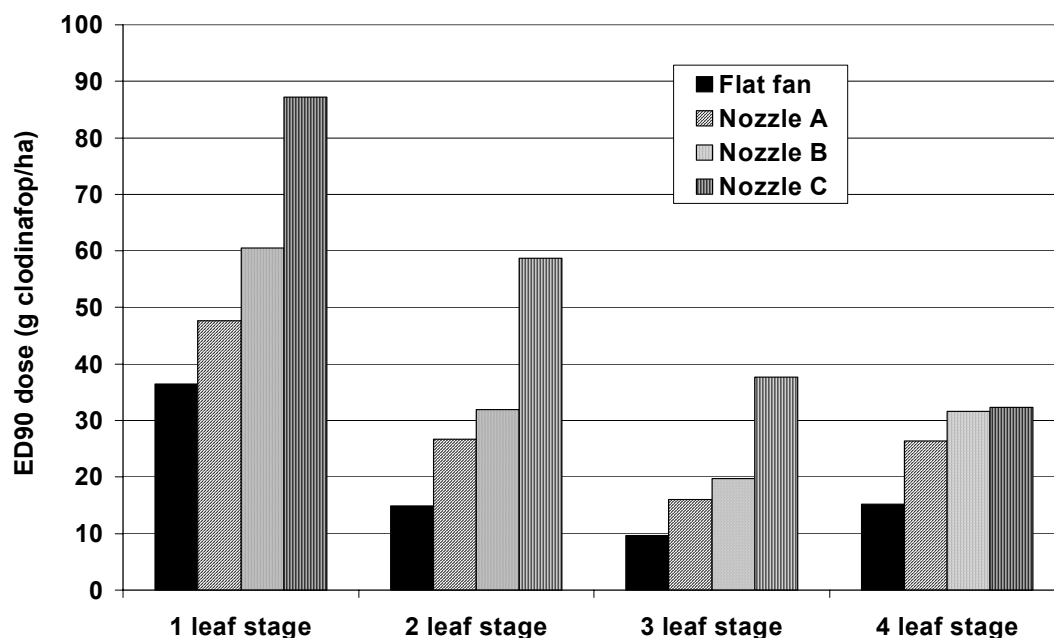
Figure 5.3.4. Calculated ED$_{90}$ doses of clodinafop-propargyl (g a.i./ha) on black-grass (*Alopecurus myosuroides*) applied with different nozzles in Year 1 of the project

5.4 Results obtained with the outdoor pot grown broad-leaved weeds

Results when applying the bromoxynil + ioxynil plus mecoprop-P tank mix to the oilseed rape (*Brassica napus*) plants in the two years of the work are shown in Figures 5.4.1 and 5.4.2. The results showed similar trends for the two years, namely:

- a reducing level of efficacy with increasing stages of growth as expected;
- differences in efficacy levels between nozzles at the earliest (cotyledon) growth stage were erratic;
- the highest levels of efficacy were found with the conventional flat fan nozzle at the later stages of growth (2leaf stage and onwards) with efficacy from the air induction nozzles at these later growth stages tending to decline with increasing mean droplet size;
- if a minimum target size exists for optimum performance of air induction nozzles it is beyond the optimum time of herbicide application.

Experiments with oilseed rape (Figures 5.4.1 and 5.4.2) showed a reduced performance of the air induction nozzles at the later growth stages (the larger the droplet size the lower the efficacy) but surprisingly this was not found at the cotyledon stage. Oilseed rape plants at the cotyledon stage constitute a relatively large target size and, in contrast to the true leaves of oilseed rape, the cotyledon leaves are easy to wet and this may explain the unexpected results.

Results obtained with the scentless mayweed (*Tripleurospermum inodorum*) target shown in Figures 5.4.3 and 5.4.4 again gave the highest level of efficacy with the conventional flat fan nozzle but less consistent trends with the air induction nozzles, even if the high ED_{90} values at the four leaf stage measured with nozzles B and C in Year 2 (Figure 5.4.4) are not included in the analysis. There was some effect of stage of growth on the levels of efficacy measured but this was much less than in the case of the oilseed rape target. The results obtained in the two seasons work were in good agreement except for the two high ED_{90} values shown on Figure 5.4.4.

Experiments with common poppy (*Papaver rhoeas*) (Figure 5.4.5) also gave the highest level of efficacy with the conventional flat fan nozzle. There was some tendency for efficacy to be reduced in relation to mean droplet size for the air induction nozzles (reduced efficacy with the largest droplet sizes) particularly at the later stages of growth. There was also a tendency for efficacy to decline with increasing weed size as expected and again particularly for applications made with the air induction nozzles.

Figure 5.4.1. Calculated ED_{90} doses (fraction of maximum dose) of the bromoxynil + ioxynil and mecoprop-P tank mix applied to oilseed rape (*Brassica napus*) plants with different nozzles in Year 1 of the project
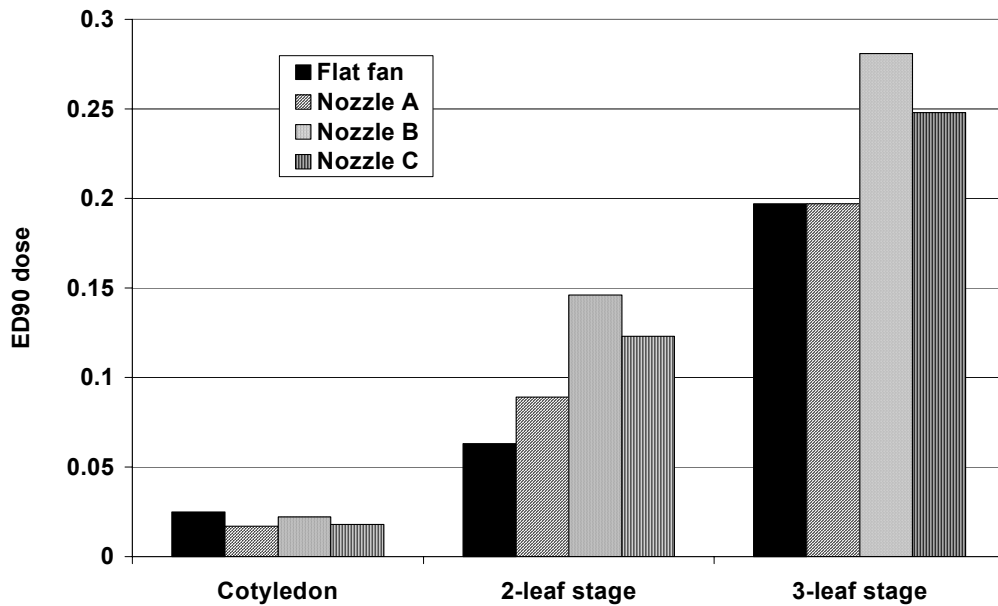
Figure 5.4.2. Calculated ED$_{90}$ doses (fraction of maximum dose) of the bromoxynil + ioxynil and mecoprop-P tank mix applied to oilseed rape (*Brassica napus*) plants with different nozzles in Year 2 of the project
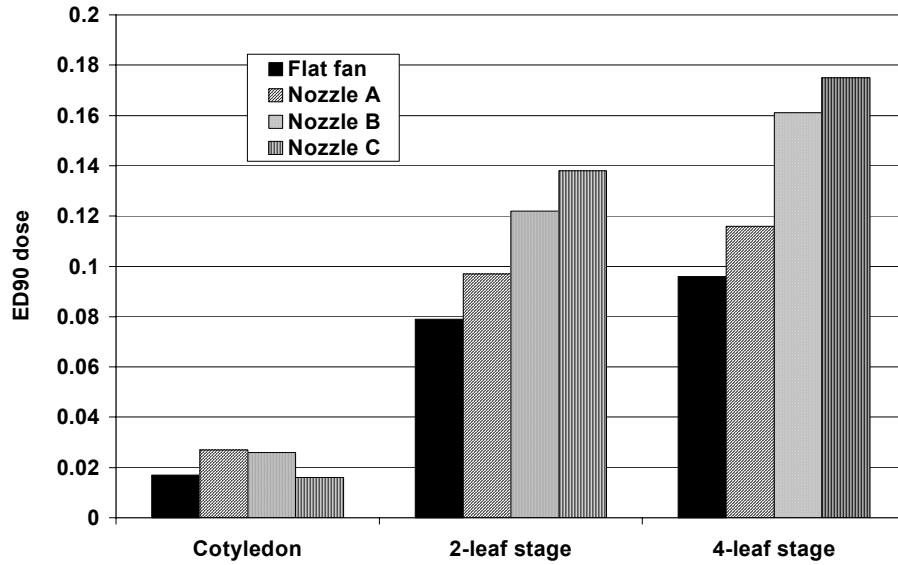

Figure 5.4.3. Calculated ED$_{90}$ doses (fraction of maximum dose) of the bromoxynil + ioxynil and mecoprop-P tank mix applied to scentless mayweed (*Tripleurospermum inodorum*) with different nozzles in Year 1 of the project

Figure 5.4.4. Calculated ED$_{90}$ doses (fraction of maximum dose) of the bromoxynil + ioxynil and mecoprop-P tank mix applied to scentless mayweed (*Tripleurospermum inodorum*) with different nozzles in Year 2 of the project
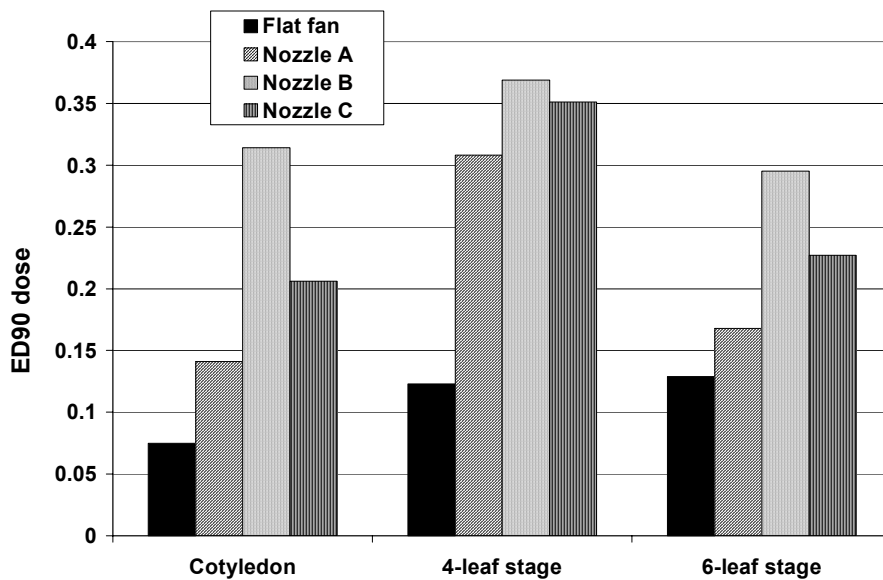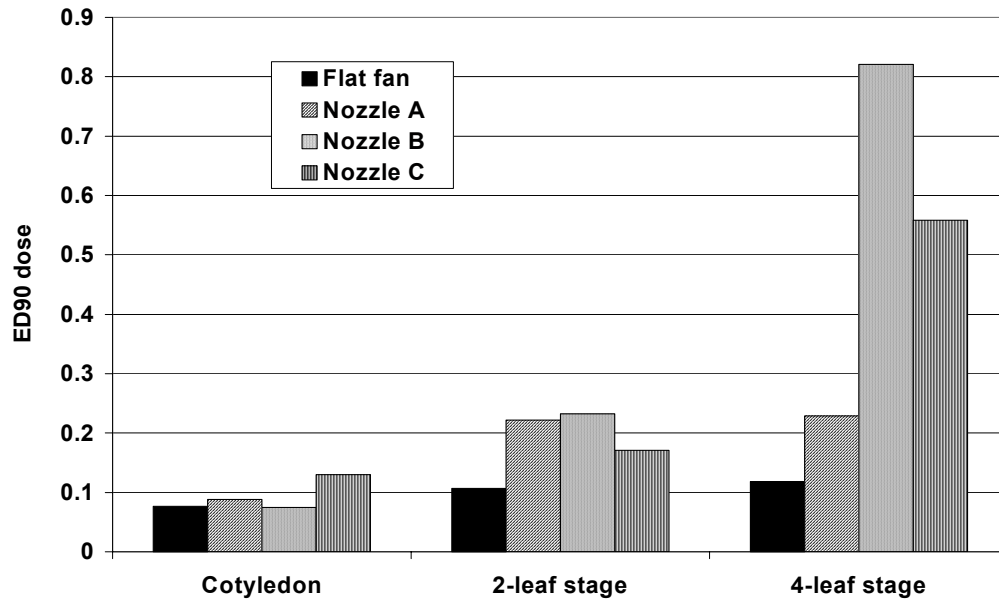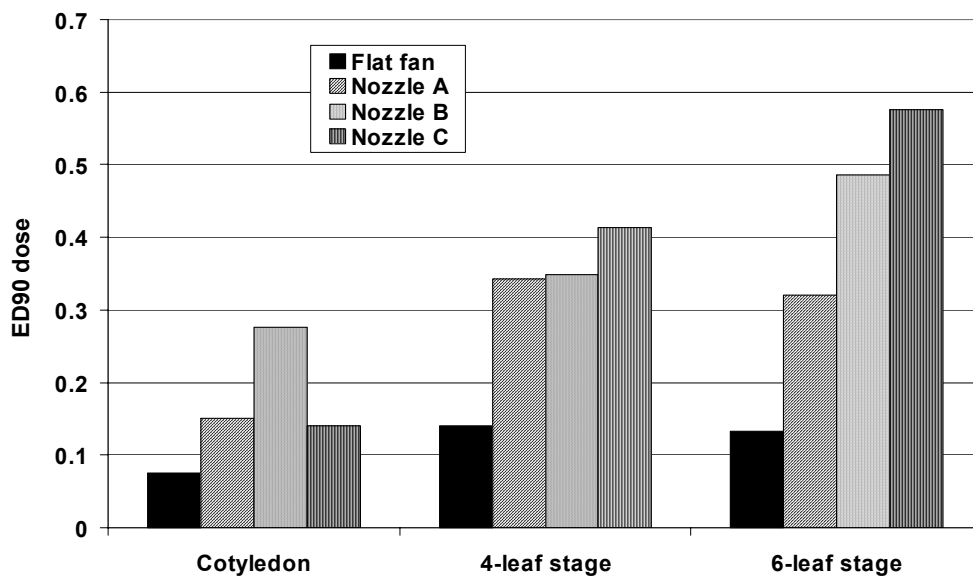

Figure 5.4.5. Calculated ED$_{90}$ doses (fraction of maximum dose) of the bromoxynil + ioxynil and mecoprop-P tank mix applied to common poppy (*Papaver rhoeas*) with different nozzles

5.5   Field trials with grass weeds

Figure 5.5.1 shows the levels of control of black-grass (*Alopecurus myosuroides*) achieved from the range of nozzles tested in the first year of the work. There was a trend for levels of control of black-grass to be higher when treated at the full dose of Hawk (clodinafop-propargyl + trifluralin) + Toil, when treated at the 1 leaf or 2-3 leaf stage of the black-grass, than compared to the reduced dose, and in some cases this was significant. Within each herbicide dose there was a trend for a greater reduction in black-grass panicles when black-grass was treated at the 2-3 leaf stage than at the 1 leaf stage and again in most cases this was significant. There was a trend for the greatest reduction in black-grass panicles to be achieved when the conventional flat fan nozzle was used and a fall off in control levels was observed when air induction nozzles were used.

Directly comparable results were obtained in the second year's field trial (Figure 5.5.2) giving increased confidence in generalising the results from these trials. The reduction in weed control observed with the air induction nozzles generally followed the same trends as the droplet size measurements with those nozzles producing the largest droplets giving the poorest control of the black-grass. The differences were more apparent when herbicide dose was reduced and/or black-grass were small when treatments were applied

Figure 5.5.1. Percentage reduction in black-grass (*Alopecurus myosuroides*) panicles when treated in the field with Hawk (clodinafop-propargyl + trifluralin) with the different nozzles in Year 1
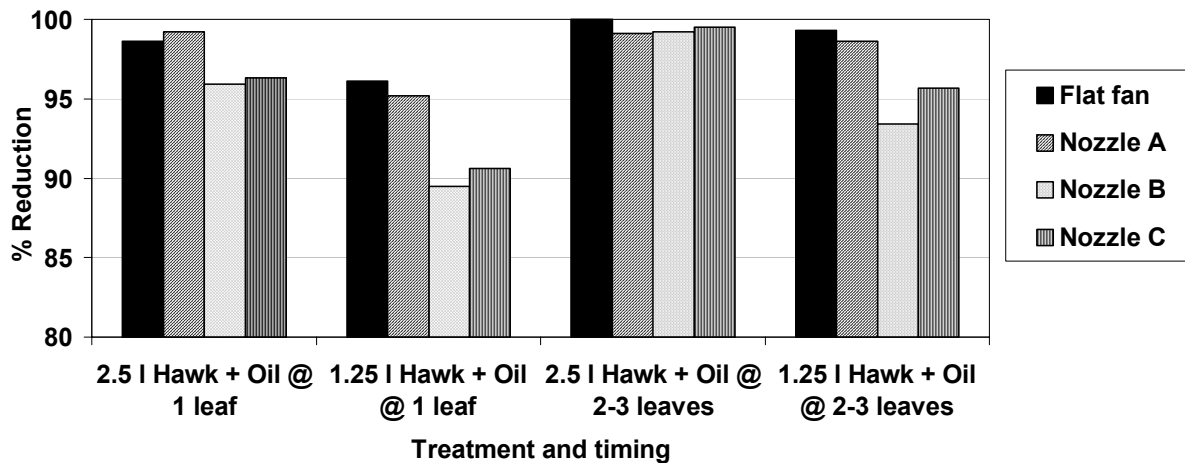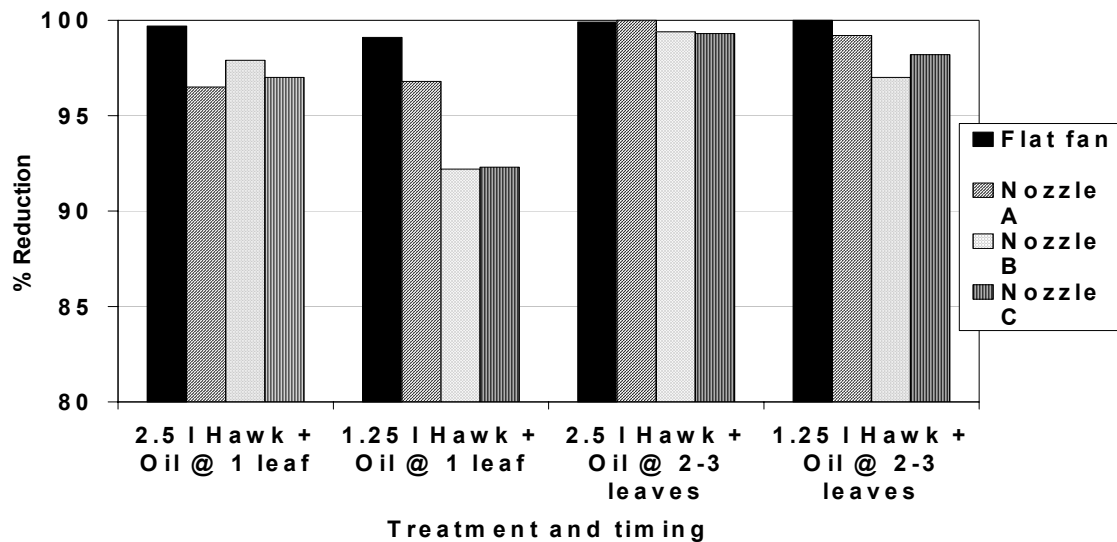
Figure 5.5.2. Percentage reduction in black-grass (*Alopecurus myosuroides*) panicles when treated in the field with Hawk (clodinafop-propargyl + trifluralin) with the different nozzles in Year 2

5.6   Field trials with broad-leaved weeds

Results from field experiments in the first year of the project in which oilseed rape (*Brassica napus*) as a simulated broad-leaved weed was treated with the bromoxynil + ioxynil plus mecoprop-P tank mix at full and half doses resulted in a complete kill of weeds for all of the nozzle treatments used.

Following discussions and consultations with other weed scientists, it was decided that the target weed in the second years trials should be common field-speedwell (*Veronica persica*) which offers a smaller weed target and that to maximise the opportunity to gain a discriminating result, four doses would be used. The results from these experiments presented in Figures 5.6.1. and 5.6.2. do not show the expected dose response characteristics at the two-leaf growth stage. At the cotyledon stage, levels of control declined with reducing dose as expected, with a tendency for a more rapid decline in control with the air induction nozzles giving the larger droplet sizes. The highest level of control was consistently achieved with the conventional flat fan nozzle at all doses. However, at the two leaf growth stages higher levels of control were apparently achieved at the quarter and eighth doses than at the full and half doses. As this appeared to be a possible mislabelling of treatments, detailed checks were made of these results but no error could be identified. Within any applied dose the conventional flat fan nozzle consistently gave the highest levels of control with the decline in control from the air induction nozzles being approximately in proportion to their measured mean droplet size.

Figure 5.6.1. Percentage reduction of common field-speedwell (*Veronica persica*) when treated with bromoxynil + ioxynil and mecoprop-P tank mix at full and half dose using the different nozzles
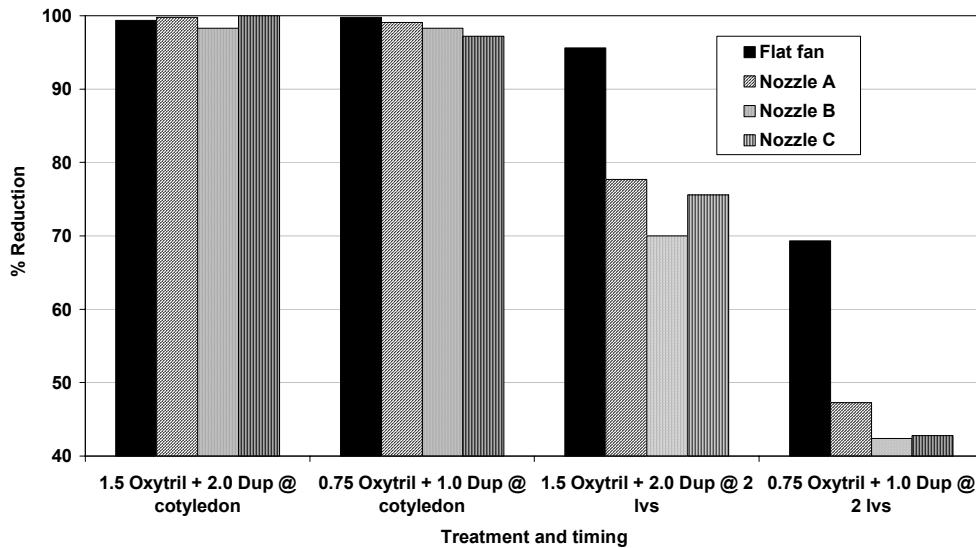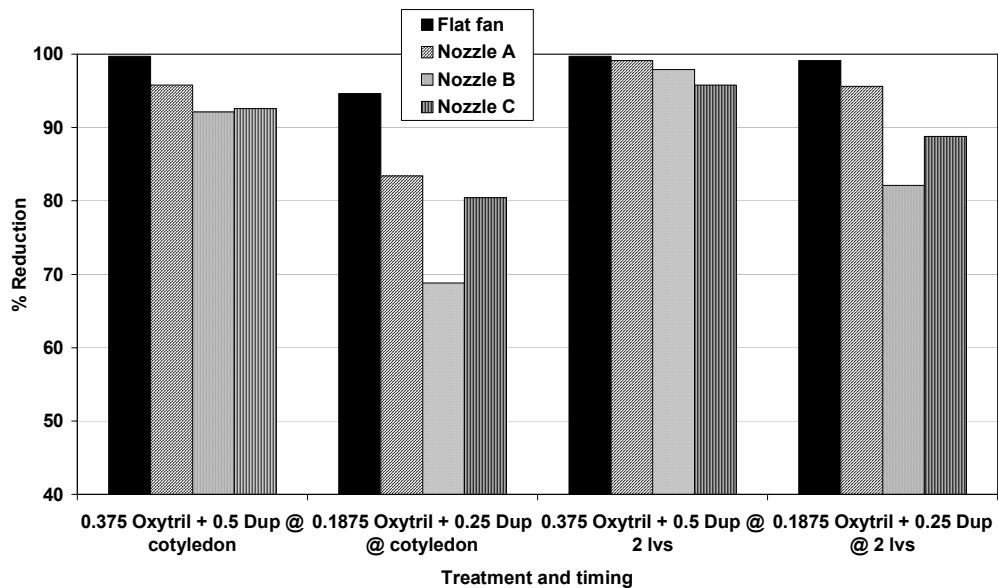

Figure 5.6.2. Percentage reduction of common field-speedwell (*Veronica persica*) when treated with bromoxynil + ioxynil and mecoprop-P tank mix at quarter and eighth doses using the different nozzles

6.   Discussion of Results

6.1   Measurement of droplet size distributions

Results from the measurements of droplet size distributions from different commercial designs of air induction nozzle showed that mean sizes could vary by more than 50% and this is in agreement with results reported elsewhere (Miller and Butler Ellis, 2000; Piggott and Matthews, 1999). The same trends in droplet size distribution were observed with all of the three measuring systems. Reasonable agreement was expected between results obtained with the Oxford Lasers and Particle Measuring Systems instruments since the basic mode of operation (droplet imaging) was the same in both cases. It is encouraging to note that differences in the way that the two instruments take samples made little difference to the numerical values obtained for the mean droplet sizes measured. The Malvern Analyser operates on the basis of light scattering and there has been concern that the internal structures of droplets with air inclusions may influence the values obtained when measuring droplet size distributions from air induction nozzles with this instrument. The reasonable agreement between the numerical values obtained for the mean droplet sizes in the sprays from each of the commercial nozzles used in this study indicates that the Malvern Analyser can be used to measure droplet size distributions in the sprays from air induction nozzles with reasonable confidence over a range of relevant conditions.

It should be noted that the measurements made as part of work on this project used only the "02" nozzle size. Results of other work has shown that:-

- for air induction nozzles the relationships between nozzle size (flow rate at a given pressure) and droplet size distribution does not follow the same form as for conventional pressure nozzles; and therefore
- the ordering of nozzle designs at a given size based on droplet sizes does not necessarily mean that the same order will be found at a different size e.g. the order for the "02" size will not necessarily be the same as for the "04" size.

In many studies, including the one reported here, the Billericay BubbleJet has been shown to consistently produce a relatively small droplet size distribution. This was also the case when operating with the range of typical tank mixes used in this project. Differences between the droplet sizes from other designs of air induction nozzle have been less consistent over a range of sizes and the results from this study indicate that differences may also be reduced when operating with realistic tank mixes. The results from this study however indicate that nozzle selection is a more important variable influencing the droplet size from air induction nozzles than properties of the tank mix liquid.

6.2   Effects on efficacy

Results from both the pot studies and the field trials show that the use of air induction nozzles tends to reduce herbicide efficacy with the greatest reductions resulting from applications made with nozzles having the largest droplet size distribution. The original hypothesis implied that sprays having a large mean droplet size would risk achieving no droplet impact/retention on very small targets. The results from both the deposit visualisation study and pot/field trials indicate that in practical situations a very high proportion of targets receive some spray but the form of the deposit and/or the coverage from the sprays from air induction nozzles leads to a reduction in efficacy. Hence while target size is an issue, in practical situations it is unlikely that weed targets will be so small as to be completely missed by the spray.

Results from both the pot studies and the field trials with grass weed species showed that target size was important for sprays applied with both conventional and air induction nozzles. When spraying clodinafop-propargyl + trifluralin (Hawk) in the field trials, higher levels of efficacy were consistently observed at the 2-3 leaf stage compared with the 1 leaf stage for all nozzle types and in both seasons (Figures 5.5.1 and 5.5.2). Equivalent results were also obtained in the pot experiments particularly when treating rye-grass with clodinafop-propargyl in years 1 and 2 of the project (Figs 5.3.1 and 5.3.2) and when treating black-grass with the same formulation (Figure 5.3.4) in year 1. This was considered to relate to the need to have an adequate area of foliage on target weed plants so as to collect at least the minimum dose of herbicide to give an efficacious effect of a formulation that has a predominately foliar mode of action.

The effects on efficacy of using air induction nozzles were not shown as clearly in the pot experiments in which black-grass was treated with clodinafop-propargyl + trifluralin – see Figure 5.3.3. This result was considered to relate to the mainly soil acting mode of action of the trifluralin component of the formulation as the pots were managed in such a way that maximised the soil action of trifluralin.

In the case of the broad-leaved weed targets, the effects on efficacy of using air induction nozzles to apply spray treatments was consistent with the grass weed observations – nozzles producing the largest droplet sizes also gave the largest reductions in efficacy. As with the grass weed targets, the difference between nozzles tended to be smaller in the field trials than in the pot experiments. With the broad-leaved weed targets the results showed that efficacy was generally higher when treating weeds at an early stage of growth for all types of nozzle. This may relate to the larger spray capture areas for broad-leaved weeds, even when weeds are small, compared with grass weeds.

6.3   Practical implication arising from the work

Results from the study suggest that when spraying grass weed targets in conditions where good control of drift is required, then the use of an air induction nozzle generating a relatively small droplet size distribution will provide a good practical compromise between efficacy and drift control.

An important driver for the work conducted as part of this project was the extent to which air induction nozzles could be used to control drift without risks to product efficacy. It has been recognised that assessing the likely effects on efficacy of using air induction nozzles based only on a measure of the mean droplet size distribution may lead to conclusions that would discourage the use of this nozzle type and hence not fully utilise the drift reducing capability of the nozzle design. Previous published data relating to the performance of air induction nozzles in terms of efficacy had shown levels of control that were higher than would have been expected from conventional nozzles delivering the same droplet size but with little evidence of substantial differences between different commercial nozzle designs. It was therefore proposed (Miller *et al.,* 2002) that all sprays with air included droplets be classified as medium in the International/BCPC spray and nozzle classification scheme providing that at least 10% of the spray volume was air when measured using defined procedures. All of the air induction nozzles used in this study would have been classified as medium if the proposals outlined by Miller *et al*., (2002) had been adopted.

The relatively robust differences in product efficacy between applications with different commercial designs of air induction nozzle found in this study and the good correlation between measured droplet sizes and efficacy suggests that there is a need to provide users with information relating to the droplet size distribution generated by different designs of air induction nozzle. Currently there is no agreed or standardised way that this can be done. Information in the Nozzle Guide published by HGCA (2002) gives only a single category for air induction nozzles.   Information relating to the ability of such nozzle designs to control spray drift can be deduced from details of the nozzle conditions qualifying for LERAP Low Drift star ratings and this information is available on a web-site maintained by the Pesticides Safety Directorate. Work reported by Butler-Ellis *et al.,* (2002) indicated that there was a good correlation between the risk of drift and the droplet size distribution for this nozzle design. However, there is unlikely to be adequate data from the LERAP Low Drift Star rating listing that could provide an improved basis for nozzle selection balancing drift control and product efficacy for defined target situations. In seeking to define methods to provide the user with further information relating to the performance of different designs of air induction nozzle it will be important to balance the increasing complexity of nozzle selection with simplicity such that systems are easily understood and used. As for all nozzle classification issues, it will be necessary to define both how data is obtained and presented to the user.

7   Conclusions

(i)   Different commercial designs of the same size of air induction nozzle give different droplet size distributions: the Billericay "BubbleJet" consistently gave the smallest size of air included droplet with nozzles from Sprays International and Delavan giving the largest sizes for the "02" nozzle size.

(ii)   Different methods of measuring the droplet size distributions from air induction nozzles gave good agreement despite the different operating principles and sampling methods of the instruments used. For the "02" size of air induction nozzle, the following were selected as representative for this study:

- Billericay "BubbleJet" – giving a relatively small droplet size.
- Hardi "InJet" – giving a medium droplet size.
- Sprays International "PneuJet" – giving a relatively large droplet size.

(iii)   Differences in droplet size when spraying different tank mixes representative of treating grass and broad-leaved weeds were small: the use of realistic tank mixes tended to reduce differences between droplet sizes from different nozzles particularly for the nozzles producing the larger droplet sizes.

(iv)   Results from both pot experiments and field trials showed that for both grass and broad-leaved weed targets, air induction nozzles tended to give a reduced level of efficacy with the greatest reductions in efficacy relating to the use of nozzles creating the larger droplet sizes. Differences in efficacy between nozzles were generally consistent over most of the experimental work conducted as part of this project.

(v)   When treating grass weed targets the highest levels of efficacy were found at the 2-3 leaf stage for all nozzle designs. It is likely that the small leaf areas at the one leaf growth stage limited the interception and capture of the applied spray. For broad-leaved weeds efficacy was consistently higher when treating at the earliest stages of growth owing to them offering a larger target than grass weeds even when weeds are small.

(vi)   The differences in the level of efficacy from different designs of air induction nozzle suggests that there is a need to give users more information about the droplet sizes generated by the different designs. Selection of an air induction nozzle giving a relatively small size of air included droplet may often be a suitable compromise between efficacy and drift control when treating grass weed targets at the 2-3 leaf growth stage. More information is required before a similar conclusion can be made for broad-leaved weeds.

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