General enquiries on this form should be made to:
Defra, Science Directorate, Management Support and Finance Team,
Telephone No. 020 7238 1612
E-mail: research.competitions@defra.gsi.gov.uk

SID 5 Research Project Final Report

- **Note**
  In line with the Freedom of Information Act 2000, Defra aims to place the results of its completed research projects in the public domain wherever possible. The SID 5 (Research Project Final Report) is designed to capture the information on the results and outputs of Defra-funded research in a format that is easily publishable through the Defra website. A SID 5 must be completed for all projects.
- This form is in Word format and the boxes may be expanded or reduced, as appropriate.
- **ACCESS TO INFORMATION**
  The information collected on this form will be stored electronically and may be sent to any part of Defra, or to individual researchers or organisations outside Defra for the purposes of reviewing the project. Defra may also disclose the information to any outside organisation acting as an agent authorised by Defra to process final research reports on its behalf. Defra intends to publish this form on its website, unless there are strong reasons not to, which fully comply with exemptions under the Environmental Information Regulations or the Freedom of Information Act 2000.
  Defra may be required to release information, including personal data and commercial information, on request under the Environmental Information Regulations or the Freedom of Information Act 2000. However, Defra will not permit any unwarranted breach of confidentiality or act in contravention of its obligations under the Data Protection Act 1998. Defra or its appointed agents may use the name, address or other details on your form to contact you in connection with occasional customer research aimed at improving the processes through which Defra works with its contractors.

Project identification

1. Defra Project code: PS2010
2. Project title: A review of methods of reducing drift without compromising product efficacy
3. Contractor organisation(s): The Arable Group
   Eastern Region Office
   The Old Rectory
   Morley St Botolph
   Wymondham
   Norfolk NR18 9DB
4. Total Defra project costs (agreed fixed price): £ 25,888
5. Project: start date .... 01 May 2006
   end date 30/09/2006

6. It is Defra's intention to publish this form.
Please confirm your agreement to do so. .... **YES** ☒ **NO** ☐

(a) When preparing SID 5s contractors should bear in mind that Defra intends that they be made public. They should be written in a clear and concise manner and represent a full account of the research project which someone not closely associated with the project can follow.
Defra recognises that in a small minority of cases there may be information, such as intellectual property or commercially confidential data, used in or generated by the research project, which should not be disclosed. In these cases, such information should be detailed in a separate annex (not to be published) so that the SID 5 can be placed in the public domain. Where it is impossible to complete the Final Report without including references to any sensitive or confidential data, the information should be included and section (b) completed. NB: only in exceptional circumstances will Defra expect contractors to give a "No" answer.
In all cases, reasons for withholding information must be fully in line with exemptions under the Environmental Information Regulations or the Freedom of Information Act 2000.

(b) If you have answered NO, please explain why the Final report should not be released into public domain

Executive Summary

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

A review of available information relating to the performance of agricultural spraying systems identified three possible mechanisms by which drift could be reduced in comparison with that from conventional hydraulic nozzles while maintaining efficacy with a wide range of products. These are:

(i) Increasing droplet size produced by a nozzle with either conventional or air included droplets;
(ii) Increasing droplet speeds by using air assistance generated, for example, by a fan and delivered from ducting mounted on the boom;
(iii) Using shrouds over the whole boom or shield and deflectors to minimise the interactions of air flows due to the natural wind or forward speed with the spray such that there is reduced detrainment of small droplets.

While the use of shrouds and deflectors on sprayers in the UK have become established for small units used in amenity applications, such approaches have major disadvantages when used with larger machines. The use of such systems is unlikely to be a practically attractive option to reducing drift, even though their use would have no major implications for product efficacy.

Air-assisted boom sprayers have been developed to enable fine sprays to be used without increasing the risk of drift. Some manipulation of distribution patterns into crop canopies has also been shown to be possible by adjusting the air flow to match both application and crop conditions. Substantial reductions in drift have been achieved with such systems while efficacy has been maintained or, in some situations, improved. However, the review noted that:

- Drift reductions tended to be lower than those achieved by air-induction nozzles and were dependent upon setting the airflow conditions appropriately;
- The use of such systems does involve an increase in both capital and operating costs.

The use of air induction nozzles has become an established way of reducing the drift from boom sprayers based on increasing droplet size and generating large droplets with air inclusions. Pre-orifice nozzles create a larger droplet size than conventional nozzles but do not generate droplets with the air inclusions that have been associated with good retention on a range of target types. The twin-fluid nozzle also produces droplets with air inclusions and can have a drift reducing performance similar to that of air-induction nozzles if operated with low input air pressures. It was concluded that the use of air-induction nozzles represented a low cost method of achieving high levels of drift reduction with boom sprayers operating in UK conditions. Drift levels typically in the order of 25% of that from conventional nozzles can be achieved by such designs. The review noted that there are large differences in the performance of nominally equivalent air-induction nozzle specifications from different manufacturers with important implications for both the levels of drift reduction and efficacy.

The results of project work examining applications at low volumes have indicated that the uniformity of deposit on the target may be more important for efficacy than total coverage. Air-induction nozzles giving a relatively large droplet size have been shown to give variable deposits and a low level of efficacy with both herbicides and fungicides in UK arable crops. Studies have also shown that target size is an important consideration when defining spray characteristics required to give high levels of efficacy and that finer sprays are needed when treating small targets such as grass weeds at an early stage of growth.

A number of field trials with herbicides and fungicides have now reported that the use of air-induction nozzles can give equivalent levels of efficacy to that achieved with conventional hydraulic flat fan nozzles. However, there is insufficient data relating to any defined target/treatment combination to enable detailed relationships between drift reduction and efficacy to be established. There is little data relating to the efficacy of insecticides applied through air-induction nozzles and none was found relating directly to UK conditions.

A default sprayer configuration based on the use of air-induction nozzles giving a droplet size distribution equivalent to the smaller end of the size range in commercial nozzle designs and operating at a pressure of 3.0 bar to deliver in the order of 100 L/ha when operating at forward speeds of 12 to 14 km/h is proposed to give the benefits of high work rates, improved timeliness and good control of spray drift. Timeliness is recognised as being an important component in achieving high levels of efficacy. This default configuration could be used on most applications made on UK arable farms except those applying herbicides to small weed targets. Results from the reviewed data suggest that such a system would give high levels of efficacy when applying fungicides at all relevant growth stages and herbicides to arable crops at the later stages of growth. Little data relating to the performance of insecticides with such systems was identified. It is estimated that this default sprayer configuration would give drift reductions nationally of some 40 to 60% when compared with conventional application approaches.

Defining a specification for air-induction nozzles in terms of a droplet size distribution needs to be relative because numerical values for droplet size parameters is dependant upon the equipment used to make a measurement and the method of sampling. As an indication of the differences between those air-induction nozzle designs giving relatively small droplet sizes and those generating larger sizes, published data reviewed in this study suggest that small droplet sizes from air induction nozzles had volume median diameters in the range 350 – 425 μm whereas those from medium/large droplet air-induction nozzles were greater than 425 μm.

The review also identified other sprayer operating variables as being critical to the control of drift from boom sprayers including boom height and forward speed. Boom height has been found to be particularly important in terms of drift control with an increase in boom height from 500 to 700 mm giving a four-fold increase in drift when using conventional nozzles and reducing the drift reduction that would be achieved with air-induction nozzles. When operating in areas where control of drift is of particular importance such as at the edges of fields, maintaining the correct boom height and travelling at a lower forward speed will ensure that the drift reductions associated with the air induction-nozzle are delivered in practice.

8. As a guide this report should be no longer than 20 sides of A4. This report is to provide Defra with details of the outputs of the research project for internal purposes; to meet the terms of the contract; and to allow Defra to publish details of the outputs to meet Environmental Information Regulation or Freedom of Information obligations. This short report to Defra does not preclude contractors from also seeking to publish a full, formal scientific report/paper in an appropriate scientific or other journal/publication. Indeed, Defra actively encourages such publications as part of the contract terms. The report to Defra should include:

- the scientific objectives as set out in the contract;
- the extent to which the objectives set out in the contract have been met;
- details of methods used and the results obtained, including statistical analysis (if appropriate);
- a discussion of the results and their reliability;
- the main implications of the findings;
- possible future work; and
- any action resulting from the research (e.g. IP, Knowledge Transfer).

1. Project objectives

To review the available information that can link the ability of nozzle designs such as the air-induction design to control drift with the minimum risk to product efficacy and to make recommendations relating to:

(i) how applications in sensitive areas could be made to use the available spraying windows most effectively while reducing the overall drift risk; and

(ii) the generic advice that may be appropriate regarding the use of different nozzle designs and droplet size distributions in different pesticide applications (e.g. advice on product labels or via leaflets detailing appropriate nozzle selection options/application strategies when applying different types of plant protection products (PPP's) or relating to the use of different products against specific targets).

Specific objectives related to:

1. Collecting data relating to drift reduction and efficacy of application systems based on the boom sprayer and designed to reduce the risk of drift by searching the existing literature.
2. Collecting data relating to drift reduction and efficacy of application systems based on the boom sprayer and designed to reduce the risk of drift by discussions with European Centres involved in the collection of such information.
3. Collating the data obtained particularly linking drift control and efficacy: nozzle systems to be defined in relation to the physical characteristics of the sprays produced (droplet size and velocity distributions together with the spray volume distribution pattern) with additional measurements made if required.
4. Analysing and interpreting the data and results obtained;
5. Reporting the findings to Defra and The Pesticides Safety Directorate.

The following report is based upon

- A review of published literature
- Data from the Morley archive
- Outcomes from a workshop held on 13th September, 2006 (list of participants and workshop notes attached in Appendix 1 to this report)
- Discussions with representatives of a number of organisations, including
  - Arvalis in France (Contact: Pierre-Yves Yeme) – discussions during a visit in Februrary 2006
  - Danish Institute of Agricultural Sciences (Contact: Peter Kryger Jesen – discussion in the UK in January 2006 and in Denmark in April 2006)
  - Via an exchange of e-mails with:
    - Tom Wolf (Agriculture Canada)
    - Heribert Koch (Germany)
    - Jan van de Zande (Netherlands)

2. Introduction

Over the last 10 years, there have been significant changes in pesticide application practices, many of which will have influenced either the potential for spray drift or the efficacy of the application, and generally both of these. A 'standard' application scenario 10 years or so ago would probably have been considered to be a 12 m boom, travelling at 8 km/h, spraying 200 L/ha through a conventional hydraulic flat fan nozzle. The most recent data obtained by Garthwaite (2004) suggests that this would no longer be typical (Table 1).

Table 1 Data indicating some current typical spray application parameters (from Garthwaite, 2004)

Parameter	Typical value	Extent of usage
Boom width	Greater than 20 m	56% area of arable land
Air-induction nozzles	Sprayed area	22% area of arable land
Water volume	Less than 150 L/ha	55% area of arable land
Sprayer speed	10 – 11 km/h	

Timeliness is a major factor influencing the performance of agricultural pesticides, and is probably one of the main drivers behind the changes shown. Timeliness is improved by systems that achieve high work rates, so that the maximum area of crop can be treated in as short a time as possible. In addition, falling prices for crops produced have resulted in a major restructuring of arable farms, including reductions in the availability of labour and machinery. This also requires farmers to maximise work rates of their sprayers. The drive for increased work rates is leading to reducing volumes of application, increasing forward speeds and wider spray booms.

These changes in practice are likely to lead to a change in spray drift and, in particular, wider booms with faster forward speeds tend to result in booms being set higher above the ground, giving a significant increase in drift. Reductions in water volume have been associated with increases in drift, because with conventional hydraulic nozzle designs, spray droplet size reduces as nozzle size reduces. However, recent developments in nozzle technology, particularly the air-induction nozzle, have broken the link between droplet size and nozzle output. This means that application volumes can be reduced through changing nozzle size without necessarily creating a smaller droplet size distribution and increasing drift.

The use of air-induction nozzles has probably been limited because of a perception of reduced efficacy. It is rare for users to be provided with specific data on product performance with air-induction nozzles, and there are no specific label recommendations that include their use that we are aware of. The LERAP scheme for protecting surface water from spray drift has encouraged their use, however, and the majority of 3-star rated equipment is based on the air-induction design. Recent research has begun to demonstrate a wide range of circumstances where air-induction nozzles give equivalent efficacy to conventional hydraulic flat fan nozzles.

A nozzle/spray classification scheme has been developed and widely used in the UK (Doble, *et al.*, 1985) in which spray quality classes of very fine, fine, medium, coarse and very coarse are assigned to sprays based on their droplet size/volume characteristics. This classification system has been successful in describing the sprays from generating systems that have characteristics similar to those of the conventional reference flat fan hydraulic pressure nozzles but has been less successful in describing the performance of systems such as the spinning disc that can produce relatively uniform droplet sizes or nozzles such as the air-induction or twin-fluid nozzle systems that generate droplets with air inclusions. The established classification system has implications for both efficacy and drift based on the assumptions made when the scheme was proposed that fine sprays will give high levels of target coverage, good product efficacy and high levels of spray drift. Conversely, coarse sprays were assumed to give good control of drift but a greater risk to efficacy. The development of nozzles such as the air-induction design and the research and development undertaken to support applications at low volumes has shown that some of the implications associated with the classification system must now be reconsidered. For example, many air-induction nozzles will give sprays that if classified based on their droplet size distributions will result in them being classed as coarse or very coarse with an expectation of low efficacy with many products. Data reviewed in section 5 of this report indicates that this classification is not generally accurate and may lead to nozzles capable of reducing drift not being used when it would be beneficial to do so.

In this review, we consider spray drift and its measurement, the application systems that are known to reduce spray drift, other application parameters that influence spray drift and the consequences for product efficacy.

2. Spray drift and its measurement

For the purposes of this review, spray drift is defined as that part of a spray application that does not deposit as droplets within the target area but is deflected outside of the target area by the action of wind and other air movements. The issue of vapour drift both at the time of an application and after an application event is not considered in this study.

2.1 Sedimenting spray drift

Droplets that fall onto horizontal surfaces outside of a treatment area are regarded as contributing to sedimenting drift profiles. Concern relating to the possible contamination of surface water by spray drift led to the development in the UK of the Local Environmental Risk Assessment for Pesticides (LERAP's) scheme. As part of this scheme, organisations supplying pesticide spray application equipment can claim "LERAP Low Drift star ratings" based on data for sedimenting spray drift profiles collected under field or wind tunnel conditions (see 1.3 below) and related to a reference application system. Claims are examined by The Pesticides Safety Directorate using accredited laboratories and supported claims are published on a web site. A LERAP Low Drift three star rating gives a level of sedimenting drift that is less than 25% of that of the reference system at a defined range of operating conditions (e.g. nozzle heights, pressures and forward speeds). LERAP Low Drift star ratings and the data packages submitted in support of claims for such ratings provide an important source of information relating to the risk of drift from different types of application system.

2.2 Airborne drift profiles

Droplets may be carried across a field boundary in the air flows generated by the natural wind and only impact when the flow meets an obstruction such as a boundary hedge, similar vegetation or other obstructions. The spray deposition depends upon air flow patterns – if the boundary structure completely blocks the flow, then air will flow around the obstruction carrying airborne droplets with it. If it is more porous (e.g. like a hedge), then spray droplets may be filtered out as the air flows through the obstruction. Airborne droplet profiles are also important when evaluating the risks of contamination to bystanders and residents.

The DIX system (Herbst and Ganzelmeier, 2000) used in Germany to define the drift risk potential from different nozzle systems is based on airborne profiles measured in standardised wind tunnel tests. The classification system again uses a reference nozzle condition and takes account of both the quantity of airborne spray and the height of the plume with respect to the nozzle since a cloud that is higher above the ground can be expected to drift to greater downwind distances.

2.3 Measurement of drift and drift potential

It is recognised that for a given type of nozzle operating on a boom sprayer, the risk of spray drift can be correlated to the percentage of spray volume contained in droplets below a defined threshold size (e.g. <100 µm in diameter). The percentage of spray volume in droplets below a defined threshold is therefore one measure by which drift risk can be assessed. Spray droplet size distribution data can also be input to models to calculate drift profiles and hence classify a nozzle system with respect to drift. This approach is currently used in The Netherlands (van de Zande *et al.*, 2000) and in the USA using the AgDRIFT model (Teske *et al.*, 2002) particularly in relation to the drift from aerial applications.

However, it is also known that, particularly for boom sprayers, drift is influenced by factors other than the droplet size distribution such as droplet trajectories, the air flow entrained within the spray, spray and droplet structures. For this reason standardised test methods based on the use of wind tunnels have been developed, (Herbst and Ganzelmeier, 2000; Miller, 1993; Miller *et al.*, 1993; Miller *et al.*, 1995). One of the main reasons for developing wind tunnel techniques for drift risk assessment is to overcome problems associated with the variability of drift measurements in field conditions although some variability in wind tunnel measurements needs to be recognised particularly when short duration sprays are used.

Standardised approaches to the field measurement of spray drift have now been defined in a draft International Standard with the aim of facilitating the comparison of results obtained in different trials. The use of standardised collectors at defined reference downwind positions goes some way to enable the direct comparison of data from different field trials but changes particularly in the wind and surface conditions between measured runs still make direct comparisons difficult.

2.4 Use of a reference condition

An approach to obtaining comparative drift risk data from field trials involves using a test and reference application systems mounted on the two sides of a boom sprayer each applying tracers that can be independently quantified (Gilbert and Bell, 1988). This method then gives a direct comparison of the drift risk between systems that can be mapped over a range of application conditions – e.g. wind speeds – see Miller *et al.*, 1991.

Spray drift profiles can vary with distance away from the treated area and with height above the ground. Statistics describing drift can therefore vary depending upon the measure and the position of samples taken. Some of the variability can be removed by defining a reference system as the basis for a comparative measure of drift and the 110^{o} conventional flat fan hydraulic pressure "03" nozzle operating at a pressure of 3.0 bar (FF110/1.2/3.0) has been taken as the reference for the LERAP scheme in the UK, for the DIX scheme in Germany and the classification method used in The Netherlands. When comparing with a reference system, it is still necessary to define sampling distance and heights in order to give comparable statistics.

3. Application systems that have been shown to reduce spray drift

Drift-reducing application systems, when referenced to conventional hydraulic pressure flat fan nozzles operating with a conventional boom sprayer design, can be grouped into the following classes:

(i) those that increase droplet size and/or reduce the percentage of spray volume in droplets in the smaller size classes:

(a) Pre-orifice nozzles and spinning discs, which generate conventional droplets;
(b) Air-induction nozzles and twin-fluid nozzles, which generate air included droplets;

(ii) those that use directed air streams to deliver the spray to the target, known as 'air assistance'

(iii) those based on the use of shrouds to prevent air flows due to the natural wind and forward from detraining spray droplets.

Of these systems, the most commonly-used is the air-induction nozzle (accounting for 22% of sprayed area, according to Garthwaite, 2004), with a smaller percentage of arable land being sprayed with twin fluid nozzles (6%). There is no data available on the use of other drift-reducing systems, but it would be anticipated that only pre-orifice nozzles and air assistance might be used in practice in the UK.

3.1 The pre-orifice flat fan nozzle design

This nozzle design commonly uses a circular metering orifice in the upstream part of the nozzle body and a relatively large final orifice to form a fan-shaped spray. Since pressure is dropped across the metering orifice the pressure drop across the final larger orifice is low and hence relatively large droplets are formed travelling at lower speeds than from conventional nozzles operating with the same pressure/flow rate characteristics. Drift reductions in comparison with conventional nozzles in the order of 50% are commonly achieved, although there is a reducing advantage in terms of drift reduction over conventional nozzles with increasing nozzle size. Measurements of droplet size distributions (percentage of spray volume in droplets <100 μm in diameter) and airborne spray profiles in wind tunnel tests in which the drift potential of a range of sizes of pre-orifice nozzle were compared with the equivalent design showed that for the smallest sizes (an "015"), drift reductions of 52% were recorded while for larger sizes ("04"), the reduction in drift was 33% (Castell, 1993). Good agreement was obtained between drift reductions assessed from either droplet size distributions or direct airborne spray profiles measured in a wind tunnel.

The "Turbo TeeJet" is also a version of pre-orifice flat fan nozzle in which the final outlet orifice is an anvil rather than a conventional fan tip design. There are relatively few published data defining the physical characteristics of this nozzle type although published LERAP Low Drift star ratings for this design indicate that it gives similar or slightly higher drift reductions than the more conventional pre-orifice flat fan design.

3.2 Air-induction nozzles

This nozzle design also employs a pre-orifice and an air entry between the initial and outlet orifices such that air is drawn into the nozzle body by a Venturi action. Many designs use a long mixing section as part of the nozzle to facilitate good mixing of air and spray liquid before the spray is delivered via a relatively large fan-shaped orifice.

Research has shown that:

- there is a wide range of performance for versions of this nozzle design produced by different manufacturers (Piggott and Matthews, 1999; Butler Ellis *et al.*, 2002; Miller and Tuck, 2005):

- different sizes of this nozzle design do not follow the same trends as for other nozzle designs and there is no correlation between nozzle size and droplet size: droplet sizes produced by nozzles from different manufacturers do not rank in the same order across the range of nozzle sizes;

- the design is able to achieve reductions in drift of more than 75% particularly with the smaller nozzle sizes and the majority nozzles qualifying for LERAP Low Drift three star ratings in the UK are of the air-induction type.

There are versions of the "Turbo TeeJet" that operate with an air inlet but there is currently little published data relating to the performance of this nozzle design.

Research into the performance of air-induction nozzles showed that the levels of sedimenting drift produced by commercial and prototype air-induction nozzles was strongly correlated with droplet size distribution (Butler Ellis *et al.*, 2001). This is shown in Figure 1, where the relationship between drift (expressed as a predicted environmental concentration, PEC, relative to that produced by the air-induction nozzle which gave the highest drift and smallest droplet size) and relative VMD is shown for a range of air induction nozzles, sizes and pressures.

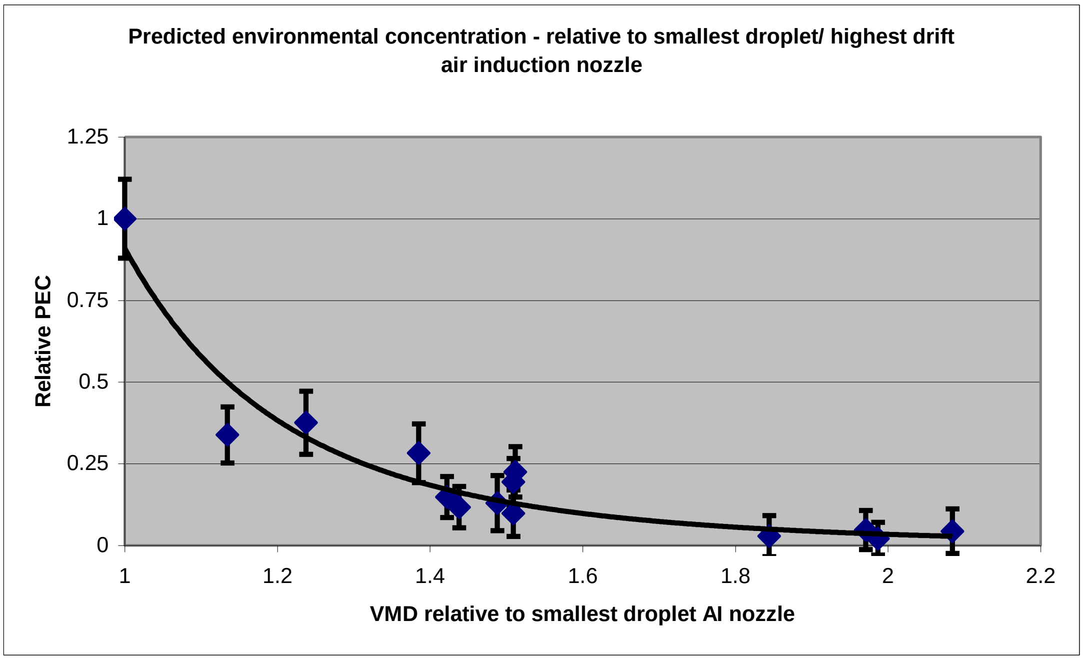

Figure 1. Relationship between relative predicted environmental concentration, PEC, (calculated according to Walklate *et al*, 2000) and relative volume median diameter (VMD). VMD and PEC are evaluated relative to the Billericay Bubblejet "02" nozzle operating at 3.0 bar.

3.3 Twin-fluid nozzles

In this design, air and spray liquid are fed into the nozzle body under pressure and the flow rate and spray quality can be adjusted by varying the air and liquid pressures independently. Field and wind tunnel studies have shown that this system typically produces in the order of 50% of the drift of conventional flat fan nozzles operating at comparable flow rates. It has been postulated (Miller *et al*., 1991) that this drift reduction is achieved by:

- the effect of a different structure within the spray fan formed immediately downstream of the nozzles such that it is relatively porous to air flows generated by the wind and forward speed of the spraying vehicle;
- generating a relatively large droplet size distribution within the spray and with the larger droplets having air inclusions within them;
- the action of the air used in the spray formation process exhausting through the output anvil nozzle.

Twin-fluid nozzles can operate to give levels of drift that are less than 25% of those from the LERAP reference system (i.e. gain a three star rating) but with current commercial designs this is achieved by operating at very low input air pressures (,0.5 bar that can be difficult to maintain accurately) to give a relatively large droplet size.

3.4 Air-assistance

An important commercial objective in the development of air-assisted boom sprayers has been to facilitate the use of fine sprays and low application volumes while also delivering advantages relating to reducing spray drift and increasing penetration into crop canopies (Taylor and Andersen, 1997). Drift reductions are achieved by increasing the velocity of the small droplet component in the spray by the interaction of the formed spray with a downward directed airflow. Results reviewed by Taylor and Andersen (1997) suggested that drift reductions in the range 61 to 90% could be achieved by using air assistance with the greatest reductions being recorded in relatively dense crop canopy situations. However, an examination of LERAP Low Drift three star ratings that have been awarded for this system, based on published literature, and particularly that by van de Zande *et al.*, (2002), suggests that high levels of drift reduction are not achieved when using fine sprays at low volume rates. It is also likely that the matching of air speed to crop canopy, surface and weather conditions may also be necessary to optimise the drift reductions that can be achieved with this type of system although there is little published data linking air delivery settings to drift control for this type of machine.

3.5 Shrouds and deflectors

Wolf (circa 1993) reviewed the results from a range of field tests conducted in Canada in the period 1986 to 1991 examining the drift performance of a range of shielded boom and shrouded nozzle designs. He concluded that drift reductions in the range 65 to 85% could be achieved when using shields and operating with fine sprays at low application volumes. Lower drift reductions of around 25% were achieved by using nozzle shrouds.

Work reported by Gohlich (1985) suggests that airborne spray observed 1.0 m downwind of a treated area and in a wind speed of 4.0 m/s at boom height could be reduced by approximately 66% by the use of a double profile boom incorporating an ”air foil” system. It was also claimed that the air movements generated by the “air foil” increased the coverage and deposition on cereal crop plants and reduced ground deposits by 30 to 50% at application volumes of between 100 and 200 L/ha.

In the UK although a number of prototype systems have been developed and evaluated, the use of shielded booms and shrouds around nozzles has not gained any commercial position except in relation to small specialised machines for treating amenity areas such as golf courses. The reasons for this probably relate to:

(a) the need to fold machines to meet with transport requirements on roads and a maximum height restriction during the folding action that requires boom structures to be as simple as possible;
(b) the risks associated with contamination of a boom structure with an increased surface area, particularly regarding the need to clean such machines in the field;
(c) difficulties in monitoring or observing the sprayer operation if it is occurring within a shrouded zone.

The use of shielded booms and shrouded nozzles is not expected to increase during the foreseeable future and is not regarded as a practical route to achieving drift control on UK arable farms.

4 <u>Other relevant application parameters that influence drift</u>

4.1 Boom height

Spray drift has been shown to be strongly dependent on boom height (Miller 1999, Nuyttens *et al.*, 2006). Recent work in the wind tunnel at Silsoe (unpublished as yet, Fig. 2) showed a four-fold increase in drift by increasing nozzle height from 0.5 m to 0.7 m, and a ten-fold increase when raised to 1.0 m height, for a conventional flat fan nozzle. An air-induction nozzle showed a much lesser response to boom height, with a four-fold increase in drift between 0.5 m and 1.0 m height.

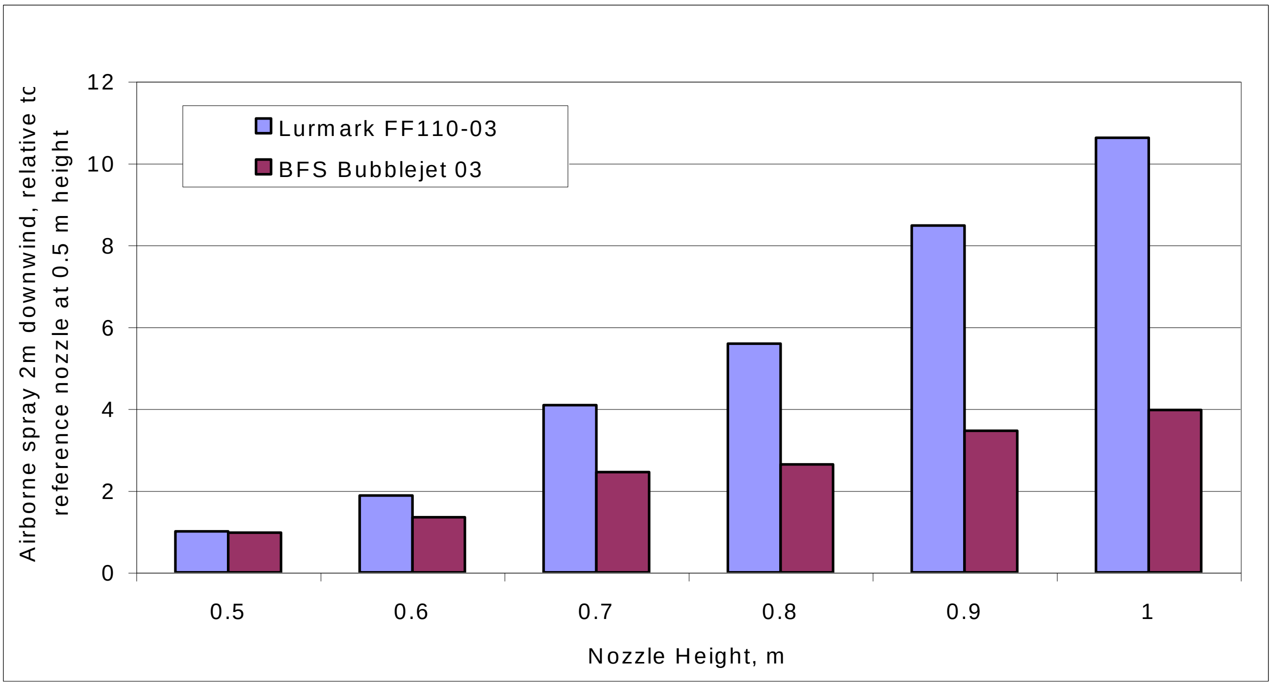

Figure 2. Wind tunnel data showing the effect of nozzle height on airborne spray 2 m downwind.

110^{o} flat fan nozzles are generally recommended to be used at a height of around 0.5 m above the crop. This can be challenging to achieve, particularly with wider booms and faster forward speeds when adequate boom stability can be difficult to maintain. A boom that dips too low will give poor coverage of the target area and in some situations might risk colliding with the ground. Consequently, spray operators will tend to increase boom height to ensure that the minimum height is always maintained. The result is likely to be significantly increased levels of drift.

4.2 Forward speed

The need to increase work rates means that there are trends towards using higher speeds and lower application volumes. For a given volume, increasing speed involves using a larger nozzle and this might be expected to reduce the risk of drift. However, research has also shown (Miller and Smith, 1997; Ghosh *et al.*, 1993) that forward speed is an important component in the detrainment of small droplets which can then be transported greater distances before depositing on the ground. There has been little research to examine the interactions between nozzle size and forward speed and this is an area requiring further investigation. Higher forward speeds and smaller nozzle sizes typically associated with application volumes of less than 100 L/ha can pose an increased risk of drift when compared with the reference FF110/1.2/3.0 nozzle travelling at 8.0 km/h to apply 180 L/ha.

The effect of forward speed is probably less than that of boom height, but the relatively high forward speeds which are now becoming common, combined with increasing boom width, are the main reason for increasing boom height and so the overall effect will be further exaggerated.

Systems that can maintain boom stability for large boom widths and increased forward speeds could have a significant effect on keeping levels of drift low as well as maintaining efficacy by ensuring adequate distribution of pesticide over the crop.

4.3 Tank Mix

The physico-chemical properties of the spray liquid have been shown to have an important effect on spray drift (Butler Ellis and Bradley, 2002). In particular, surfactants, which are generally part of the formulation and may also be added as tank mix adjuvants, can be an important component of ensuring product efficacy and yet are known to increase spray drift. Research has also shown that formulations that are based on solutions and include surfactants are likely to give higher levels of drift than those involving emulsions and suspensions. The need to control drift may therefore be greater for some products, and some tank mixes of products, than others.

Some additives have been formulated specifically to reduce drift when added to a tank mix but the use of these is not common in the UK. The use of large chain molecules to increase viscosity has been shown to give a drift performance that varies with time as materials are re-circulated in the sprayer (Zhu *et al*., 1997).

5. Efficacy and Application

The objectives of spray application are to achieve the timely and efficacious application of pesticides whilst minimising drift. In today’s commercial climate there is a need to maximise work rates by adopting wide booms, low volumes and high forward speeds. All these can, directly or indirectly, increase spray drift.

There is a growing body of evidence that suggests an interaction between nozzle type and water volume with respect to product efficacy, so that it is not possible to review these factors entirely separately. With conventional hydraulic nozzles, drift increases with reduced nozzle output (and lower water volumes) and therefore the need to control drift is greater as volumes reduce.

Pesticide manufacturers generally recommend on their label a volume of application of 200 L/ha. It is important to note that this is not a ‘gold’ standard but merely the volume that can easily be applied by knapsack sprayers in field trials during the development of a product.

Experimental evidence suggests that for most situations, an application volume of 100 L/ha provides equivalent, or better, levels of biological performance for herbicides and fungicides to 200 L/ha (Morley Archive, Knoche, 1994, Butler Ellis *et al*, 2007).

The recent survey (Garthwaite, 2004) suggests that farmers, on average, are applying pesticides in an average volume of 150 L/ha, with a significant proportion of arable land being sprayed at volumes around 100 L/ha and lower.

There is a common belief that droplet size and efficacy are negatively correlated, i.e. the larger the droplet the poorer the biological control. There is some evidence to support this, particularly for the case of herbicides (Knoche, 1994) although a significant minority of the trials reviewed by Knoche showed the opposite to be true. This belief is, at least in part, responsible for the conviction that large-droplet low-drift nozzles cannot give as good control as conventional flat fan nozzles.

5.1 Air-Induction Nozzles

5.1.1 Fungicide application

There have been a number of experiments comparing air-induction nozzles with standard flat fan nozzles for the application of foliage acting fungicides to control foliage disease in cereals. Some show that for applied volumes of 100 L/ha and above, air induction nozzles give equivalent levels of disease control to standard flat fans (The Morley Archive, Butler Ellis *et al.*, 2006, Marshall *et al.*, 2000), whereas others show poorer performance (Butler Ellis *et al.*, 2004). Air-induction nozzles also gave at least equivalent control to standard flat fan nozzles for fungicides applied to the ears of wheat (Parkin *et al.*, 2006). In Denmark, both pre-orifice nozzles and air-induction nozzles have provided at least as effective control as standard flat fan nozzles with some fungicides for potato blight (P K Jensen, University of Aarhus, personal communication). Butler Ellis *et al* (2004 and 2006) showed that the droplet size produced by the air-induction nozzle was an important factor, with ‘small’ and ‘medium’ droplet air induction nozzles generally performing as well as conventional nozzles at volumes down to 50 L/ha, with ‘large’ droplet air induction nozzles performing significantly worse at all volumes.

It is necessary to describe the performance of all nozzle systems with respect to the droplet size distributions produced in relative terms because numerical values for droplet size parameters are a function of the measuring system and type of sample taken. For this reason, the BCPC spray/nozzle classification scheme has been developed (Doble *et al*., 1985) and has been used successfully with conventional nozzle designs. This system does not relate directly to nozzles creating sprays with air included droplets. Specifications for “small droplet”, “medium droplet” and ”large droplet” air-induction nozzles will therefore also depend upon the measurement systems used to determine droplet size distributions. An indication of typical droplet size values for these nozzle specifications can be seen from published size data obtained with three different measuring arrangements (Miller and Tuck, 2005). This suggests that “small droplet” air-induction nozzles will have a volume median diameter (vmd) in the range 350 – 425 μm, “medium droplet” air induction nozzles a vmd in the range 425 – 500 μm and “large droplet” air induction nozzles a vmd of between 500 and 575 μm.

There appears to be no research on the impact on nozzle type for the control of stem base or root diseases in cereals with foliage applied fungicides.

4.1.2 Herbicide application

Wolf (2002) concluded that air included sprays can provide similar performance to conventional sprays provided the operator is given information on how to make initial nozzle selections and optimise their operation.

While air-induction nozzles have been shown to be as effective as standard flat fan nozzles when using volumes 100 L/ha and above, (Robinson *et al*, 2001, Butler Ellis *et al.*, 2005), there is evidence of an interaction between droplet size and target size such that the larger droplet air-induction nozzles combined with small targets may give reduced performance. Miller *et al.,* 2003 concluded that air induction nozzles are not as effective as the equivalent standard flat fan nozzles when applying foliage-acting herbicides to small weeds. This is likely to be a result of poorer collection efficiencies for small targets and large droplets, and also the more uneven levels of deposit from air induction nozzles resulting in small targets having a higher probability of receiving inadequate doses of herbicide (Butler Ellis *et al.,* 2007). Experiments have clearly demonstrated that air induction nozzles from different manufacturers were likely to provide different levels of weed control, despite the fact that they both had the same throughput at specified pressures (Miller *et al.,* 2003). This was most likely due to significant differences in drop size between the two air induction nozzles. Hence, it is important to avoid making generic conclusions on the biological efficacy of air-induction nozzles because similarly rated air-induction nozzles may have very different drop size distributions (Piggott and Matthews, 1999).

There is little information on the impact of nozzle type when attempting to control small weeds with a foliage-acting herbicide under a dense crop canopy that can occur in winter crops at around the ear at one cm stage, although a single experiment by Robinson *et al.,* (2001) showed no significant differences in control between conventional and air-induction nozzles, but there was a suggestion that at 100 L/ha, conventional nozzles performed most consistently. At this growth stage there may also be a requirement for the control of stem base or root diseases with foliage applied fungicides and for the application of plant growth regulators. These all share the same challenge of transferring pesticide through to the base of a crop canopy.

Droplets from air-induction nozzles might be expected to be less able than conventional droplets to penetrate a canopy due to their lower velocities (Butler Ellis *et al.,* 2001), although Marshall *et al.,* (2000) showed greater deposition on the lower leaves of a cereal canopy with an air-induction nozzle than with a conventional nozzle.

Klein *et al*., (2006) concluded that the efficacy of glyphosate was insensitive to application and therefore nozzle selection could be made entirely on the basis of drift control.

Few comparisons have been made on the impact of nozzle type for the application of soil applied herbicides because retention of droplets is not a problem and a high level of surface coverage is not thought to be required. Palmer and Blance (2005), reporting experiments carried out on a site with very high levels of resistance to herbicides in black-grass (*Alopecurus myosuroides*) showed no differences in efficacy between nozzle types, including pre-orifice, air-induction and extended range types of flat fan nozzle.

Field experience suggests that there is less flexibility in all the factors, including nozzles, which affect efficacy in the presence of resistance. The preliminary results of a current experiment being conducted jointly by The Arable Group and Agrovista Ltd indicate that air induction nozzles are providing inferior control of black-grass to flat fan nozzles, particularly angled variable pressure flat fan nozzles that are alternating facing forwards and backwards along the boom. The site has very herbicide resistant black-grass and the seedbed was cloddy; both factors that may demand good distribution of herbicides. In addition, the herbicides used, flufenacet and pendimethalin, are not very soluble and enter the plant through the emerging shoot, thus presenting a small target and demanding a good surface distribution.

5.1.3 Plant growth regulators

There is little available research on the application of plant growth regulators in cereals. Limited information suggests that air-induction nozzles can provide equivalent shortening of the crop to standard flat fan nozzles when used at 200 L/ha but inferior shortening at a spray volume of 80 L/ha (Robinson – Personal communication with data). This result complies with general advice given in France that suggests that any loss of efficacy because of the adoption of air-induction nozzles at volumes of around 80-100 L/ha can be overcome by increasing the volume of application (P Y Yeme, Personal communication).

5.1.4 Insecticides

No information has been found relating to the use of air-induction nozzles to apply insecticides to arable crops from boom sprayers operating under UK conditions. Results of a study conducted in the US by Leonard *et al*., (2006) examined the treatment of cotton pests using both air-induction and hollow cone nozzles. They found that the efficacy levels when using the air-induction design was consistently lower than for the hollow cone nozzles and this is likely to relate to the droplet size requirements for this type of target.

5.2 Twin-fluid nozzles

Field trials with commercial designs of twin-fluid nozzle have given a range of results probably reflecting the flexibility of this nozzle design to produce a wide range of physical spray characteristics depending upon the air and liquid pressures at input to the nozzle. A review of the performance of a twin-fluid nozzle including spray retention on plant surfaces reported by Miller *et al*., (1990) showed that retention was reduced as volume was increased from 100 to 200 L/ha. Similar trends can be observed in field trials results reported with this system with levels of efficacy greater or equal to that of conventional systems when the unit was operating at low volumes (<100 L/ha) and fine/medium spray qualities (e.g. Robinson, Private communication: Cooke and Hislop, 1987) but poorer performance at higher volumes and coarser sprays (e.g. Jeffrey and Rutherford, 1990). Butler Ellis *et al.,* (2007) showed that twin-fluid nozzles, set to give a coarse, low-drift spray, gave equivalent performance of a fungicide application to a conventional flat fan nozzle.

5.3 Pre-orifice nozzles

Relatively few field trials have been undertaken examining the efficacy of pre-orifice nozzles in arable crop conditions. Some information can be implied from trials that have used low pressure flat fan nozzles to generate a large droplet size distribution. Results reported by Western and Woodley (1987) indicated that the larger droplets gave lower levels of retention and in some circumstances this was reflected in reduced levels of efficacy. There is some evidence from herbicide application experiments in Denmark (Jensen, 2006), suggesting that efficacy with pre-orifice nozzles may be poorer than conventional nozzles.

5.4 Forward speed

The mean forward speed of sprayers in commercial practice is approximately 10 - 11 km/h, with a significant proportion of arable land being sprayed at forward speeds greater than 12 km/h (Garthwaite, 2004). Many application experiments are done at lower forward speeds.

There is a suggestion in experiments that increasing forward speeds above 8 km/h may provide increased deposit on vertical targets (Webb *et al.*, 2004, Butler Ellis *et al.*, 2007) and improved biological performance (Morley archives, Marshall *et al.*, 2000). However, there is some evidence that efficacy may be reduced at speeds of 16 km/h and above; the more so when volumes significantly below 100 L/ha are being used, particularly with air induction nozzles (Morley archives). One potential cause of this loss of efficacy is the loss of boom stability resulting in uneven spray distribution. Relevant boom movements are both in the roll and yaw directions and a number of studies have been conducted aimed at improving boom suspension performance and establishing methods by which boom suspension performance can be assessed (Sinfort *et al*., 1997).

5.5 Air-assistance

The use of air-assistance in transporting the spray to the crop does not influence the droplet size distribution, but can change the quantity and distribution over the target. Inappropriate amounts of air could give poorer efficacy, crop damage and/or poorer drift control. Particular problems have been reported verbally with higher levels of air-assistance due to the movement of soil particles resulting in abrasion to plant stems

Results reviewed by Taylor and Andersen (1997) suggest that the use of air-assistance can manipulate both the magnitude and distribution of target deposits with implications for efficacy. For example, spray retention of the stems of a winter wheat crop were increased by 26% when using a vertical air curtain and by 60% when the air curtain was angled rearwards. Using air-assistance when applying diquat to desiccate linseed at application volumes of 100 to 400L/ha, reductions in crop moisture of up to 33% were achieved with the largest reductions achieved at the lowest application volumes. Treating potato crop canopies with air-assistance increased the under-leaf coverage substantially and the numbers of aphids post treatment in the air-assisted plots was less than 20% of those in the conventionally treated plots. Leonard *et al.,* (2000) demonstrated equivalent blight control in potatoes with and without air-assistance, Jensen (2002) showed improved control of ryegrass with the addition of air assistance, although the settings used and therefore the likely drift reduction was not reported in either case.

6. <u>Discussion</u>

From a practical point of view, air-induction nozzles, which are the most cost-effective and widely-used spraying system for controlling spray drift, are the most important for consideration when evaluating drift and biological control. While there is evidence that droplet size is an important component in determining efficacy with both conventional and air-induction nozzles, the experimental evidence suggests that the presence of air inclusions is also an important factor and therefore there are many situations where the larger droplet size produced by air-induction nozzles compared with conventional flat fans does not result in poorer biological control.

Figure 3 shows the effect of droplet size on the form of the deposit. The more patchy distribution from air-induction nozzles results in a higher coefficient of variation of pesticide deposit between small target plants and offers a possible explanation for poorer control of small weeds with foliage-acting herbicides (Miller *et al*, 2003). The circles drawn on Figure 3 have not been accurately scaled and are used to illustrate the likely scale of variation in deposit with different nozzle designs. However, it is estimated that the circles are of approximately 25 mm diameter.

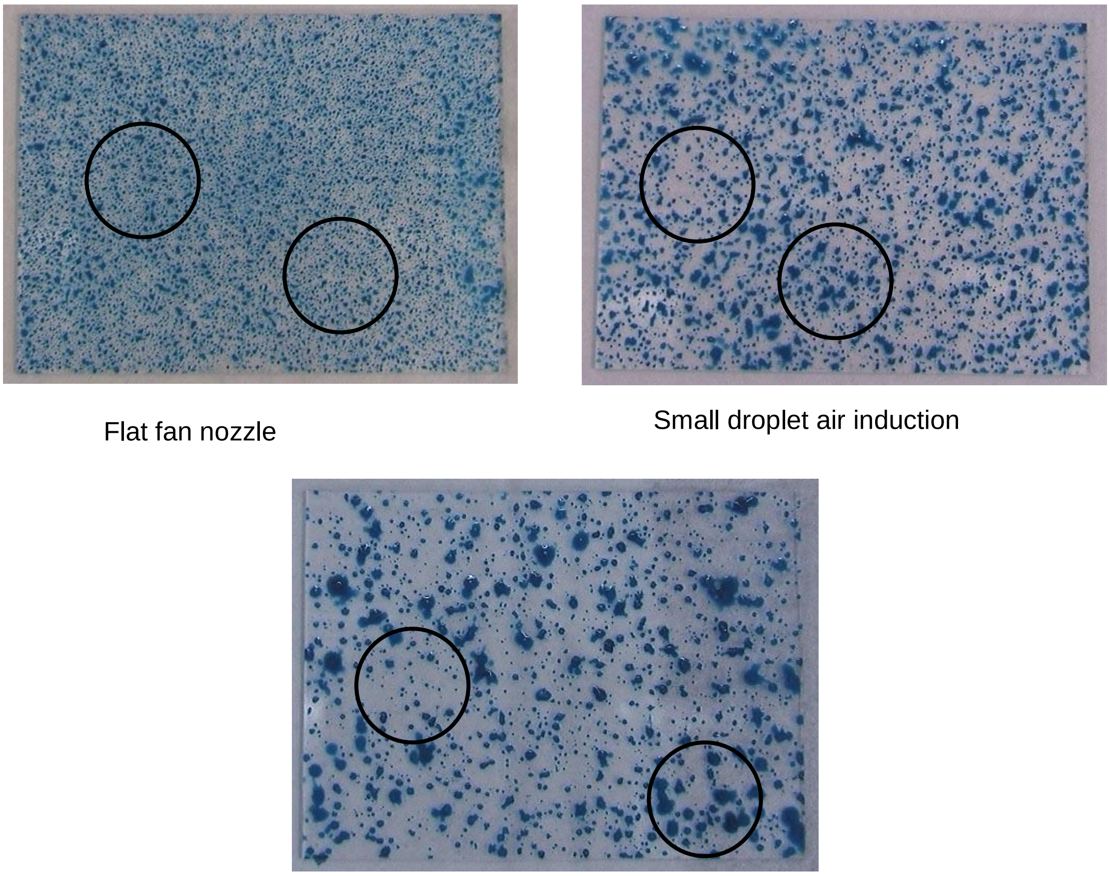

Figure 3. The effect of nozzle type on the form of the deposit, and how potential variability in quantity deposited on small targets increases with droplet size.

The correlation between droplet size and efficacy has not yet been satisfactorily explained. Experiments where physical and biological results of spray application have been recorded suggest that:

- Reducing droplet size increases the quantity retained on the target yet biological efficacy is not explained by the amount of pesticide on the target (e.g. Parkin *et al.*, 2003, Robinson *et al.*, 2001);
- Reducing droplet size increases the coverage of the target, in terms of the percentage area of the target covered by spray solution, and can be associated with efficacy, although increasing coverage by increasing application volume does not have the same effect (Butler Ellis *et al.*, 2007);
- There is evidence to suggest that the coefficient of variation of pesticide deposition between target plants is important (Butler Ellis *et al.,* 2007), and this increases with droplet size but only becomes apparent at the very large droplets associated with some air induction nozzles
- It is more important to achieve pesticide deposition on some parts of the plant rather than others (Merritt, 1982 a and b) and yet we have a very limited understanding, and little relevant data, that links application system with distribution of spray over the target plant.

As well as influencing coverage and variability of quantity deposit, droplet size also influences the distance between deposits, which may be another factor in determining the efficacy of the application. A simple model of deposit on a flat surface shows that the same level of coverage can be achieved with two different volume rates by manipulating the droplet size, but the mean distance between deposits will be highest for the larger droplet size/higher volume setting (Figure 4). It also shows that the difference in estimated coverage between small and large droplet air induction nozzles is relatively small, but there is a much greater difference in mean deposit distance between the two, supporting the hypothesis that this might be linked to efficacy in some instances.

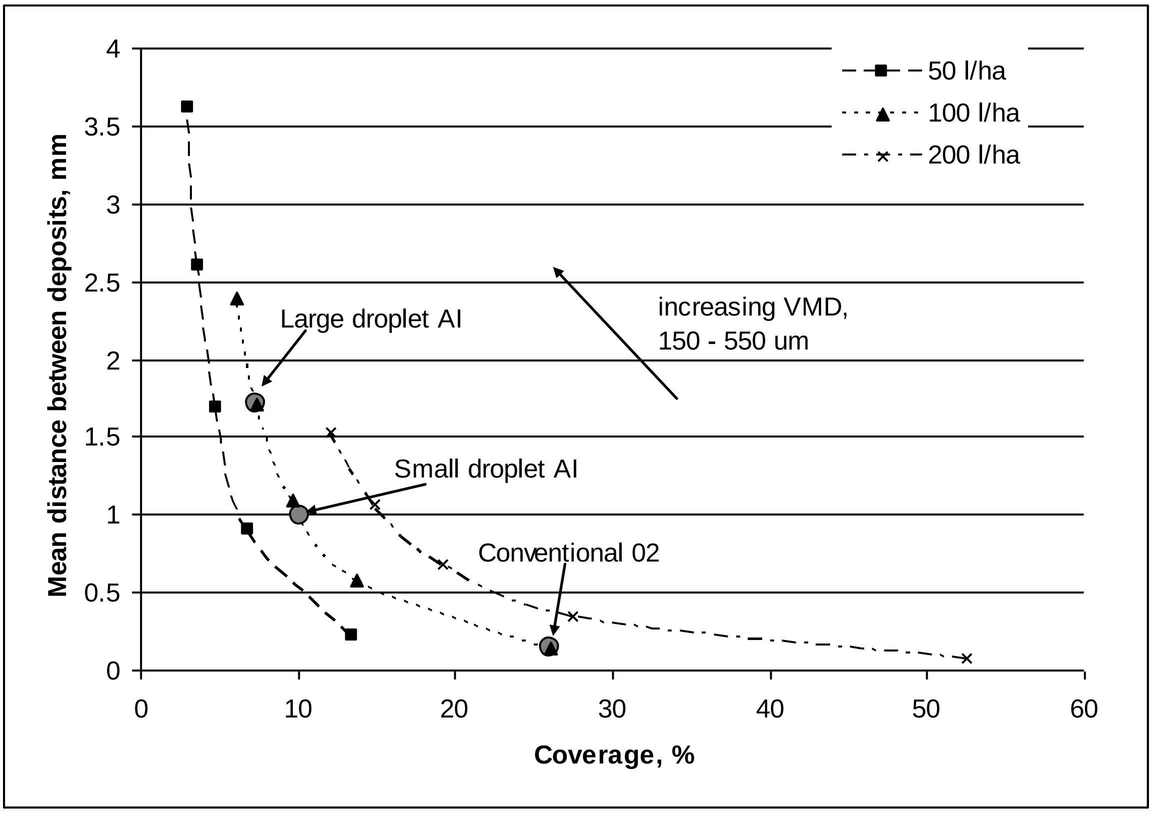

Figure 4. Output from a simple model of a distribution of deposit sizes evenly spread over a horizontal surface showing the likely relationship between droplet size distribution, volume rate, coverage and mean deposit separation.

Future work to investigate the interactions between the factors shown in Figures 1 and 4 and efficacy will allow the relationship between drift and efficacy to be defined for particular product/crop/application combinations. This will in turn enable users to select the most appropriate application settings for minimising drift and optimising efficacy.

The use of air-induction nozzles on conventional boom sprayers is a relatively low cost means of achieving drift control. The use of both twin-fluid nozzles and air-assisted sprayers provides greater flexibility and the potential to adjust spray delivery to match conditions but at the costs of higher capital investment, increased operating costs and a more complex system to operate effectively. Given that the results from this review indicate that for many targets, levels of efficacy can be maintained then the use of such systems should be adopted where possible. Feedback from TAG members and others suggests that many technically-aware farmers have adopted, as the default standard application method, volumes of 100 L/ha applied through appropriate air-induction nozzles at forward speeds of 12–14 km/h. They believe this has provided the ability to achieve high work rates and biological effectiveness (in part due to timely application) whilst significantly reducing spray drift (and typically compliance with LERAPs) when compared to the standard flat fan equivalent. Standard flat fan nozzles are adopted on these farms only for specific instances, such as the application of foliage acting herbicides to small weeds. In particular, air-induction nozzles are adopted to apply fungicides to wheat from the second node detectable stage onwards.

The results of this review have shown that for boom sprayers operating over arable crops in the UK, substantial reductions in drift can be achieved by using air-induction nozzles. If designs giving a relatively small droplet size are used, then there are no detectable risks to efficacy when treating cereals from growth stage GS 31 in cereals and onwards. It should be noted that air-induction nozzles giving a relatively small droplet size distribution will not give as large a drift reduction over conventional nozzles compared with designs giving a larger droplets size. However, when operating in areas where drift control is particularly important, such as at the edge of a field, then further drift reductions can be achieved by:

(i) Ensuring that the boom is at its lowest height above the crop consistent with establishing a uniform volume distribution pattern;
(ii) Reducing travelling speed so as to reduce the detrainment of small droplets from the spray and improve boom stability.

7. Conclusions

Air-induction nozzles can significantly reduce drift and have been shown to give equivalent biological control to flat fan nozzles in a wide range of situations. However, there may be some circumstances where particular target sizes, volumes, forward speeds and product resistance cause a reduction in control with air-induction nozzles.

- Small-droplet air-induction nozzles can provide the equivalent control of foliage diseases of cereals as standard flat fan nozzles for foliage acting fungicides when applied at volumes of 100 l/ha and, for cereal fungicides, with forward speeds up to 16 km/h. Research in Denmark has come to the same conclusion for some fungicides for the control of potato blight.

- Air-induction nozzles provide the equivalent control to standard flat fan nozzles of cereal ear diseases with foliage acting fungicides. The impact of volume of application has not been fully evaluated in experiments.

- Standard flat fan nozzles give better control than air-induction nozzles with foliage acting herbicides for small weeds of less than three leaves for grasses and perhaps for broad-leaved weeds less than approximately 2.5 – 5.0 cm across. Air-induction nozzles provide equivalent control to standard flat fan nozzles of larger weeds with foliage acting herbicides. Limited information about soil-acting herbicides suggests equivalent performance with air-induction nozzles.

There appears to have been little or no application experimentation on the efficacy of insecticides when applied through air-induction nozzles in Northern Europe.

Unlike standard flat fan nozzles, the spray quality varies significantly between nominally similar air-induction nozzles from different manufacturers and there is some evidence that this can influence biological efficacy, with smaller droplet air-induction nozzles tending to give better performance than the largest droplets. Hence, there is a danger of arriving at generic conclusions on the efficacy of air induction nozzles on the assumption that other nozzles with the same flow rate and pressure have a similar droplet spectrum.

It is possible that increasing the volume of application with air induction nozzles will overcome any decrease in biological control at volumes of approximately 100 L/ha.

Twin-fluid nozzles would be expected to be able to produce a range of droplet sizes for a given flow rate and could therefore produce a small droplet air included spray (with highest efficacy and least drift control) or a large droplet air included spray (with poorer efficacy but highest drift control), depending on the settings used.

Limited evidence suggests that pre-orifice nozzles may be less flexible than air induction nozzles in terms of target deposition and potential efficacy and the drift reductions over conventional flat fan nozzle designs achieved will be lower than for air-induction nozzles.

The interaction between nozzle type and spray volume at commercially adopted forward speeds has not been extensively tested.

The increase in work rates has, in some situations, resulted in an increased risk of spray drift because of smaller droplet sizes, higher forward speeds and wider booms. Maintaining the correct boom height is critical in terms of spray drift control.

8. Recommendations for further work.

It is impossible to research all the combinations of pesticides and targets that are used in practice and hence a focussed approach is required to investigate principles that may present particular issues. On this basis, more research information is desirable on:

- Optimising nozzle selection, nozzle angle, volume and forward speed for the control of targets at the base of a crop canopy: Crop canopies in cereals are at their most dense for key applications at around the ear at 1 cm stage and this is a very important pesticide timing; hence this is a priority for research;
- Determining how to overcome instances where air-induction nozzles produce inferior efficacy to conventional flat fan nozzles at volumes around 100 L/ha – e.g. by increasing the application volume: This will provide the information necessary on the feasibility of the universal adoption of air-induction nozzles that in turn will provide significant reductions in spray drift;
- Obtaining generic information on the impact of spray volume on the efficacy of the individual components of complex tank mixes;

- Identifying the characteristics of air-included sprays that give control equivalent to conventional flat fan nozzles and developing a classification scheme for such sprays to ensure users have access to appropriate information;
- Examining the performance of air-induction nozzles over a wide range of operating pressure in terms of the volume distribution pattern, droplet sizes and velocities: does operating such nozzles at higher pressures give a droplet size distribution and drift reduction that would facilitate the wider use of such designs?;
- Investigating the relationships between nozzle spray angle, boom height and drift so that appropriate recommendations can be given for nozzle choice and boom height for optimising spray distribution and minimising drift.

References

Butler Ellis, M.C.; Swan, T.; Miller, P.C.H.; Waddelow, S.; Bradley, A.; Tuck, C.R. (2002) Design factors affecting spray characteristics and drift performance of air induction nozzles. *Biosystems Engineering,* **82**, (3), 289-296.

Butler Ellis, M.C.; Knight, S.; Miller, P.C.H. (2006) The effects of low application volumes on the performance of a T2 fungicide application. *Aspects of Applied Biology,* **77** International Advances in Pesticide Application, 433-438.

Butler Ellis, M.C.; Scotford, I.; Robinson, T.H.; Knight, S. (2004) *Aspects of Applied Biology*, **71**, International Advances in Pesticide Application, 223 – 230

Butler Ellis, M.C.; Bradley, A. (2002) The influence of Formulation on Spray Drift. *Aspects of Applied Biology*, **66** 251-258

Butler Ellis, M.C.; Bradley, A.; Tuck, C.R. (2001) The characteristics of sprays produced by air induction nozzles. *Proceedings of the BCPC Conference*, Nov 2001, 665-670

Butler Ellis, M.C.; Lane, A .G.; Knight, S. (2005) The low volume application of herbicides. *The BCPC Congress – Crop Science and Technology*, 2005, 909 – 914

Butler Ellis, M.C.; Knight, S.; Miller, P.C.H. (2007) Spray behaviour and efficacy of herbicides and fungicides applied to wheat at reduced volumes. HGCA project report 408

Castell, J.A. (1993) The development of drift reducing hydraulic fan nozzles. Proceedings, *International Symposium on Pesticide Application, Strasborg*, 227 – 234.

Cooke, B.K.; Hislop, E.C. (1987) Novel delivery systems for arable crop spraying – deposit distribution and biological activity. *Aspects of Applied Biology*, **14,** Studies of pesticide transfer and performance. 53 – 70.

Doble, S.J.; Matthews, G.A.; Rutherford, I.; Southcombe, E.S.E. (1985) A system for classifying hydraulic nozzles and other atomisers into categories of spray quality. Proceedings, *British Crop Protection Conference – Weeds,* 3, 1125 – 1133.

Garthwaite, D (2004) A summary of the results of a survey of Farm Sprayer Practice. *Aspects of Applied Biology*, **71,** International Advances in Pesticide Application, 9 – 18.

Ghosh, S.; Hunt, J.C.R.; Phillips, J.C.; Miller, P.C.H. (1993) Dynamics of turbulent air-flow in droplet driven sprays. *Applied Scientific Research*, **51**, 257-262

Gilbert, A.J.; Bell, G.J. (1988) Evaluation of the drift hazards arising from pesticide spray application. *Aspects of Applied Biology*, **17**, 363-376

Gohlich, H. (1985) Deposition and penetration of sprays. BCPC Monogram No. 28. *Proceedings, Symposium on Application and Biology,* 173 – 182.

Herbst, A.; Ganzelmeier, H. (2000) Classification of sprayers according to drift risk – a German approach. *Aspects of Applied Biology*, **57**. Pesticide Application, 35-40.

Jeffrey, W.A.; Rutherford, I. (1990) An evaluation of some alternative application systems for spraying cereals in Northern Britain. Proceedings, *Crop Protection in Northern Britain, 251 - 258*

Jensen, P.K. (2002) Influence of air-assistance to flat fan and air-induction nozzles and the use of nozzle sledge on the activity of haloxyfop against ryegrass. *Aspects of Applied Biology,* **66,** International advances in pesticide application, 73-78

Jensen, P.K. (2006) Influence of volume rate on herbicide efficacy of flat fan, low drift and air induction nozzles under field conditions. *Aspects of Applied Biology,* **77,** International Advances in Pesticide Application, 439 – 444.

Knocke,M (1994) Effect of droplet size and carrier volume on performance of foliar-applied herbicides. *Crop Protection*, 13, 3, 163 – 178.

Klein, R.N.; Golus, J.A.; Martin, A.R.; Roeth, F.W.; Kappler, B.F. (2006) Glyphosate efficacy with air induction, extended range, Turbo Floodjet and Turbo TeeJet nozzle tips. *Aspects of Applied Biology***, 77** International Advances in Pesticide Application 453 – 460.

Leonard, B.R.; Gore, J.; Temple, J.; Price, P.P. (2006) Insecticide efficacy against cotton insect pests using air induction and hollow cone nozzles. Proceedings, Beltwide Cotton Conference, Jan 2006.

Leonard, R.; Rice, B.; Dowley, L.J. (2000) The effect of air assistance on spray deposition and biological effect in the control of *Phytophthora infestans* in potatoes. *Aspects of Applied Biology*, **57,** Pesticide Application, 243-250.

Marshall, D J, Robinson, T H, Scott, T A J (2000) The effects of forward speed, spray quality and nozzle types on the deposition and biological performance of strobilurin fungicide. *Aspects of Applied Biology,* **57** Pesticide Application, 235-242

Merritt, C.R. (1982(a)) The influence of form of deposition the phytotoxicity of difenzoquat applied as individual drops. *Annals of Applied Biology*, **101**, 517 – 525.

Merritt, C.R. (1982(b)) The influence of form of deposition the phytotoxicity of MCPA,paraquat and glyphosate applied as individual drops. *Annals of Applied Biology*, **101**, 527 – 532.

Miller, P.C.H. (1999) Factors influencing the risk of drift into field boundaries. Proceedings, *Brighton Crop Protection Conference – Weeds*, 439 – 446.

Miller, P.C.H. (1993) Spray drift and its measurement. In: *Application Technology for Crop Protection* (eds. G. A. Matthews and E. C. Hislop), 101-122, CAB International.

Miller, P.C.H.; Hislop, E.C.; Parkin, C.S.; Matthews, G.A.; Gilbert, A.J. (1993) The classification of spray generator performance based on wind tunnel assessments of spray drift. Proceedings, *International Symposium on Pesticide Application. Strasbourg*, 1, 109-116.

Miller, P.C.H.; Powell, E.S.; Orson, J.H.; Kudsk, P.; Mathiassen, S. (2003) Defining the size of target for air induction nozzles. HGCA project report 317.

Miller, P.C.H.; Merritt, C.R.; Kempson,A. (1990) A twin-fluid nozzle spraying system: a review of research concerned with spray characteristics, retention and drift. . Proceedings, *Crop Protection in Northern Britain,* 243 – 250.

Miller, P.C.H.; Smith, R.W.; Tuck, C.R.; Walklate, P.J. (1995) The classification of agricultural sprays based on droplet size distribution and the results from wind tunnel tests. *Proceedings, Brighton Crop Protection Conference - Weeds,* 1125-1134

Miller P.C.H.; Smith R.W. (1997) The effect of forward speed on the drift from boom sprayers. *Proceedings, Brighton Crop Protection Conference – Weeds*, 399-407.

Miller, P.C.H., Tuck, C.R (2005) Factors influencing the performance of spray delivery systems: a review of recent developments. *Journal of ASTM International,* **2,** (6), June 2005.

Miller, P.C.H.; Tuck, C.R.; Gilbert, A.J.; Bell, G.J. (1991) The performance characteristics of a twin fluid nozzle sprayer. *BCPC/AAB Symposium on Air-Assisted Spraying in Crop Protection.* BCPC Monogram No. **46**, 97-106

Nuyttens, D.; De Schampheleire, M.; Steurbaut, W.; Baetens, K.; Verboven, P.; Nicolai, B.; Ramon, H.; Sonck, B. (2006) Experimental factors influencing the risk of drift from field sprayers, Part 2: Spray application technique. *Aspects of Applied Biology,* **77,** International Advances in Pesticide Application 331-339.

Palmer, M.J.; Blance, D.M. (2005) Adjuvant improves performance of pre-emergence residual herbicides in cereals. *The BCPC International Congress – Crop Science and Technology,* 2005, 453-458.

Parkin, C.S.; Miller, P.C.H.; Powell, E.S.; Orson, J.H.; Gill, J.; Magan, N.; Aldred, D. (2006) Improving the deposition and coverage of fungicides on ears to control Fusarium ear blight and reduce mycotoxin contamination of grain. HGCA project report 383

Piggott, S.; Matthews, G.A. (1999) Air induction nozzles: a solution to spray drift? International Pest Control, Jan/Feb, **41**, (1), 24-28

Pesticide Safety Directorate (2001) Local Environmental Risk Assessment for Pesticides (LERAP) Horizontal Boom Sprayers.
http://www.pesticides.gov.uk/uploadedfiles/Web_Assets/PSD/LERAP_Horizontal_boom_sprayers(1).pdf

Robinson, T.H.; Scott, T.; Read, M.A.; Mills, L.J.; Butler Ellis, M.C.; Lane. A.G. (2001) An investigation into the deposition and efficacy of pesticide sprays from air induction nozzles. *The BCPC Conference – weeds,* 2001, 671 – 676.

Robinson, T.H.; Butler Ellis, M.C.; Power, J.D. (2003) Evaluation of nozzles for the application of a late fungicide spray. *The BCPC International Congress – Crop Science and Technology*, 2003, 273 -284.

Sinfort, C.; Lardoux, Y.; Miralles, A.; Enfalt, P.; Alness, K.; Andersson, S. (1997) Comparison between measurements and predictions of spray pattern from a moving boom sprayer. *Aspects of Applied Biology*, **48** Optimising Pesticide Applications, 1 – 8.

Taylor, W.A.; Andersen, P.G. (1997) A review of the benefits of air assisted spraying in arable crops. *Aspects of Applied Biology,* **48,** Optimising pesticide applications, 163 – 174.

Teske, M.E.; Bird, S.L.; Esterly, D.M.; Curbishley, T.B.; Ray, S.L.; Perry, S.G. (2002) AgDRIFT: a model for estimating near-field spray drift from aerial applications. *Environmental Toxicology and Chemistry*, **21**, (3), 659-671

van de Zande, J.C.; Porskamp, H.A.J.; Michielsen, J.M.G.P.; Holterman, H.J.; Huijsmans, J.F.M. (2000) Classification of spray applications for driftability, to protect surface water. *Aspects of Applied Biology*, **57**. Pesticide Application, 57-65

van de Zande, J.C.; Michielsen,J.M.G.P.; Stallinga, H.; Porskamp, H.A.J.; Holterman, H.J.; Huijsmans, J.F.M. (2002). Environmental risk control. *Aspects of Applied Biology*, **66**, International advances in pesticide application, 165 – 176.

Walklate, P.J.; Miller, P.C.H.; Gilbert, A.J. (2000). Drift classification of boom sprayers based on single nozzle measurements in a wind tunnel. *Aspects of Applied Biology*, **57**, Pesticide Application, 49 – 56

Webb, D.A.; Parkin, C.S.; Taylor, W.A.; Taylor, B.P. (2004) Influence of nozzle design, application speed and air assistanceon the variability of spray deposits under arable boom sprayers. *Aspects of Applied Biology*, **71**, International advances in pesticide application, 83 – 90.

Western, N.M.; Woodley, S.E. (1987) Influence of drop size and application volume on the effectiveness of two herbicides. *Aspects of Applied Biology*, **14**, Studies of Pesticide Transfer and Performance, 181 – 192.

Wolf, T.M. (1993) The effect of protective cones, screens and shrouds on the drift and deposition characteristics of field sprayers. By hand from the author.

Wolf, T.M. (2002) Optimising herbicide performance – biological consequences of using low-drift nozzles. *Aspects of Applied Biology,* **66,** International advances in pesticide application. 79-86.

Zhu, H.; Dexter, R.W.; Fox, R.D.; Reichard, D.L.; Brazee, R.D.; Ozkan, H.E. (1997) Effects of polymer composition and viscosity on droplet size of re-circulated spray solutions. *Journal of Agricultural Engineering Research*, **67**, 35-45.

Appendix 1

PROJECT WORKSHOP – 13th September 2006

A REVIEW OF SPRAY APPLICATION METHODS THAT CAN REDUCE DRIFT AND THE IMPLICATIONS FOR EFFICACY: NOTES FROM THE WORKSHOP

Present:

Paul Miller (Chairman and presenter)	Silsoe Spray Applications Unit (part of the Arable Group)
Jim Orson (Presenter)	The Arable Group
Paul Hamey, David Richardson and Hans Dobson (NRI)	Pesticide Safety Directorate
Laurence Oades	Bayer Crop Science (UK) Ltd
Colin Mountford Smith	BASF plc
Anne Thompson	Dow AgroSciences Ltd
Tudor Dawkins	Nufarm UK Limited
Tom Robinson	Syngenta Crop Protection
Mark Hemmant	Agrovista UK Limited
Libby Alexander	H L Hutchinson Ltd
Stephen Kateley	Billericay Farm Services Limited
Peter Wiles	Hardi Ltd
Trevor Swan	Hypro EU Ltd
Richard Riley	Lechler Limited
Clive Christian	Micron Sprayers Ltd
Martin Baxter	Spraying Systems (TeeJet)
Robert Willey	Househam Sprayers Limited
Clare Kelly, Vicky Foster and Alan Bide	Home-Grown Cereals Authority (HGCA)
Mark Prentice	British Potato Council
Mike May	British Beet Research Organisation
Colin Lloyd	Dalgety
Adrian Sisson	Dupont
Hazel Doonan	Agricultural Industries Confederation Ltd
Geoff Richardson	Silsoe Spray Applications Unit, TAG
Christine O'Sullivan	Silsoe Spray Applications Unit, TAG

Background

The chairman opened the project workshop by welcoming all those who provided valuable representation for the purposes of the workshop. The aims of the workshop were established before the chairman invited Paul Hamey (PSD) to provide the background behind the need for the project's investigations. *(See Note 1 attached)*

The results of the project's investigations were given as two presentations titled:

(i) **The application systems reviewed, the physical characteristics of the sprays produced and the implications for drift control – Prof Paul Miller**
(Circulated to Workshop participants)

(ii) **The implications for efficacy with a range of products – Mr Jim Orson**
(Circulated to Workshop participants)

Research conclusions

- *There are a number of application systems that reduce drift in comparison with that from conventional hydraulic flat fan nozzles and some of these are able to maintain efficacy in a wide range of operating conditions.*
- *The largest drift reductions are generally achieved using air induction nozzles and these can be used on conventional boom sprayers involving no modifications and a low capital cost.*
- *Strong arguments for making 100 L/ha applied at 12 – 14 kph through air induction nozzles having flow rates in the range 0.8 to 1.2 L/min at a pressure of 3.0 bar as the default method of application in order to:*
    - *retain efficacy*
    - *maximise work rate*
    - *minimise drift*
- *Need to recognise that the performance of air induction nozzles varies with different manufacturers and is not consistent over nozzle size ranges.*
- *Small targets – avoid the use of large droplet such as those from air induction nozzles*
- *Little of no information of impact of nozzle type and volume when it is necessary to penetrate a thick crop canopy – function of drop size (and velocity) and/or volume?*
- *Infinitely variable systems such as twin fluid nozzles, air assistance and CDA pose problems because of the need to define operating conditions and associated performance for such systems.*
- *With regard to efficacy, the following conclusions had been reached:*

i. For soil applied herbicides – the above default is acceptable unless in a poor seed bed or high levels of herbicide resistance when higher volumes and conventional hydraulic nozzles may be better.
ii. For small weeds up to 3-4 leaves with foliage applied herbicides – use conventional flat fan nozzles at 100 L/ha. There may be an advantage from angling.
iii. For larger weeds in an open crop canopy (up to GS 30) – use the default as above. Angling does not reduce performance and may improve it.
iv. For weeds under a large crop canopy, use conventional flat fan nozzles to apply 100 L/ha which may give better results than air induction nozzles at the same volume. Field experience and very limited trials evidence suggests that 100 L/ha is acceptable.
v. For eyespot and PGR at GS 32 – again use conventional flat fan nozzles at 100 L/ha which may give better results than air induction nozzles. Field experience and very limited trials evidence suggests that 100 L/ha is acceptable.
vi. For foliage applied fungicides to treat foliar diseases, use the default as above.
vii. For ear sprays the default is acceptable, but volumes above 100 L/ha may give better results, as indicated by data from Denmark and France.
viii. For oilseed rape and perhaps potatoes, the same rules apply regarding volumes, nozzles for weed control and fungicides in relation to the size of weed, canopy and nozzle angling.

Workshop discussions

The chairman opened the discussions by posing the following questions to help evaluate the significance of their research conclusions and explore avenues for future work:

Opening questions

- *Do you have additional data to support or not support the arguments put forward?*
- *Are there any common themes on application parameters from customer's experience?*
- *Do you broadly accept the arguments put forward?*
- *If not, what information would convince you?*
- *Would you be willing to develop recommendations that comply with the 'default'?*
- *If not, why not – cost, complexity of tank-mixing or risk?*
- *Are there ways of dealing with infinitely variable systems?*

Main points of workshop discussions

1. Boom height

Achieving the correct boom height was considered one of the most significant factors in controlling drift. As boom widths and forward speeds increase, the sprayer operators are put under considerable pressure to maintain the most efficient operational height above the crop. Manufacturers are developing new systems that can control and monitor the height throughout operation and improved control features would allow actual boom heights to be logged.

2. Manufacturer’s need to understand what is required by the end users

It was recognised that the review had challenged some of the assumptions on which the development of spraying equipment had been based for a number of years. There was a need for manufacturers to consider how to respond to the information that was now becoming available in terms of nozzles, spray systems and formulations. There is a need for improved communication between industry sectors and an understanding of on-farm requirements.

3. Educational trends

As more is learnt about from research and product development moves forward, it is important to have an ongoing transfer of knowledge to all interested parties. The avenues suggested included:

- NROSO training / BASI Professional Register
- Marketing information driven by manufacturers

Generic advice was required on topics such as:

- Guidance on nozzle selection to minimize drift in given situations
- Optimal and minimum volumes of formulation for safe and effective application.
- The level of caution to be exercised with changing water volume with complex tanks mixes

4. Air induction nozzles

Perceptions of the value of AI nozzles were confused and there was a tendency to avoid their use mainly on grounds of efficacy concerns. This indicated the need for AI nozzles to be included in a classification system so that default settings can be established and recognised. The HGCA nozzle chart is a commonly used reference for nozzle selection and would be a beneficial exercise to update and incorporate more information on AI nozzles.

5. Angled Nozzles

Perceptions vary on how nozzles should be angled, the conditions they should operate under and the effectiveness of doing so in given situations. It was recognised that in open canopy conditions, angling could increase deposition but that drift may be increased unless good control of boom height was maintained. It was also suggested that further scientific information is needed to gain an understanding of the advantages of nozzle angling in different circumstances.

6. Other issues

(i) The management of field margins is an important component of spray drift management at the farm level.

(ii) The “Pesticide incident reports” from the Health and Safety Executive may provide useful inputs to the research analysis.

(iii) Pesticide Resistance may make application strategies more critical.

Future Work

Follow-up research

The discussions highlighted the need for key follow-up research:

- Develop an extended nozzle/spray classification system that can include air induction nozzles
- Define application requirements for soil applied herbicides for grass weed where herbicide resistance is high – TAG (under National Agronomy Centre funding) with Agrovista is currently leading some research on this topic.
- Establish the relative role of droplet size and volumes in penetrating a thick crop canopy. A concept note has been sent to HGCA.
- Establish volumes for ear sprays. This can be a problem given that severe ear disease is not a regular occurrence and so the experiment will not be carried out if GS 65 occurs during hot and dry conditions.

Summarized actions emanating from the workshop

1. European researchers meet to resolve reasons for differences in research conclusions (under EPPO?)
2. Advise nozzle manufacturers that finer air induction nozzles are giving better efficacy than coarser air induction designs. Further clarity is needed in marginal situations and the use of finer air induction nozzles must be encouraged in technology transfer initiatives.
3. Clear coordination of technology transfer initiatives by AIC, CPA and HGCA is required. Jim Orson to contact representatives of all parties and also to look at NRoSO and BASIS training.
4. Jim Orson to contact Monsanto regarding the application of glyphosate in low volumes through AI nozzles.
5. A meeting to be arranged with Syngenta to discuss conclusions from relevant trails that could add value to this project.
6. Contact to be made with French and Danish counterparts to consolidate information on ear sprays.

Note 1

PSD INTRODUCTION FOR PROJECT WORKSHOP
Paul Hamey

This project was set up as a fact finding exercise to address PSD's need for an understanding of the relationship between drift reduction and efficacy. It obviously fits within our interests of improving safety, but we also want to understand any efficacy implications of changes in application methods as any reduction in efficacy may have unintended consequences.

The background to the proposal was from anecdotal reports we had for sometime been aware of a potentially widespread uptake of LERAP rated low drift equipment, largely air induction nozzles, as numbers of growers could see environmental and operational benefits from adopting such technology.

Then the two Sprayer Practice Surveys that the Central Science Laboratory did for the Crop Protection Association in 2001/2002 and 2004 provided some objective evidence of the increase in availability and probable use of such technology.

The first survey found that sprayers with a LERAP-Low Drift star rating were on farms accounting for 62% of the UK arable area (although, the area treated with such equipment would be somewhat less). While in 2004 the proportion covered by farms with such equipment had increased to 70% of the arable area.

More specifically looking at LERAP 3* equipment, this was reported on holdings representing at least 48% of the area in 2002 and 65% in 2004. In 2004 when nozzle use was taken into account it was estimated that 3* rated equipment was used on 41% of the area.

These figures suggest an increased use of application equipment with higher standards of drift control and this maybe a good outcome for the environment.

However, although we had a reasonable understanding of the environmental benefits from the use of such technology we recognized that a broad understanding of the efficacy aspects was not available: a number of papers on the biological implications of low drift technology had been published and presented at conferences but these findings had not been drawn together.

Nevertheless, from discussions within PSD and with other groups we considered that without compromising product efficacy there may be a potential for opportunities to encourage more spray applications to be made with systems that are likely to reduce drift compared with conventional nozzle systems. However, before considering doing so we wanted to get a firm understanding on the implications for efficacy. There is a huge diversity of targets for pesticide applications. In many cases we believe that application does not affect efficacy, but there is a concern for specialist targets – for example newly emerged weed seedlings, especially black grass or for fungicide applications to crops such as onions, where any reduction in spray cover could impact significantly on performance. Therefore this we commissioned this project to explore this possibility for boom sprayers with specific objectives to:

Search the open literature for data relating to drift reduction and efficacy of application systems designed to reduce drift;

Collect similar “grey literature” and other data from European Research Centre’s involved in generating such data

Collate the data linking drift control and efficacy; while defining nozzles systems in relations to the physical characteristics of the sprays produced; and

Analyze and interpret the results.

At the outset we considered one of the main benefits from the work potentially relates to the overall reduction in drift that may be achieved by an increased use of application systems able to deliver significant drift reductions without substantially compromising product efficacy.

Obviously this would be of wide interest and have potential implications for a range of industry stakeholders and in discussions with TAG we agreed with their proposal that there should be a workshop to discuss the draft findings before the project was completed. This is the purpose of today.

References to published material

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