SESSION 3C

SPRAY APPLICATION TECHNIQUES

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Papers: 3C-1 to 3C-6

The current and future role of application in improving pesticide use

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ABSTRACT

In arable crops, increasing boom widths and forward speeds together with the use of low volume rates leads to high work rates, improved timeliness and high levels of efficacy but with an increased risk of drift. The development of systems for improved drift control, particularly when involving the use of large droplets, means that the balance between timeliness, efficacy and drift control is now an important issue. Developments in sensors and control systems provide a basis for the improved matching of sprayer outputs to target requirements and it is suggested that future application systems will make greater use of sensors and automatic control systems. The need to generate reliable records of applications will also be an important driver in the future.

INTRODUCTION

The use of pesticides continues to be the subject of active public scrutiny with particular concerns relating to the effects on the environment, and the risks posed by residues in food and drinking water. The farmer/user also has concerns relating to the effective use of plant protection products for both financial and environmental reasons. In UK winter cereal production, pesticides typically account for 47% of the variable costs of production and for some high value fruit and vegetable crops this figure can be as high as 92% if picking and packaging costs are excluded.

Application methods have been shown to have an important role in minimising any adverse effects relating to pesticide use by:

- optimising the timing and targeting of delivery such that the minimum quantities of active chemical, consistent with achieving the required biological response, are applied;
- reducing the risk of contamination of non-target organisms by drift and run-off from the target sites.

Considerable research and many of the developments in pesticide application technology in the past decade have been directed at improving the control of spray drift (Miller, 1999). The development of nozzle systems such as the air induction design and air assisted boom sprayers have enabled levels of drift to be reduced such that many complete systems are capable of operating to give levels of drift less than 25% of those from conventional systems operating at typical volume rates. There is concern that the use of sprays with relatively large droplets to give drift control may influence efficacy and the balance between drift control, efficacy and timeliness is now an important issue in relation to spray application.

Technological developments concerning in-field location, sensing and control systems are now influencing the specifications of agricultural machinery, with important implications for the future. Location systems based on, for example, the Global Positioning System (GPS) together with low cost and rugged computer-based control units are already influencing the design and operation of application machinery. It is likely that these trends will continue.

This paper reviews some of the recent research commercial developments concerned with spray application and considers the future potential changes to meet requirements for using less active ingredient, improved targeting, minimised residues and accurate traceability.

FACTORS INFLUENCING PESTICIDE USE RATES

The application factors that have probably contributed the greatest benefits in terms of reducing pesticide use, particularly in arable crops, have been those that relate to improved timeliness. Recent studies with weeds grown outdoors in a pot experiment and sprayed with conventional nozzles for example showed that for black-grass (*Alopecurus myosuroides*) growing from the three to the four leaf stage increased the ED_{90} dose of clodinafop propargyl by 56% (Miller *et al.*, 2003). For the broad-leaved weed scentless mayweed (*Tripleurospermum inodorum*), delaying the application of a bromoxynil + ioxynil and mecoprop-P tank mix from the cotyledon to four leaf stage increased the ED_{90} dose by 62% whereas for poppy (*Papaver rhoeas*) the increase was 93%. These data, while only for one set of trials with foliage acting products, do illustrate the importance of application timing in minimising the dose of herbicides needed to achieve a given level of control.

Timeliness relates directly to work rates, and for a boom sprayer operating over arable crops, this is a function of the width of the boom, the forward speed and the volume application rate. Recent developments in boom and vehicle suspensions has meant that forward speeds of 12-14 km/h are now common when travelling with booms 24 m wide to treat arable crops. Figures 1 and 2 show the results from a simulation model predicting the work rates for a typical sprayer set up on an arable holding.

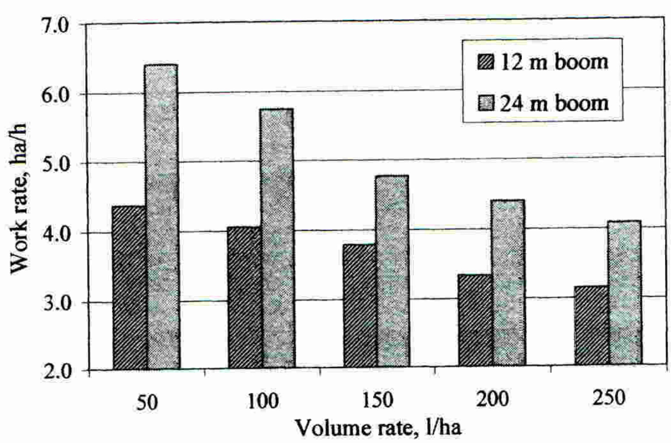

Figure 1. The effect of volume rate on work rate for two sizes of boom sprayer operating over arable crops – the results from a simulation model.

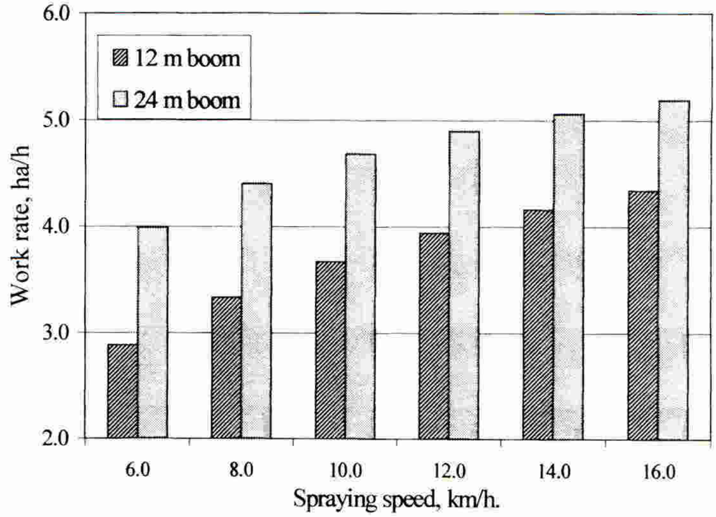

Figure 2. The effect of forward speed on work rate for two sizes of boom sprayer operating over arable crops – results from a simulation model.

Although doubling the width of the boom has a considerable effect on work rates, the time taken to load the sprayer means that work rates are not doubled over the range of volume rates and forward speeds used in these calculations. This underlines the importance of providing good logistical support to the sprayer in the field via a bowser or mixing tank. It also demonstrates the advantages in work rate that could be achieved by, for example, using an injection metering system with an in-field water bowser minimising the weed to return to a central loading point particularly when changing from one field to another when a change of chemical mix may necessitate washing out the sprayer.

Increasing boom widths, forward speeds and reducing volume rates with conventional hydraulic pressure nozzles all have components that tend to increase the risk of drift and increase the need to address drift control – see below. Increasing forward speed for a given volume rate also involves:

- using a conventional nozzle with a larger output and larger droplet size that can have implications for product efficacy;
- a larger acceleration time/distance such that the control system may need to accommodate a wider speed range.

The effect of physical spray characteristics including the droplet size distribution is likely to be related to the characteristics of the target and the mode of action of the chemical. The results from a total of 159 herbicide trials reviewed by Knocke (1994) showed that 71% gave an improvement in efficacy associated with using a smaller droplet size distribution. However, the requirements for timeliness may mean that the options of using a finer spray for improved efficacy must be balanced by the drift control characteristics of using larger droplets (Wolf, 2002) unless air assisted systems are to be used. The nozzle selection chart published by the Home Grown Cereals Authority provides some basis and simplified decision rules for aiding nozzle selection. There is however scope for making nozzle selection more precise particularly as further information relating to the performance of a range of nozzle designs is developed. Nozzle selection modules have already been incorporated into sprayer control strategies (Miller *et al.*, 1997) and work is now in progress to include similar algorithms into decision support systems.

An example of where information is being gathered, but a further definition of performance characteristics is required, relates to air induction nozzles. A number of authors have shown that different commercial nozzle designs give very different droplet size distributions for the same specification in terms of spray angle and flow rate at a defined pressure. Results from field laboratory and outdoor pot trials with this nozzle design indicated that levels of efficacy were generally higher than would have been predicted on the basis of comparing droplet size distributions with those from conventional pressure nozzles. However, initial trials suggested little difference in efficacy between the different commercial designs of this nozzle type (Robinson *et al.*, 2001) and hence the proposal was made that all sprays having more than 10% of droplet volume as included air measured by defined techniques should be classified as producing a medium quality spray (Miller *et al.*, 2002). Recent results from both field and outdoor pot experiments with this nozzle design have now shown relationships between efficacy and droplet size distributions that strongly indicate a need to differentiate between different commercial designs of air induction nozzle on the basis of droplet size distribution and expected efficacy. The risk of drift from this nozzle design has also been shown to be a function of the droplet size produced (Butler Ellis *et al.*, 2001) and hence it is possible to establish relationships that link drift control and efficacy via nozzle selection for this design of unit. Improved information of this type is important if the operator or automated control system are to make valid decisions relating to nozzle selection where the balance between efficacy and drift control may be critical.

Other methods by which overall pesticide use can be minimised relate to matching applications to the crop target geometry and accounting for spatial variability in target requirements within a field.

MATCHING APPLICATIONS TO TARGET CROP CANOPY

A good example of an approach that seeks to match applications to crop canopy structure when spraying fruit trees has been described by Walklate *et al.*, (2002). This assumes that an application made to a reference apple orchard canopy in full leaf will give a level of surface deposit that is adequate to give full biological control. Treatments earlier in the season when the trees vary from bare wood to full leaf can then be adjusted to match the tree area density. Techniques have been developed for characterising the canopy using a tractor-mounted LIDAR system and results from a series of experiments conducted over three years in which deposit distributions and canopy structure were measured showed that tree area density accounted for the highest percentage of deposit variation (78%) in the treated canopy. While it may be feasible to add a rotating laser light sheet LIDAR system to each sprayer together with an appropriate signal processing and sprayer control unit, this would represent additional cost and complexity that may be difficult to justify economically. The approach taken has therefore used the LIDAR system to generate pictograms of a range of canopy conditions that can be used, in conjunction with information about the reference condition, to set air-assisted orchard sprayers to optimise pesticide use. The use of this approach has been shown to reduce usage rates by up to 75% when making early season applications.

In cereal crops, some advantages have been shown from matching fungicide applications to localised crop density and from adjusting the angle of spray delivery when treating crops at early stages of growth. A number of approaches to sensing canopy conditions have been evaluated principally aimed at managing overall growing conditions by manipulating fertiliser and growth regulator inputs. Systems based on spectral reflectance measurements have been widely used but have been shown to be relatively insensitive to differences in canopy structure at growth stages beyond GS 32. Recent work has investigated the use of both spectral reflectance and ultrasonic sensors mounted on a boom, with the aim of being able to describe the development of a winter cereal crop canopy throughout the growing season. Experiments have been conducted over two seasons with different varieties and seed rates to generate canopies with different structural densities (Scotford & Miller, 2003). A typical result for a late drilled winter wheat crop on heavy land is shown in Figure 3. It can be seen that in the period up to mid to late April there was no substantial increase in the height of the crop, as measured by the ultrasonic sensor but an increase in the normalised difference vegetation index (NDVI) as the crop began to tiller. By early May the rate of increase in the measured NDVI has declined because with little exposed soil, this system is starting to saturate. The crop is however growing rapidly, increasing in height as shown by the output from the ultrasonic sensor and adding green leaf area. It has been postulated that a combination of the outputs from both types of sensor can be combined to give robust estimates of green leaf areas that could be the basis for the improved targeting of surface acting plant protection products and other inputs such as fertilisers and growth regulators.

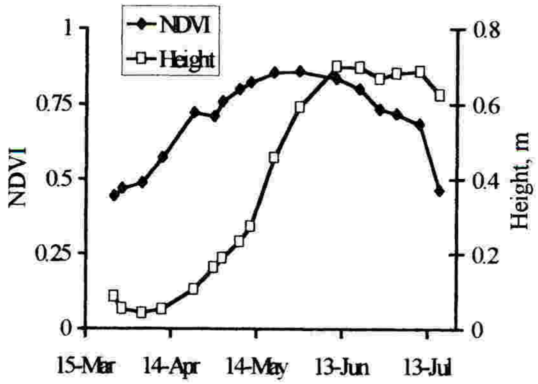

Figure 3. Measured normalised difference vegetation index (NDVI) and crop height for a winter wheat crop over the growing season.

Penetration into an arable crop canopy is also a factor that influences the performance of some herbicides and the control of stem based diseases. Penetration is related to the "openness" of a canopy particularly the size and distribution of gaps. Signals from both the spectral reflectance and ultrasonic transducers are being analysed to determine the extent to which the variability in the output from these sensors can be used to describe canopy density and the effective porosity of the canopy structure. Results from limited trials to-date are encouraging and it is likely that with the further development of the sensor systems and the methods of analysis of the output signals, improved information will be available as the basis for the control of application machinery and crop management options.

Improved targeting can also relate to the spatial variability within a field. The main focus for research and development in this area has been the control of grass weeds in cereal crops. Such weeds are known to be patchy with patches that are relatively stable within a season and from season to season. Approaches have been developed (Lutman *et al.*, 2002) based on:

- mapping the distribution of weed patches using manual detection with an appropriate positioning and logging system;
- transforming the detected weed patch map into a treatment map accounting for factors such as weed seed movement, uncertainty in the performance of the positioning system and the response characteristics of the application equipment;
- adjusting the output of the sprayer to apply different dose levels or different tank mixes to defined parts of a field.

Results from field studies showed that cost savings in the range of 2 to 10 £/ha could be achieved by adopting such approaches although this cost did not include an allowance for the capital investment required in machinery. These capital costs are falling as the specifications of agricultural machinery becomes more sophisticated with items such as positioning systems now a standard option from many manufacturers.

CONTROL OF SPRAY DRIFT

The introduction in the UK of the Local Environmental Risk Assessment for Pesticides (LERAP) scheme in 1999 has had important implications for the development of drift reducing application equipment. This scheme enables the width of buffer zones, specified to protect surface water from contamination by spray drift, to be adjusted according to a number of parameters. These include the ability of application equipment to reduce drift in comparison with a reference conventional boom sprayer fitted with FF110/1.2/3.0 nozzles. The ability to reduce drift is officially recognised by the Pesticides Safety Directorate using a star rating system. The highest three star rating representing levels of drift that are less than 25% of the reference system as demonstrated by the results from either field experiments with complete machines or wind tunnel tests with single nozzles. To date, three star ratings have mainly been achieved by air induction nozzles in a range of sizes and operating pressures claimed on the basis of results from wind tunnel tests. Air assisted boom sprayers have successfully claimed three star ratings based on the results from field trials with such ratings relating to defined nozzles and air settings on the boom. The LERAP Low Drift rating scheme is the first time that the performance of spraying equipment has been formally recognised in the UK and similar schemes relating to the drift performance of sprayers now exist in Germany and the Netherlands. A proposed draft International Standard suggests classifying complete spraying systems based on the risk of drift as measured in field-scale trials conducted to a standardised protocol and again compared to a reference system.

Draft International and some national standard protocols for drift measurement have components relating to airborne and sedimenting spray but interpretation has concentrated on sedimenting deposits because of the need to relate to the contamination of surface water. There is now concern that datasets generated in relation to sedimenting drift may not be relevant when assessing the risk of contamination in field boundary vegetation such as hedgerows and the implications for biodiversity. Results from both field and wind tunnel studies have shown that vegetation at the field boundary acts as a filter for drift and changes air flow patterns over boundary structures. There is a need to review how risk assessments relating to spray behaviour of a field boundary are conducted and the research needs to support such assessments.

FUTURE DEVELOPMENTS

The development of relatively cheap, robust, computer-based sensing and control strategies offers important opportunities for the design of application machinery. When delivering research results that will input to the manual operation of equipment there is a need to keep things clear and simple. The use of sensors enables data to be collected relating to weather and crop conditions at the time of application that together with information about the formulations to be applied can be used to control the application system (Figure 4).

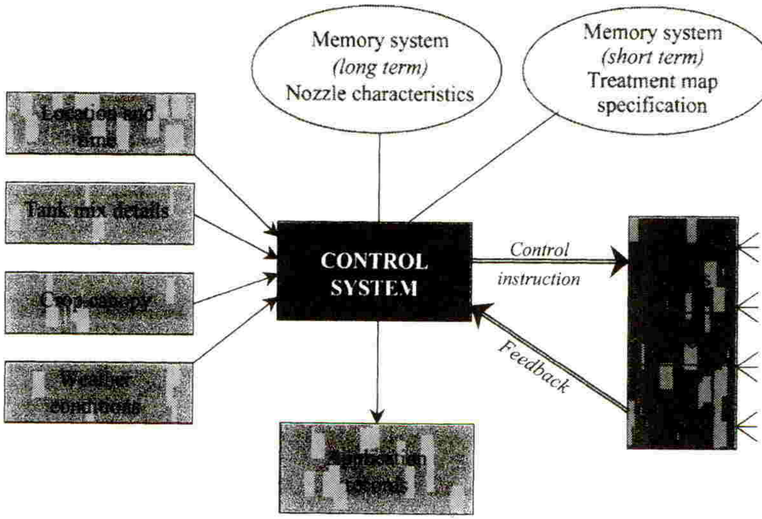

Figure 4. Possible structure of a sensing and control system for agricultural crop sprayers in the future.

A major driver relating to the implementation of more advanced control strategies is the generation of reliable records for traceability purposes. Research and developments are delivering systems that enable the application machinery to identify the amounts and the description of chemicals being loaded through a conventional induction hopper (Watts *et al.*, 2003) that will then enable improved control and record generation procedures to be adopted. The integration of such automatic records into a full traceability log will have important implications for food quality, environmental security and Health and Safety legislation.

Regulators are currently not prepared to consider factors such as wind speed and direction in risk assessment procedures such as the LERAPs scheme. This is because of the variability and unpredictability of such factors. The use of sensors, mapping and positioning systems together with appropriate control algorithms may enable this approach to be reviewed particularly if output actions are to be implemented automatically.

CONCLUSIONS

There is a need to establish ways in which timeliness, efficacy and drift can be balanced to optimise pesticide use. Relationships are needed that can be used in decision support systems and in control strategies for application machinery. Some of these relationships already exist particularly linking some of the parameters that define the risk of drift. Further work is required to:

- classify nozzle performance in a way that will give improved resolution where needed such as with different air induction nozzles;
- improve the relationships between spray droplet size and velocity, efficacy and timing that may need to relate to products or groups of products;
- better define the interactions between crop canopy structure and the behaviour of sprays in terms of deposition and drift.

REFERENCES

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

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

Lutman P J W; Perry N H; Hull R I C; Miller P C H; Wheeler H C; Hale R O (2002). Developing a weed patch spraying system for use in arable crops. *HGCA Project Report No: 290.* Home Grown Cereals Authority, London.

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

Miller P C H; Butler Ellis M C; Gilbert A J (2002). Extending the International (BCPC) spray classification scheme. *Aspects of Applied Biology,* ***66***, *International Advances in Pesticide Application*, 17-24.

Miller P C H; Paice M E R; Ganderton A D (1997). Methods of controlling sprayer output for spatially variable herbicide application. *Proceedings of Brighton Crop Protection Conference – Weeds*, 641-644.

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 No. 317e.* Home Grown Cereals Authority, London.

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. *Proceedings of The BCPC Conference – Weeds,* 671-676.

Scotford I M; Miller P C H (2003). Monitoring the growth of winter wheat using measurements of normalised difference vegetation index (NDVI) and crop height. *Proceedings of Fourth European Conference on Precision Agriculture*, 627-632.

Walklate P J; Cross J V; Richardson G M; Baker D E; Murray R A (2002). Comparison of different spray deposition models using LIDAR measurements of apple orchards. *Biosystems Engineering* **82** (3), 253-267.

Watts A J; Miller P C H; Godwin R G (2003). Automatic recording of sprayer inputs to improve traceability and control. *These proceedings.*

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.

Pesticide formulation and drift potential

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ABSTRACT

Measurements of the drift potential in a wind tunnel and droplet size spectra were made for 11 types of spray nozzles and 9 different spray liquids. A standard measurement protocol was used to characterise the driftability of the sprays by the Drift Potential Index (DIX). The results show a large influence of the spray liquid on the drift potential, although no general trend could be found even for spray liquids of the same formulation type. The DIX values for water are generally in the middle range of values for the formulations used in this study.

INTRODUCTION AND OBJECTIVES

When pesticides are applied, a certain part of the chemical may drift from the target area. This can cause environmental hazards. In order to avoid inappropriate risks especially for aquatic organisms, buffer zone restrictions have been given to several pesticides according to their toxicity.

The Federal Biological Research Centre (BBA) determines drift potential of spray nozzles in a wind tunnel. These tests are done following a special protocol using water with a tracer dye as spray liquid (Herbst, 2001). Many other research groups use water with a non-ionic surfactant for measuring spray drift or droplet sizing. There is some evidence that the atomisation is effected by the formulation of the pesticide and hence the droplet size spectra and drift potential from nozzles can differ from those of water significantly (Butler Ellis & Bradley, 2002).

The objective of this work was to investigate how the drift potential from several flat fan nozzles is influenced by pesticides of different formulation types. The robustness of the BBA protocol for drift potential determination should be tested and proposals for the choice of an appropriate standard liquid in tne framework of a new ISO working item should be derived.

MATERIAL AND METHODS

The tests were made in a wind tunnel. It is built as a closed loop. Air temperature and humidity can be adjusted, and were set to 20°C and 80% rh during the tests. At the end of the measuring chamber, a filter wall is mounted to remove airborne evaporated chemicals both as droplets and vapours.

The nozzle under test was mounted in the wind tunnel with the spray fan oriented perpendicular to the air flow direction to simulate the air movement due to the forward motion of the sprayer. The drift potential was measured in a cross section 2.0 m downwind from the nozzle at a wind speed of 2 m/s. The development of the experimental approach is shown in Figure 1.

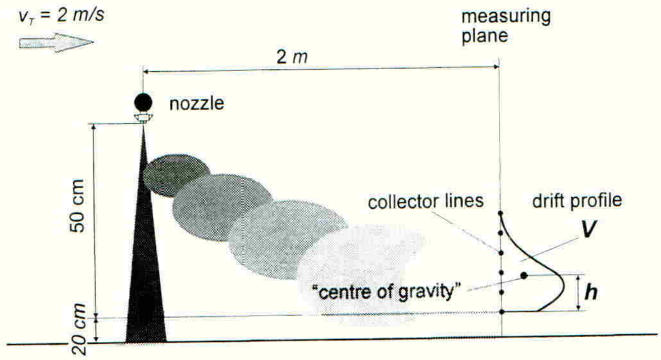

Figure 1. Experimental arrangement in the wind tunnel for drift potential measurement.

Passive line type drift collectors (polythene, 2.0 mm in diameter) were used for the measurements. They were mounted horizontally with a spacing of 100 mm perpendicular to the wind direction. After spraying for 5 or 10 s, the dried collector lines were removed from the wind tunnel and washed with a known amount of de-ionised water which was then analysed using a fluorimeter. A Drift Potential Index *DIX* was then calculated from the vertical drift potential profile (Herbst, 2001).

Several flat fan nozzles of conventional, pre-orifice and air induction type were tested. Spray pressure was adjusted for each nozzle type to produce a flow rate of approximately 1.6 l/min, measured when spraying water (Table 1).

Table 1. Flat fan nozzles tested

Manufacturer	Type	Spray pressure bar	Volume rate, l/min	nozzle design
Lurmark	F110/1.2/3.0	3.0	1.26	conventional
TeeJet	XR 11003	5.0	1.52	conventional
Teejet	XR 11004	3.0	1.54	conventional
Teejet	XR 11005	2.0	1.52	conventional
TeeJet	DG 11003	5.0	1.51	pre-orifice
Teejet	DG 11004	3.0	1.57	pre-orifice
Lechler	IDK 120-04	3.0	1.57	compact air induction
Agrotop	Airmix 11005	2.0	1.60	compact air induction
Lechler	ID 120-03	5.0	1.58	air induction
Lechler	ID 120-04	3.0	1.57	air induction
Lechler	ID 120-05	2.0	1.58	air induction

Water with and without a surfactant as well as pesticides of different formulation types were used as spray liquids.

Table 2. Spray liquids

Spray liquid	Concentration	Formulation type
Water		
Break-Thru S240	0.1%	non-ionic surfactant
Juwel Top (SE)	1%	suspo-emulsion (SE)
Terpal C (SL)	1%	soluble concentrate (SL)
Roundup (SL)	1%	soluble concentrate (SL)
Arelon (SC)	1%	suspension concentrate (SC)
Brasan (EC)	1%	emulsifiable concentrate (EC)
blank EC	1%	emulsifiable concentrate (EC)
blank WP	1%	wettable powder (WP)

Before conducting the wind tunnel trials, all the chemicals were tested to determine whether they would influence the fluorimetric properties of the tracer dye used in the study (0.1% Brillantsulfoflavine - BSF). A number of standard concentration solutions were prepared and analysed for each chemical.

RESULTS

With the preliminary test it could be shown that there are no interactions of the chemicals with the tracer dye (BSF). The correlation of the measured emission with the normalised BSF concentration was measured and a correlation coefficient of greater than 0.998 for any chemical established.

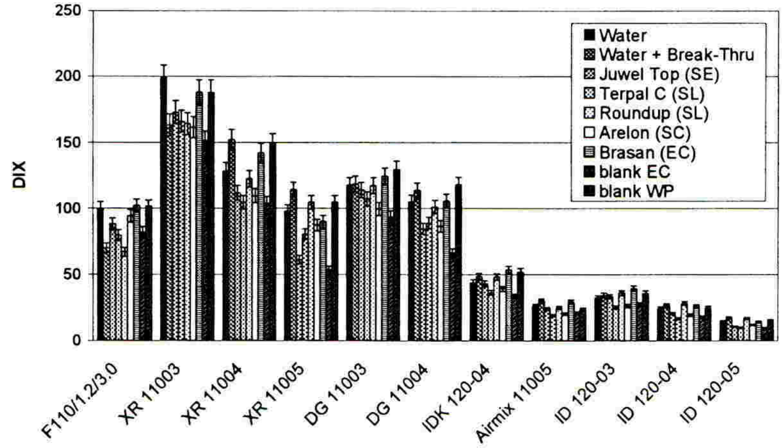

Figure 2. Drift potential from several nozzles and spray liquids related to the Lurmark F110/1.2/3.0 spraying water.

The wind tunnel tests showed that the properties of the spraying liquid have a great influence on the driftability of the spray. The results are shown in Figure 2 with the Lurmark F110/1.2/3.0 nozzle spraying water as the reference.

The results show a strong tendency for increased drift reduction with increasing nozzle size and from conventional to pre-orifice and air induction nozzles for each spray liquid as expected. However, the relationships between DIX values from several nozzle types are dependent on the liquid applied. No general trend for pesticides of the same formulation type was apparent. The blank EC in most cases gave the lowest DIX values while with the EC Brasan every nozzle produced a high drift potential compared to other spray liquids. Terpal C and Roundup as soluble concentrates gave DIX values that were approximately equal.

The results show that there are specific effects of the spray liquids on atomisation with nozzles of each type. Again, there are no general trends for either the nozzle types nor for nozzle sizes. A statistical evaluation of the results showed that a typical value for the confidence interval of DIX is ± 5%. These intervals are shown in Figures 2 and 3.

For driftability classification purposes, the Lurmark F110/1.2/3.0 nozzle with each spray liquid would be the reference as shown in Figure 3.

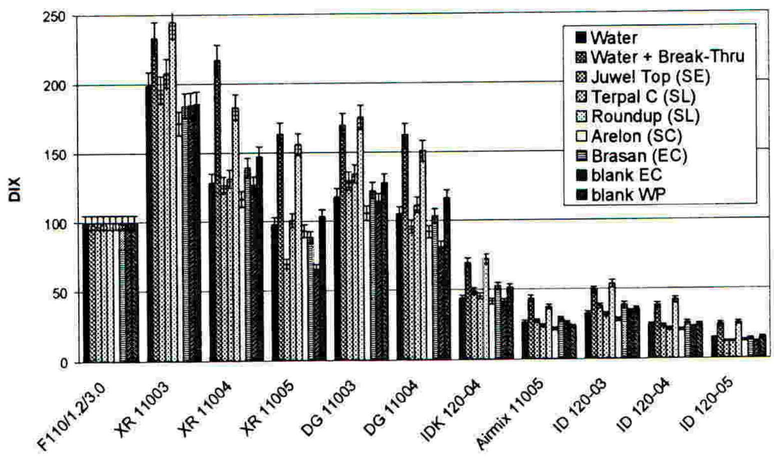

Figure 3. Drift potential from several nozzles and spray liquids related to the Lurmark F110/1.2/3.0 with each spray liquid.

It is obvious that the classification results are strongly affected by the spray liquid. Relatively high DIX values and hence a high drift classification was measured with Water + Break thru and Roundup for each nozzle. One reason for this in both cases is the relative low drift potential from the reference nozzle with those liquids. But specific behaviour of the spray liquid within different nozzle types at a certain spray pressure seems to be the main reason for deviations in drift potential evaluation.

Differences in drift potential classification become even more obvious looking at the DIX values from "low drift nozzles" for each spray liquid (Figure 4).

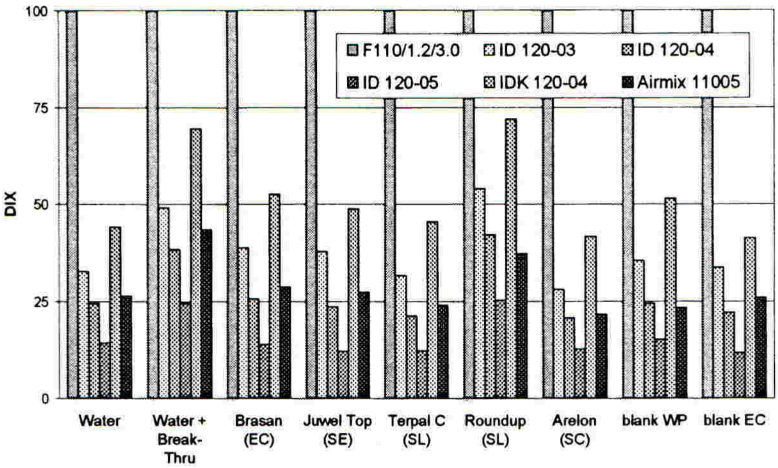

Figure 4. Drift potential from several low drift nozzles with different spray liquids related to the Lurmark F110/1.2/3.0 with each spray liquid.

For example, the Lechler IDK 120-04 with a spray pressure of 3.0 bar would be classified as 50% drift reducing with water but would not be classified as drift reducing with Roundup. The concentration of the chemical in the spray liquid can also have an influence on drift potential. This was tested for the reference Lurmark nozzle and a Lechler air induction nozzle with Roundup (Figure 5).

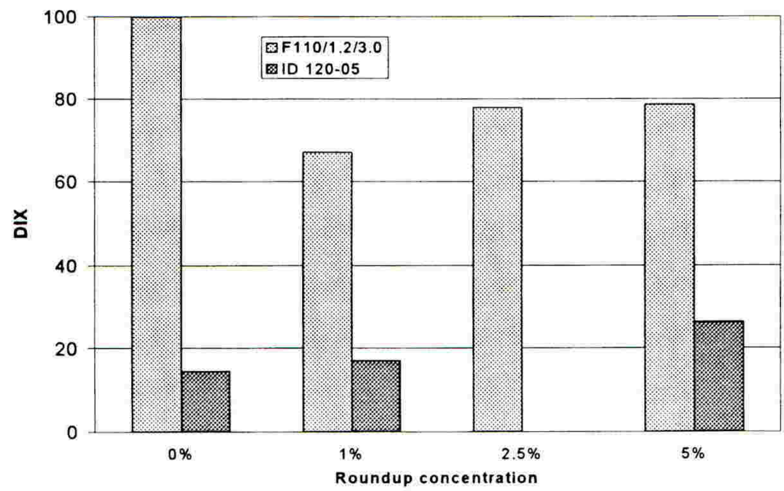

Figure 5. Drift potential from a conventional and an air induction nozzle and spray liquids related to the Lurmark F110/1.2/3.0 with each spray liquid.

Drift potential from the air induction nozzle increases with Roundup concentration in the spray liquid. With 5% Roundup concentration drift is almost doubled compared to water. The Lurmark nozzle behaves differently and this nozzle has the highest drift potential with water.

The drift potential decreases significantly with a low Roundup concentration and then gets higher as the concentration of the chemical is increased.

DISCUSSION

The properties of the spray liquid have a great influence on the driftability of the spray. These effects are significantly influenced by the nozzle type.

There was no general trend for a drift reduction or increase neither for any nozzle and all spray liquids nor any spray liquid and all nozzles. Even chemicals from the same formulation type gave completely different results on drift potential from the nozzles tested.

At first view the DIX protocol used by BBA to determine drift potential from nozzles seems not to be very robust. The results can strongly deviate dependent on the spray liquid used, particularly as the drift potential may be influenced by the concentration of the chemical in the spray liquid. If an exact result for any spray liquid is required, drift potential measurements should be conducted with this liquid using a range of nozzles.

The results show that it is difficult to define a test liquid that is representative of real spray liquids. However, the DIX values for water are in general in the middle range of the values. Considering this, it is an option to continue to use water as the test liquid to determine drift potential. It is likely that the DIX protocol with water will give an average of the drift potential in most cases.

REFERENCES

Butler Ellis C; Bradley, A (2002). The influence of formulation on spray drift. *Aspects of Applied Biology* **66**, 251-258.

Helck C; Herbst A (1998): Drift Potential Index - eine neue Kennzahl zur Beurteilung von Pflanzenschutzdüsen hinsichtlich ihres Abtriftpotentials. *Nachrichtenbl. Deut. Pflanzenschutzd.* **50**, 225-232.

Herbst A (2001). A method to determine spray drift potential from nozzles and its link to buffer zone restrictions. *ASAE paper no. 01-1047*

Effect of drop evaporation on spray drift and buffer zone risk assessments

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ABSTRACT

The influence of evaporation on spray drift was investigated in a wind tunnel with controlled humidity using 2 m/s airspeed and wet bulb depressions ranging from 2 to 11°C. Horizontal profiles of spray drift from three BCPC/International reference nozzles and an air-induction nozzle were measured. For a given spray, the volume of airborne spray increased with wet bulb depression. Analysis of the results using a LERAP calculation procedure and reference data obtained under high humidity conditions indicated that wet bulb depressions (ΔT) > 7°C could cause increases in drift equivalent to a reduction in LERAP star rating. Although humidity in this range is rare in the UK, it often occurs in more arid climates. The LERAP categories for the reduced drift nozzles remained unchanged when the data was compared to reference data obtained at a similar humidity.

INTRODUCTION

Unsprayed buffer zones are often used around crops to reduce off-target contamination from pesticides. A key feature of their management is the development of systems to evaluate risk of pesticide contamination. The ability to reduce drift has been identified as being particularly important. This has led to the introduction of schemes such as Local Environmental Risk Assessments for Pesticides (LERAP) (Gilbert, 2000) to approve reduced drift equipment and the development of appropriate testing methods for sprayers (Ganzelmeier & Rautmann, 2000). An alternative to the field testing of whole sprayers has been the testing of single nozzles in wind tunnels and the use of scaling calculations to predict behaviour at full-scale (Walklate, *et al.*, 2000). Testing in wind tunnels involves the release of spray upwind of a series of collectors. The results from a single nozzle are scaled to a boom-sprayer using a power-law model based on a similarity scaling principle (Walklate, *et al.*, 1998). Although comparisons with UK field data have shown the method to be robust (Walklate, *et al.*, 2000) the influence of drop evaporation on the test method and the influence of changes in humidity on drift has not been investigated. Here we describe a series experiments carried out in a wind tunnel using a range of nozzle designs. Humidity was varied and its influence on drift measured. The implications for the LERAP rating are examined and the results used to discuss how climatic conditions and drop evaporation could increase the risk of spray drift.

MATERIALS AND METHODS

The experiments were carried out in the Silsoe Research Institute re-circulating wind tunnel. The arrangement is shown in Figure 1. A fixed air velocity of 2.0 m/s was used for all tests with a nozzle height of 0.6 m. Spray drift was collected using an array of 2.0 mm diameter polyethylene lines positioned at 0.1 m height and 2, 3, 4, 5, 6 and 7 m downwind of the nozzle. The lines covered the full working width of the tunnel. The spray liquid was an aqueous solution of 0.2 % *wt/v* Green-S dye with 0.1% *v/v* Agral non-ionic surfactant. Collectors were exposed to spray for 10 s using a solenoid valve and electronic timer. This gave a practical working range of dye concentrations when lines were washed with 10 ml of water. Dye concentration was measured using a spectrophotometer and the deposits normalised via a tank sample. Wind speed was monitored using Solent Research Model ultrasonic anemometer and humidity measured using a Michell Dewmet cooled mirror dew point meter.

The wind tunnel has systems for increasing and decreasing the humidity. The dehumidification facility consists of a by-pass circuit with a cooling coil, circulation fan and re-heat coil. The system has the capacity to remove a nominal 18 litres/hr of water from the tunnel air flow making it possible to operate below ambient humidity but with performance dependent on atmospheric conditions. With airflow circulating in the tunnel at 2 m/s and maximum cooling, steady state conditions are reached in ~ 15 min. The humidification system consists of a series of twin-fluid nozzles that inject a fine water mist into the main recirculation.

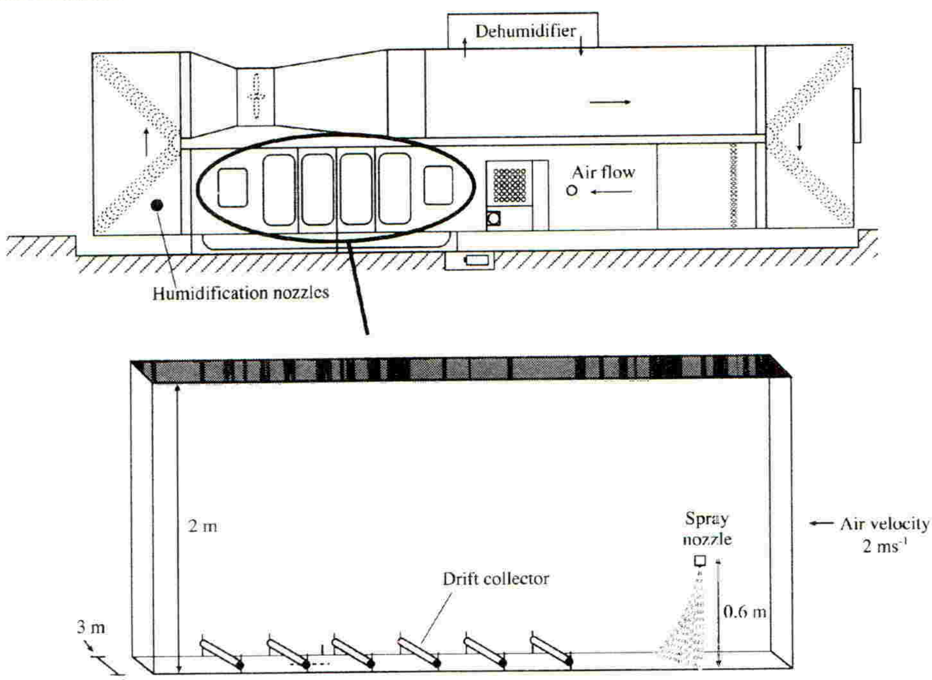

Figure 1. Wind-tunnel arrangement showing location of drift collectors and spray nozzle.

Four sprays were used in the experiments (Table 1). Three of the sprays defined the boundaries in the BCPC (International) spray classification scheme; the fourth was a typical reduced drift spray produced by an air-induction nozzle and with a LERAP *** rating. The BCPC Fine/Medium spray is the standard for the LERAP scheme (Gilbert, 2000). Different levels of humidity in the wind tunnel were obtained by using ambient conditions, using maximum dehumidification, and humidification to obtain near saturation. Experiments with each spray/humidity combination were replicated four times.

Table 1. Details of nozzles and pressures used for experiments

Manufacturer	Nozzle	BCPC code	Operating pressure, bar	Description
Lurmark	01F110	F110/0.4/3.0	4.5	BCPC Very Fine/Fine
Lurmark	03F110	F110/1.2/3.0	3.0	BCPC Fine/Medium
Lurmark	08F80	F80/3.2/3.0	2.5	BCPC Coarse/Very Coarse
Hardi	Injet 03	AI110/1.2/3.0	3.0	Air-induction nozzle

The scaling procedure outlined by Walklate, *et al.*, (1998) was used to calculate the length scale of spray drift from a 12 m (24 nozzles) boom sprayer. Assuming a buffer zone distance of 6 m the relative Predicted Environmental Concentrations (PECs) for the field scale treatments were determined and the LERAP star rating established. Reductions in drift from the standard in the range 50-75% receive a * rating; 25-50% a ** rating and <25% a *** rating (Gilbert, 2000). By grouping the data according to nozzle and humidity the LERAP star ratings for each nozzle and humidity combination could be determined and compared.

RESULTS

Table 2 shows that, for all the nozzles tested, the mean length scale of spray drift increased with increasing wet bulb depression (ΔT). However, it is not clear how this influences the LERAP star rating calculation. To reduce the risk of errors caused by variations in evaporation in LERAP wind tunnel tests, the standard operating procedure requires the relative humidity of the tunnel to be above 80% (i.e. $\Delta T < 3°C$). In Table 3, the LERAP star ratings for the air-induction and Coarse/Very Coarse nozzles were calculated using two bases; by comparing the results to the standard nozzle at the same humidity; and by comparing to the results of the standard nozzle at the high humidity. Within a given humidity range, the LERAP star ratings remain the same suggesting that controlling humidity is not critical for LERAP wind tunnel tests as long as the reference standard results are taken within the same humidity range. However, it appears from using $\Delta T < 3°C$ as a reference, that changes in humidity can alter drift equivalent to one or two LERAP star ratings depending on nozzle. Furthermore the results suggest that the air-induction nozzles are less sensitive to changes in humidity than conventional nozzles.

A more detailed analysis on the effect of humidity on drift can be derived by examining the influence of wet bulb depression on individual calculations of drift length scale (Figure 2). For the four nozzles tested, drift length scale increased with wet bulb depression. The regression coefficients varied in from R^2=0.75 for the 03F110 nozzle to R^2 =0.425 for the 01F110 nozzle.

Table 2. Influence of humidity on the calculated length scale (m) ± SE of drift from a 12 m boom

Nozzle & pressure	Drift length-scales for three humidity categories		
	Increased ΔT <3°C	Ambient ΔT 3-7 °C	Reduced ΔT 7- 10°C
01F110 @ 4.5 bar	12.01±0.76	14.11±1.59	20.64±3.33
03F110 @ 3 bar	6.00±0.51	7.70±1.20	12.01±2.16
08F80 @ 2.5 bar	1.40±0.11	2.47±0.48	3.53±0.88
Injet 03 @ 3 bar	1.64±0.12	1.97±0.28	2.25±0.38

Table 3. Influence of humidity on LERAP star rating for reduced drift nozzles referenced to the standard spray in same humidity range and in parentheses to the standard spray at high humidity (ΔT <3°C)

Nozzle & pressure	LERAP Star ratings for three humidity categories		
	Increased ΔT <3°C	Ambient ΔT 3-7 °C	Reduced ΔT 7- 10°C
08F80 @ 2.5 bar	***(***)	*** (**)	*** (*)
Injet 03 @ 3 bar	*** (***)	*** (***)	*** (**)

The increased sensitivity of the finer sprays to evaporation is also shown by examining the slopes of the regression lines (Table 4). Because drop size has a major influence on evaporation rate (Equation 5), the drop spectra of the nozzles used were measured using a Malvern Spraytec laser diffraction analyser (Kippax, *et al*., 2001) and their Volume Median Diameters (VMDs) added to Table 4. The results reinforce our earlier suggestion that sprays from the Injet 03 air-induction nozzle were less sensitive to changes in humidity than the conventional 08F80 nozzle because the air-induction nozzle produced a coarser spray.

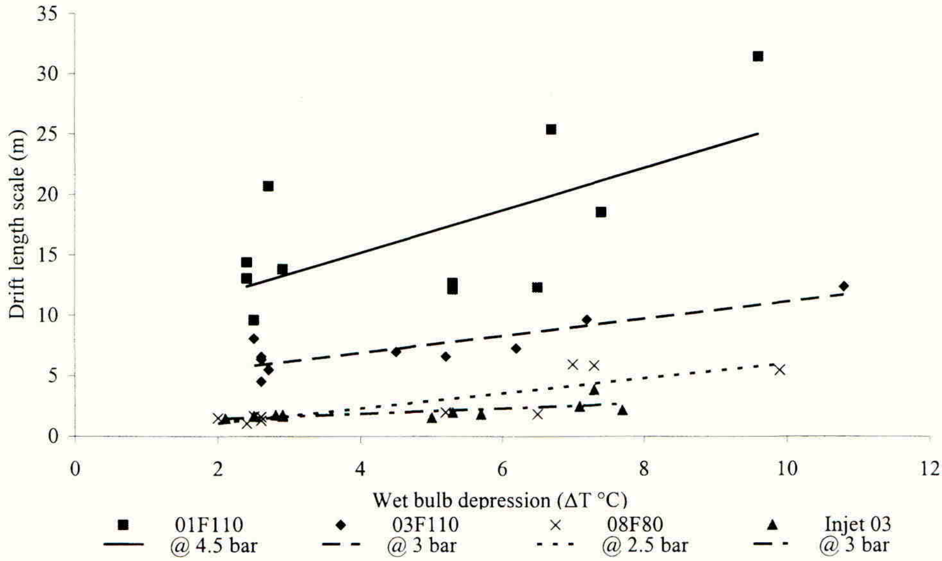

Figure 2. Variation of drift length scale calculated for a 12 m sprayer with wet bulb depression (ΔT °C)

Table 4. Rate of increase in drift length scale with wet bulb depression (ΔT °C) and drop spectra data

Nozzle	Rate of increase in spray drift (m/°C) ± SE	Drop size VMD (μm) ± SE
01F110 @ 4.5 bar	1.75±0.68	122±0.9
03F110 @ 3 bar	0.70±0.14	169±0.5
08F80 @ 2.5 bar	0.62±0.14	323±1.5
Injet 03 @ 3 bar	0.22±0.08	439±1.3

DISCUSSION

Although it is clear that humidity can influence evaporation from drops and hence drift, the extent to which this constitutes an effect that could influence the safety of field buffer zones requires investigation. It is clear from Tables 2 and 3 that there is an increased risk to the integrity of buffer zones when humidity is low. The number of occasions during a spraying season when wet bulb depression is large enough to cause increased drift could indicate the level of risk. An examination of UK weather data from the 1970's showed that the number of occasions during the growing season when wet bulb depression is large varies from year to year but there are few occasions when it exceeds 7°C in the UK. Even during the drought of 1975 ΔT exceeded 7°C only during 15% of daylight hours. However, arid climates can pose a more serious problem. Typical data from Warren, 500 km west of Sydney in the Macquarie River cotton growing area of Australia, showed ΔT exceeding 7°C during 40% of daylight hours. This has led to interest in evaporation reducing adjuvants and operating recommendations that restrict spraying to the more humid periods of the day such as the early morning or late evening (Woods, *et al.*, 2001).

CONCLUSIONS

Increased spray drift can occur at low humidity (i.e. large ΔT) and this can influence the behaviour of sprays during wind tunnel tests. However, the procedure of referencing the results of LERAP nozzle tests against standards taken at similar humidity, gives similar results. This indicates that, as a mechanism to establish reduced drift applications, the wind tunnel procedure for LERAP assessments is robust.

Although the results indicate that low humidity can increase spray drift equivalent to one or possibly two LERAP star ratings, this is unlikely to cause significant problems in the UK because of the generally moist climate. However, drop evaporation may cause significant spray drift problems for applications in arid climates unless mitigating steps are taken. Drift from coarse sprays appears to increase less rapidly with wet bulb depression (ΔT) and air-included sprays may offer advantages in terms of maintaining drift control under arid conditions.

ACKNOWLEDGEMENT

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REFERENCES

Gilbert A J (2000). Local Environmental Risk Assessment for Pesticides (LERAP) in the UK. *Aspects of Applied Biology* **57**, 83-90.

Ganzelmeier H; Rautmann D (2000). Drift, drift reducing sprayers and sprayer testing. *Aspects of Applied Biology* **57**, 1-10.

Kippax P; Parkin C S; Tuck C R (2002). Particle size characterisation of agricultural sprays using laser diffraction. *Proceedings of ILASS –Europe 2002*, Zaragoza, Spain. 9-11 September

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**, 49-56.

Walklate P J; Miller P C H; Richardson G M; Baker D E (1998). A similarity scaling principle for risk assessment of spray drift. *14th Conference on liquid atomisation and spray systems, ILASS Europe 98*, p 499-504.

Woods N; Craig I P; Dorr G; Young B (2001). Spray drift of pesticides arising from aerial application in cotton. *Journal of Environmental Quality* **30** (3), 697-701.

Defining the size of target for air induction nozzles

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ABSTRACT

The use of air induction nozzles, which produce droplets containing air that are larger than those produced by conventional flat fan nozzles, has increased considerably over recent years as one method of reducing drift. There is concern that, because of the larger droplets, there may be a minimum target size below which a reduction in efficacy of foliar-acting pesticides may occur when using these nozzles. A range of air induction nozzles was tested in the laboratory, outdoor pot experiments and field trials to determine the critical growth stage for use of these nozzles for the control of grass weeds, which can offer a small target. Air induction nozzles were selected that gave small, medium and large droplets with water or water plus a non-ionic surfactant as the spray solution. Herbicide applications to *Alopecurus myosuroides* and *Lolium perenne* at the one and two to three leaf stages suggested that particularly at the earlier growth stage a reduction in efficacy with a foliar-acting herbicide may be observed when using air induction nozzles. The effect of target size may be more pronounced when using nozzles that produce the largest droplets.

INTRODUCTION

High levels of spray drift control when using boom sprayers can be achieved by using 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; Miller & 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 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 & Matthews, 1999). Research has also shown that for all nozzle types, performance is influenced by formulation (Miller & Butler Ellis, 2000) with the effects with air induction nozzles being different to those with conventional pressure nozzle designs (Butler Ellis & Tuck, 2000). Most assessments of nozzle performance have examined sprays generated from liquids with a single adjuvant or formulation type while the work reported in this paper has examined air induction nozzle performance when spraying tank mixes typical of many practical application conditions.

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 *A. myosuroides* occurs when finer quality sprays are used, i.e. when droplets are small. Research by Jensen (1999) showed that herbicide efficacy can be reduced with low air induction nozzles at low volumes, spraying larger droplets, when treating small targets. However it is still unknown if there is a minimum target size below which a reduction in efficacy may be observed with air induction nozzles and it is this question that this paper aims to address. The work evaluated herbicide efficacy on both grass and broad-leaved weeds, however only the grass weed work is reported within this paper. Further information on the broad-leaved weeds work is reported in the HGCA report for this project (Miller *et al.*, 2003).

MATERIALS AND METHODS

Measurement of droplet size distributions

Measurements of the droplet size distributions from three commercial designs of air induction nozzle were made in the spray chamber at Silsoe Research Institute using the Oxford Lasers "Visisizer" instrument configured to measure droplets in the size range 50-2000 µm in diameter. Measurements were made with a single nozzle mounted on a computer-controlled transporter programmed to move the nozzle at 40 mm s^{-1} 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 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 all based on mixtures including clodinafop-propargyl, typical of those that might relate to the application of foliar-acting herbicides to control grass weeds. Details may be found in the HGCA Final report (Miller *et al.*, 2003). In addition data was also collected when spraying water only and 0.1% of a non-ionic surfactant.

Nozzles were selected for the experimental work on the basis of previous measurements with the aim of using nozzles giving a range of mean droplet sizes. All measurements were made with a nozzle size giving a nominal flow rate of 0.8 litres min^{-1} at a pressure of 3.0 bar. The nozzles 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

Outdoor pot experiments

Plants of perennial rye-grass (*L. perenne*) and black-grass (*A. myosuroides*) were grown outdoors in 2 litre pots in a potting mixture (soil + sand + peat, 2:1:1 w/w) at the Danish Institute of Agricultural Sciences. Pots were sown on three (2000) or four (2001) occasions and consequently plants at three or four different growth stages could be sprayed simultaneously. The pots were sub-irrigated automatically up to five times daily. The experimental design was a randomised block design with growth stages as blocks. The same three air induction nozzles (A-C) were examined as in the droplet size distribution measurements along with a conventional flat fan nozzle (D). The nozzles were examined 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^{-1} respectively. The plants were sprayed with six doses of clodinafop-propargyl in mixture with 2.5% Toil (a methylated vegetable oil adjuvant). At the time of application 3 pots of each growth stage were harvested and dry weights were recorded. Plants were harvested 37 days after treatment and dry weights were recorded and results of the experiments calculated in terms of ED_{90} dose values as reported by Powell *et al.* (2002).

Field trials

Field trials 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 grass weeds for use of air induction nozzles without a reduction in herbicide efficacy. *A. myosuroides* seeds were sown at a seedrate of 400 seeds/m^2 (Year 1) or 500 seeds/m^2 (Year 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 while also applying a treatment used commercially by farmers in the UK to control *A. myosuroides*. This was applied at full and half recommended dose at one leaf and two to three leaf stages of the *A. myosuroides*. 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 as described above at 50 cm spacing. Control of *A. myosuroides* was measured by counting the number of panicles in ten 30 cm x 30 cm quadrats per plot.

RESULTS

Measurements of droplet size distributions

Mean droplet sizes as expressed by the volume median diameter (VMD) for the herbicide mixtures sprayed through the three nozzles are shown in Figure 1. 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 (3-8) were less than both the water (1) and non-ionic surfactant (2) and this is likely to be due to the presence of the oil emulsion in the spray liquid (Butler Ellis & 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.

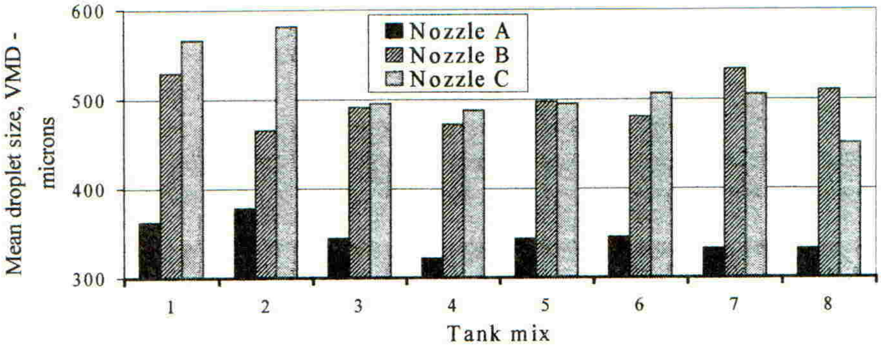

Figure 1. Measured mean droplet sizes for three different air induction nozzles operating with different tank mixes at a flow rate of 0.8 litres min^{-1}.

Outdoor pot experiments

The activity of clodinafop-propargyl on grass weeds was only slightly affected by growth stage with maximum activity being found when the grass weeds were at the larger growth stages, as illustrated by Figure 3. The lower activity at the earlier growth stages can most likely be attributed to lower spray retention on the more erect plants.

The experiments revealed that the performance of clodinafop-propargyl was significantly better when applied with a standard flat fan nozzle than compared to the three air induction nozzles irrespective of growth stage (Figure 3). The reduced efficacy with the air induction nozzles was evidence that the form of deposit based on the larger droplet sizes may also have an adverse affect on product efficacy.

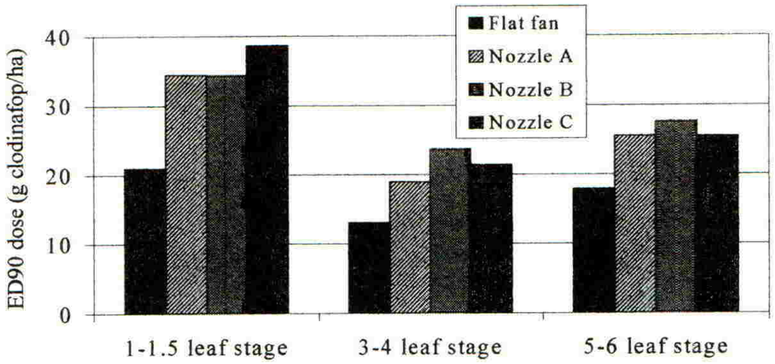

Figure 2. Calculated ED_{90} doses of clodinafop-propargyl (g a.i./ha) on *Lolium perenne* applied with different nozzles in Year 1.

Field trials

Figure 3 shows the control of *A. myosuroides* achieved from the range of nozzles tested in Year 1 and directly comparable results were obtained in the second years' field trial. There was a trend for levels of control of *A. myosuroides* to be higher when treated at the full dose of clodinafop-propargyl/trifluralin + oil, when treated at either growth stage of the *A. myosuroides*, 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 *A. myosuroides* panicles when *A. myosuroides* 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 *A. myosuroides* to be achieved when the conventional flat fan nozzle was used and a fall off in control was observed when air induction nozzles were used. These differences were more apparent when herbicide dose was reduced and/or *A. myosuroides* were small when treatments were applied. 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 *A. myosuroides*. Differences were more apparent when herbicide dose was reduced and/or *A. myosuroides* were small when treatments were applied.

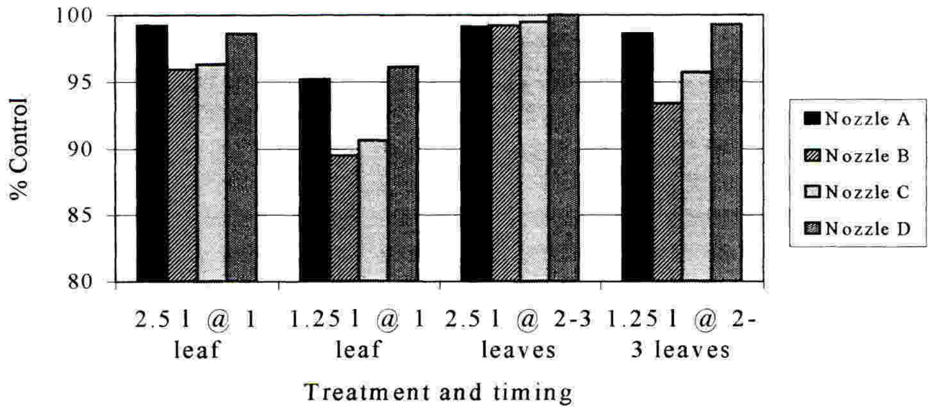

Figure 3. Percentage reduction *A. myosuroides* panicles treated with clodinafop-propargyl/trifluralin + oil at a range of dose rates using three air induction nozzles (A-C) and a conventional nozzle (D).

DISCUSSION

The selected nozzles as being representative of air induction nozzles giving a relatively small, medium and large droplet size was confirmed by the measurements of droplet size distributions and suggests that ultimately this could result in small targets getting very low or zero deposits.

The outdoor pot experiments aimed to determine the critical growth stage of grass weeds below which a reduction in efficacy may be observed when treating small targets with herbicide mixtures. The work suggested that maximum herbicide efficacy was at the larger growth stages of grass weeds and that there was a reduction in efficacy when using air induction nozzles compared to a conventional flat fan nozzle.

The field trials aimed to confirm the results from the laboratory and outdoor pot experiments. The results supported the earlier work in that higher levels of control of *A. myosuroides* were achieved when the weed was treated at the larger growth stage. The results from the outdoor pot experiments further reflected the higher levels of control achieved from the conventional flat fan nozzle compared with the air induction nozzles. There was a trend for the control of *A. myosuroides* that was achieved from the air induction nozzle producing smaller droplets, to be higher than from those which produced larger droplets. Differences between field and pot experiments may have also related to the air flow conditions around the weeds and spray at the time of treatment.

In conclusion, this work suggests that there may be a minimum target size for use of air induction nozzles, below which a reduction in efficacy of foliar-acting pesticides may be observed. For grass weeds, such as *A. myosuroides* this may be at about the 3 leaf stage, below which air induction nozzles should not be recommended. It is also apparent that not all air induction nozzles produce the same spectra of droplet sizes and that the effect of target size may be more pronounced when using nozzles that produce larger droplets.

ACKNOWLEDGEMENTS

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REFERENCES

Butler Ellis M C; Tuck C R (2000). The variation in the characteristics of air-included sprays with adjuvants. *Aspects of Applied Biology,* **57**, *Pesticide Application*, 155-162.

Butler Ellis M C; Swan T B; Miller P C H; Waddelow S; Bradley A (2001). Factors affecting the spray characteristics and drift performance of air induction nozzles. Submitted to *Journal of Agricultural Engineering Research*, March 2001.

Cawood P N; Robinson T H; Whittaker S (1995). An investigation of alternative application techniques for the control of blackgrass. *Proceedings of the BCPC Conference - Weeds*, 521-528.

Jensen P K. (1999). Herbicide performance with low volume low-drift and air-inclusion nozzles. *Proceedings of the BCPC Conference – Weeds,* 453 – 460.

Miller P C H; Lane A G (1999). Relationship between spray characteristics and drift risk into field boundaries of different structure. *Aspects of Applied Biology* **54**, *Field margins and buffer zones: ecology, management and policy*, 45-51.

Miller P C H; Butler Ellis M C (2000). Effects of formulation on spray nozzle performance for applications from ground-based boom sprayers. *Crop Protection* **19**, 609-615.

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 Report No. 317e*, HGCA London.

Piggott S; Matthews G A (1999). Air Induction nozzles: a solution to spray drift? *International Pest Control, January/February 1999*, 24-28.

Powell E S; Orson J H; Miller P C H; Kudsk P; Mathiassen S (2002). Defining the size of target for air induction nozzles. *Aspects of Applied Biology,* **66**, *International advances in pesticide application*, 65-72.

Tuck C R; Butler Ellis M C; Miller P C H (1997). Techniques for measuring droplet size and velocity distributions in agricultural sprays. *Crop Protection,* **16**, (7) 619-628.

Evaluation of nozzles for the application of a late fungicide spray

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ABSTRACT

A new nozzle was designed to optimise the application of a late fungicide spray. This paper reports on the laboratory tests undertaken to identify an appropriate design, and the subsequent field tests, farmer survey and drift measurements.

INTRODUCTION

In order to optimise the application of a late fungicide (T3) spray, the farmer needs to apply the product in the right place in the right manner at the right time. The criteria for the ideal nozzle were defined as being that it should: maximise the proportion of spray in the top 30 cm of a cereal crop; improve all-round coverage of the ear; minimise the risk of blocking; allow high work rates (apply 100 litres/ha at 12 km/hr), minimise drift, allowing more spraying days, be simple to fit and operate. The aim was to identify a nozzle design that would deliver as many of these factors as possible.

Silsoe Research Institute undertook a series of experiments to test the ability of existing and prototype nozzles to meet the first two specifications. Hypro EU Ltd then designed and produced a prototype nozzle, and subsequently manufactured the final Amistar nozzle. This nozzle was tested by Syngenta in the field, and a survey of farmers was conducted after the first season. As a result, small changes were made to the nozzle design and drift tests were undertaken in order to apply for a LERAP star rating. This paper reports the initial tests undertaken to design the nozzle, the field trials, the farmers' survey and the drift measurements.

LABORATORY EXPERIMENTS

In order to establish quickly and reliably the potential for improving evenness of coverage, artificial targets were used to simulate a cereal crop. These were made of five sections of plastic, coating a 90 cm tall, 1 cm diameter stainless steel rod and were denoted top, upper front, upper back, lower front and lower back. A three-nozzle boom section was mounted on a transporter that was operated at a speed of 3.3 m/s, i.e. 12 km/hr. The nozzles were positioned 0.5 m apart, 0.5 m above the top of the targets. Three targets were positioned 0.25 m apart, with the centre target vertically below the centre nozzle. The spray liquid used was 0.1% Agral with 1.0 g/litre "Green S" dye added.

Following spraying, the plastic sections were removed from each target, washed in distilled water and the quantity of spray liquid retained on each section determined. Deposits were also measured on pot–grown wheat plants. Three pots were sprayed per run in an array surrounded by guard pots, with three replicate runs per treatment. The artificial targets were also sprayed simultaneously. Plants were divided into the ear (top), flag leaf (middle) and the rest of the plant (bottom), washed in distilled water and analysed for total spray liquid recovered. A range of nozzles types was evaluated, including air induction, hollow cone, standard and extended pressure range. These were used at a range of nozzle angles, from vertically down to 45 degrees backwards. Only the most significant results are shown below.

Results and Discussion

The effect of angle on deposit was measured with three nozzles, a standard flat fan, FF110/1.2/3.0, an extended range flat fan (both Hypro EU Ltd) and an air induction AI110/1.2/3.0 nozzle (BubbleJet, Billericay Farm Services Ltd) at angles of 0, 10 20, 30 and 45° to the vertical. Figures 1 and 2 show the deposits on the top 30 cm section of the targets with the standard and AI nozzles; vertical bars represent Standard Deviations of the means. The highest total deposits occurred with all nozzles angled at 45° and the largest total deposit occurred with the air induction nozzle.

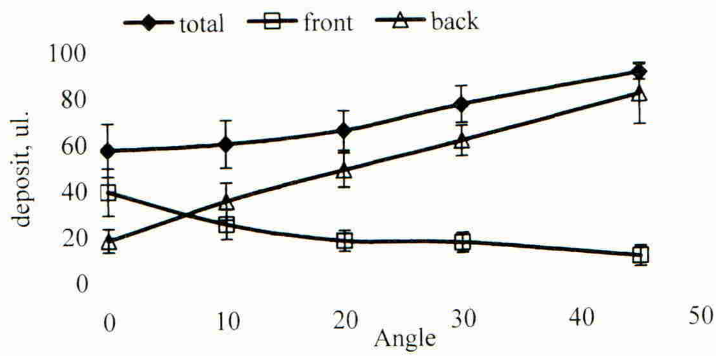

Figure 1. Variation in deposit on top 30 cm of artificial targets with angle – F110/1.2/3.0 standard nozzle.

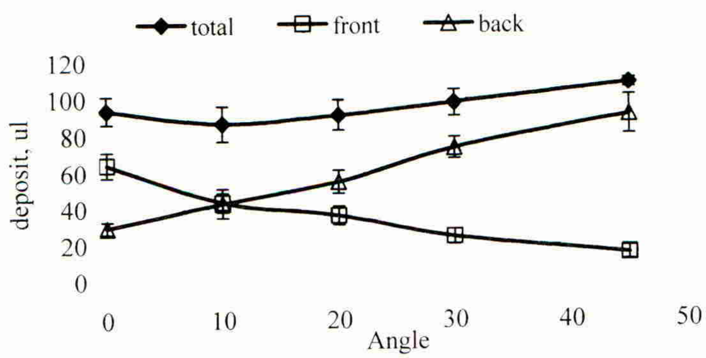

Figure 2. Variation in deposit on top 30 cm of artificial targetswith angle – AI110/1.2/3.0 air induction nozzle.

The optimum angle for equal front and back deposit occurred at around 10° for the air induction nozzle and around 7° for the standard and extended range nozzles. The total upper deposit for the air induction nozzle at 10° was higher than the deposit for the other two nozzles at any angle apart from the standard flat fan at 45°.

A prototype T3 nozzle was manufactured, based on the principle of air induction and aiming for a droplet size at the smaller end of the possible range achievable in the design of an air induction nozzle. The performance of the prototype was then compared with conventional nozzles, vertical and angled as well as an air induction nozzle. The same artificial targets were used to evaluate front and back deposits and in addition, pot-grown wheat plants were used to determine the distribution of deposit on a wheat crop.

Results from the artificial targets showed that the prototype nozzle had the highest deposit, although there was still too much on the front, similar to the vertical standard nozzle. This suggested that a greater backwards angle was required for this prototype nozzle, indicating lower droplet velocities and larger droplets than the AI nozzle. Further refinements were made to the prototype nozzle, and the final T3 nozzle was then used to repeat the measurements on artificial targets and pot-grown plants, where it was compared with a conventional F110/1.2/3.0 "03" nozzle.

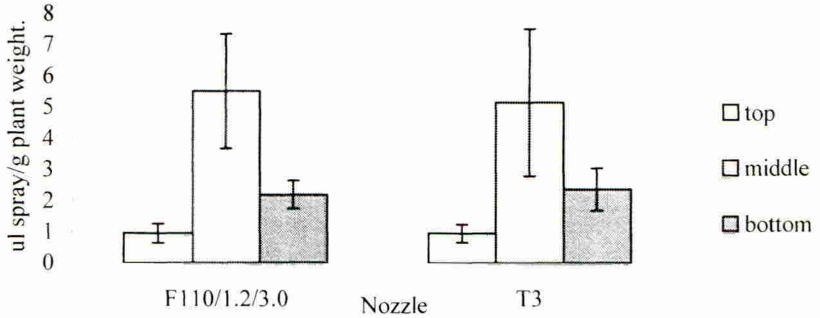

Figure 3. Distribution of spray on pot-grown plants; vertical bars denote SDs of means.

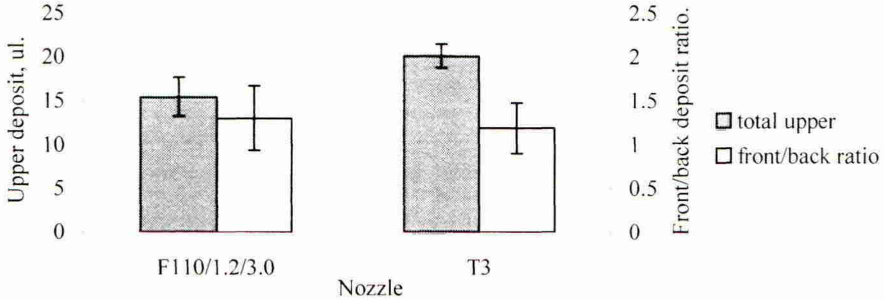

Figure 4. Deposits on upper 30 cm of artificial targets; vertical bars denote SDs of means.

Variability between samples masked any differences between nozzles in the deposition on plants (Figure 3). Although it was not possible to draw any conclusions from this, it gave us confidence to take the prototype nozzle out into the field. In addition, deposits on the artificial targets (Figure 4) showed that the T3 nozzle had the most even front and back deposit (i.e. front/back ratio nearest to 1.0), and had significantly higher deposits on the top 30 cm than the standard 03 nozzle.

FIELD TRIALS

In spring 2002, field trials were conducted to compare the yield following application of 0.3 litres/ha Amistar and 0.3 litres/ha Folicur through the T3 as well as conventional F110/1.2/3.0, F110/2.4/3.0 nozzles and an air induction nozzle, AI110/1.2/3.0 (all Hypro EU Ltd). In a second experiment, measurements were made of deposit on the flag leaf and ear with conventional, air induction and T3 nozzles applying 100 litres/ha, and artificial targets were planted within the crop to indicate front and back deposits. In both experiments, there were three replicate plots, 30 m x 5 m, for each treatment. The applications of azoxystrobin 75 g.a.i./ha + tebuconazole 75 g.a.i./ha were made with a commercial 12 m boom sprayer.

Results and discussion

Deposits on plants is shown in Figure 5. The T3 nozzle gave the highest level of deposit on plants, with 10% more on the ear and 36% more on the flag leaf than the conventional F110/1.2/3.0 nozzle. The T3 nozzle also gave the best front and back coverage on artificial targets, with a front/back ratio of 0.9 compared with 3.5 for the F110/1.2/3.0 nozzle.

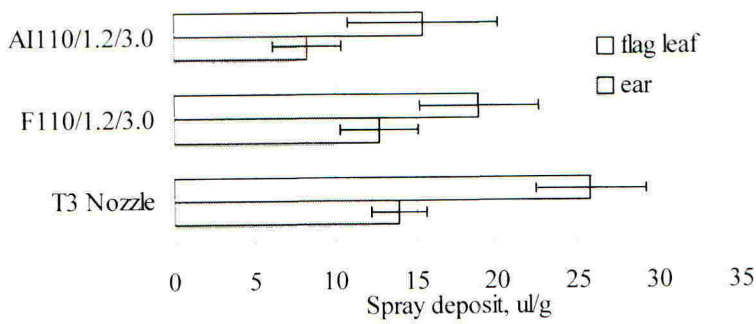

Figure 5. Field trial: spray deposit partitioning on plants; vertical bars denote SDs of means.

Figure 6 shows that the T3 nozzle produced the best yield, with a small (around 3%) but significant increase over the conventional F110/1.2/3.0 nozzle. Figure 6 also shows that applications at 100 litres/ha out yielded an application at 200 litres/ha.

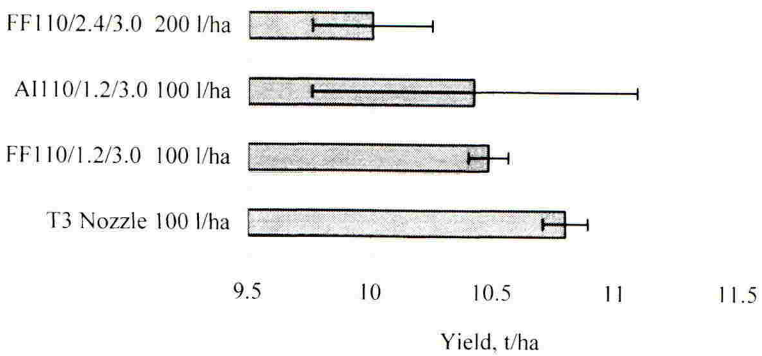

Figure 6. Field trial: yield after a T3 spray with a range of nozzles; vertical bars denote SDs of means

FARMERS' SURVEY

There were 229 responses to a survey about the performance of the T3 nozzle, showing high levels of satisfaction, particularly with drift and field performance (Table 1). Comments indicated that there were some problems with accidental breakage and difficulty cleaning the nozzle, and therefore small changes were made to the design to include reinforcement and the ability to dismantle it for cleaning.

Table 1. Results of T3 nozzle survey – farmer satisfaction with different criteria

Criteria	Number of farmer responses			Number of respondents to question
	Very satisfactory	Satisfactory	Not satisfactory	
Drift	125	82	2	209
Coverage	110	99	0	209
Ease of fitting	83	120	7	210
Disease control	65	135	4	204

Total number farmers responding to survey = 229. Nine incomplete surveys. 220 analysed.

SPRAY DRIFT

Measurements were made in a wind tunnel of horizontal drift profiles for the T3 nozzle at a range of pressures (Figure 8), compared with a reference F110/1.2/3.0 flat fan nozzle according to the LERAP protocol (Walklate *et al.*, 2000). The drift reduction with the T3 nozzle was not as great as might be expected for an air induction nozzle, but this was likely to be due to the relatively small droplets that the T3 nozzle produces, along with the small backwards angle. The spray was angled with the wind direction, towards the drift collectors, for these measurements.

By reducing the pressure, it was possible to significantly reduce the drift. Subsequent measurements were made at low pressures and reduced boom heights to enable a 75% drift reduction (three star rating) to be achieved at 450 mm boom height and 1.0 – 1.5 bar pressure.

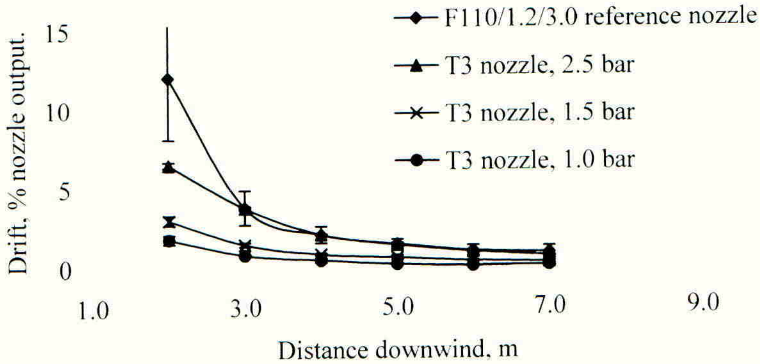

Figure 7. Horizontal drift profile for the T3 nozzle, measured in a wind tunnel, compared with a reference flat fan nozzle, at 500 m boom height; vertical bars denote SDs of means.

CONCLUSIONS

Tests have shown that the T3 nozzle, which is a small droplet air-induction nozzle designed to produce a 10° backwards angle, has the potential to significantly improve the evenness of deposit between the front and back of the ears of cereal crops compared with the standard F110/1.2/3.0 flat fan nozzle.

Field trials showed a 10% increase in deposit on ear and 36% on flag leaf with the T3 nozzle compared with a standard F110/1.2/3.0 nozzle. This resulted in a small but significant increase in yield.

While the T3 nozzle is designed to be used at 3.0 bar and 12 kph, when using a category B tank mix, users can comply with LERAP legislation to reduce buffers zones by reducing speed on the LERAP headland, dropping the pressure to 1.5 bar and keeping the boom at 450 mm above the crop.

ACKNOWLEDGEMENTS

Thanks to Trevor Swan of Hypro EU Ltd for the design and manufacture of the Amistar Nozzle.

REFERENCES

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**, 49-56.

The deposit characteristics of pesticide sprays applied at low volumes

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ABSTRACT

Reducing spray application volumes is seen as an important route for improving timeliness, and therefore the efficiency, of pesticide use. A series of laboratory tests were undertaken to investigate the characteristics of sprays used to apply pesticide at water volumes from 25 to 200 litres/ha. A range of application techniques were used, including conventional flat fan, air induction and twin fluid nozzles, CDA and air assistance. The results shown in this paper relate to deposit and coverage on artificial targets. Some changes in characteristics were observed at volumes below 50 litres/ha, particularly with large droplet sprays, although in general the differences between application techniques were greater than the differences between different application volumes. Work to date indicates that, if there is a reduction in performance with reducing volume rates, then this is likely to be due to greater variability or poorer coverage rather than reduced mean deposit levels.

INTRODUCTION

Reducing water volume rates below 200 litres/ha is one of the most useful methods of increasing work rates, improving timeliness and efficiency of the application. In practice, there are two limiting factors preventing volumes from being reduced: spray drift and a lack of reliable data concerning the consequences for efficacy. While spray drift can be overcome by developments in application techniques, maintaining efficacy is more difficult since it depends upon a range of factors, including active ingredient, dose rate and timing as well as application technique. There may be limits below which volumes cannot be reduced without compromising the quantity of pesticide retained and the distribution of deposits on the target. These limits are likely to depend upon the application equipment and operating parameters. The properties of the spray liquid, which will be influenced by the tank mix of formulations, adjuvants and water volume, also modify the quantity and distribution of deposit (Holloway *et al.*, 2000). The crop canopy (density, structure and surface) and the target site are also important factors.

It is clear that there are too many variables influencing the efficacy of spray application to easily evaluate reducing water volumes. There is a substantial amount of relevant literature (e.g. Knoche, 1994), but most studies consider only one or two variables over a limited range, and cannot be extrapolated to different application methods, crops or pesticides because the underlying mechanisms are not understood. The aim of this work is to begin to define the limits to which volume can safely be reduced in some common scenarios, and provide some information about appropriate application techniques.

The main scenario that is considered here is that of the control of small weeds. Powell *et al.*, 2002 suggest that large air-included droplets may not provide adequate control with small grass weeds, and a common assertion is that there are insufficient droplet numbers. This is likely to be exaggerated at lower volumes, and therefore one of the hypotheses that we aim to test is that, with some application systems, small targets may risk receiving an inadequate dose as volumes are reduced below 100 litres/ha. This paper reports the first phase of a project, where the characteristics of sprays were assessed in the laboratory, to determine how they are influenced by a range of techniques that can be used to reduce application volume.

MATERIALS AND METHODS

Sprays have conventionally been characterised by measuring parameters such as droplet size distributions, droplet velocities and volume distribution patterns (Tuck *et al.*, 1997).

Table 1. Application systems used in laboratory tests

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

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

The relationship between these parameters and deposit on a target plant is not straightforward, and therefore it was seen as appropriate to use parameters directly related to deposits to characterise each of the sprays under investigation.

Since the hypothesis to be tested was that small targets are vulnerable when applying low volumes, small artificial targets were used to characterise the spray. These consisted of plastic discs of diameter 15 mm, placed horizontally, and drinking straws of diameter 5 mm and length 50 mm, placed vertically, on wooden battens laid on the ground In addition, pieces of chromatography paper were both placed on the battens and wrapped round some of the vertical targets to allow estimation of coverage. A matrix of targets was placed underneath a track sprayer with a 3–nozzle boom attached, the range of treatments is shown in Table 1. Three replicate measurements were made for each treatment. The spray liquid was a tracer dye (Green S or Sodium Fluorescein) added to a 0.1% solution of Agral. The targets were left to dry, then each one was washed in deionised water and the quantity of spray liquid assessed using spectrophotometry. The values were normalised to 100 litres/ha. The percentage area covered of chromatography paper was assessed using an Optimax image analysis system. Two experiments were conducted, one at Silsoe Research Institute, and one at Hardi International in Denmark, with slightly differing layouts (see Table 1).

RESULTS AND DISCUSSION

The mean levels of deposit on horizontal targets did not differ significantly either with volume or with application system. This was expected, since the chosen targets are good collectors and would be expected to reflect the quantity applied. The mean deposit on vertical targets was expected to differ, since the droplet trajectory is a crucial component in determining whether a droplet will contact a vertical surface. Those application systems that have a significant horizontal component (CDA, twin fluid, angled air assistance) would be expected to have higher levels of vertical deposit; fine sprays can take advantage of horizontal air movements to increase vertical deposits, and higher forward speeds also might increase vertical deposition. Figures 1 (UK) and 2 (Denmark) show the mean vertical deposits obtained for the different application systems.

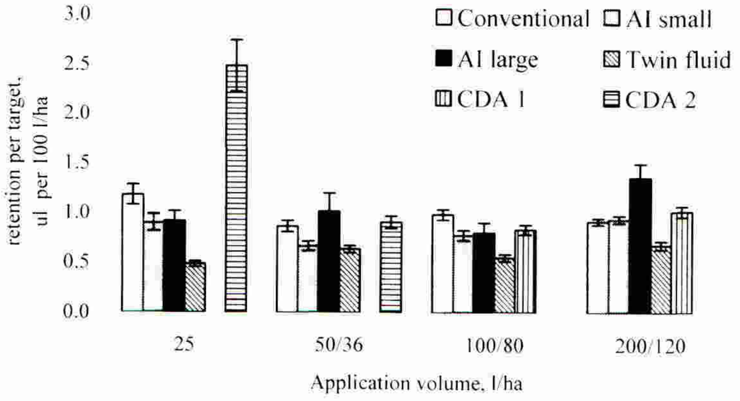

Figure 1 Deposit on vertical targets at Silsoe Research Institute, UK (error bars show SEM)

Differences between application systems are small, but significant in some cases, particularly at 25 litres/ha, where the CDA treatment gave extremely high levels, probably due to high horizontal droplet velocities. The expected higher levels of deposit with conventional and twin fluid nozzles was not seen, nor with the increase of speed that occurred between 100 and 50 litres/ha in the SRI experiments (Figure 2). There was therefore, little effect of reducing volume. However, at Hardi, there was a noticeable increase in deposit with reducing volume (Figure 3). The angled treatment also showed higher levels of deposit, particularly at 25 litres/ha, and there may be a forward speed effect since deposits were higher at 50 litres/ha than 100 litres/ha. The difference between the two experiments is likely to be as a result of different experimental layouts. In Denmark, there was less space and more blockage from the boom than in the laboratory at SRI, leading to more turbulence and higher vertical deposits. Neither situation is entirely representative of the situation in the field, which may be somewhere between the two. Deposition will be different on real plants with real spray liquids. The data indicate the likely differences between application systems and volume.

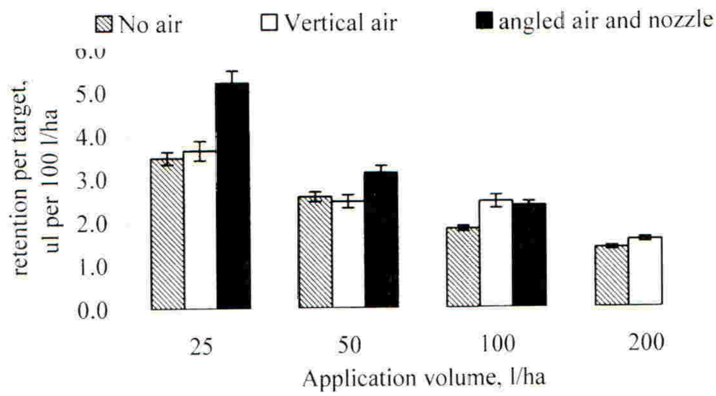

Figure 2. Deposit on vertical targets at Hardi International, Denmark (error bars show SEM).

Table 2. Coefficients of variation (CV), %, of the deposit per target, normalised to 100 litres/ha, for different application systems and volumes

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

The hypothesis that small targets may risk receiving inadequate doses with some low volume treatments cannot be tested by looking solely at mean deposit levels. Table 2 shows the coefficients of variation for each of the replicate measurements for each treatment, which indicates the level of variability. The greatest values for each volume rate are shaded, and it can be seen that the large droplet air induction treatment is always the most variable. It must be pointed out that the low pressures deliberately used to generate very large droplets were at or below the limit of manufacturers' recommendations and the results do not necessarily reflect normal practice. There are few other differences in the horizontal CVs. There is a tendency, although not strong, for the CV to increase with reducing volume, and this trend is more noticeable for vertical deposit CVs. These high CVs indicate that there may be some targets which receive less than an acceptable dose, leading to potential poorer performance. However, no treatments resulted in a zero deposit, even at the lowest volumes and with the largest droplets.

A second parameter that may influence efficacy is the surface coverage. It has been suggested that finer sprays associated with lower volumes with conventional treatments give better levels of coverage. The percentage target area covered by droplets was estimated and examples are shown in Figures 4 and 5 to show the range. This data is not normalised to 100 litres/ha but shows the absolute coverage. There were some differences between application systems, with conventional sprays giving the best coverage on horizontal targets, and large AI droplets and vertical air assistance the worst.

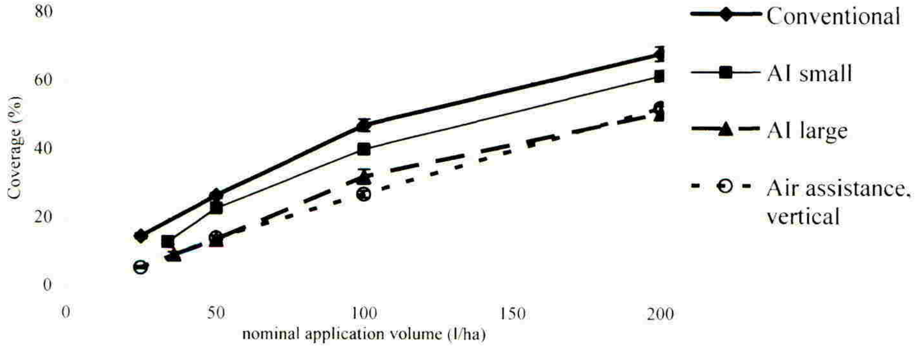

Figure 3. Coverage of horizontal targets (error bars show SEM).

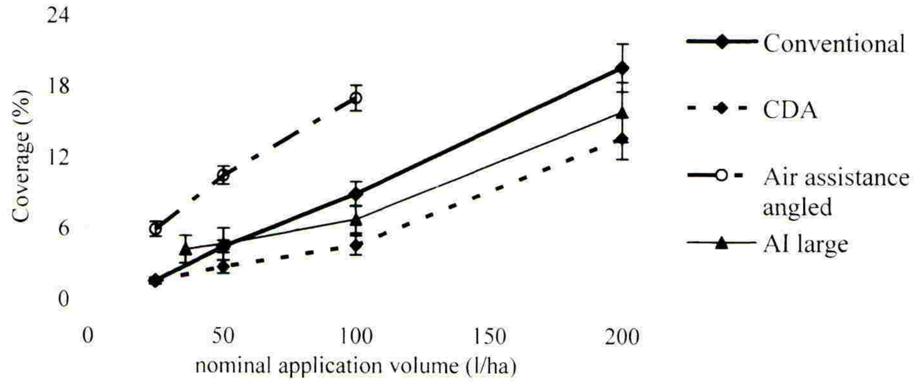

Figure 4. Coverage on vertical targets (error bars show SEM).

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

CONCLUSIONS

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

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

This suggests that, if there is a reduction in performance with reducing volume, it is not because of mean deposit levels, but may be because of greater variability or poorer coverage. The high variability with large AI droplets may be a factor in the poorer performance of these nozzles on small grass weeds, demonstrated by Powell *et al*. (2002).

Any increase in performance with reduced volume could be because of increased concentration, or because of a direct link between deposit size or number and behaviour of the pesticide on the plant. Work continues to evaluate whether these results are repeated on plants and under field spraying conditions, and the consequences for weed and disease control.

ACKNOWLEDGEMENTS

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REFERENCES

Holloway P J; Butler Ellis M C; Webb D A; Western N M; Tuck C R; Hayes A L; Miller P C H (2000). Effects of some agricultural tank-mix adjuvants on the deposition efficiency of aqueous sprays on foliage. *Crop Protection* **19**, 27-37.

Knoche M (1994). Effect of droplet size and carrier volume on performance of foliage-applied herbicides. *Crop Protection* **13**, 163-177.

Powell E S; Orson J H; Miller P C H; Kudsk P; Mathiassen S (2002). Defining the size of target for air induction nozzles. *Aspects of Applied Biology* **66**, 65-72.

Tuck C R; Butler Ellis M C; Miller P C H (1997). Techniques for measuring droplet size and velocity distributions in agricultural sprays. *Crop Protection* **16**, (7) 619-628.