Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/issn/15375110

Research Paper

Wind tunnel investigation of the ability of drift-reducing nozzles to provide mitigation measures for bystander exposure to pesticides

M. Clare Butler Ellis [a,*], Andrew G. Lane [a], Christine M. O'Sullivan [a], Steven Jones [b]

[a] Silsoe Spray Applications Unit Ltd, Building 42, Wrest Park, Silsoe, Bedford, MK45 4HP, UK
[b] Syngenta Crop Protection, Jealott's Hill International Research Centre, Bracknell, Berkshire, RG42 6EY, UK

ARTICLE INFO

Article history:
Received 9 July 2020
Received in revised form
8 December 2020
Accepted 11 December 2020

Keywords:
Spray drift
pesticide
wind tunnel
bystander exposure
drift reduction
nozzle

Models recently developed for assessing the potential exposure of residents and bystanders to pesticides through spray drift have highlighted the need for mitigation strategies to reduce exposure of members of the public. Drift-reducing equipment is readily available in many countries and is accepted as mitigation for the exposure of surface water to drifting pesticide sprays but there is concern that the drift-reduction measurement methods used to define the exposure of surface water might not be relevant to bystanders. Airborne spray is an important component in bystander exposure. Two wind tunnel experiments were undertaken to evaluate whether reductions in airborne spray are as great as the reductions in measured spray drift that occur using protocols designed to classify nozzles for protecting surface water. Results, with nozzles and pressures with a range of nominal drift reduction, and three different spray liquid types, suggested very strongly that the nominal drift reduction of a nozzle/pressure combination will give at least the same level of reduction in airborne spray for distances 3–5 m downwind. These data should be considered in the context of field data and model simulations in order to establish robust mitigation measures for regulatory exposure assessment. They indicate that the nominal drift reduction, measured using UK, Netherlands or German protocols, can be used to reduce bystander exposure up to 90%. The BREAM2 model for bystander exposure to spray drift can therefore be extended to include drift mitigation, with reductions in exposure up to 90% for classified equipment used in the appropriate way.

1. Introduction

A series of models has been developed for assessing the potential exposure of residents and bystanders to pesticides through spray drift (BREAM, Kennedy et al., 2012, BROWSE, Kennedy & Butler Ellis, 2017 and BREAM2, Butler Ellis et al., 2018). They have provided more reliable predictions of exposure, but this has highlighted the need to introduce mitigation measures to ensure that all efforts are made to reduce

* Corresponding author.
E-mail address: clare.butlerellis@ssau.co.uk (M.C. Butler Ellis).
https://doi.org/10.1016/j.biosystemseng.2020.12.008
1537-5110/

Nomenclature

BCPC	British Crop Protection Council
BREAM	Bystander and Resident Exposure Assessment Model
BROWSE	Bystander, Resident Operator, Workers Exposure models for plant protection products
EC	Emulsion Concentrate
EFSA	European Food Safety Authority
LERAP	Local Environmental Risk Assessment for Pesticides
OBO	Onderzoek Bestrijdingsmiddelen en Omwonenden (Research on Pesticides and Local Residents)
SSAU	Silsoe Spray Applications Unit
SC	Suspension Concentrate
UKAS	United Kingdom Accreditation Service

exposure of members of the public, and that these measures are based on sound science.

Drift reduction through the use of specifically-designed equipment, particularly nozzles, has been common for more than 20 years and is part of the regulatory system for protecting surface water from spray drift in many European countries. Similar schemes to protect bystanders would be advantageous both to farmers and to the public.

The European Food Safety Authority (EFSA) defines how risk assessments for pesticides should be conducted. Currently EFSA guidance for estimating bystander exposure (EFSA, 2014) allows a maximum of 50% drift reduction based on the use of nozzles classified as 50% drift reduction or greater, despite 75%, 90% and even 95% drift-reducing techniques being available. However, bystander exposure, by both dermal and inhalation routes, relates to airborne spray drift whereas the component of spray reaching surface water is sedimenting drift, i.e. falling due to gravity. There has been concern that the drift reduction measurement protocols used to define the exposure of surface water might not be relevant to bystanders, hence the current limit of 50% used for the exposure reduction permitted for bystanders.

In order to determine the reduction in potential bystander exposure we therefore need to quantify the reduction in potential airborne spray drift with current drift reduction technology. Moreover, since the only information available to users of spraying equipment relates to drift reduction for surface water, we need to establish that the airborne spray drift reduction is at least as great as the drift classification suggests if we are to use this measure as a surrogate for the possible reduction in bystander exposure.

There are different laboratory-based approaches for classifying drift reduction of nozzles or spraying equipment in different European states. The UK, Germany and France use wind tunnel measurements of drift from an individual nozzle (Walklate et al., 2000; Herbst & Ganzelmeier, 2000; Douzals & Al Heidary, 2014). Measurement protocols and calculation methods differ between the three countries, with France and the UK using the variation of drift with downwind distance (a horizontal profile) and Germany using the variation of drift with height above ground (a vertical profile) at a specified single downwind distance. The German approach is therefore based on a measure of airborne spray and it would be expected to be well correlated with bystander exposure. The Netherlands uses a different approach −a combination of spray characterisation and a model simulation of sedimenting drift as a function of distance downwind (Van de Zande et al., 1999). Because the model is validated against field data (Holterman et al., 1997), it would be expected to be strongly correlated with a wind tunnel measurement of drift at different downwind distances, which is also correlated with field measurements of sedimenting drift.

All four countries also accept field trials as a basis for determining drift reduction, which is necessary when the equipment under test is not amenable to small-scale laboratory experiments, and such trials tend to be very similar across the countries as they are based on an international standard (ISO 22866, 2005). Butler Ellis et al. (2017) showed that drift reduction measured in the SSAU wind tunnel using a horizontal profile was correlated with field measurements of drift reduction using ground deposits. This study also showed that using the UK wind tunnel, drift reduction determined with a horizontal profile was very similar to the airborne spray drift reduction determined with a vertical profile. Thus, while there are differences between the different methods, there are strong scientific reasons to support the assertion that they will give the same levels of drift reduction for the same test and reference nozzle conditions.

The greatest difference between the schemes is the reference nozzle that is used. The nozzle previously used to define the fine-medium threshold nozzle in the British Crop Protection Council (BCPC) spray classification scheme (Southcombe et al., 1997), would appear to be the ideal choice, but it is restricted in its availability. Therefore a commercially-available nozzle is required for field trials in sufficient quantities for a complete boom. The UK selected a flat-fan nozzle which at the time was manufactured by Lurmark Ltd, Cambridge, UK but is now obsolete, and this nozzle was also used in wind tunnel tests. The Netherlands has used the BCPC nozzle for laboratory measurements, but uses a different nozzle (Teejet XR110 04, Teejet, Glendale Heights, IL, USA) for field trials. The German wind tunnel test also uses the BCPC nozzle as its wind tunnel reference, but the French scheme uses an Albuz flat-fan 110 02 nozzle (Solcera, Evreux, France) which produces a finer spray and generates a much higher level of drift. Thus each of the UK, German, Dutch and French schemes is likely to be using a different nozzle. However, the differences between the German, Dutch and UK reference nozzles are relatively small, and in a field study to evaluate drift reduction of spraying equipment, the Netherland field reference nozzle was used as an acceptable alternative to the UK reference nozzle (Stallinga et al., 2018). This study showed that the drift reduction measured according to the UK and NL field protocols was similar, but drift reduction from the French protocol was significantly different from that for the UK and NL. It should be noted that the UK has recently changed its reference nozzle to one which is similar to the original obsolete model but potentially slightly closer to the existing German and Dutch reference nozzles (Butler Ellis et al., 2020). When operated at 300 kPa, it defines the fine-medium

Table 1 – Nozzles used in Experiment 1.

Manufacturer	Nozzle	Pressure, kPa	Drift reduction	Nominal applied volume[a], l ha^{-1}
Teejet	TP110-03 SS	300	UK reference	180
Teejet	XR110-04	300	Netherlands reference	240
Lurmark	F110-03 SS (BCPC No.11)	300	German reference	180
Lechler	ID-120-03	200	A –90% drift reducing	147
Lechler	ID-120-03	300	B –75%–90% drift reducing	180
Lechler	ID-120-03	500	C - 50%–75% drift reducing	232

[a] at 8 km h^{-1} and 0.5 m nozzle spacing.

threshold nozzle in the recent International Standard (ISO25358:2018) for spray classification.

In order to be certain that the potential exposure reduction for bystanders is independent of the reference nozzle used to classify the equipment, we included the three similar reference nozzles in our experimental studies. However, because the French reference condition is very different, we have not included this.

Measurements of drift reduction traditionally use a solution of a tracer dye (ISO 22866, 2005). It is recognised, however, that product formulation can also influence drift (Hilz & Vermeer, 2013) and that drift reduction might not always be consistent across all combinations of products and nozzles (Butler Ellis et al., 2016). It is important to establish that there are no major discrepancies in drift reduction measured with a product formulation, and therefore some drift measurements were also made with two commercial products.

Thus, this paper describes two experiments that were conducted in the wind tunnel at Silsoe Spray Applications Unit in the UK, one which evaluated the effect of drift reduction relative to the three main reference nozzles on the reduction in airborne spray, and the other that explored the interaction between nozzle and product formulation on drift reduction.

Wind tunnel experiments were chosen as being more repeatable for measuring spray drift than field trials and capable of providing a higher resolution for comparing drift values between systems. The distribution of airborne spray with height above the ground, however, is significantly different from that which occurs in the field because there is less turbulence within the wind tunnel compared with atmospheric flows, and it is turbulence that causes vertical dispersion of the spray plume. However, the total quantity of spray that is detrained from the spray plume is expected to be similar to that which would occur in the field under similar conditions. Therefore airborne spray from a drift-reducing nozzle can be compaed with airborne spray from a reference nozzle to determine the potential reduction of bystander exposure.

This work is part of a larger study which also considered field data and model predictions in order to ensure that the conclusions are robust under a wider range of conditions.

Table 2 – Drift Reduction class for each country for the Lechler ID3 nozzle ID-120-03.

Country Code	Pressure		
	200 kPa	300 kPa	500 kPa
UK	90%	90%	75%
DE	90%	75%	50%
NL	90%	75%	50%

2. Materials and methods

2.1. Nozzles and spray liquid

2.1.1. Experiment 1

The reference nozzles from the UK, the Netherlands and Germany were included in tests (Table 1). The ID3 nozzle, ID-120-03 (Lechler GmbH, Metzingen, Germany) has been classified in the three countries at 50–90% drift reduction, depending on the operating pressure (Table 1). This nozzle was therefore also used in tests to determine both the potential drift reduction for each of the three countries and the potential reduction in airborne spray.

The spray liquid for all tests in Experiment 1 was a solution of 0.1% Tween 20 (VWR International, Lutterworth, Leicestershire, UK) and 1.0 g l^{-1} Green S food dye (E142) in tap water (Fast Colours, Huddersfield, UK).

2.1.2. Experiment 2

Nozzles used in Experiment 2 are given in Table 3, and the tank mixes used as spray liquids are given in Table 4.

Compatibility and spike tests were carried out to ensure the Green S tracer could be Independently quantifiable without interference with the products sprayed and extracted from the target material after deposition, with recoveries of at least 97%.

2.2. Measurement protocol

The measurement protocol used was identical to that used for LERAP (Local Environmental Risk Assessment for Pesticides) star rating measurements in the UK (Butler Ellis et al., 2020), with some additional collectors to obtain vertical profiles. Work was carried out to ISO 17025:2017 to which SSAU Ltd are accredited by UKAS (United Kingdom Accreditation Services). The basic principles of the protocol are outlined below.

The same collectors as those that have been used in field studies to capture airborne spray drift (Butler Ellis et al., 2010) were used in the wind tunnel. The wind tunnel was set up with a single moving nozzle mounted at 0.5 m above the lowest collecting lines (which were 0.1 m above the floor) on

Table 3 – Nozzles used in Experiment 2.

Manufacturer	Nozzle	Pressure, kPa	UK Drift reduction, %	Nominal applied volume[a], l ha^{-1}
Teejet	TP110-03 SS	300	UK reference	180
Lechler	ID-120-05	300	D –90% drift reducing	300
Teejet	TTI 110 05	200	E –90% drift reducing	245
Hypro[b]	Guardian Air 03	150	F - 75% drift reducing	127

[a] at 8 km h^{-1} and 0.5 m nozzle spacing.
[b] Hypro, Cambridge, UK.

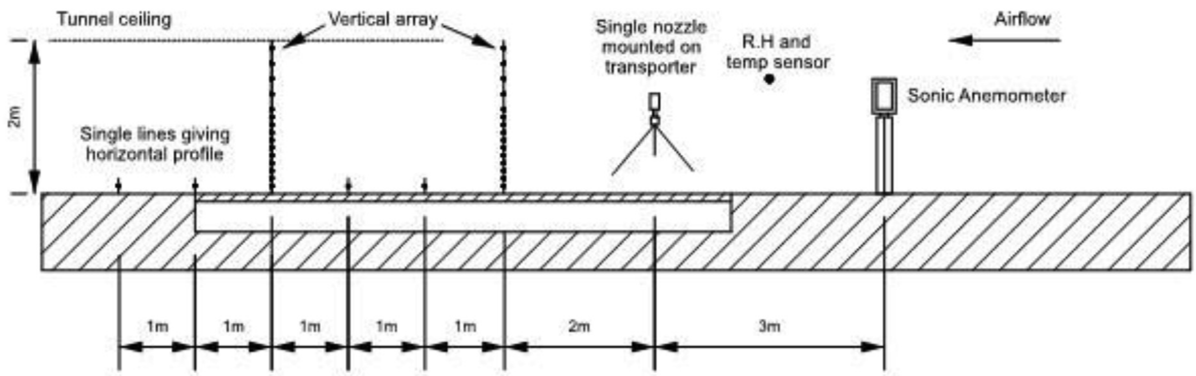

Fig. 1 – Wind tunnel layout.

a track sprayer. The layout is shown in Fig. 1 and a photograph of the tunnel setup prior to the measurements being made is shown in Fig. 2. The speed of movement of the nozzle was 8 km h^{-1} to simulate the constant vehicle speed of the sprayer in the field. The wind speed was set to 2 m s^{-1} for all tests, which is the most commonly-used wind speed for determining drift reduction in wind tunnels (ISO22856, 2008).

The number of passes of the nozzle across the wind tunnel required to achieve quantifiable drift deposits is dependent upon the level of drift. Hence, 10 passes were used for the reference nozzles but up to 80 passes for the drift-reducing nozzles.

Polythene collector lines (0.5 m long, 0.002 m diameter) were mounted across the tunnel, downwind of the nozzle output to measure both horizontal and vertical profiles.

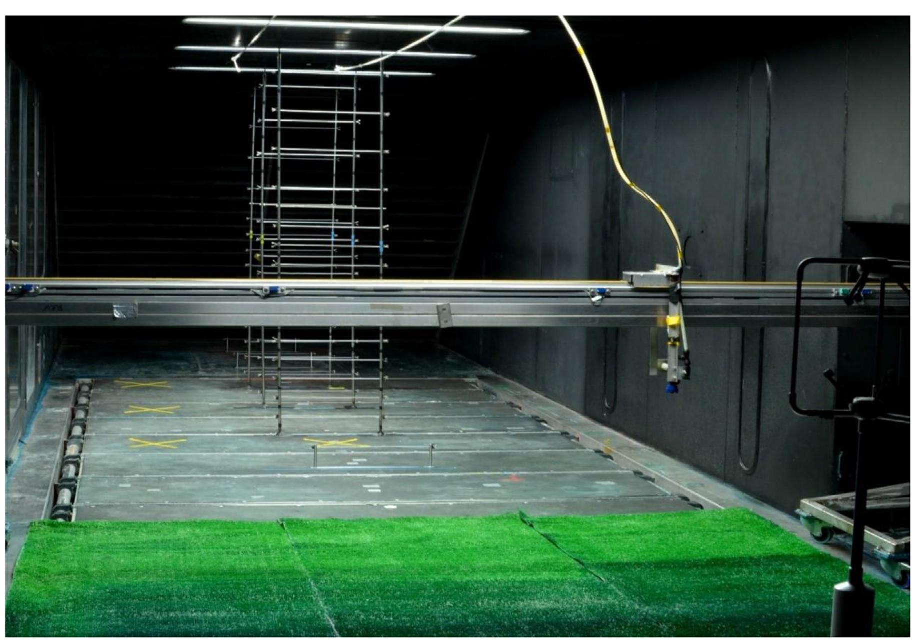

Fig. 2 – Wind tunnel set up with an ultrasonic anemometer (foreground, right side) upstream of the air flow and collector lines downwind of the nozzle.

Table 4 – Tank mixes used in Experiment 2.

Product	Concentration/ dose	Green S (E142) tracer, g l^{-1}
Tween 20	0.1% v/v	1.0
Difenoconazole EC (Score, Syngenta Crop Protection)	225 l ha^{-1}	1.0
Difenoconazole SC (Revus Top, Syngenta Crop Protection)	262 l ha^{-1}	1.0

Table 5 – Vertical profile sampling regimes. Lines with the same sample number were combined as a single sample for analysis.

Height of line above ground, m	Analysis sample number	
	Experiment 1	Experiment 2
1.9	8	3
1.7	8	3
1.5	8	3
1.3	8	3
1.1	8	3
1.0	7	2
0.9	7	2
0.8	7	2
0.7	7	2
0.6	6	2
0.5	5	2
0.4	4	2
0.3	3	2
0.2	2	2
0.1	1	1

Horizontal profile: Collector lines mounted at 0.1 m about ground level, at 2, 3, 4, 5, 6 and 7 m distances from the nozzle.

Vertical profile: Collector lines mounted at the heights given in Table 5. The majority of airborne spray is collected in the lower half of the wind tunnel, and therefore the vertical profile collectors are concentrated in the height range 0–1.0 m. Vertical profiles were obtained at 2 and 5 m downwind distances from the nozzle (Experiment 1) and at 3, 4 and 5 m distances (Experiment 2). Lines were combined in different ways for analysis so it was possible to determine drift reduction according to the German method in the first experiment, and also according to the UK method in both experiments. This is shown in Table 5, with lines having the same sample number being combined together for analysis.

The experiments included vertical profile measurements at different distances because of the differing experimental objectives at the time. Experiment 1 was designed to be able to measure both drift reduction according to national protocols as well as the potential bystander exposure at two distances. It therefore required a measurement of vertical profile at 2 m; Experiment 2 (which was the first to be conducted) was aimed at quantifying the reduction in the potential bystander exposure for different nozzle/product and distance combinations, and it did not require a 2 m vertical profile measurement. The 5 m vertical profile and the 2–7 m horizontal profile measurements were common to both experiments. Three replicate tests were made per treatment.

The deposited spray was recovered from each collector following agitation in a known volume of either deionised water for Experiment 1 or an acetonitrile: deionised water (1:1) solution for Experiment 2. Samples were analysed using UV/

Table 6 – Mean values of collected spray (μl) per 10 passes for Experiment 1. (Three replicate measurements).

Flow rate, l min^{-1}	Reference nozzle – country code						Test conditions					
	UK		NL		DE		A		B		C	
	1.171		1.544		1.197		0.968		1.181		1.509	
Sample number[a]	Mean	st.dev	Mean	st.dev	Mean	st.dev	Mean	st.dev	Mean	st.dev	Mean	st.dev
2.1	25.77	4.63	31.96	1.79	26.51	1.69	0.77	0.06	1.48	0.07	3.48	0.32
2.2	17.60	2.40	25.10	2.55	15.11	0.63	0.50	0.04	0.97	0.06	2.36	0.19
2.3	4.26	0.42	6.71	1.09	1.87	0.31	0.23	0.03	0.46	0.10	0.74	0.07
2.4	0.65	0.52	1.98	0.23	0.45	0.30	0.09	0.03	0.15	0.11	0.09	0.02
2.5	0.42	0.45	0.80	0.44	0.52	0.41	0.03	0.02	0.11	0.12	0.03	0.01
2.6	0.39	0.36	0.72	0.40	0.44	0.39	0.02	0.02	0.09	0.11	0.01	0.02
2.7	0.69	0.61	2.73	0.24	1.28	0.49	0.06	0.03	0.13	0.14	0.06	0.02
2.8	1.02	0.55	1.79	0.59	1.01	0.60	0.06	0.04	0.13	0.11	0.08	0.04
3.1	12.17	1.33	14.40	2.25	9.06	0.28	0.33	0.02	0.72	0.16	1.50	0.09
4.1	6.10	0.39	7.18	1.41	4.21	0.42	0.22	0.01	0.37	0.10	0.70	0.02
5.1	3.88	0.39	4.64	0.66	2.87	0.42	0.16	0.02	0.21	0.04	0.40	0.03
5.2	2.67	0.31	3.55	0.34	2.13	0.70	0.12	0.02	0.13	0.07	0.25	0.03
5.3	1.68	0.30	2.37	0.27	1.18	0.51	0.11	0.04	0.08	0.08	0.10	0.03
5.4	1.06	0.43	1.41	0.06	0.84	0.47	0.10	0.07	0.05	0.08	0.04	0.02
5.5	1.00	0.55	1.42	0.14	0.58	0.50	0.11	0.08	0.06	0.10	0.02	0.03
5.6	0.85	0.69	1.19	0.12	0.30	0.19	0.08	0.05	0.06	0.11	0.03	0.05
5.7	1.05	0.38	2.95	0.59	1.22	0.27	0.06	0.02	0.09	0.09	0.09	0.02
5.8	1.12	0.25	2.81	1.13	0.91	0.25	0.06	0.01	0.10	0.09	0.10	0.05
6.1	2.29	0.33	3.40	0.45	1.91	0.50	0.10	0.03	0.22	0.14	0.26	0.04
7.1	1.52	0.29	2.78	0.22	1.34	0.41	0.08	0.02	0.16	0.14	0.16	0.03

[a] Sample number x.y where x is the distance downwind and y is defined in Table 5.

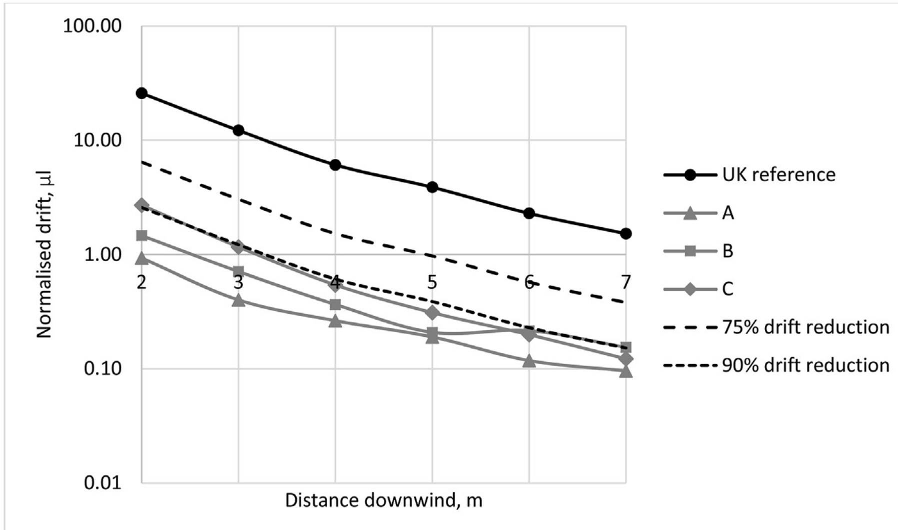

Fig. 3 – The drift on the lowest collecting lines between 2 and 7 m downwind (horizontal profile), normalised to the flow rate of the UK reference nozzle for drift reduction A, B and C.

visible spectrophotometry. Standard curves were prepared from each tank mix at concentrations of 0.5, 1, 5 and 10 µl ml^{-1}. Quantifications were made with a Thermo Fisher Scientific Evolution 201 spectrophotometer (S/N 5A4W018102, Fisher Scientific, Loughborough, UK) set to a λ_{max} of 634 nm (8/5/2018). System suitability test (SST) samples were used to confirm the instrument's performance during setting up with analytical quality control (AQC) samples to check ongoing performance during sample runs. The results were referenced against respective calibrations curves and adjusted to allow for extraction volumes.

2.3. *Data analysis*

The quantity of spray liquid recovered from each of the collecting lines from the nozzle/pressure combinations tested was analysed in the following way:

The data were normalised for the number of passes and for the nozzle flow rate, relative to that for the reference nozzle under consideration, i.e.

$$D = \frac{q\,N_r\,F_r}{N_t F_t}$$

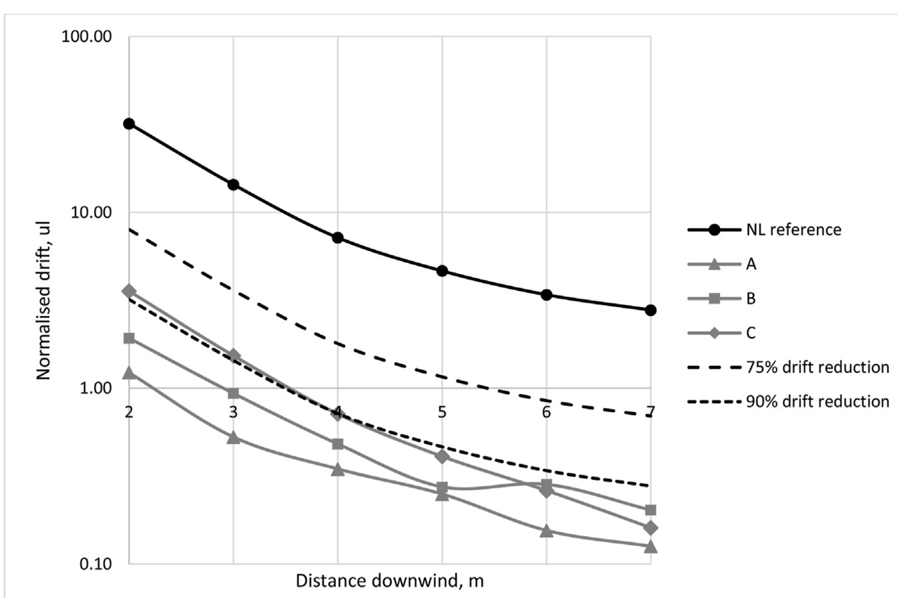

Fig. 4 – The drift on the lowest collecting lines between 2 and 7 m downwind (horizontal profile), normalised to the flow rate of the NL reference nozzle for drift reduction A, B and C.

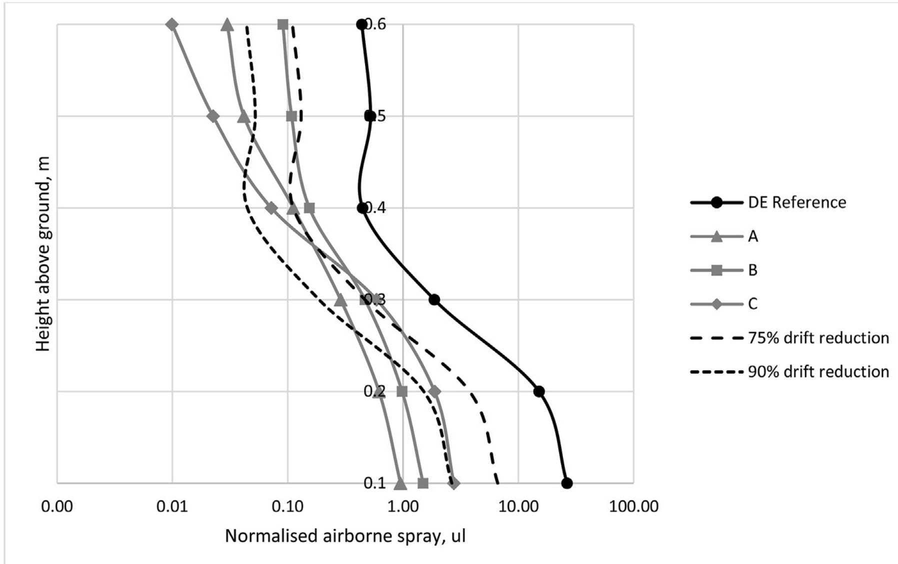

Fig. 5 – Drift collected on the 2 m downwind lines between 0.1 and 0.6 m above the floor (vertical profile), normalised to the flow rate of the DE reference nozzle for drift reduction A, B and C.

Table 7 – Drift reduction (%) relative to each reference nozzle, using a calculation method comparable with the method from each country.

Reference nozzle – country code	Drift reduction %		
	A	B	C
UK	95.4	92.9	91.1
NL	96.3	93.7	89.1
DE	94.4	90.5	87.4

where D is the drift per collector, N_r and F_r are the number of passes and the flow rate for the reference, and N_t and F_t are the number of passes and the flow rate for the test condition. This takes account of the fact that a higher nozzle flow rate would deliver a higher applied volume and any active substance would therefore be used at a lower concentration to maintain a constant dose.

The lowest collecting lines (0.1 m above the floor, from 2.0 to 7.0 m downwind) for the UK and NL reference nozzles were used as the baseline for zero drift reduction for the two countries. For the UK, the average of collecting lines 2–7 m downwind was taken, and for NL, the average of lines 2–3 m downwind.

The 2.0 m vertical profile from the DE reference nozzle (0.1–0.6 m above the ground) was used to calculate a 'DIX' drift value (Herbst & Ganzelmeier, 2000) which was then used as the zero drift reduction level for Germany. This is based on the summation

$$\sum_{h=0.1}^{0.6} h\ drift(h)$$

where h is the height above the wind tunnel floor and $drift(h)$ is the normalised quantity of spray liquid on the collecting line at height h.

The same values were obtained from the three drift-reducing nozzle/pressures, to give an estimate of the drift reduction that would be achieved by the different classification schemes (as opposed to the classification shown in Table 2). It must be emphasised that these are not identical to the values that were originally measured by the testing laboratory, which are not in the public domain, but they are determined using principles similar to those used in each of the testing laboratories.

The total airborne spray was then determined for the six treatments at 2.0 and 5.0 m downwind (Experiment 1) and for 12 treatments at 3, 4 and 5 m (Experiment 2). These averaged airborne spray values were then used to determine a potential dermal exposure reduction compared with each of the reference nozzles.

3. Results

3.1. *Experiment 1*

The mean quantity of spray recovered from each collecting line is given in Table 6. The horizontal profiles for test nozzle conditions A, B and C relative to the UK and NL reference nozzles are given in Figs. 3 and 4, and the vertical profile

Table 8 – Reduction in airborne spray (%) in the wind tunnel, relative to the three reference nozzles.

Reference nozzle - country Code	2.0 m downwind			5.0 m downwind		
	A	B	C	A	B	C
UK	95.7	93.0	89.6	92.8	94.0	94.0
NL	96.0	93.5	90.3	94.1	95.1	95.0
DE	95.3	92.4	88.6	90.3	91.9	91.9

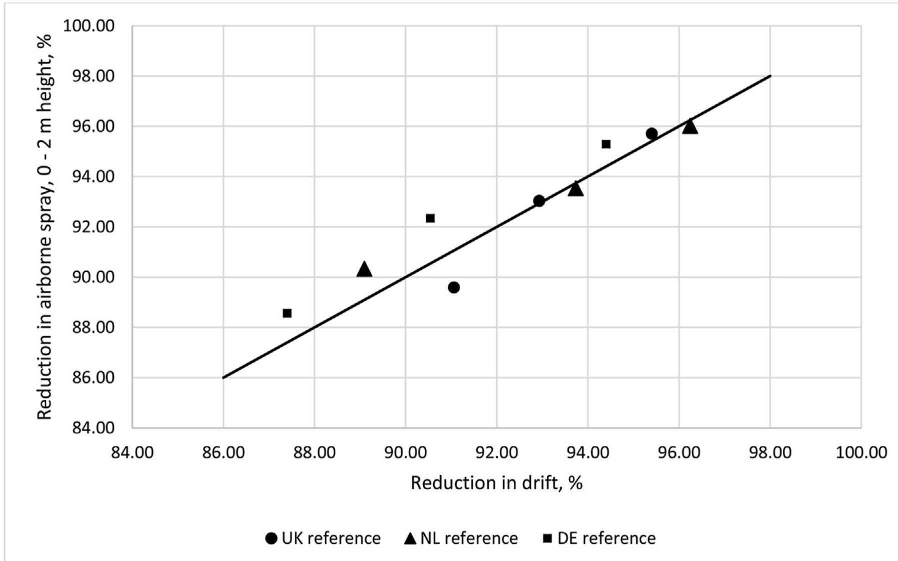

Fig. 6 – Comparison of reduction in total airborne spray at 2.0 m downwind with reduction in drift relative to the UK, NL and DE reference nozzles. The black line indicates equivalence.

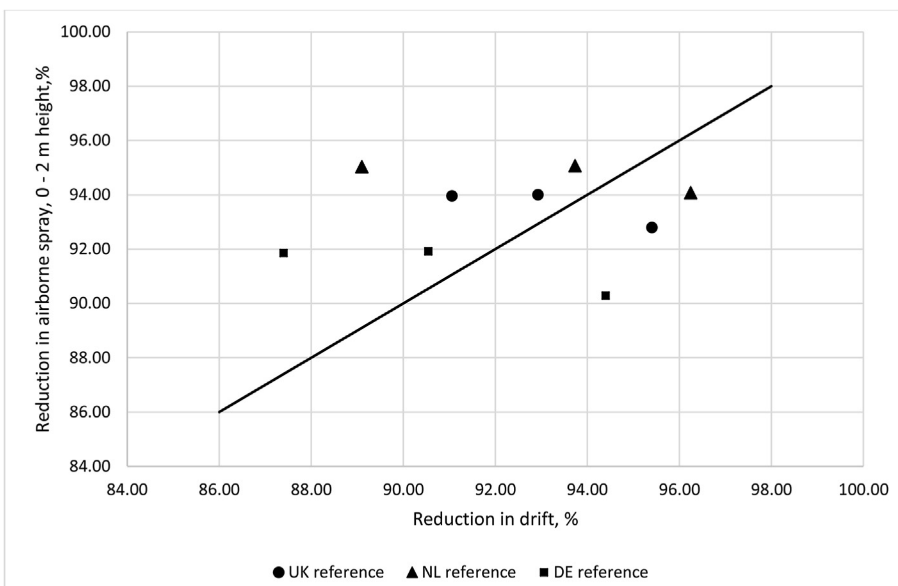

Fig. 7 – Comparison of reduction in total airborne spray at 5.0 m downwind with reduction in drift relative to the UK, NL and DE reference nozzles. The black line indicates equivalence.

relative to the DE reference nozzle is given in Fig. 5. These data are then used to determine the actual drift reduction relative to each reference nozzle, using the calculation methods outlined above and shown in Table 7.

The measured drift reduction in Table 6 is higher than the classification would suggest for conditions B and C. This is likely to be caused by differences in the data produced by using the UK wind tunnel, the German wind tunnel and the Dutch model which we cannot quantify in this study. It shows, however, that the other differences, between using vertical and horizontal profiles, and between the reference nozzles, are relatively small. It should be noted that the German and Netherland protocols are based on measured drift closer to the nozzle than the UK protocol (2.0 m, 2–3 m and 2–7 m respectively) which is probably one reason why the difference in drift reduction between the three nozzle settings are the least for the UK protocol. Table 8 shows the reduction in total airborne spray collected at 2.0 and 5.0 m downwind of the nozzle.

These data are summarised in Figs. 6 and 7, where the potential exposure reduction is plotted against the actual drift reduction measured according to a standard protocol as close as possible to that used in each of the three countries (i.e. the data given in Table 7).

3.2. *Experiment 2*

The mean quantity of spray recovered from each collecting line is given in Table 9. The horizontal profiles of drift for the three spray liquids are shown in Figs. 8–10. It should be noted that the drift reduction classification procedure uses only the reference liquid 0.1% v/v Tween 20, which is included in Figs. 9 and 10 for comparison as well as the calculated 75% and 90% drift reduction curves. Table 10 shows the reduction in airborne spray for the three nozzles and 3 liquids relative to the reference nozzle and reference liquid.

Figure 11 combines the data in Table 8 with the drift reduction determined from the horizontal profile at the same downwind distance, including all three spray liquids for drift-reduction D, E and F, and two spray liquids for the reference nozzle.

4. Discussion

Figure 6 shows that, at 2 m downwind, there was a good correlation between airborne drift reduction and reduction in drift determined by an appropriate method for the three different countries, with $R^2 = 0.89$ for the data combined, and differences are all within 2%. At 5 m downwind (Fig. 7), there was more scatter in the data, and the correlation is poorer ($R^2 = 0.001$). There appears to be a much weaker relationship between nominal drift reduction class and reduction in airborne spray at this distance. Nozzle condition A gave lower airborne spray reduction than B and C when, based on its classified drift reduction, it would be expected to give the greatest. Further investigations would be needed to identify an explanation for this. However, all differences between drift reduction and airborne spray reduction are less than 5% and

Table 9 – Mean values of collected spray (µl) per 10 passes for Experiment 2. Three replicate measurements.

		UK reference		D		E		F	
	Flow rate, l min^{-1}	1.18		1.95		1.58		0.95	
	Sample No[a].	Mean	StDev	Mean	StDev	Mean	StDev	Mean	StDev
Tween 20	2.1	31.00	3.95	2.50	0.11	0.74	0.06	2.81	0.05
	3.1	13.76	2.44	1.17	0.03	0.29	0.03	1.18	0.04
	3.2	9.02	2.33	0.83	0.07	0.41	0.09	1.30	0.02
	3.3	0.44	0.13	0.06	0.02	0.06	0.06	0.07	0.01
	4.1	5.62	1.15	0.48	0.01	0.13	0.04	0.56	0.01
	4.2	4.96	1.07	0.46	0.06	0.26	0.09	0.74	0.07
	4.3	0.38	0.06	0.08	0.03	0.07	0.07	0.11	0.04
	5.1	3.33	0.30	0.25	0.01	0.09	0.05	0.32	0.01
	5.2	4.40	0.40	0.31	0.04	0.22	0.15	0.53	0.02
	5.3	0.59	0.26	0.07	0.03	0.12	0.15	0.09	0.03
	6.1	2.09	0.47	0.14	0.02	0.09	0.08	0.20	0.01
	7.1	1.49	0.31	0.08	0.01	0.04	0.01	0.13	0.00
EC	2.1	11.88	0.08	1.72	0.14	1.37	0.02	1.31	0.03
	3.1	6.09	0.59	0.71	0.06	0.49	0.03	0.47	0.10
	3.2	4.87	0.25	0.56	0.16	0.61	0.09	0.55	0.02
	3.3	0.00	0.00	0.01	0.02	0.01	0.01	0.00	0.00
	4.1	2.69	0.17	0.28	0.04	0.41	0.21	0.17	0.07
	4.2	2.38	0.25	0.31	0.13	0.36	0.05	0.28	0.01
	4.3	0.06	0.10	0.01	0.01	0.01	0.01	0.00	0.00
	5.1	1.47	0.05	0.15	0.02	0.11	0.02	0.09	0.01
	5.2	1.99	0.58	0.30	0.21	0.24	0.08	0.13	0.04
	5.3	0.11	0.19	0.03	0.03	0.02	0.04	0.02	0.03
	6.1	0.72	0.17	0.09	0.05	0.05	0.02	0.03	0.03
	7.1	0.28	0.05	0.06	0.03	0.01	0.02	0.01	0.01
SC	2.1	13.87	2.19	1.43	0.03	0.75	0.03	1.26	0.08
	3.1	7.24	0.95	0.63	0.02	0.28	0.01	0.46	0.02
	3.2	5.21	1.21	0.41	0.05	0.43	0.06	0.56	0.05
	3.3	0.10	0.09	0.00	0.00	0.01	0.01	0.02	0.03
	4.1	2.85	0.60	0.24	0.04	0.14	0.05	0.21	0.03
	4.2	2.60	0.48	0.15	0.02	0.31	0.16	0.33	0.04
	4.3	0.00	0.00	0.00	0.00	0.02	0.03	0.01	0.01
	5.1	1.00	0.92	0.11	0.01	0.04	0.01	0.11	0.01
	5.2	1.95	0.45	0.11	0.05	0.18	0.08	0.15	0.07
	5.3	0.10	0.17	0.00	0.00	0.06	0.09	0.08	0.09
	6.1	0.78	0.19	0.07	0.01	0.03	0.02	0.08	0.03
	7.1	0.53	0.08	0.04	0.01	0.02	0.02	0.03	0.02

[a] Sample number x.y where x is the distance downwind and y is defined in Table 5.

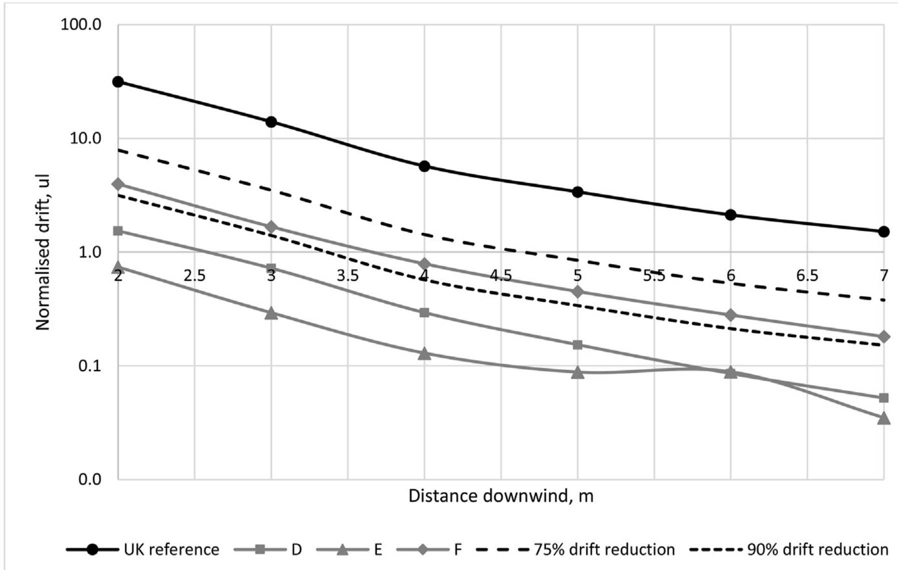

Fig. 8 – Horizontal profiles of UK reference nozzle and drift reduction D, E and F spraying 0.1% Tween 20 (the UK reference liquid for drift reduction measurement).

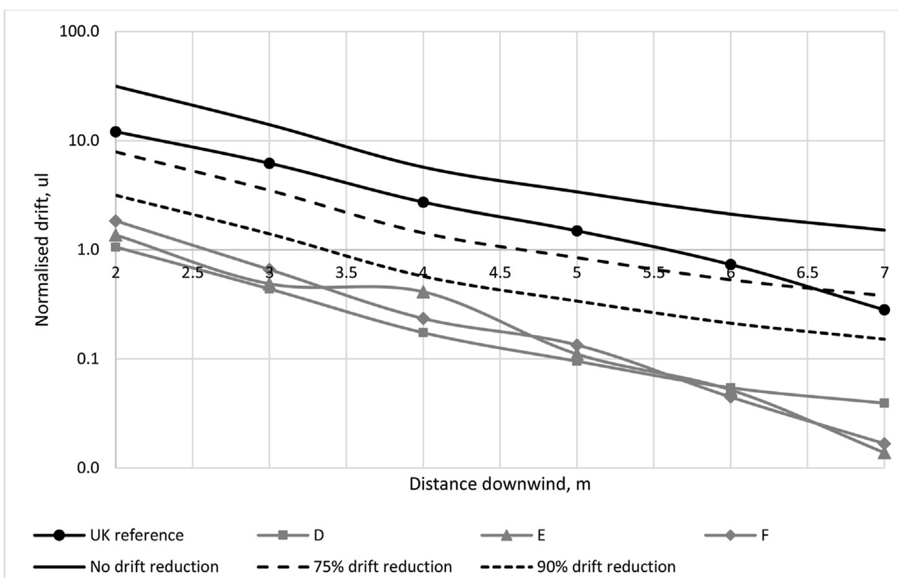

Fig. 9 – Horizontal profiles of UK reference nozzle and drift reduction D, E and F spraying an EC formulation.

the reduction in airborne spray was greater than 90% in all cases.

Figure 11 also shows there was a good correlation between drift reduction and airborne spray across the nozzles and formulations tested, with an R^2 of 0.99. Again, all differences between drift reduction and airborne spray reduction are within 5%. The reduction in airborne spray was in all cases greater than the nominal reduction in drift (given in Table 3).

While small differences can be detected in wind tunnel tests, it is important not to attach too much weight to these. There is a surprising level of variability in the wind tunnel replicate experiments, because there is still a random element in the mechanisms involved in the release and transport of droplets in an airflow. The data in Tables 6 and 9 shows the standard deviation of the 3 replicate measurements of each collecting line, which can be relatively high, particularly where the collected volume of spray is low. Experience suggests that it is unlikely that differences of 5% in drift reduction would be detected in normal field conditions, where variability is much higher and is challenging even in well-controlled field trials. Therefore, we believe that reductions in airborne spray, measured using controlled laboratory methods, that are within 5% of measured reductions in drift would not give significant differences in practical field conditions.

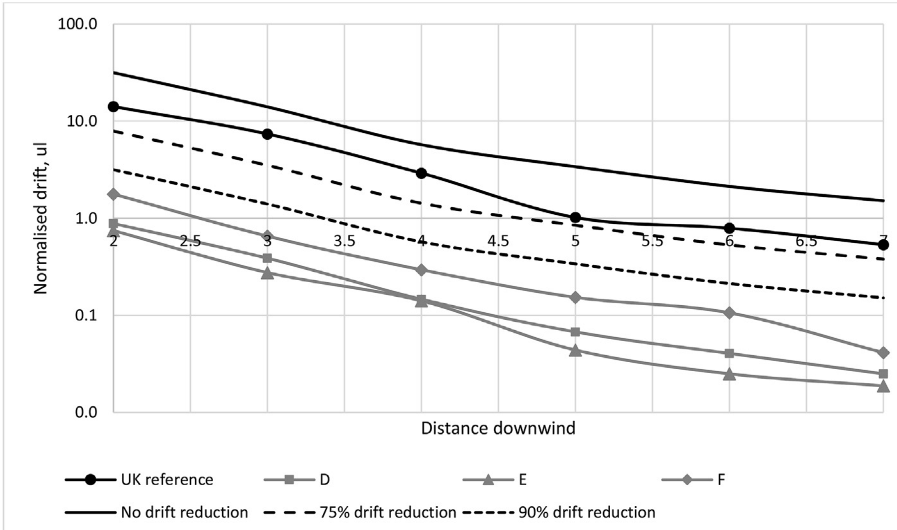

Fig. 10 – Horizontal profiles of UK reference nozzle and drift reduction D, E and F spraying an SC formulation.

Table 10 – Reduction in airborne spray (%) compared with the UK reference nozzle spraying 0.1% Tween 20.

	Downwind distance m	% Reduction against UK reference	D	E	F
Tween 20	3		94.6	97.4	84.6
	4		94.2	96.5	81.4
	5		95.2	95.4	83.9
EC	3	53.67	96.7	96.5	94.1
	4	54.35	96.8	94.8	94.6
	5	58.71	96.5	96.7	96.1
SC	3	46.55	97.4	97.8	93.8
	4	51.86	97.9	97.0	93.5
	5	66.87	98.5	98.2	96.0

These two experiments suggest very strongly that the nominal drift reduction of a nozzle/pressure combination, whether determined in the UK, the Netherlands or Germany, will give at least the same level of reduction in airborne spray, and therefore potential bystander exposure, up to 90% drift reduction. This was true for distances 2–5 m downwind, a range of nozzles and pressures with a range of nominal drift reduction, and the three typical spray liquid types.

It is important to establish that the results obtained in these wind tunnel experiments also translate into field conditions. The wind tunnel was limited in scale, with 5 m being the maximum distance that airborne spray up to 2 m height can be determined reliably. Wind tunnels, unless specially modified to mimic boundary layer flows, provide a different type of air flow than the natural atmosphere, with plug flow and low turbulence. This means that the level of dispersion of the spray plume is much lower in the wind tunnel than in the field, and the behaviour of droplets close to the ground is also different. However, Butler Ellis et al. (2017) showed that field data on sedimenting drift and wind tunnel data for drift reduction based on vertical and horizontal profiles were highly correlated, so there is evidence that the wind tunnel provides a sound physical model for some aspects of spray drift.

The BREAM2 model uses wind tunnel data to explore the collection efficiency of a human body (i.e. the relationship between airborne spray, measured in a similar way to this study and potential dermal exposure) and this model has also been tested against field data (Butler Ellis et al. 2018). Thus, a given reduction in spray drift is predicted to lead to the same reduction in bystander exposure and this has been validated with field measurements.

It has previously not been possible to compare wind tunnel data with field data relating to airborne spray drift reduction or bystander exposure reduction because the relevant field data available is limited. However, the recent OBO project (https://www.bestrijdingsmiddelen-omwonenden.nl/) has provided new data and an initial assessment, as yet unpublished, suggests that its field data is consistent with the findings of this wind tunnel study.

Further investigations are also possible using modelling approaches, which can provide a cost-effective method of exploring the impact of drift-reducing nozzles on drift and non-target exposures (Teske et al., 2011). Data from SiMoD, the UK spray drift model (Butler Ellis & Miller, 2010), also suggest that similar results occur under field conditions up to 20 m downwind.

Higher levels of drift reduction are available in some European countries, with 95% and even 99% drift reducing nozzles being available. There are few nozzles that achieve such high levels of drift reduction, however, and these often need to be operated at very low pressures. In addition, measuring drift at such low levels becomes challenging, even in controlled wind tunnel conditions, and the levels of variability can make it difficult to achieve the necessary resolution. A 95% drift-reducing nozzle will, in theory, give half the bystander exposure of a 90% drift-reducing nozzle but it is likely that the difference between the two would be very difficult to validate in the field

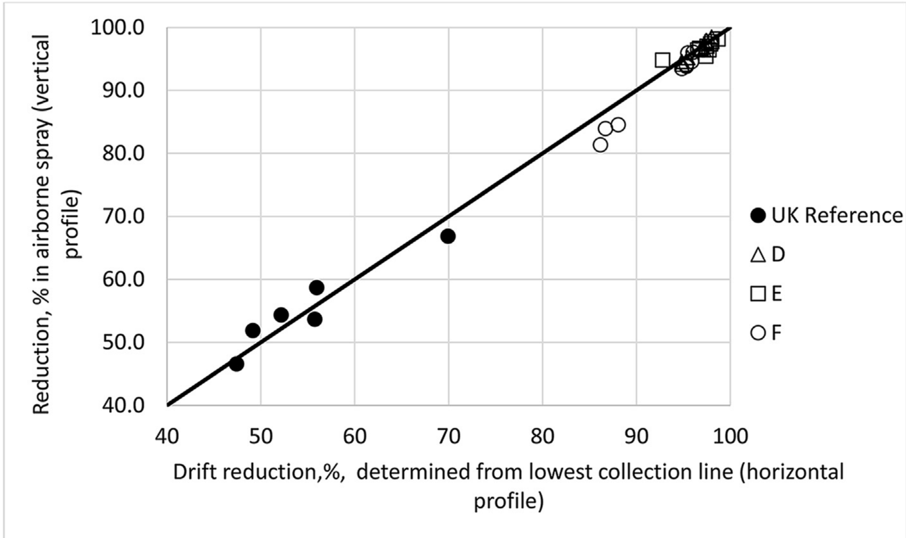

Fig. 11 – Correlation between drift reduction measured using the lowest collecting line from the horizontal profile and the reduction in total airborne spray, at distances of 3, 4 and 5 m downwind and all liquids and nozzles, relative to the UK reference nozzle spraying 0.1% Tween 20. The black line shows equivalence.

without very consistent wind conditions and a large number of repeated measurements. Under conditions of normal use (rather than under a controlled field experiment) it is debatable whether it would be possible to demonstrate the difference in exposure between 90% and 95% drift-reducing nozzles. For these reasons, we chose to focus our investigations on the mitigation of bystander exposure to a maximum of 90% drift reduction.

5. Conclusions

In the analysis the aim was to identify consistent trends which suggest that the use of drift reducing nozzles might not give the levels of exposure reduction indicated by their nominal classification. Such trends were not apparent.

The reduction in airborne spray, and therefore the potential reduction in bystander exposure, from the use of drift reducing nozzles is at least as great as the drift reduction determined from standardised tests for a range of drift reducing nozzles, pressures and spray liquids.

This wind tunnel data need to be considered in the context of field data and model simulations in order to establish robust mitigation measures for regulatory exposure assessment, but it has been indicated that the nominal drift reduction, measured using UK, NL or German drift classification protocols, can be used to reduce bystander exposure up to 90%.

The BREAM2 model for bystander exposure to spray drift can therefore be extended to include drift mitigation, with reductions in exposure up to 90% for classified equipment used in the appropriate way.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Steven Jones is employed by one of the funders of the work.

The work was funded by the agrochemical industry.

SSAU Ltd undertakes contract R&D for the agrochemical industry.

Acknowledgements

This work was supported by Syngenta Crop Protection and the European Crop Protection Association.

REFERENCES

Butler Ellis, M. C., Alanis, R., Lane, A. G., Tuck, C. R., Nuyttens, D., & van de Zande, J. C. (2017). Wind tunnel measurements and model predictions for estimating spray drift reduction under field conditions. *Biosystems Engineering*, 154, 25–34. https://doi.org/10.1016/j.biosystemseng.2016.08.013

Butler Ellis, M. C., Harris, D., Lane, A. G., & Tuck, C. R. (2016). Novel spray adjuvants to decrease spray drift. *Aspects of Applied Biology* 132. *International Advances in Pesticide Application*, 257–263.

Butler Ellis, M. C., Kennedy, M. C., Kuster, C. J., Alanis, R., & Tuck, C. R. (2018). Improvements in modelling bystander and resident exposure to pesticide spray drift: Investigations into new approaches for characterizing the 'collection efficiency of the human body. *Annals of Work Exposure and Health*, 62, 622–632. https://doi.org/10.1093/annweh/wxy017

Butler Ellis, M. C., Lane, A. G., O'Sullivan, C. M., Hamey, P., & MacDonald, A. (2020). Recent changes to the UK protocol for determining star ratings for drift-reducing nozzles and equipment for boom spraying. *Aspects of Applied Biology*, **144**. *International Advances in Pesticide Application*, 175–182.

Butler Ellis, M. C., Lane, A. G., O'Sullivan, C. M., Miller, P. C. H., & Glass, C. R. (2010). Bystander exposure to pesticide spray drift: New data for model development and validation. *Biosystems Engineering, 107*, 162–168. https://doi.org/10.1016/j.biosystemseng.2010.05.017

Butler Ellis, M. C., & Miller, P. C. H. (2010). The Silsoe spray drift model: A model of spray drift for the assessment of non-target exposures to pesticides. *Biosystems Engineering, 107*, 169–177. https://doi.org/10.1016/j.biosystemseng.2010.09.003

Douzals, J. P., & Al Heidary, M. (2014). How spray characteristics and orientation may influence spray drift in a wind tunnel. *Aspects of Applied Biology. 122 International Advances in Pesticide Application*, 271–278.

EFSA (European Food Safety Authority). (2014). Guidance on the assessment of exposure of operators, workers, residents and bystanders in risk assessment for plant protection products. *EFSA Journal, 12*, 3874. https://doi.org/10.2903/j.efsa.2014.3874, 55.

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

Hilz, E., & Vermeer, A. W. P. (2013). Spray drift review: The extent to which a formulation can contribute to spray drift reduction. *Crop Protection, 44*, 75–83. https://doi.org/10.1016/j.cropro.2012.10.020

Holterman, H. J., van de Zande, J. C., Porskamp, H. A. J., & Huijsmans, J. F. M. (1997). Modelling spray drift from boom sprayers. *Computers and Electronics in Agriculture, 19*, 1–22. https://doi.org/10.1016/S0168-1699(97)00018-5

ISO 17025. (2017). *General requirements for the competence of testing and calibration laboratories*.

ISO 22866. (2005). *Equipment for crop protection — methods for field measurement of spray drift*.

ISO 22856. (2008). *Equipment for crop protection — methods for the laboratory measurement of spray drift — wind tunnels*.

ISO 25358. (2018). *Crop protection equipment — droplet-size spectra from atomizers — measurement and classification*.

Kennedy, M. C., & Butler Ellis, M. C. (2017). Probabilistic modelling for bystander and resident exposure to pesticides using the Browse software. *Biosystems Engineering, 154*, 105–121. https://doi.org/10.1016/j.biosystemseng.2016.08.012

Kennedy, M. C., Butler Ellis, M. C., & Miller, P. C. H. (2012). BREAM: A probabilistic bystander and resident exposure assessment model of spray drift from an agricultural boom sprayer. *Computers and Electronics in Agriculture, 88*, 63–71. https://doi.org/10.1016/j.compag.2012.07.004

Southcombe, E. S. E., Miller, P. C. H., Ganzelmeier, H., van de Zande, J. C., Miralles, A., & Hewitt, A. J. (November 1997). The international (BCPC) spray classification system including a drift potential factor. In *Proceedings Brighton Crop Protection Conference, Weeds* (pp. 371–380).

Stallinga, H., Michielsen, J. M. G. P., Van Velde, P., Butler Ellis, M. C., Douzals, J. P., & Van de Zande, J. C. (2018). Effect of differences in international reference technique and evaluation zone on the classification of spray drift reducing techniques. *Aspects of Applied Biology* **137**. *International Advances in Pesticide Application*, 333–341.

Teske, M. E., Thistle, H. W., Schou, W. C., Miller, P. C. H., Strager, J. M., Richardson, B., Butler Ellis, M. C., Barry, J. W., Twardus, D. B., & Thompson, D. G. (2011). A review of computer models for pesticide deposition prediction. *Transactions of ASABE, 54*, 1–14. https://doi.org/10.13031/2013.37094

Van de Zande, J. C., Porskamp, H. A. J., Michielsen, J. M. G. P., Stallinga, H., Holterman, H. J., De Jong, A., & Huijsmans, J. F. M. (1999). Drift measurements in The Netherlands as a basis for differentiation of risk mitigation measures. In *Proceedings of workshop on risk assessment and risk mitigation measures in the context of the authorization of plant protection products (WORMM)* (pp. 27–29). September 1999.

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. Pesticide Application.