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Special Issue: Spray Drift Reduction

Research Paper

Wind tunnel measurements and model predictions for estimating spray drift reduction under field conditions

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A UK scheme to enable the protection of surface water from spray drift allows farmers to reduce the size of a buffer zone according to the drift-reducing capability of the sprayer. Recent changes to UK regulations have allowed buffer zones greater than 6 m to be included, providing that 75% drift reduction conditions are used. However, there is an implicit assumption that the level of drift reduction is independent of distance downwind, so that measurements relating to a 6 m buffer zone can be applied to 20 m.

An investigation of the relationship between wind tunnel and field data was carried out with the purpose of establishing if drift reduction measured between 2 and 7 m in the Silsoe wind tunnel can be extrapolated to 20 m in the field. A computer-based spray drift model was used to explore some of the factors influencing downwind spray drift to support this extrapolation.

It was concluded that spray drift reduction is dependent on distance downwind, but that wind tunnel measurements can be used to estimate this at least up to 20 m downwind. Improvements to the wind tunnel protocol were identified, which will need to take account of how the data will be used in the regulatory process before implementing. Further discussions are needed to harmonise methods for determining spray drift reduction across EU member states, but this approach of mapping the wind tunnel data onto field data is one that should be possible with other methods.

Abbreviations: CSL, Central Science Laboratory; Fera, The Food and Environment Research Agency; LERAP, Local Environment Risk Assessment for Pesticides; DIX, Drift Potential Index.

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Nomenclature

α	rate at which drift deposits decline with distance, dimensionless
α_{test}	rate at which deposits decline for test conditions, dimensionless
α_{ref}	rate at which deposits decline for reference conditions, dimensionless
A	magnitude of the drift at 1 m downwind, arbitrary units
A_{test}	magnitude of the drift at 1 m downwind for test conditions, arbitrary units
A_{ref}	magnitude of the drift at 1 m downwind for reference conditions, arbitrary units
d	ground deposits of drift, arbitrary units
$D5_{test}$	Value of d at around 5 m downwind for test values
$D5_{ref}$	Value of d at around 5 m downwind for reference values
x	distance downwind

1. Introduction

A scheme for protecting surface water from spray drift was introduced into the UK in 1999. Known as the Local Environmental Risk Assessment for Pesticides (LERAP) it has operated successfully for a number of years, introducing a 6 m buffer zone and allowing farmers to reduce the size of a buffer zone according to the drift-reducing capability of the spraying equipment (Defra, 2001) for some categories of pesticides. The potential of equipment to reduce spray drift, relative to a reference condition, is denoted by a 'one, two or three star rating' and these ratings can be determined from either field or wind tunnel drift data. The wind tunnel reference condition is defined as a commercially-available standard flat fan nozzle, 110° fan angle (current reference nozzles are F110-03 nozzles, Hypro EU Ltd. Longstanton, Cambridge, United Kingdom), operating at 300 kPa fluid pressure at a height of 0.5 m above the spray drift collectors. The field reference condition is the same, but the nozzles are mounted on a 12 m boom sprayer operating at 8 km h^{-1} over a short crop or bare ground (Gilbert, 2000). The majority of LERAP star ratings that has been claimed to date is based on wind tunnel assessments, largely because the smaller scale and controlled conditions allow the necessary data to be obtained in the most cost-effective and timely manner.

Recent changes to UK regulations relating to spray drift have allowed buffer zones greater than 6 m to be included, provided that three-star-rated application conditions (i.e. 75% drift reduction) are used (Chemicals Regulation Directorate, 2014). There is an implicit assumption in this development that the level of drift reduction is independent of distance downwind, so that measurements relating to a 6 m buffer zone can be applied to 20 m. It is important to establish whether or not this is the case.

Wind tunnel data relevant to the original LERAP scheme have been compared with limited field data (Walklate, Miller, & Gilbert, 2000). It showed that drift reduction measured in the wind tunnel is comparable with drift reduction in the field. There would be benefits from extending this comparison to a wider range of field data in order to demonstrate more robustly that the drift reduction determined from wind tunnel experiments can be mapped onto drift reduction in full-scale field conditions, and to identify the range of circumstances, particularly distances downwind, for which this drift reduction applies. It would also be beneficial to assess whether modifications to the LERAP star rating protocol – either the measurement or subsequent analysis – would improve the correlation between wind tunnel and field data for a wider range of conditions.

This paper reports an investigation of the relationship between wind tunnel and field data, based on existing field data, and new measurements of spray drift in the Silsoe wind tunnel. A computer-based drift model is used to explore some of the factors influencing the downwind drift profile and to support the extrapolation between wind tunnel and field. The objectives of the study were to:

(a) Determine the extent to which drift reduction measured in the wind tunnel is equivalent to drift reduction in the field, and particularly if it can be extrapolated to distances up to 20 m;
(b) Identify any possible improvements in the protocols for wind tunnel measurements and data analysis
(c) Explore options for harmonising the different European schemes for determining drift reduction.

2. Theoretical analysis of drift curves

The current LERAP star rating system relates to 25, 50 and 75% drift reduction compared with the reference spray application determined from data obtained between 2 and 7 m downwind and using 6 m as a reference distance. In order to extend the system to buffer zones greater than 6 m, it is possible that changes to the calculation are required.

A number of researchers have proposed that the relationship between sedimenting drift (i.e. ground deposits) and distance downwind follows a power law decay (e.g. Walklate et al., 2000; De Schampheleire, Baetens, Nuyttens, & Spanoghe, 2008), i.e.

$$d = Ax^{-\alpha} \quad (1)$$

where d is ground deposits of drift (arbitrary units), A defines the magnitude of the drift at 1 m downwind, x is the distance downwind and α defines the rate at which drift deposits decline with distance. Zero distance is taken as the centre line of the last downwind nozzle for our analysis.

This equation is valid only for x > 0, and other equations might give a better fit, particularly close to the treated area – for example Holterman and van de Zande (2003) use two exponential curves and Nuyttens, De Schampheleire, Baetens, and Sonck (2007) use a single exponential equation. Continuing to use a simple power law has many advantages, however, since it is relatively easy to compare curves, and also there are only two unknowns for any drift curve, so curves can be fitted with relatively few data points.

Extending the existing LERAP scheme to greater buffer zone widths would be straightforward if the value of α were the same for all nozzles. Then the relative drift between a test condition and the reference condition would be simply

$$relativedrift = \frac{A_{test}}{A_{ref}}$$

and could be measured at any distance since it is independent of x.

The analysis of Walklate et al. (2000) suggested that α was considered to be the same for both test and reference conditions, and the value $\alpha = 1.24$ was used. No evidence to support this assumption was provided, however. An analysis by Herbst (2001), building on earlier work by Brauer (1971) suggested that, for spray released with zero initial velocity into a non-turbulent air flow with uniform wind speed, $\alpha = 1.5$ for a single nozzle, and 0.5 for an infinite number of nozzles, but was independent of droplet size. Our own simple consideration of Stokes Law, in terms of settling velocities of droplets, indicates that the distance travelled by a droplet before it reaches the ground is dependent on the square of its diameter, and therefore the relationship between drift and distance would be expected to be strongly dependent on spray quality (i.e. droplet size distribution). However, such a simplistic analysis does not take into account initial droplet velocities which would also be expected to influence spray drift. Therefore, it was assumed initially that define both A and α need to be defined for reference and test conditions.

$$relativedrift = \frac{A_{test}}{A_{ref}} x^{(\alpha_{ref} - \alpha_{test})} \tag{2}$$

If a reduction in buffer zone distance based on the measured drift reduction, is required, the relationships between drift and distance need to be used to allow a reduced buffer zone to be specified for drift reducing nozzles.

An example of this is shown in Fig. 1, where drift curves for hypothetical reference and test conditions are shown. The value of α is the same for both curves (1.5) and $A_{test}/A_{ref} = 0.5$ (i.e. 50% drift reduction at all distances). If a buffer zone of 6 m is required with the reference condition to ensure environmental concentrations are below a certain threshold value, then a buffer zone of 3.8 m is required with the test condition. Thus a 50% drift reduction does not translate into a 50% buffer zone reduction: this would only occur if $\alpha = 1$.

The generic relationship between the buffer zones for reference (x_{ref}) and test conditions (x_{test}) is given by

$$x_{test} = \left(\frac{A_{test}}{A_{ref}}\right)^{\frac{1}{\alpha_{test}}} x_{ref}^{\left(\frac{\alpha_{ref}}{\alpha_{test}}\right)} \tag{3}$$

which, if $\alpha_{ref} = \alpha_{test}, = \alpha$ becomes

$$\frac{x_{test}}{x_{ref}} = \left(\frac{A_{test}}{A_{ref}}\right)^{\frac{1}{\alpha}}$$

And this is independent of distance.

When extrapolating from wind tunnel to field conditions, therefore, we need to be confident that the calculated value of α is either the same as that in the field, or there is a consistent relationship between wind tunnel and field measurements, such that the value of α can be determined with sufficient accuracy for both reference and test conditions.

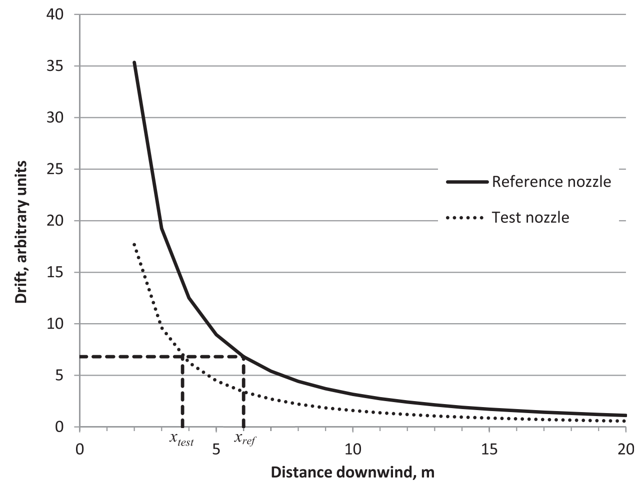

Fig. 1 – Example of a calculation of buffer zone requirement for a test nozzle. If x_{ref} is the buffer zone required with the reference nozzle, x_{test} is the buffer zone required with a test drift reducing nozzle.

This study explores the relationship between the drift curves measured in wind tunnel and field conditions, with the aim of identifying the most robust methods, of both measurement and calculation, for determining the parameters needed to define the relationship between drift and distance.

3. Published field data

There is a significant body of published field measurement of spray drift ground deposits. However, there is also a wide range of measurement techniques, or protocols, and conditions under which the experiments were carried out, as well as limitations on the availability of raw data.

Byron and Hamey (2008) showed that field data can vary between different reference datasets, with further details reported by Anon (2007a), where it was noted that the one dataset showed a much more rapid reduction in spray drift deposition than others.

This study has focused on two more recent datasets, both of which have been published. Some criteria for selecting data for analysis were defined at the start of the project, shown in Table 1, although some compromises were needed to ensure sufficient data was available. These criteria are largely consistent with the international standard for spray drift measurements (ISO, 2005). The two datasets chosen are Nuyttens et al. (2007), with additional data for two nozzles types (Nuyttens, personal communication) and van de Zande, Michielsen, Stallinga, and van Velde (2014). It should be noted that these data were obtained using a forward speed of 8 and 6 km h^{-1} respectively. It would have been advantageous to have data which was obtained at a higher forward speed, since in the UK, greater speeds are now frequently used (Garthwaite, 2004). Some additional analysis of reference data obtained by The Food and Environment Research Agency

Table 1 – Criteria for selecting field data for analysis.

Collector type	Flat ground collectors (sheets, laths etc)	The collection efficiency of petri dishes has not been characterised and therefore deposits in Petri dishes cannot be predicted reliably. There is evidence (Mathers, Wild, & Glass, 2000) to suggest that they do not collect as much spray as a flat collector and if (as is likely) the collection efficiency is droplet-size dependent the field measurement of drift reduction may be affected by the collector. A collection technique that is as similar as possible to surface water is required.
Tracer	Inert tracer	Previous work (Anon, 2007b) showed that unexplained losses resulted from the use of actives. Well-characterised stable tracers are important in drift measurement protocols
Distance downwind	Distances between 2 and 20 m downwind of the sprayed area are required as a minimum and up to 50 m would be advantageous	Distances of greater than the maximum possible buffer zone are required otherwise it will not be possible to assess the potential effect of the buffer zone on ground deposits.
Details of environment	Wind speed and direction at a single height as a minimum – and conditions for individual spray runs should be available.	A measure of wet bulb depression (i.e. temperature and humidity) would be advantageous at least as an average across a number of drift measurements.
Application conditions	Nozzle, pressure, flow rate, boom height, boom width, treated area, forward speed data should be available.	Reference condition should be something recognised as typical spraying conditions.
Spray drift data	Relatively raw data should be available …	… rather than data that has been subject to significant analysis as this can lose useful information particularly relating to variability.

(Fera), published in their final project report (Anon, 2010) was also included in the comparison of reference spray drift data. This was obtained at 12 km h^{-1}. Unfortunately there were no data available for drift reducing nozzles in this dataset, so could not be included in our analysis of drift reduction.

These data are compared with other recognised data, including Rautmann, Streloke, and Winkler (2001) which is commonly used in regulatory exposure assessments, and UK data obtained by Central Science Laboratory (CSL) in the 1990s (Byron & Hamey, 2008; Gilbert, 2000) which has been used as the reference curve in the LERAP scheme for field measurement. This is shown in Fig. 2, where again, a wide range of curves, and in particular the slope of the curve, α, are seen. The data have been adjusted, as required, to ensure a consistent 'zero' distance, which is defined as the centre of the last downwind nozzle. Table 2 shows the value of α for each of the data sets, ranging from 0.99 to 2.00.

It should be noted that there is a striking difference between some datasets, despite being obtained under similar conditions. It would not be expected that such dramatic differences would occur from ostensibly similar experiments, although it is possible that the higher forward speed used for the Fera data (Anon, 2010) contributed to the noticeably greater slope. There is limited field data available to evaluate the potential for sprayer forward speeds above 8 km h^{-1} to change the drift curve in this way, but the analysis of Nuyttens et al. (2007) suggests that this is unlikely.

An inspection of the experimental conditions for the two largest datasets where all the data is available did not reveal any other large differences, apart from potentially the ground surface conditions: Van de Zande data was obtained spraying over soil, whereas the Nuyttens data was obtained over cut grass, with the same conditions for both the treated area and the downwind drift area. The other datasets were obtained with a range of crop types, including bare ground (Rautmann et al., 2001) and unknown conditions (CSL data). The Fera data (Anon, 2010) was reported to be obtained from a short crop 'such as cut grass < 0.15 m' and is therefore consistent with the experimental conditions for the other datasets.

Given the range of drift curves from field data, there will be a difficulty in establishing an appropriate value of α for a regulatory reference condition, α_{ref}. It is important to determine whether a drift-reducing nozzle would have a significantly different value of α. The Nuyttens data has many fewer replicate measurements for drift reducing nozzles than for the reference nozzle because a drift prediction equation was used to account for variations in meteorological conditions, and therefore there will be a lower confidence in the calculated exponent than that for the reference curve. There is, however, a strong suggestion that drift-reducing nozzles are likely to have a lower value of α (Table 3). The measurements relating to drift-reducing nozzles undertaken by van de Zande, where there were similar numbers of replicate measurements for both the reference and the drift-reducing nozzles, show a clear correlation between α and the level of drift reduction (Table 4). These data suggest that at greater distances, the level of drift reduction achieved with these nozzles will reduce with distance downwind, which is consistent with the previous analyses (van de Zande et al., 2014;; Nuyttens et al., 2007).

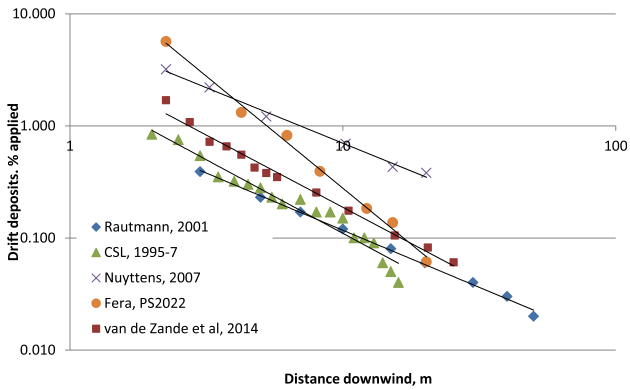

Fig. 2 – Mean drift, expressed as a percentage of the applied dose, as a function of distance downwind for five datasets spraying with similar (but not identical) reference conditions. Solid lines represent a fitted power law. Details of the treatments and the fitted exponent are given in Table 2.

4. Model simulations

In order to explore the possible factors influencing α, the Silsoe spray drift model (Butler Ellis & Miller, 2010) was used.

A 'reference' treatment was defined as a single pass of a 24 m boom (48 nozzles) at 0.5 m above a 0.1 m high 'crop', 3 m s^{-1} wind speed at 3 m height and 8 km h^{-1} forward speed, with a flat fan 110 03 nozzle operating at 300 kPa (fine-medium boundary nozzle for spraying quality) (Southcombe et al., 1997) and a wind angle at 90° to the direction of travel. Variables were changed one at a time, and the exponent of the resulting power law fitted to the predicted sedimenting drift between 2 and 20 m downwind was calculated. Table 5 shows the resulting values of α.

Those tests most likely to give significantly different values of α from the reference condition are shown in bold (there is some variation in exponent with a single set of conditions due to the random component of the model, so small differences will not be significant). It can be seen that the predicted value of α for the reference condition (1.47) is roughly in the middle of the measured range in Table 2, although perhaps higher than the majority of field data. Factors which strongly affect α are turbulence, number of nozzles (i.e. the upwind dimension of the treated area), wind speed and the ability of vegetation to collect spray. Spray quality does not appear to have a large effect on the exponent, although the air induction nozzle had the lowest exponent of all nozzles simulated and gives the lowest levels of drift, consistent with field data. De Schampheleire et al. (2008) suggested a range of α between 0.78 and 1.54 for a wide range of experimental conditions.

It is possible that the range of exponents seen in field data for reference conditions could be explained largely by differences in the ground surface and in turbulence, factors which are not generally reported quantitatively in field studies. This highlights the need to ensure that when field measurements are made relating to drift reduction, reference and test conditions must always be measured at the same time and on the same site to ensure that wind conditions are as similar as possible. Measurements of wind characteristics other than wind speed at a single height would also be useful. Characterising the ability of the ground surface to 'filter' drifting droplets, both within the treated area and downwind, is a more challenging task, however, and an area where more research is needed.

Table 3 – Calculation of α obtained from field measurements of drift (Nuyttens et al., 2007) for a reference nozzle (Flat fan 03, Hardi Ltd. Sharnford, Hinckley, UK) and seven drift reducing nozzles. All nozzles operated at 30 kPA. Calculation of drift reduction (%DR) is according to the method defined by Nuyttens et al. (2007) and averaged over 1–20 m.

Nozzle	α	%DR
Flat fan 110 03 (reference)	0.99	–
injet 02	0.74	67
injet 03	0.45	90
injet 04	0.22	78
LD03	0.72	38
LD04	0.75	55
TTI 025	0.53	85
TTI 06	0.53	96

Table 4 – Calculation of α obtained from field measurements of drift (van de Zande et al., 2014) for a reference nozzle (XR110 04, Spraying Systems Ltd. Farnham, Surrey, UK) and five drift reducing nozzles. Calculation of drift reduction (%DR) is according to the method defined by van de Zande et al. (2014) and averaged over 1–20 m.

Nozzle	Pressure, kPa	α	%DR
XR 110 04 (reference)	300	1.31	–
DG 110 04	300	1.08	69
XLTD 110 04	300	1.32	87
IDN 120 03	300	0.88	91
AI XR 110 04	100	0.78	92
Airmix 110 05	100	0.56	95

Table 2 – Value of α for a fitted power law curve to field data between 2 and 20 m downwind.

Data set	Reference nozzle	Forward speed, km h^{-1}	Ground conditions	α
Nuyttens et al., 2007	Hardi flat fan 110 03	8	Cut grass	0.99
Rautmann et al., 2001	Range of nozzles	6	Bare ground, short crop, tall crop	1.02
van de Zande et al. 2014	Teejet XR 110 04	6	Bare ground	1.29
CSL, 1995-7	Flat fan 110 03	8	Short grass	1.31
PS2022 (Fera)	Flat fan 110 03	12	Short crop/cut grass	2.00

Table 5 – Values of α calculated from model simulations, based on a reference condition with one variable changed for each simulation. Variables in bold indicate values of α most likely to be significantly different from the reference condition.

Variable changed from reference condition	α
6 nozzles	**1.819**
Wind speed 1.5 m s^{-1}	**1.773**
High level of collection by vegetation	**1.770**
Boom height 0.8 m	**1.613**
Coarse spray	1.543
Forward speed 16 km h^{-1}	1.523
Boom height 0.4 m	1.493
Forward speed 4 km h^{-1}	1.486
Reference condition	1.472
Wind angle 30°	1.440
Fine spray	1.435
v coarse spray	1.393
Air Induction nozzle[a]	1.386
480 nozzles (i.e 10 upwind passes)	**1.310**
wind speed 6 m s^{-1}	**1.288**
Low level of collection by vegetation	**1.181**
High turbulence (x10)	**1.037**

[a] Defined as an ‘025’, 110°, very coarse spray, with 20% air inclusion in droplets and droplet velocities approximately half that of a conventional flat fan.

5. Wind tunnel measurements

A set of wind tunnel measurements were made according to the existing LERAP protocol (Walklate et al., 2000), with further measurements included to allow alternative protocols to be explored. Ground deposits are not measured under this protocol, but instead airborne spray at 0.1 m above the ground is collected on passive lines. The locations for drift sampling with passive line collectors are shown in Fig. 3. Each nozzle was mounted in the centre of the wind tunnel, in a stationary position, with the long axis of the fan normal to the direction of air flow. Three replicate measurements were made for each nozzle setting.

It was initially proposed that extending the measurement distance in the wind tunnel from 7 m (as in the current protocol) to 10 m downwind would provide further information that might enable a more reliable extrapolation to 20 m. However, while some data looked quite promising, other measurements showed that at the greater distances, measured drift began to increase, which might be as a result of changes in air flow at the end of the wind tunnel working section. Analysis to date has therefore focused on collecting lines between 2 and 7 m.

The wind tunnel protocol involves a single, usually stationary, nozzle. In order to represent a multiple boom with 0.5 m nozzle spacing, further analysis of the measured data is undertaken. A power law is fitted to the downwind drift data, then the spray drift at any point downwind is calculated as the sum of the deposited spray drift from all nozzles at 0.5 m intervals upwind. A power law is then fitted to this calculation for comparison with field data and model predictions.

Measurements were made at a range of wind speeds, initially at 2 and 4 m s^{-1} for the nozzles used by Nuyttens, and then later including 3 m s^{-1} for some of the nozzles used by van de Zande. The nozzles and pressures selected for measurement are those for which field data is available and would be expected to give some drift reduction.

6. Comparison between wind tunnel measurements and field data

6.1. *Determination of α*

The wind tunnel data relating to the passive line collectors nearest to the ground (0.1 m height) between 2 and 7 m downwind of the nozzle was determined and then analysed as described above to determine a power law for the wind tunnel data, and for a simulated 27 m boom (Tables 6 and 7). The value of α from wind tunnel data alone is significantly higher than that from field data; summing over the 27 m boom reduced the value of α, but was still much higher than field measurements.

There was a correlation between wind tunnel and the field values of α only for the 2 m s^{-1} wind speed, as shown in Fig. 4 for the 27 m boom calculation. As expected, there appears to be a different relationship between the two datasets, and combining the data gives a very weak correlation.

Figure 5 shows the relationship between wind tunnel and field calculations of $\alpha_{ref}/\alpha_{test}$, needed to determine the relative size of a buffer zone as given in Eq. (3). This has a better correlation, and it also suggests that there is possibly a single

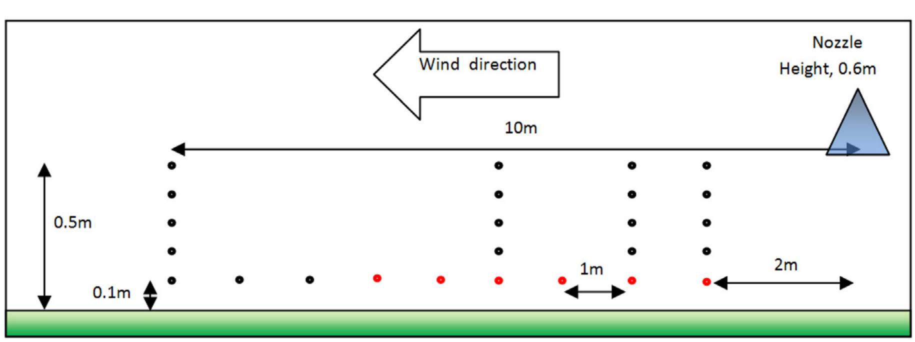

Fig. 3 – Layout of wind tunnel for drift measurements. Small circles indicate a passive line collector of 1.98 mm diameter mounted across the width of the wind tunnel. Red circles indicate those used in the current LERAP protocol.(For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 6 – Values of α calculated from wind tunnel data with two different analyses and two wind speeds using nozzles used by Nuyttens et al. (2007) (all nozzles at 300 kPa spray pressure).

Nozzle	2 m s^{-1} wind speed		4 m s^{-1} wind speed	
	Single nozzle	27 m boom	Single nozzle	27 m boom
Reference	2.6	1.8	0.91	0.47
injet 02	2.08	1.32	1.46	0.81
injet 03	2.13	1.37	1.43	0.79
injet 04	2.37	1.58	1.29	0.69
LD03	2.55	1.75	1.09	0.56
LD04	2.62	1.82	1.09	0.55
TTI 025	1.66	1.00	1.90	1.11
TTI 06	2.14	1.39	1.80	1.10

relationship for both field datasets. The wind tunnel calculation $\alpha_{ref}/\alpha_{test}$ overestimates the field calculation.

The difference in the value of α is also needed to calculate the relative drift, as given in Eq. (2). Figure 6 shows the relationship between $\alpha_{ref} - \alpha_{test}$ determined from field and wind tunnel data. Again, both data sets appear to have the same relationship, allowing data to be combined. The wind tunnel calculation again overestimates the field value.

Thus it appears that, in terms of determining the value of α for a given spray application condition, the wind tunnel cannot be used to predict α in the field, because the field value is likely to depend on environment and location. However, there is a strong relationship between either $\alpha_{ref}/\alpha_{test}$ measured in field and wind tunnel, or $\alpha_{ref} - \alpha_{test}$ measured in the field and wind tunnel. This also implies that field data sets with very different values of α would have the same values of $\alpha_{ref}/\alpha_{test}$ and $\alpha_{ref} - \alpha_{test}$ although it would require data relating to different sets of field measurements with the same nozzles to test this.

6.2. *Calculation of A_{test}/A_{ref}*

While the value of A given in Eq. (1) relates to the quantity of drift at 1.0 m downwind, this distance is too close to the treated area to ensure that the power law relationship is relevant, and these data are not always available in field data. Instead, we focussed upon the value of drift at around 5 m downwind for field data, (D_5) which was related to A by a constant dependant on α, and was potentially a more reliable distance to calculate drift reduction. The actual distance available from field data was 5.25 m from the centre of the downwind nozzle.

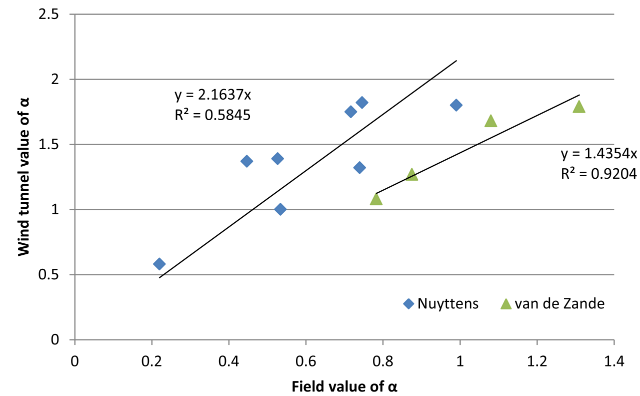

Fig. 4 – Relationship between the values of α calculated from wind tunnel data measured with a wind speed of 2 m s^{-1} and extrapolated to a 27 m boom, and two sets of field data (Nuyttens et al., 2007; van de Zande et al., 2014).

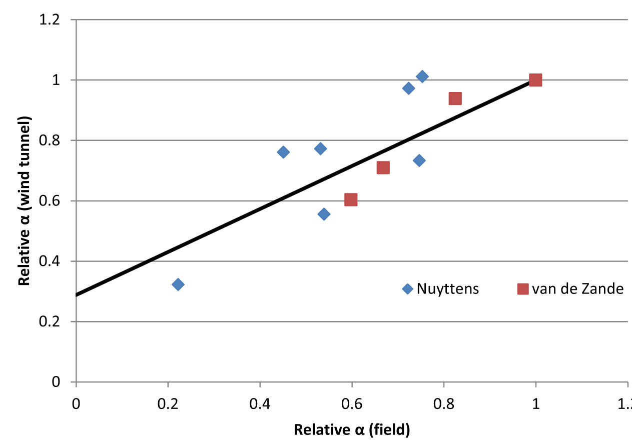

Fig. 5 – Relationship between the values of $\alpha_{ref}/\alpha_{test}$ calculated from wind tunnel data measured at 2 m s^{-1} wind speed and field data for both data sets (Nuyttens et al., 2007; van de Zande et al., 2014). The solid line shows a linear fit passing through the point (1,1) with a gradient of 0.711, and R^2 = 0.7.

There are many different values that can be used as a relative measurement of drift in the wind tunnel, with the aim of correlating with field values of $D_{5\ test}/D_{5\ ref}$. A range of different options were tested, and correlation coefficients between these and field values of $D_{5\ test}/D_{5\ ref}$ were determined. However, there are practical limitations to what might be chosen in a regulatory test, and using a single measurement

Table 7 – Values of α calculated from wind tunnel data with two different analyses and three wind speeds using nozzles used by van de Zande et al. (2014).

	2 m s^{-1} wind speed		3 m s^{-1} wind speed		4m s^{-1} wind speed	
	Single nozzle	27 m boom	Single nozzle	27 m boom	Single nozzle	27 m boom
Reference	2.59	1.79	1.64	0.98	0.91	0.47
DG 110 04	2.47	1.68	1.1	0.59	1.13	0.61
IDN 120 03	2	1.27	1.53	0.9	1.39	0.79
AI XR 110 04	1.77	1.08	1.77	1.08	1.64	0.98

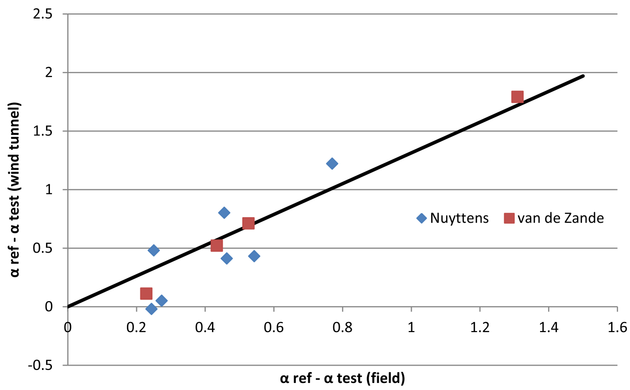

Fig. 6 – Correlation between the values of $\alpha_{ref} - \alpha_{test}$ calculated from wind tunnel data measured at 2 m s^{-1} wind speed and field data for both data sets (Nuyttens et al., 2007; van de Zande et al., 2014). The solid line shows a linear fit passing through the point (0,0) with a gradient of 1.314 and $R^2 = 0.83$.

(for example, only one passive sampling line) would be vulnerable to error and would therefore require higher replication. Table 8 shows the correlation between wind tunnel and field measurements for wind tunnel measures that involve several measurements (i.e. a number of passive sample lines) for the combined field data sets. The full range of measures tested for each field dataset are given in Appendix 1.

It can be seen that there is a strong correlation between all measures of relative drift in the wind tunnel and field data, which improves with increasing wind speed of the wind tunnel. The current LERAP protocol is similar (but not identical) to using the fitted power law for a 27 m boom and 2 m s^{-1} wind speed, evaluating drift reduction at 5 m distance from the nozzle, which gives one of the poorer correlations, suggesting that this more complicated calculation might be unnecessary, and potentially counter-productive. The best correlation for the combined data was achieved by the power law based on a single nozzle, shown in Fig. 7 for the 4 m s^{-1} wind speed.

However, none of the measures tested in Table 8 were poor, and the regression between field and wind tunnel measures gave a gradient of unity, within the standard error, for every measure tested, suggesting that the wind tunnel measurement method is robust, and the choice of the particular measure to use can be made on practical grounds.

Table 8 – Correlation coefficient between different measures of relative drift obtained from wind tunnel data, and relative drift at 5 m from the treated area (5.25 m from the centre of the downwind nozzle) from combined field data.

Wind tunnel data, test/reference	2 m s^{-1} wind speed	4 m s^{-1} wind speed
2 m total (Σ 0.1–0.5 height)	0.70	0.83
3 m total (Σ 0.1–0.5 height)	0.87[a]	0.97[a]
5 m total (Σ 0.1–0.5 height)	0.79	0.83
2 m first moment[b]	0.79	0.83
5 m lowest line based on fitted power law	0.82	0.97
5 m lowest line based on fitted power law to 27 m boom calculation	0.73	0.97

[a] Nuyttens et al. (2007) data only.
[b] Equivalent to the DIX calculation, used in Germany for defining drift reduction classes (Herbst & Ganzelmeier, 2000).

7. Practical considerations

The use of ground deposit drift curves, such as those included in this study for determining exposures of surface water, are well accepted, but there is a problem in terms of defining an agreed set of data. There is a wide range of possible curves, which are likely to be dependent on uncontrollable environmental conditions, so that it is not possible to say what is the 'right' dataset to use. While the variability of drift is apparently included in the regulatory drift curves by using the 90th percentile of the data from a single dataset, this is unlikely to cover the true variability from a range of datasets. The available data shows only that there is a range of possible drift curves, not the probability of them occurring, and therefore it is not known how to combine datasets in a way that represents the 'real world' probability of particular levels of drift occurring.

A practical solution to this might be to continue the approach adopted by Walklate et al. (2000) and use a fixed value for α for all nozzles, i.e. assuming that drift reduction is independent of distance. This was clearly a reasonable assumption when the focus is only on distances between 2 and 6 m. An alternative proposal is to fix the value of α for the reference condition, and use wind tunnel data obtained under the current LERAP protocol to determine the relative value of α that can then be used to extrapolate up to 20 m downwind.

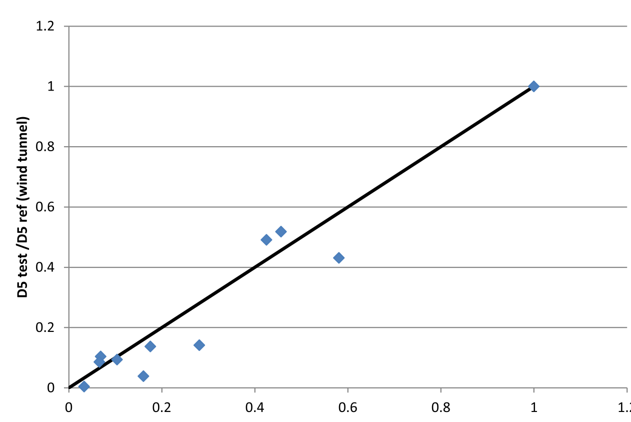

Fig. 7 – The relationship between wind tunnel and field measures of relative drift at 5 m downwind for the combined data, with the wind tunnel calculation based on a power law fitted to data between 2 and 7 m downwind from the last nozzle, obtained at 4 m s^{-1} wind speed. The solid black line indicates a one-to-one relationship.

In terms of determining a drift classification for a nozzle based on wind tunnel data, two factors are needed, one that describes the drift relative to a reference condition at a single location, and one that describes how that changes with distance. However, in order to provide clear, usable information to spray operators, a single 'drift reduction classification', (such as the LERAP star rating, or the Drift Potential Index (DIX) rating, Herbst & Ganzelmeier, 2000) is likely to be most effective. Using only a single 'drift reduction' measure in the regulatory system will lead to an underestimate of drift that increases with distance downwind, but when viewed in the context of the variability of field data, it might be argued that these errors are trivial. However, it has been shown that is possible to determine reductions in buffer zones more accurately than this by using appropriate wind tunnel data.

The correlations between field and wind tunnel data suggest that measurements made in the wind tunnel at 2 m s^{-1} are necessary to determine the value of α, but measurements at higher wind speeds, up to 4 m s^{-1}, give the best estimates of relative drift. If there is no requirement to determine α, then a change in protocol to 4 m s^{-1} might be advantageous, although there are then practical considerations relating to saturating collecting lines close to the nozzle, particularly for the reference condition. The 2 m s^{-1} wind tunnel wind speed is similar to the 6–8 km h^{-1} forward speed used to obtain the two field datasets, which might account for the good correlation. However, model predictions suggest that forward speed does not significantly change α (Table 6) and therefore it seems unlikely that higher wind tunnel wind speeds would be necessary to correlate α with field data obtained with higher forward speeds. Further field data, obtained at a higher forward speed, is necessary to evaluate this. Unfortunately, the international standard for drift classification using field data (ISO, 2010) specifies a forward speed between 6 and 8 km h^{-1}, which may account for the limited field data relevant to UK conditions. Recent modifications to the LERAP protocol now allow for a nozzle to be moved across the wind tunnel air stream at a realistic forward speed. This was introduced to enable LERAP assessments of angled sprays to be undertaken. Some advantages have been identified with this technique and therefore it would be useful to repeat the analysis in this study for the 'moving nozzle' protocol to establish if similar relationships can be established with field data.

This study was not aimed at establishing whether the current DIX and LERAP drift reduction ratings are equivalent. However, because a comparison between the DIX rating and the other wind tunnel ratings had correlations for the nozzles used in this study, it is suggested that there is already a reasonable equivalence between the two ratings if only drift reduction at a single distance is considered. Any changes to the LERAP procedure that arise from this work will not compromise any potential harmonisation between LERAP and DIX and might make this easier. Further work is needed to establish whether other processes for establishing drift reduction, such as the use of a spray drift model or alternative experimental techniques, are also consistent with the field data and wind tunnel methods.

8. Conclusions

The rate of decline of ground deposits of spray drift with distance is an important factor in determining the ability of nozzles or equipment to reduce drift and thereby enable a reduction in buffer zone. The different approaches of field measurements, modelling or wind tunnel measurements are likely to give rise to different results if data is extrapolated from short distances to longer distances unless we are able to take account of the relationships between these approaches.

The rate of decline in drift with distance, as measured in the wind tunnel, is correlated with the equivalent parameter from field measurements, but the relationship between the two, for a given field measurement technique, appears to depend on field conditions which are at present undefined, but which might be related to the surface conditions and wind turbulence. A single relationship is not therefore possible to establish with the data currently available. A wider data set obtained in a range of locations and conditions would enable further investigation of this to be undertaken.

The data obtained so far suggest that while it is difficult to predict absolute field spray drift curves reliably from wind tunnel measurements, this is likely to be due to variability in field conditions rather than problems with a wind tunnel technique. It is clear that drift reduction in the field is likely to reduce with distance, and therefore some analysis of wind tunnel data is required if we need to know this relationship. It has been shown that it is possible to provide a reasonable estimate of relative spray drift between a test and reference condition, for downwind distances up to 20 m. However, an estimate of relative buffer zone requires the absolute spray drift curve for the reference to be defined.

If drift reduction at shorter distances is the concern, the very good correlation between wind tunnel measurements and field data provides the means to potentially improve the correlation with field data by increasing the wind tunnel wind speed.

Further work is needed to establish a harmonised approach across Europe for determining drift reduction, but these initial steps show that there is scope to use field data as a means of achieving this. If all EU member states' schemes can be mapped onto agreed field data, then it will be possible to map also them onto one another. There may still be some significant obstacles, to this, however, in terms of (a) agreeing the reference condition, and (b) agreeing a field 'drift curve' for the reference condition, whether based on a real dataset, an analysis of a number of datasets, or a theoretical curve based on model predictions.

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Appendix 1

Correlation coefficients between different measures of relative drift, obtained in wind tunnel experiments and relative drift at 5 m downwind, obtained from two different sets of field data.

Wind tunnel data, test/reference value	Nuyttens et al. (2007)		van de Zande et al. (2014)			Combined	
	2 m s^{-1} wind speed	4 m s^{-1} wind speed	2 m s^{-1} wind speed	3 m s^{-1} wind speed	4 m s^{-1} wind speed	2 m s^{-1} wind speed	4 m s^{-1} wind speed
2 m lowest line	0.93	0.96	0.98	0.81	0.8	0.92	0.84
2 m total (Σ 0.1–0.5 height)	0.90	0.96	0.58	0.78	0.77	0.70	0.83
3 m lowest line	0.84	0.97	0.44	0.87	0.82	0.59	0.85
3 m total (Σ 0.1–0.5 height)	0.87	0.97					
5 m lowest line	0.75	0.97	0.53	0.67	0.88	0.61	0.89
5 m total (Σ 0.1–0.5 height)	0.93	0.98	0.77	0.50	0.79	0.79	0.83
2 m first moment (equivalent to DIX measurement)	0.92	0.97	0.74	0.78	0.78	0.79	0.83
5 m lowest line based on fitted power law	0.83	0.97	0.89	0.94	0.999	0.82	0.97
5 m lowest line based on fitted power law to 27 m boom calculation	0.76	0.97	0.87	0.77	0.999	0.73	0.97

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