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Spray drift: An investigation of the relationship between field, wind tunnel measurements and model predictions for determining drift reduction

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Summary

This paper reports an investigation of the relationship between wind tunnel and field spray drift data, based on existing field data, and new measurements in the Silsoe wind tunnel. The aim was to explore the ability to use wind tunnel data to deduce drift reduction at distances greater than the 6 m which was the maximum buffer zone in the original LERAP scheme. We conclude that it is very likely that drift reduction will decrease with distance downwind, but wind tunnel measurements can be used to estimate this at least up to 20 m downwind. Possible improvements to the LERAP wind tunnel protocol have been identified, but these will need to take account of how the data will be used in the regulatory process and practical considerations.

Key words: Spray drift, wind tunnel, field, drift reduction

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 can be determined from either field or wind tunnel drift data. Recent changes to UK regulations relating to spray drift have allowed buffer zones greater than 6 m to be included, providing 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 has been compared with limited field data (Walklate *et al*., 2000) and 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.

Theoretical analysis of drift curves

A number of researchers have used a power law relationship between depositing drift and distance downwind (e.g. Walklate *et al*, 2000, De Schampheleire *et al.*, 2008), i.e

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

where d is 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 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. 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 can be fitted with relatively few data points.

Applying 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

$$relative\ drift\ = \frac{A_{test}}{A_{ref}}$$

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

The original analysis of Walklate *et al.* (2000) considered the case of α the same for both test and reference conditions, and the value $\alpha = 1.24$ was used. However, we assume initially that we need to define both A and α for reference and test conditions.

$$relative\ drift\ = \frac{A_{test}}{A_{ref}}\ x^{(\alpha_{ref}-\alpha_{test})}$$

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.

Published field data

There is a significant body of published field measurement of spray drift. However, there is also a wide range of measurement techniques, of protocols, and of conditions under which the experiments were carried out, as well as limitations on the availability of raw data. Byron & Hamey (2008) showed that field data can vary between different reference datasets, with further details reported by Anon. (2007), 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: Nuyttens *et al.* (2007), with additional data for two nozzles (D Nuyttens, pers comm.); and (Zande *et al.*, 2014). These data are compared with other recognised data, including (Rautmann *et al.,* 2001), which is commonly used in regulatory exposure assessments, and UK data obtained by the Central Science Laboratory (CSL) in the 1990s (Gilbert *et al.*, 2000, Byron & Hamey, 2008), used as the reference curve in the LERAP scheme for field measurement. Data obtained by The Food and Environment Research Agency

(Fera), published in the final project report (Anon., 2010) is also included as reference data. This is shown in Fig. 1, where 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 1 shows the value of α for each of the data sets, ranging from 0.99–2.00.

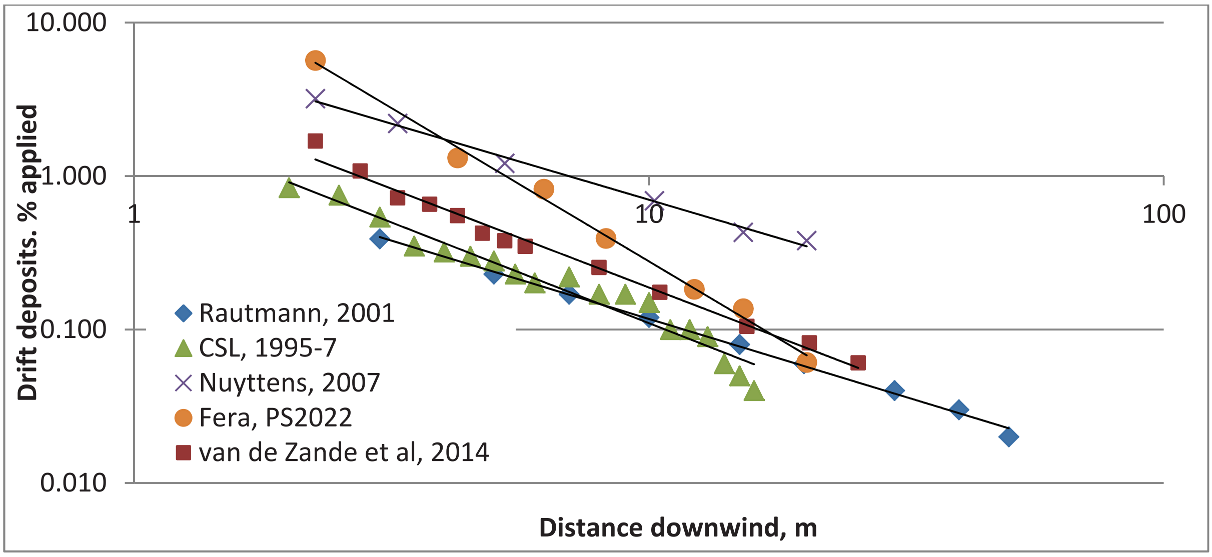

Fig. 1. Mean drift, expressed as a percentage of the applied dose, as a function of distance downwind for five datasets spraying a short crop, stubble or bare ground with similar (but not identical) reference conditions. Solid lines represent a fitted power law.

Table 1. *Value of α for a fitted power law curve to field data between 2 and 20 m downwind*

Data set	Reference nozzle	Driving speed, km h^{-1}	Ground conditions	α
Nuyttens, 2007	Hardi FF 110 03	8	Cut grass	0.99
Rautmann, 2001	Range of nozzles	6	Bare ground, short crop, tall crop	1.02
van de Zande 2014	Teejet XR 110 04	8	Bare ground	1.29
CSL, 1995–7	FF 110 03	8	Short grass	1.31
Anon. (2010) (Fera)	FF 110 03	12	Short crop/cut grass	2.00

An inspection of the experimental conditions for the three most recent datasets do not reveal large differences, apart from potentially the ground surface conditions and driving speed: Zande data was obtained spraying over soil, whereas Nuyttens data was obtained over cut grass, with the same conditions for both the treated area and the downwind drift area. The Fera data was reported to be obtained from a short crop such as cut grass < 0.15 m and therefore consistent with the experimental conditions for the other datasets, however the driving speed was higher (12 km h^{-1} compared with 8 km h^{-1}). This would not be expected to have a large effect on drift. The other datasets were obtained with a range of crop types, including bare ground (Rautmann *et al.*, 2001) and short grass (CSL data).

Given the range of drift curves from field data, there will be a difficulty in establishing an appropriate value of α for the reference condition, α_{ref}. A similar analysis was undertaken for the drift-reducing nozzles in the two datasets to determine whether a drift-reducing nozzle would have a significantly different value of α under the same conditions. Tables 2 and 3 strongly suggest that this is the case, with the value of α reducing as drift reduction increases. 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 previous analyses (Zande *et al.*, 2014; Nuyttens *et al.*, 2007).

Table 2. *Calculation of α obtained from field measurements of drift (Nuyttens* et al.*, 2007) for a reference nozzle (FF03, Hardi Ltd) and seven drift reducing nozzles. All nozzles operated at 3.0 bar. 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
FF 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 3. *Calculation of α from field measurements of spray drift (Zande* et al.*, 2014) for a reference nozzle (XR110 04, Spraying Systems Ltd) and five drift reducing nozzles. Drift reduction values are averaged over 1–20 m based on those given by Zande* et al. *(2014)*

Nozzle	Pressure, bar	α	%DR
XR 110 04 (reference)	3.0	1.31	–
DG 110 04	3.0	1.08	69
XLTD 110 04	3.0	1.32	87
IDN 120 03	3.0	0.88	91
AI XR 110 04	1.0	0.78	92
Airmix 110 05	1.0	0.56	95

Model simulations

In order to explore the possible factors influencing α, the Silsoe spray drift model (Butler Ellis & Miller, 2010) was used. Fuller details will be published elsewhere, but the model showed that the predicted value of α for a typical reference condition (1.47) was slightly 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 α, although the air induction nozzle had the lowest α 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 0.78–1.54 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.

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. The locations for drift sampling with passive line collectors are shown in Fig. 2. 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. 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 spray drift at any point downwind is calculated

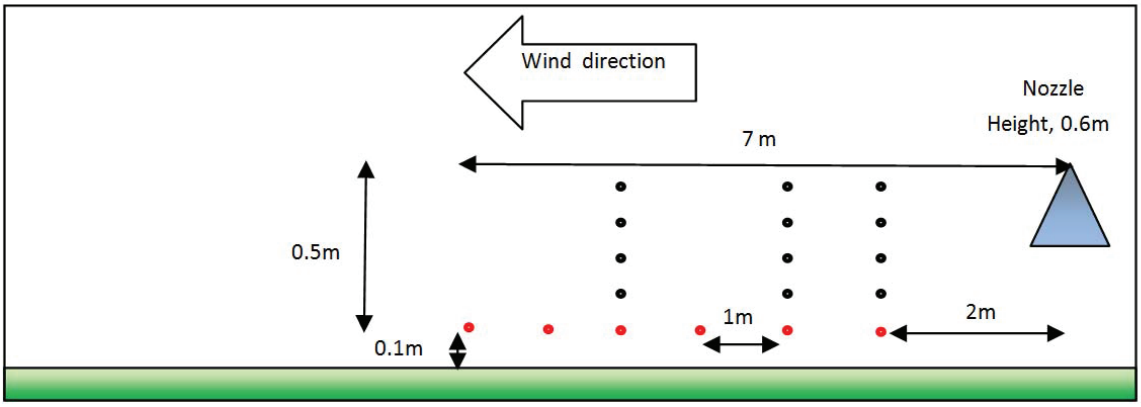

Fig. 2. Layout of wind tunnel for drift measurements. Small circles indicate a passive line collector of 1.98 mm diameter mounted across the width of the wind tunnel. Red circles indicate those used in the current LERAP protocol.

as the sum of the deposited spray drift from all nozzles at 0.5 m intervals upwind. Another power law is 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 were those for which field data was available and would be expected to give some drift reduction.

Comparison between wind tunnel measurements and field data

The wind tunnel data relating to the passive line collectors nearest to the ground (0.1 m height) between 2–7 m downwind of the nozzle were analysed as described above to determine a power law for the single nozzle, and for a simulated 27 m boom (Tables 4 and 5). The value of α from single nozzle data was reduced when summed over a 27 m boom, but was still much higher than field measurements. There was a correlation between wind tunnel and field values of α for only the 2 m s^{-1} wind speed, shown in Fig. 3 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.

Table 4. *Values of α calculated from wind tunnel data with two different analyses and two wind speeds using nozzles used by Nuyttens (all nozzles at 3.0 bar spray pressure)*

	2 m s^{-1} wind speed		4 m s^{-1} wind speed	
Nozzle	Single nozzle	27 m boom	Single nozzle	27 m boom
reference	2.60	1.80	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

The difference in the values of α is needed to calculate relative drift, as given in Eqn 2. Fig. 4 shows the relationship between $\alpha_{ref} - \alpha_{test}$ determined from field and wind tunnel data. Both data sets appear to have the same relationship, allowing data to be combined. The wind tunnel calculation overestimates the field value.

Table 5. *Values of α calculated from wind tunnel data with two different analyses and three wind speeds using nozzles used by van de Zande*

	2 m s^{-1} wind speed		3 m s^{-1} wind speed		4 m 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	1.10	0.59	1.13	0.61
IDN 120 03	2.00	1.27	1.53	0.90	1.39	0.79
AI XR 110 04	1.77	1.08	1.77	1.08	1.64	0.98

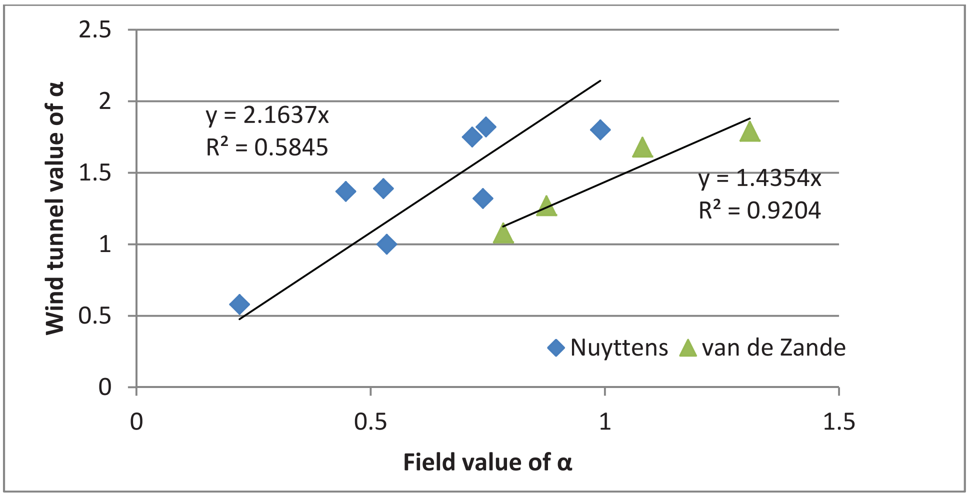

Fig. 3. Relationship between the values of α calculated from wind tunnel data measured with a wind speed of 2 m s^{-1} and extrapolated to a 27 m boom, and two sets of field data.

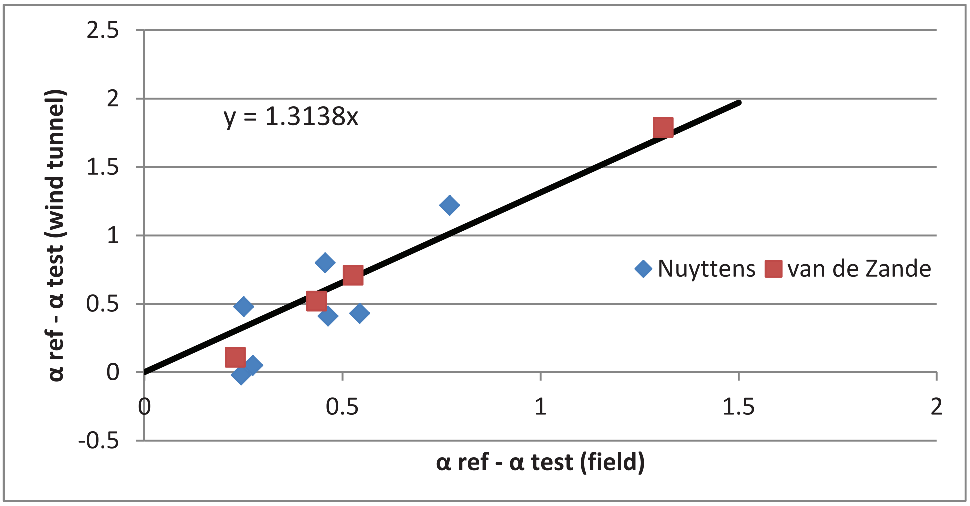

Fig. 4. Correlation between the values of $\alpha_{ref} - \alpha_{test}$ calculated from wind tunnel data measured at 2 m s^{-1} wind speed and field data for both data sets.

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 depends upon, probably, 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 field and wind tunnel and therefore, potentially, between different field data sets, although it would require data relating to different sets of field measurements with the same nozzles to test this.

Calculation of A_{test}/A_{ref}

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

Table. 6. *Correlation coefficient between different indicators 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[1]	0.97[1]
5 m total (Σ 0.1–0.5 height)	0.79	0.83
2 m first moment [2]	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

[1] Nuyttens data only.

[2] Equivalent to the DIX calculation, used in Germany for defining drift reduction classes (Herbst & Ganzelmeier, 2000).

There are many different values that can be used as a measurement of relative 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. Table 6 shows the correlation between wind tunnel and field measurements for some wind tunnel measures for the combined field data sets.

There is a good correlation between all indicators of relative drift in the wind tunnel and field data, which improves with increasing wind speed in the wind tunnel. The current LERAP protocol is similar to using the fitted power law for a 27 m boom evaluating drift reduction, at 5 m distance from the nozzle and 2 m s^{-1} wind speed, which gives one of the poorer correlations, suggesting that this more complicated calculation might be unnecessary, and potentially counter-productive. The best correlation for all data at both wind speeds was achieved by the power law based on a single nozzle, shown in Fig. 5 for the 4 m s^{-1} wind speed.

The regression between field and wind tunnel indicators gave a gradient of unity, within the standard error, for every indicator tested, suggesting that the wind tunnel measurement method is a very robust one, and the choice of the particular indicator to use can be made on practical grounds.

Conclusions

The rate of decline 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 or wind tunnel measurements are likely to give rise to different results if data are extrapolated from short distances to longer distances unless we are able to take account of the relationships between them.

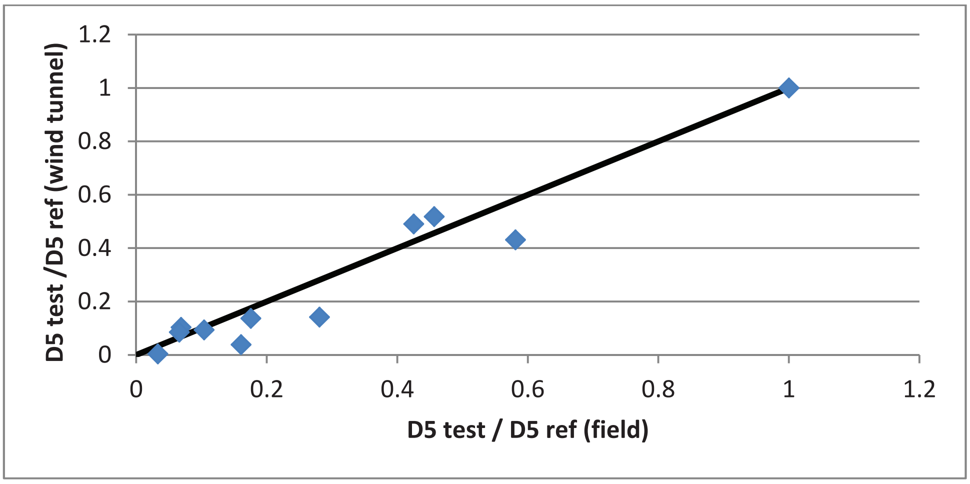

Fig. 5. The relationship between wind tunnel and field indicators of relative drift at 5.25 m downwind for the combined data, with the wind tunnel calculation based on a power law fitted to data between 2 and 7 m downwind from the last nozzle, obtained at 4 m s^{-1} wind speed. The solid black line indicates a one-to-one relationship.

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 might be related to the surface conditions and wind turbulence. A single relationship is not therefore possible to establish with the data currently available.

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. We have 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. For up to 6 m considered in the original LERAP scheme, we have shown a very good correlation between wind tunnel measurements and field data, and we can 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. The first steps will be to agree (a) the reference condition, and (b) 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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