Human exposure to spray drift: investigations into modelling the spray exposure of residents and bystanders and its variability

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Abstract

The BREAM (Bystander and Resident Exposure Assessment Model) model for bystander and resident exposure to spray drift has recently been incorporated into the European Food Safety Authority (EFSA) guidance for determining non-dietary exposures of humans to plant protection products. The component of BREAM which relates airborne spray concentrations to bystander and resident dermal exposure has been reviewed to identify if it is possible to improve the description of the relationship between dermal exposure and airborne spray. A semi-mechanistic model has been developed based on established studies combined with new data obtained in a wind tunnel. The implications of this model for the regulatory values for the 75th and 95th percentiles of the exposure distribution are explored.

Key words: Spray drift, BREAM, impact parameter, wind tunnel, collection efficiency

Introduction

The BREAM model (Bystander and Resident Exposure Assessment Model) (Kennedy *et al.*, 2012) for bystander and resident exposure to spray drift has a mechanistic component that predicts airborne spray and ground deposits, and an empirical component that relates airborne spray to deposits on the human body, from which dermal exposure can be calculated. The European Food Safety Authority (EFSA) guidance (EFSA, 2014) requires the 75th and 95th percentiles of exposure distributions to be used to represent long-term and acute exposures respectively, and it is important, therefore, that the predicted distributions are comparable with those that might occur in practice. It has been suggested that the relatively high values for the 95th percentile predicted by BREAM could be reduced by addressing some of the uncertainties and the causes of variability.

The empirical component, relating field measurements of airborne spray to dermal exposure, has a high level of variability captured within it. This relationship is currently represented very simply in the model as a normally-distributed variation around a regression line.

Two approaches to determining the relationship between airborne spray concentrations and potential bystander exposure have been explored: a more rigorous statistical analysis of the empirical data, and a semi-mechanistic model based on established studies of 'collection efficiency' of objects exposed to airborne spray droplets combined with new data obtained in a wind tunnel. A statistical comparison between field data and model outputs was used to determine which approach gave the better prediction of exposures. These approaches have been described in more detail and compared with each other in a separate paper (Butler Ellis *et al*., submitted for publication). In this paper, we focus on the experimental system for determining collection efficiency of objects in an air flow containing a drifting spray, and how it could be used in regulatory exposure models.

Materials and Methods

Modelling the impact of small droplets on obstacles in an air flow

May & Clifford (1967) provided basic data, subsequently used by Spillman (1984) on collection efficiency of objects exposed to drifting spray droplets. These showed that there was a unique relationship between an impact parameter, P, and the collection efficiency of the object for a given object geometry, with cylinders, spheres, ribbons and discs under consideration. Collection efficiency is defined by the droplet volume impacting on an object as a fraction or percentage of the droplet volume passing through the cross-sectional area if the object were not there, i.e.

$$CE = \frac{Q}{AS.AX} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

where *Q* is the quantity deposited on the object, *AS* is the quantity of spray per unit area in the absence of the object, and *AX* is the cross-sectional area of the object. The impact parameter is defined as

$$P = \rho_d \, d^2 \, v \, / \, 18 \, \mu \, W \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where ρ_d = droplet density, d = droplet diameter, v = air velocity (assumed equal to droplet velocity), μ = air viscosity and W = width (or characteristic dimension) of the object.

A unique relationship between CE and P, was reported (May & Clifford, 1967) for droplets 20–40 μm in wind speeds of 2–6 m s^{-1}, impacting on objects measuring 0·1–2·9 cm wide. Although these droplet sizes and wind speeds are not inconsistent with the situation of a bystander, the characteristic dimension we are interested in is significantly larger and a wider range of droplet sizes is likely. These might be outside the envelope for which the May and Clifford relationship applies.

Measurement of collection efficiency under controlled condition

Since the impact parameter defined by May and Clifford depends on droplet size and wind speed, we developed a system that could generate a repeatable set of data and encompasses a range of droplet sizes and wind speeds relevant to spray drift scenarios.

Two 110 degree Flat Fan ‘0050’ stainless steel nozzles (Teejet, London, UK) were mounted at the ceiling of the Silsoe wind tunnel which has a 2.0 m high, 3.0 m wide and 7.0 m long working section. The nozzles were separated by 0.55 m, operated with a flow rate of 0.16 L min^{-1} and a pressure of 2.0 bar. The aim was to create a uniform distribution of a relatively fine spray across the centre of the tunnel and to characterise the spray at a range of locations downwind.

A droplet imaging technique (Visisizer, Oxford Lasers Ltd, UK) was used to determine droplet size distributions and spray fluxes between 0.6 and 1.4 m above the wind tunnel floor, across a width of 0.5 m (Fig. 1). This was undertaken for three distances downwind and at three wind speeds in order to identify a range of conditions for determining the collection efficiency of different objects. For this study, the collection object was a cylinder, considered to be a simple representation of a bystander.

A set of measurements were then made to establish whether the relationship between impact parameter and collection efficiency established by May & Clifford (1967) applies to the situation of a bystander exposed to spray drift. The impact parameter was varied by varying the wind speed, the cylinder diameter and the droplet size. The droplet size was characterised by the volume median diameter, which was used to calculate a representative impact parameter.

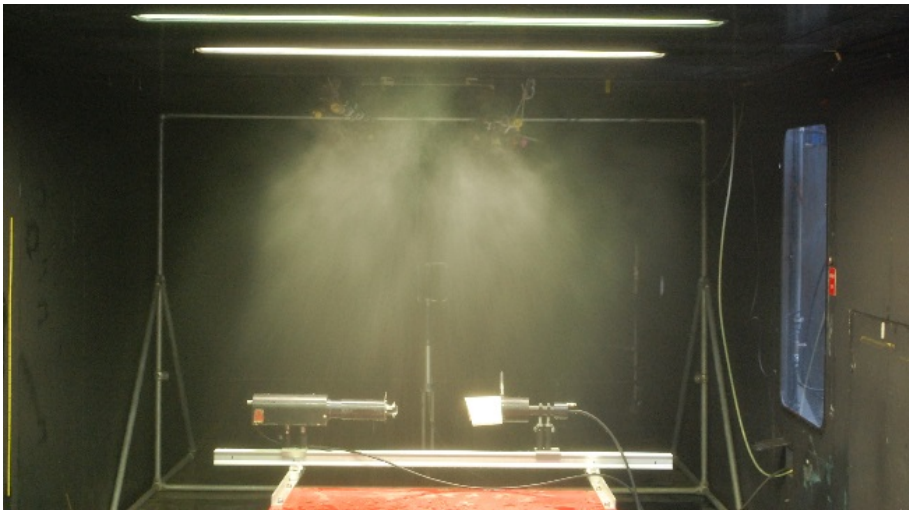

Fig. 1. Nozzle layout and instrumentation for droplet size measurements: view from the end of the tunnel looking upwind into the spray cloud with the Visisizer mounted on a moveable platform.

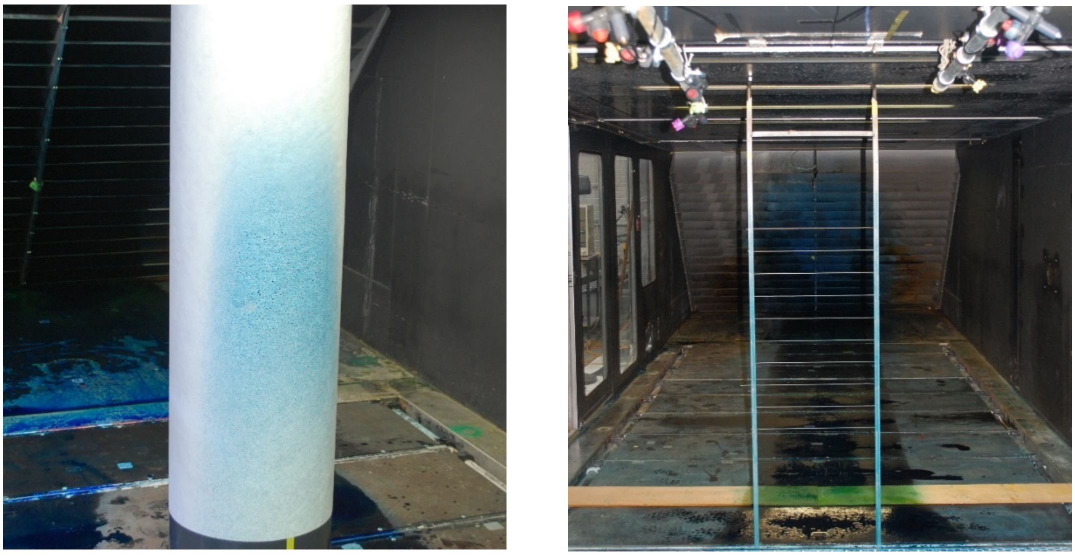

Fig. 2. Tyvek® sheet wrapped around the 0.4 m cylinder (left) and set of lines for collecting airborne spray (right).

Plastic drain pipes with diameters 0.225 m, 0.3 m and 0.4 m, 2.0 m tall were mounted vertically in the centre of the wind tunnel so that they touched the floor and ceiling. Each cylinder was wrapped with a 1 m wide piece of Tyvek® sheet, i.e. the same material as the coveralls used in field experiments (Butler Ellis *et al.*, 2010). The sheet was located between 0.5 and 1.5 m above the floor, where the droplet size had previously been measured (Fig. 2). Measurements were made with only one cylinder at a time to prevent any disruption of the air flow or spray flux.

The spray was created from tap water mixed with 0.1% dye (Green S E142, Fast Colours LLP, UK) for which analytical procedures are available using spectrophotometry. Following exposure to the spray for a known duration, the sheet was removed, cut into five 0.2 m strips and washed in a known quantity of water. The spray captured on each strip was quantified using protocols accredited under quality standard ISO 17025.

A third set of measurements determined the airborne spray at the same locations and under the same conditions as the cylinders, using a set of horizontal line collectors identical to those used to determine airborne spray in the field experiments. The lines were 0.00198 mm diameter, 0.5 m long and 0.1 m spacing, with two lines measuring the incident spray for each strip of material (Fig. 2). Each line was cut into three lengths, the deposited spray washed in a known volume of water and analysed using spectrophotometry. This enabled the airborne spray for the cross-section of each cylinder to be determined at each height above the ground.

Table 1. *Settings for wind tunnel measurements*

Collector	Wind speed, m s^{-1}	Distance, m
0.4 m cylinder	1.5 m s^{-1}	7 m
0.4 m cylinder	5.5 m s^{-1}	7 m
0.4 m cylinder	1.5 m s^{-1}	3 m
0.4 m cylinder	5.5 m s^{-1}	3 m
0.225 m cylinder	3 m s^{-1}	7 m
0.225 m cylinder	3 m s^{-1}	3 m
0.11 m cylinder	5.5 m s^{-1}	7 m
0.11 m cylinder	5.5 m s^{-1}	3 m

For each Tyvek strip, the collection efficiency was calculated based on the measured airborne spray on lines and the measured spray collected by the material. The impact parameter was also determined, from the measured spray volume median diameter for the location and wind speed, the wind speed itself, and the diameter of the cylinder, as given in Equation (2).

Calculation of collection efficiency, CE, and impact parameter, P, for field data

To establish whether the data relating to collection efficiency and impact parameter obtained in the wind tunnel are relevant to field measurements of bystander exposure, we need to make an estimate of these parameters for the field data. Collection efficiency was estimated using Equation (1). The impact parameter depends upon wind speed, collector diameter and droplet size. We do not know droplet size at the location of the bystander for field data. We know the nozzle and pressure and so can determine the droplet size of the source, but the droplet size distribution of the spray plume changes with wind speed, height and distance downwind. We therefore take a pragmatic approach, and attempt an order-of-magnitude estimate for the impact parameter, using some simple relationships, as follows:

For a droplet or particle released at its terminal velocity into an airstream of given velocity and at a given height, Stokes' law allows an estimate of how far downwind droplets of different sizes will travel.

$$d^2 = \frac{18\mu}{\rho_d\, g}\, \frac{v\, \Delta h}{x} \quad \text{......................(3)}$$

where x is the distance downwind, Δh is the height difference between the release height of the spray and the bystander and g is acceleration due to gravity. We can substitute this into Eqn 2, which gives

$$P = \frac{v^2\, \Delta h}{W\, x\, g} \quad \text{..................................(4)}$$

An impact parameter was calculated using Eqn 4 for each value of bystander exposure, based on known values taken from the experimental conditions. Some adjustments were needed:

- Wind speeds were measured at 2.0 m height, whereas we are interested in the wind speed at the point of impact on the bystander, which will range from around 0 to 1.82 m for adults, and 0 to 0.93 m for children. As a first step, wind speed, *v,* was taken to be 0.8 × measured wind speed, estimated to be the wind speed at the middle of an adult bystander.

- The height difference is problematic, because the spray is released below the full height of the bystander, and the simple model we have used above suggests that droplets travel only downwards. In practice, air turbulence can increase droplet height. Since the distance travelled by droplets of a given size increases with release height, we need a 'height' parameter in our calculation. As a first step, we use height of the boom above the ground (i.e. crop height plus boom height) to represent Δh, recognising that this is overly simplistic.
- Bystanders have a more complex shape than cylinders so we need to identify a characteristic bystander dimension. As a first attempt, we have taken cross sectional area divided by height.
- Finally, so that we can ensure that wind tunnel data is consistent with field data, we adjust the impact parameter by eye, using an arbitrary factor. This can take account of any inaccuracies in our estimation of the above variables.

A curve was then fitted to the relationship between collection efficiency and impact parameter, based on the wind tunnel data so that it could be incorporated into the BREAM software. The resulting alternative model is referred to as BREAM2-IP.

Results

Wind tunnel tests

An example of the volume median diameter (VMD) and flux for all the heights and lateral locations, for one distance downwind and wind speed are shown in Fig. 3. It can be seen that the VMD is relatively constant across the width measured, so we have assumed that an average value can be used and that objects up to 0.5 m width can be accommodated. The flux, however, is not uniform across 0.5 m, and therefore a measurement of flux will need to be obtained that is consistent with the width of the collecting object.

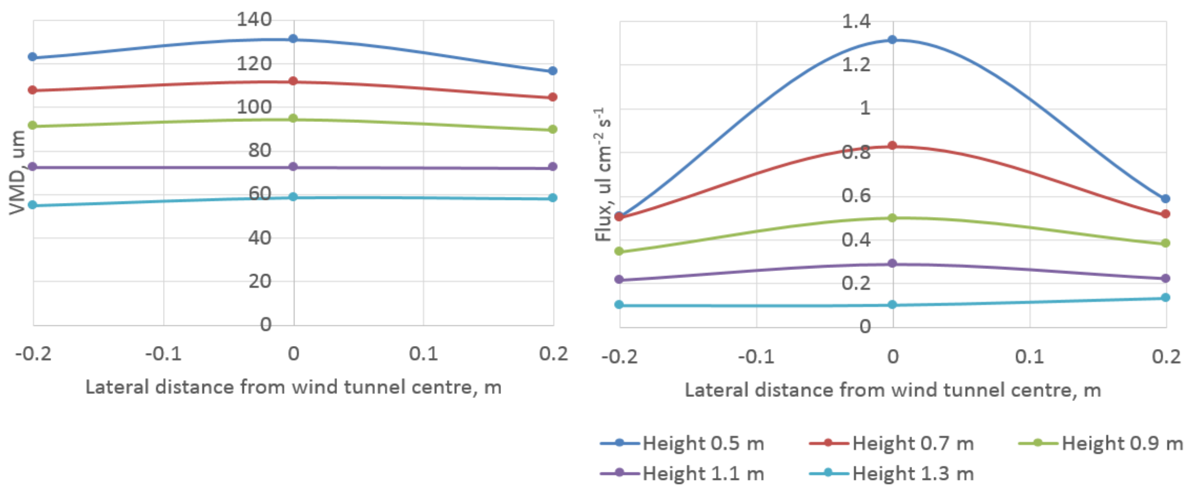

Fig. 3. Variation of VMD (left) and flux (right) with lateral position in the wind tunnel, 4.5 m downwind and with a wind speed of 1.5 m s^{-1}.

The mean VMD of the droplet size distribution for all distances, wind speeds and height in the wind tunnel is given in Fig. 4. At each location, there will be a wide range of droplet sizes, with the range of droplet sizes reducing as VMD reduces because the larger particles will fall out of the measurement zone. VMD values between 50 and 317 µm were measured, although the lowest VMDs related to low wind speeds and greatest distances downwind, where fluxes were small, and it would be expected that the quantity of collected spray might therefore be very small and subject to inaccuracies. From these data, the potential impact parameter, using VMD as a characteristic droplet size, can be calculated for the different diameters of cylinder. P ranged from 0.03 to 15.2.

The measured collection efficiency is shown as a function of calculated impact parameter in Fig. 5. These data suggest that there is a unique relationship between impact parameter and collection efficiency for the conditions prevailing during bystander exposure to spray drift. If we compare the data above with the May and Clifford curve, we see that our data are lower, but follow a similar relationship. The reason for the difference is likely to be related to the main differences in the experimental technique, plus the different range of experimental parameters used. The experimental technique we have used to generate collection efficiency data was designed to be relevant specifically to agricultural spray drift.

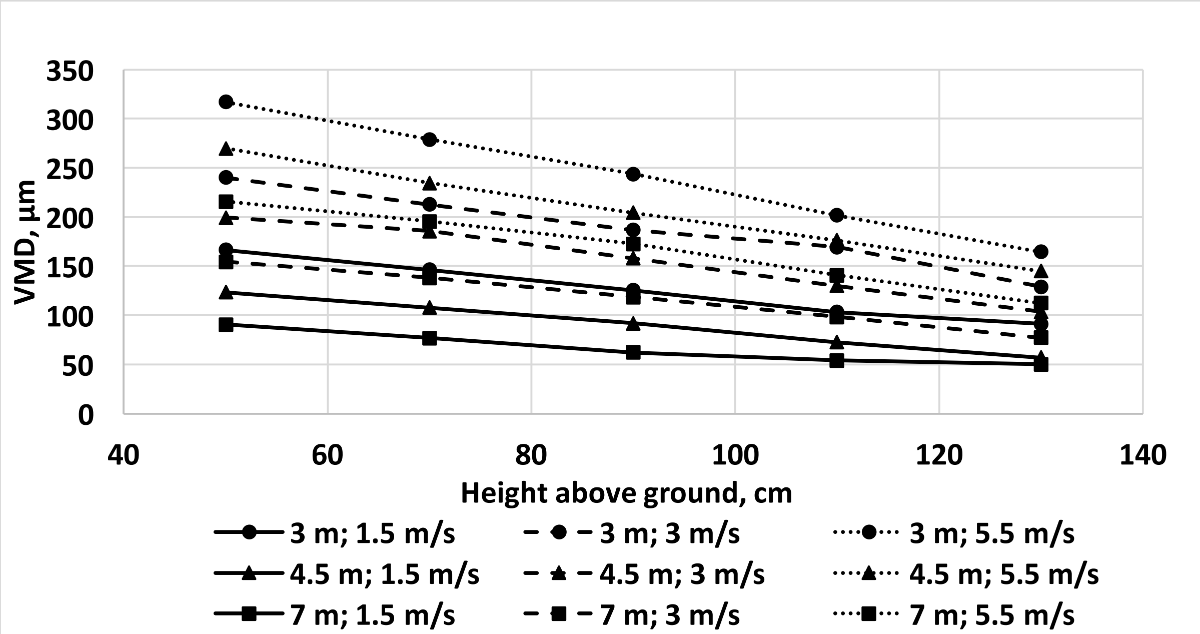

Fig. 4. Variation of mean VMD (averaged over three lateral values) of spray with distance, height and wind speed.

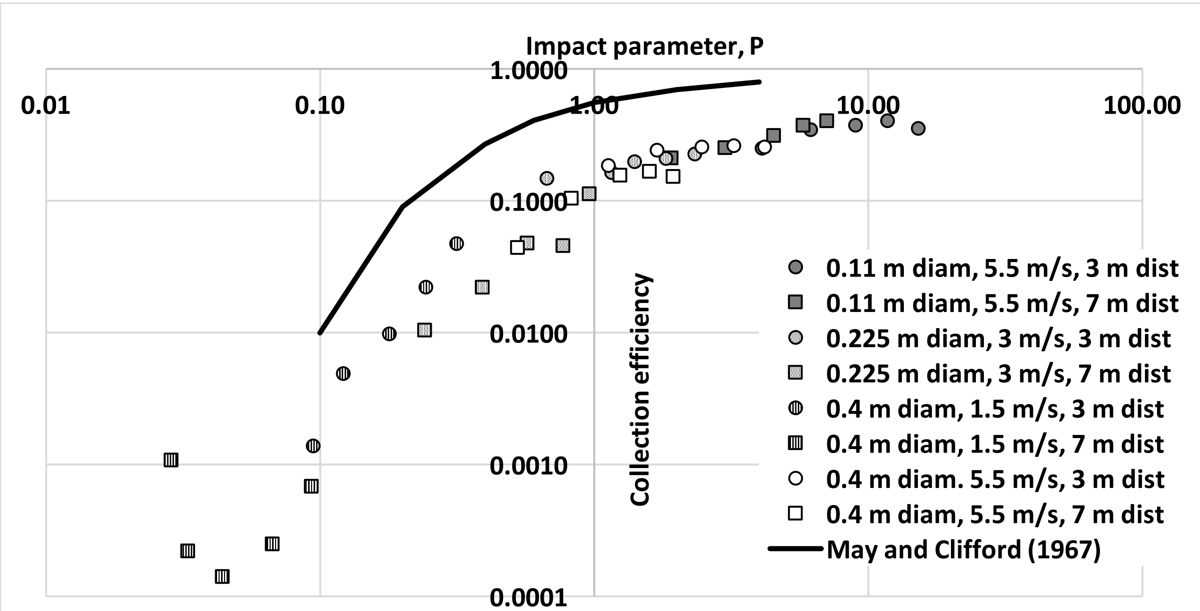

Fig. 5. The relationship between impact parameter and collection efficiency for a range of cylinder diameters, wind speeds and distances downwind.

Impact parameter and collection efficiency relating to experimental bystander exposure data

An equation was fitted to the wind tunnel data shown in Fig. 5:

$$CE = \alpha/\{1 + (K/P)^n\} \quad (5)$$

The parameters (α,K,n) were estimated via Bayesian inference. The posterior mean estimates were (0.434, 2.044, 1.203). The parameter α is the upper limit on the collection efficiency fraction.

A reasonable match between wind tunnel measurements and field data was achieved by adjusting Eqn. 4 by a factor of 1.5 (Fig. 6). The final equation for impact factor is

$$P_{field} = \frac{1.5\,(0.8\,Ws)^2\,(Ch+Bh)H}{AX\ x\ g} \quad \text{........................(6)}$$

where *Ws* is the wind speed measured at 2.0 m, *AX* is the cross-sectional area of the bystander, *H* is bystander height, *Ch* is crop height, *Bh* is boom height above crop. Fig. 6 shows that there is a good correlation between wind tunnel and field data at the higher values of impact factor, which will relate to the higher levels of exposure.

It appears probable, therefore, that a mechanistic model of the impaction of droplets on a human body could be developed, based on the use of an impaction parameter as previously defined in the literature. A curve can be fitted to the wind tunnel data, which is more reliable than the field data, and bystander exposure can be determined from the calculated values of airborne spray and collection efficiency.

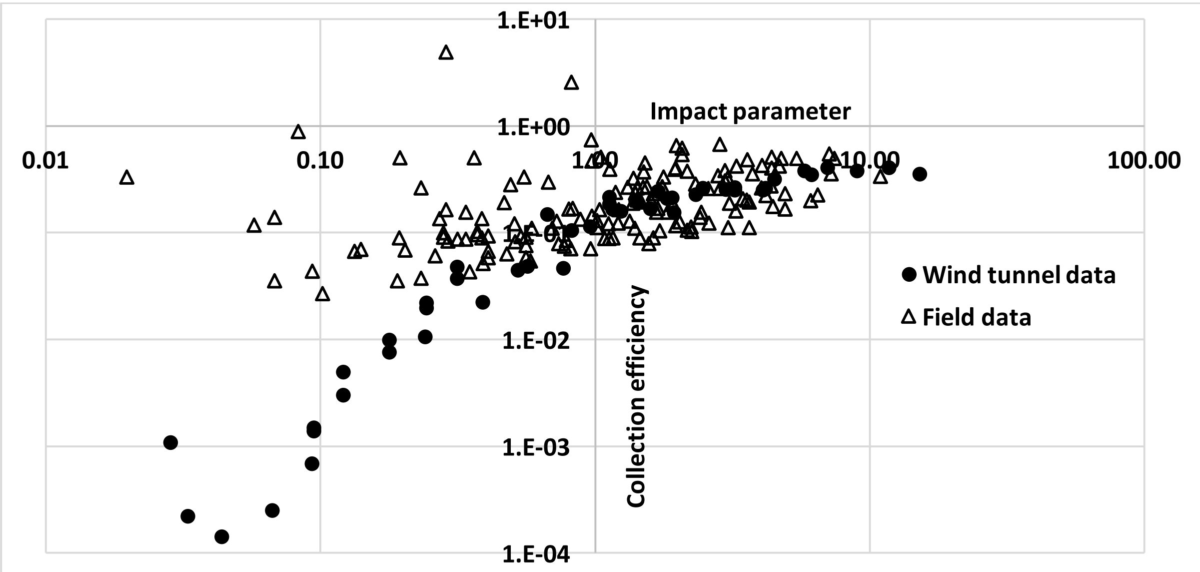

Fig. 6. Comparison of the relationship between measured collection efficiency and impact parameter for wind tunnel data (using Eqn 6), and that estimated for field data using Eqn (4).

Implications for Regulatory Exposure Assessment

The new method of predicting bystander contamination from airborne spray was incorporated into the BREAM model, and has been named BREAM2-IP. Using BREAM2-IP in the same way

Table 2. *Comparison of EFSA guidance exposure values (BREAM) with the corresponding values calculated by the new models BREAM2 and BREAM2-IP*

		BREAM (EFSA calculator)	BREAM2-IP
Adult	Median	0.22	0.1722
	75th percentile	0.47	0.3037
	95th percentile	1.21	0.5793
Child	Median	0.18	0.1257
	75th percentile	0.33	0.2164
	95th percentile	0.74	0.3947

as BREAM is currently used in the EFSA guidance, suggests that the 75th and 95th percentiles of the exposure distributions will have lower values than BREAM. A comparison of the different approaches is shown in Table 2.

A formal statistical evaluation of the different approaches showed that BREAM2-IP provided the best estimation of the distribution of exposures achieved in field trials (Butler Ellis *et al.*, submitted for publication).

Conclusions

A technique for exploring the spray drift collection efficiency of non-target objects using a wind tunnel has been developed and tested for the scenario relating to dermal exposure of bystanders. This showed that there is relationship between collection efficiency and impact parameter, similar to that developed by May & Clifford (1967), for this scenario. The same technique could be employed for a wide range of non-target objects particularly non-target terrestrial plants, which will allow improvements in exposure assessment to be implemented and mitigation methods to be explored using models. This technique will be much more cost effective than the large number of field trials that would be needed to gain data over a wide range of environmental conditions.

Some empirical fitting of data was required, however, to establish an equation for the impact parameter relevant to a bystander to ensure that field data are consistent with the wind tunnel measurements of collection efficiency of cylinders. This approach results in a revised model (BREAM2-IP) that gives improvements in the predictions of exposures compared with field data, and lower values for the 75th and 95th percentiles than the current BREAM model.

A semi-mechanistic model of bystander exposure is therefore proposed, whereby the relationship between impact factor and collection efficiency is based on wind tunnel data, and the impact factor is estimated from other model input variables.

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