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Original Article

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Improvements in Modelling Bystander and Resident Exposure to Pesticide Spray Drift: Investigations into New Approaches for Characterizing the 'Collection Efficiency' of the Human Body

M. Clare Butler Ellis[1,*], Marc C. Kennedy[2], Christian J. Kuster[3], Rafael Alanis[1] and Clive R. Tuck[1]

[1]Silsoe Spray Applications Unit, Wrest Park, Silsoe, Bedford MK45 4HP, UK; [2]Fera Science Ltd (Fera) National Agri-Food Innovation Campus, Sand Hutton, York, YO41 1LZ, UK; [3]Occupational and Residential Exposure, Bayer AG Crop Science Division, 40789 Monheim, Alfred Nobel Straße 50, Germany

*Author to whom correspondence should be addressed. Tel: +44 1525 306810; e-mail: clare.butlerellis@ssau.co.uk

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Abstract

The BREAM (Bystander and Resident Exposure Assessment Model) (Kennedy et al. in BREAM: A probabilistic bystander and resident exposure assessment model of spray drift from an agricultural boom sprayer. *Comput Electron Agric* 2012;**88**:63–71) for bystander and resident exposure to spray drift from boom sprayers 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 whether it is possible to improve this and its description of variability captured in the model. Two approaches have been explored: a more rigorous statistical analysis of the empirical data and a semi-mechanistic model based on established studies 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. The semi-mechanistic approach gave the better prediction of experimental data and resulted in a reduction in the proposed regulatory values for the 75th and 95th percentiles of the exposure distribution.

Keywords: BREAM; impact parameter; spray drift; statistical analysis; wind tunnel

Introduction

The BREAM (Bystander and Resident Exposure Assessment Model) (Kennedy *et al.*, 2012) for bystander and resident exposure to spray drift from boom sprayers has recently been incorporated into the European Food Safety Authority (EFSA) guidance for determining non-dietary exposures of humans to plant protection products (EFSA, 2014). The underlying principles of the model have therefore come under increased scrutiny. The BREAM 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 mechanistic component is based on the Silsoe Spray Drift model (Butler Ellis and Miller, 2010), which is a particle-tracking model that predicts the movement of individual droplets released from a sprayer. However, instead of incorporating this model directly into BREAM, an emulator is used instead which captures the main behaviour and can be run very rapidly. The empirical component is based on data derived from two sources: Butler Ellis *et al.* (2010) and Glass *et al.* (2002). These are combined into a calculator which runs the algorithms multiple times, sampling inputs from distributions to produce a distribution of outputs (Kennedy *et al.*, 2012).

The EFSA guidance 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 proposed 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.

In the current BREAM, variability is captured in two ways, as described by Kennedy *et al.* (2012):

(a) Wind speed, wind direction, and boom height are known to be important factors influencing spray drift. Fluctuations in wind speed and direction are as a result of turbulence, and this is captured as normal distributions around the mean. Boom height varies according to the characteristics of the boom suspension, which is also included as a normal distribution around a user-defined mean. These distributions of inputs are then sampled from in multiple model runs;

(b) The empirical component of the model has a significant level of variability captured within it. This component relates measured airborne spray concentrations to measured bystander dermal exposure, based on a series of field trials (Glass *et al.*, 2002; Butler Ellis *et al.*, 2010), and includes variability due to wind turbulence and boom fluctuations. This relationship is represented as a normally distributed variation around a regression line.

Thus, the BREAM for a given set of input values produces a distribution of outputs. However, the variability described in (b) includes the variability described in (a), and therefore, there is potentially some 'double accounting' in the current version of BREAM which could result in a wider predicted distribution than would occur in practice.

In addition, the empirical regression equation which relates (airborne spray concentration) × (bystander height) to bystander dermal exposure takes account of none of the model input factors which could, in theory, affect it. These factors include nozzle type and pressure (which influence droplet size), wind speed, boom height, and sprayer speed. It is recognized that some of the variability in the empirical data might arise from these factors, which could be determined from further data analysis and then taken account of explicitly in a more sophisticated regression equation.

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 in Glass *et al.* (2002) and Butler Ellis *et al.* (2010) to establish whether any of the model inputs affected the relationship 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. The implications for predictions of bystander exposure for the different approaches taken are considered.

Materials and methods

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

Investigations into the physics of small droplets impacting on larger objects have been reported in a number of classic studies. May and Clifford (1967) provided the basic data that were then used by Spillman (1984) to consider the implications for agricultural sprays.

The studies 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.

The impact parameter is defined (Spillman, 1984) as

$$P = \rho_d d^2 v / 18 \mu W \qquad (1)$$

where ρ_d is the droplet density, d is the droplet diameter, v is the air velocity (assumed the same as droplet velocity), μ is the dynamic viscosity of air, and W is the width (or characteristic dimension) of the object.

A unique relationship between collection efficiency and impact parameter was reported (May and Clifford, 1967) for droplets of 20–40 µm in wind speeds of 2–6 m s^{-1} impacting on objects measuring 0.1–2.9 cm wide. Thus, although these droplet sizes and wind speeds are not inconsistent with the situation of a bystander, the characteristic object dimension we are interested in is significantly larger than those used previously, a wider range of droplet sizes is likely and these might be outside the envelope for which the May and Clifford relationship applies.

Measurement of collection efficiency under controlled condition

Measurements were made in the wind tunnel at Silsoe Spray Applications Unit to establish whether the relationship between impact parameter and collection efficiency established by May and Clifford (1967) applies to the situation of a bystander exposed to spray drift. The collection object was a cylinder, considered to be a simple representation of a bystander. The impact parameter was varied by varying the wind speed, the cylinder diameter, and the droplet size. In contrast to the work of May and Clifford, though, hydraulic nozzles were used to generate a spray, and therefore, a range of droplet sizes were present at each measurement point. The droplet size was characterized by the volume median diameter (VMD) and used to calculate a representative impact parameter.

Two 110 degrees Flat Fan ‘0050’ stainless steel nozzles (Teejet, London, UK) were mounted at the ceiling of the wind tunnel which has a 2.0 m high, 3.0 m wide, and 7.0 m long working section. The two nozzles were 2.0 m above the floor, 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 as uniform a distribution as possible of a relatively fine spray across the centre of the tunnel.

The droplet size distribution was determined for a range of heights above the floor, distances downwind of the nozzles and wind speeds (Fig. 1), to identify a range of conditions for determining the collection efficiency of different cylinders. A droplet imaging technique was used (Visisizer, Oxford Lasers Ltd., UK, Murphy *et al.*, 2001) to determine droplet size distribution between 0.6 and 1.4 m above the wind tunnel floor, at 0.2 m intervals. The magnification setting of the instrument gave a minimum droplet diameter of around 30 µm.

Wind speeds, distances downwind of the nozzles, and cylinder diameters (Table 1) were then selected to encompass the range of possible impact factors and to ensure that the same impact parameters were achieved with

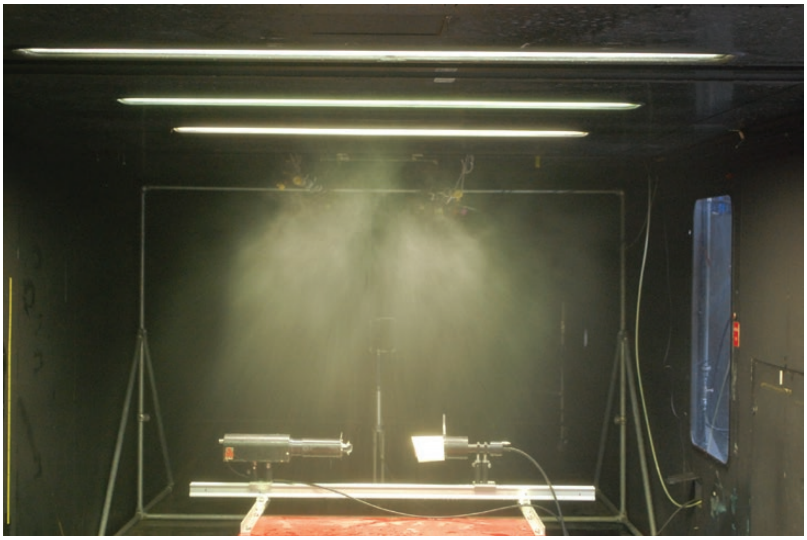

Figure 1. Nozzle layout and instrumentation for droplet size measurements: view from the end of the tunnel looking upwind into the spray cloud.

different variables so that we could establish whether a single relationship can be used, as suggested by May and Clifford.

Cylinders made from plastic drain pipes with diameters 0.225, 0.3 m and 0.4, 2.0 m tall were mounted vertically in the centre of the wind tunnel so that they touched the floor and ceiling (Fig. 2). Each cylinder was wrapped with a 1 m wide piece of Tyvek® sheet, which is the same material that the mannequins or volunteers wore as coveralls in the field experiments (Butler Ellis *et al.*, 2010). The sheet was located between 0.5 and 1.5 m above the floor, where the measurements of droplet size had previously been made. 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, using a set of horizontal line collectors identical to those used to determine airborne spray in the field experiments. The lines were 0.00198 m 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 the same spectrophotometry methods as the material strips. This enabled the airborne spray for the cross section of each diameter of cylinder to be determined at each height above the ground.

All experiments were conducted at high humidity levels (>75% relative humidity [RH]) so that droplet evaporation was not an important factor in spray behaviour.

For each 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

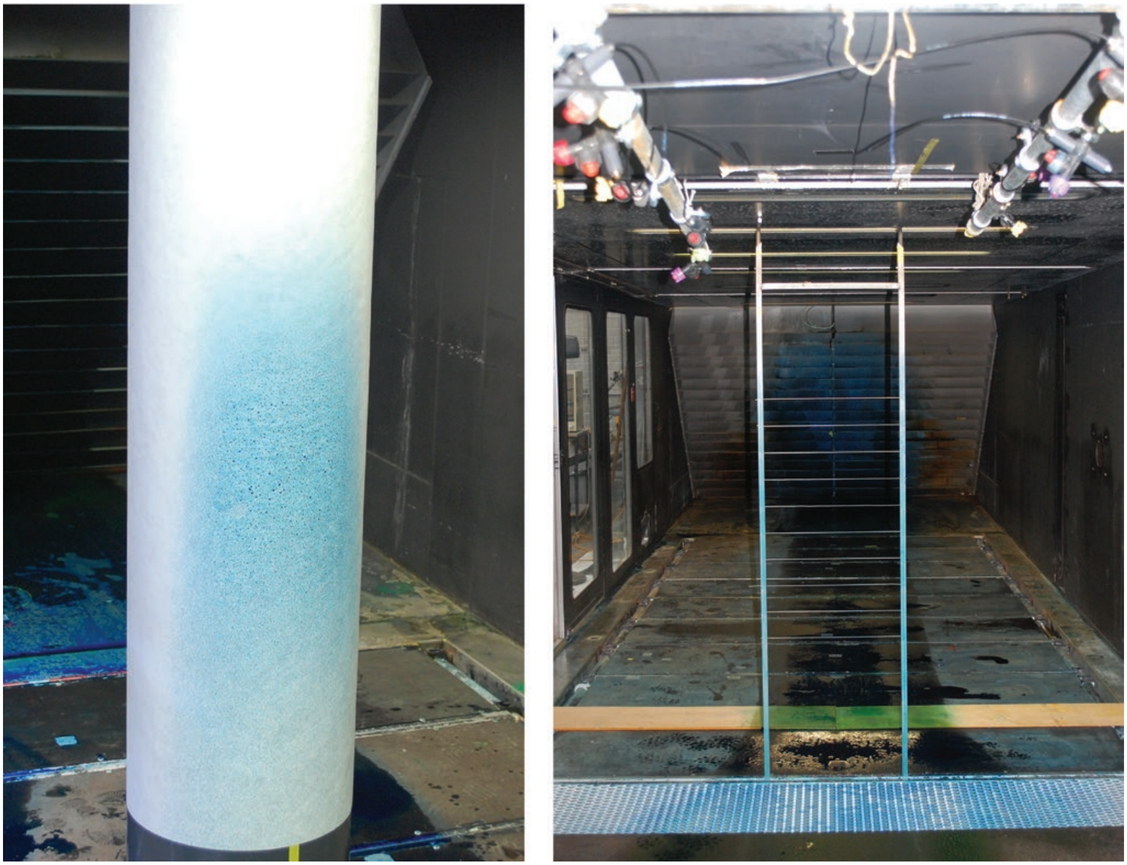

Figure 2. Tyvek® sheet wrapped around the 0.4 m cylinder (left) and set of lines for collecting airborne spray (right).

was also determined, based on the measured spray VMD for the location and wind speed, the wind speed itself, and the diameter of the cylinder, as given in equation (1).

An alternative approach would be to take the measured distribution of droplet sizes at each location and use it to calculate a volume-weighted impact parameter. However, the intention with this study is to find a practical and pragmatic method of predicting exposures which can be incorporated into existing regulatory exposure assessments, and since droplet size distributions in the field are not known (and would be very difficult to measure accurately), this has not been undertaken at this stage.

Statistical analysis of existing field data

The empirical data used to translate airborne spray to bystander exposure were reviewed and extended slightly by including additional data. This was not available early enough for inclusion in the original BREAM, although was used for validation (Kennedy *et al*., 2012). Also, information relating to the application conditions for each pair of data was obtained from original records for further analysis. These data included nozzle and pressure, sprayer speed, distance downwind, wind speed measured at 2.0 m height above the ground, boom width, crop height, approximate bystander height, and approximate bystander cross-sectional area. In the original model, the only factor which was considered was the bystander height.

The relationship between bystander exposure and airborne spray was also re-parameterized as collection efficiency to enable the field data to be compared with the results of the wind tunnel study. Two points were first removed as outliers, as their collection efficiency values were greater than 100%.

A regression model was then fitted using the derived (dimensionless) measurements of collection efficiency, *CE*, defined as

$$\mathrm{CE} = \frac{\mathrm{BC}}{\mathrm{AS} \cdot \mathrm{AX}} \qquad (2)$$

where BC is the quantity of spray liquid deposited on the bystander (ml), AS is the quantity of airborne spray per unit area in a vertical plane (ml m^{-2}), and AX is the approximate cross-sectional area of the bystander in a vertical plane (m^2).

This model was tested against field data and incorporated into the BREAM software, to create an improved model which we have called BREAM2.

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 has been estimated using equation (2).

The impact parameter depends upon only wind speed, collector diameter, and droplet size. Unfortunately, for the field data, we do not know droplet size at the location of the bystander. 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, v_t, into an airstream of given velocity and at a given height, it is possible to estimate how far downwind droplets of different sizes will travel. The time taken to travel a vertical distance Δh is given by $\Delta h/v_t$, and therefore, the distance downwind travelled, x, is $v\,\Delta h/v_t$ where v is the air velocity. Substituting in the equation for terminal velocity of a sphere (e.g. Massey, 1984)

$$v_t = \frac{d^2 \rho_\mathrm{d} g}{18\mu}$$

it can be shown that

$$d^2 = \frac{18\mu}{\rho_\mathrm{d}\, g} \frac{v\,\Delta h}{x} \qquad (3)$$

where, as before, ρ_d is the droplet density, d is the droplet diameter, μ is the air viscosity, Δh is the height difference between the release height of the spray and the bystander, and g is acceleration due to gravity.

This analysis does not take account of any possible evaporation. A reducing droplet size would lead to droplets travelling further. However, the field data were obtained in conditions where evaporation was likely to be low, and the relatively short distances involved would also limit the extent to which evaporation could be a factor. Any effect of evaporation which occurred in practice will be captured as part of the data variability.

We can substitute equation (3) into the equation for impact parameter [equation (1)], which gives

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

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

1. Measured wind speeds are 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 times measured wind speed, estimated to be the wind speed at the middle of an adult bystander, based on a logarithmic profile of wind speed over short vegetation or bare ground and a height above ground of 0.8 m.
2. The height difference is problematic because with boom sprayers, usually the spray is released below the full height of the bystander, and the simple model we have used above [equations (3) and (4)] suggests that spray droplets travel only downwards. In practice, air turbulence can increase droplet height. We know that the distance travelled by droplets of a given size increases with release height, and therefore, we need 'release height' to be a 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, recognizing that this is overly simplistic but ensuring that a relationship with release height is captured.
3. Bystanders have a more complex shape than cylinders, so we need to identify a characteristic bystander dimension, equivalent to the diameter of a cylinder which gives the same collection efficiency. As a first attempt, we have taken cross-sectional area divided by height.
4. Finally, so that we can ensure that wind tunnel data, which we want to use to further develop the model, is consistent with field data, we adjusted the impact parameter by a scale correction factor γ, estimated by comparing the wind tunnel and field datasets. This can take account of any inaccuracies in our estimation of the above variables, plus any potential effect that turbulence might have directly on the collection efficiency of a bystander. The statistical model was fitted to only those points with impact parameter $P>0.5$ as these are the cases leading to the highest exposures, and the uncertainties associated with lower values of P might be very high. For fixed but unknown parameters $(\beta_0, \beta_1, \delta)$, the statistical model assumed

$$\log_{10}(\mathrm{CE}) = \beta_0 + \beta_1 \log_{10}(P) + \varepsilon;$$
$$\log_{10}(\mathrm{CE_f}) = \beta_0 + \beta_1(\log_{10}(P_\mathrm{f}) + \delta) + \varepsilon_\mathrm{f}$$

where δ is the shift parameter to make the field data consistent, and subscript f is used here to denote field data. We allow for different stochastic error terms $\varepsilon, \varepsilon_\mathrm{f}$ because the field data have greater variation. Using Bayesian inference to estimate the unknown parameters provides a sample from the distribution of β_1 and δ. Finally, these are used to derive a sample from the distribution of $\gamma = 10^{\beta_1 \delta}$ on the back-transformed scale. The full sample is used to account for the uncertainty in this correction factor.

Thus, there is still an empirical element to the proposed model, but we are able to take account of the most important variables in a semi-mechanistic way. This approach is similar to a dimensional analysis, whereby we use our knowledge of the underlying principles to group the important parameters together but need empirical data to fully define the relationship.

Finally, a curve was 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.

Comparing model performance

BREAM, BREAM2, and BREAM2-IP were compared in terms of their ability to predict the field data and to accurately characterize the variation. As BREAM allows predictions of an FF110 03 nozzle only, the data for other nozzles were excluded from this comparison, leaving 66 field observations. The models are probabilistic, so for all 66 input scenarios, they were each run 10 000 times to capture the output distributions. Four model fit criteria were used: (i) RMSE—root mean squared error, where the error is the prediction mean BC minus the measured BC, (ii) RMSRE—root mean squared relative error, where each error is divided by the measured BC value, (iii) RMSSE—root mean squared standardized error, where each error is divided by the simulated standard deviation, and (iv) average width of 95% credible interval. A good model should have small values of RMSE, RMSRE, and 95% interval width. It should also have a value of RMSSE around 1 to demonstrate that the probability distribution of outputs is consistent with actual deviations from the central estimates.

Results

Wind tunnel study of collection efficiency

The VMD of the droplet size distribution at each location in the wind tunnel is given in Fig. 3.

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 very low, and it would be expected that the quantity of collected spray might therefore be very small and subject to inaccuracies. The limitation of the smallest droplet diameter measured being around 30 µm could be significant where the VMD is lowest, and there is a suggestion of the measured relationship between VMD and height reaching a minimum of around 50 µm, whereas we would expect it to continue to fall. This could have implications for subsequent calculation of impact parameter, although the volume of liquid contained in these smaller droplets is likely to be small and might be negligible.

From these data, the potential impact parameter can be calculated for the different diameters of cylinder ranging from 0.03 to 15.2.

The measured collection efficiency is shown as a function of calculated impact parameter in Fig. 4.

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. Establishing the reason for the differences would probably be a significant undertaking,

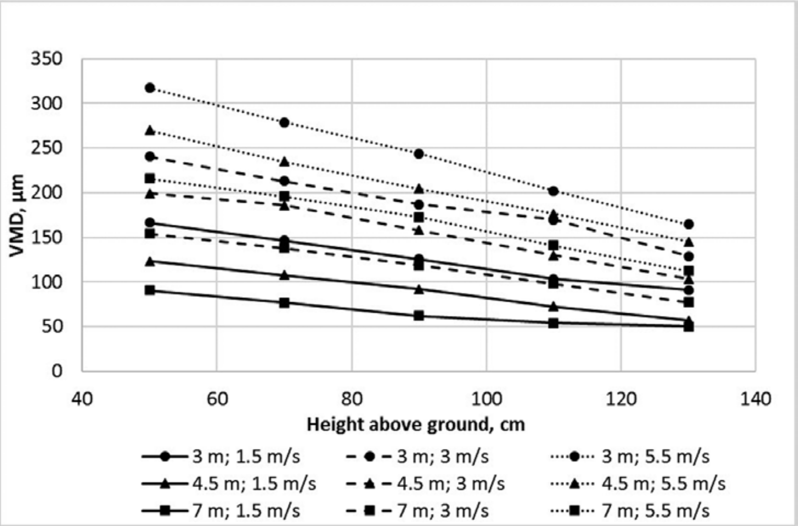

Figure 3. Variation of volume median diameter (VMD) of spray with distance, height, and wind speed.

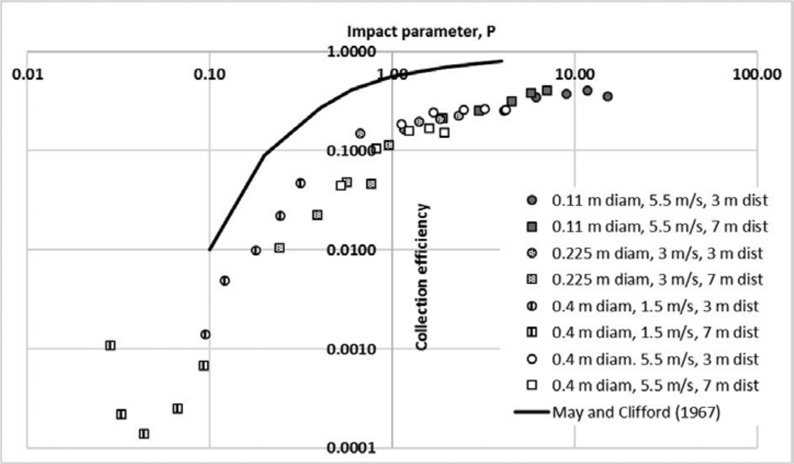

Figure 4. The relationship between impact parameter and collection efficiency for a range of cylinder diameters, wind speeds, and distances downwind. Each set of data includes measurements at five heights above the wind tunnel floor, with impaction parameter reducing with increasing height.

but is likely to be related to the main differences in the experimental technique, plus the different range of experimental parameters used. Our data suggest that collection efficiency reaches a plateau of around 0.43, which is not consistent with May and Clifford, but other investigations we have made (as yet unpublished) show that collection efficiencies close to 1.0 are possible for much higher values of P than those achieved here. Further investigations at intermediate values of P to explore the transition from low to high collection efficiencies would be beneficial.

The use of an impact parameter based on the distribution of droplet sizes, rather than the VMD, will be explored in future work. An initial theoretical analysis suggests that this would yield a different value of *P*, generally greater than that calculated from the VMD. The wider the distribution of droplet sizes, the greater the value of the volume-weighted average impact parameter is likely to be. This suggests that the difference between our measurements and those of May and Clifford could be even greater than Fig. 4 suggests. This might be important in use of these data for other purposes. However, the experimental techniques we have used to generate collection efficiency data, and the subsequent data analysis, have been designed to be relevant specifically to bystander exposure in the field and to allow a practical method of prediction for regulatory purposes.

Improvements to the regression model

The following regression model was fitted to the final dataset relating field estimates of collection efficiency to three variables:

$$\log_{10}(\mathrm{CE}) = -1.3758 + 0.13744Ws + 1.97162Ch - 0.02707x - 0.31999Ws \cdot Ch + \varepsilon \quad (5)$$

where CE is collection efficiency, *Ws* is wind speed measured at 2.0 m height (m s^{-1}), *Ch* is crop height (m), *x* is distance downwind (m), and ε is a random variable representing the noise due to residual variation and measurement error. The noise term ε is assumed to be independent between observations and distributed as $N(0, 0.1876^2)$.

Impact parameter and collection efficiency relating to experimental bystander exposure data

An equation was fitted to the wind tunnel data shown in Fig. 4, based on the Hill family of curves:

$$\mathrm{CE} = \alpha / \{1 + (K/P)^n\} \quad (6)$$

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

Using equation (1) and following the adjustment steps in Materials and methods, Statistical analysis of existing field data, the final equation for impact factor is

$$P_{\text{field}} = \frac{\gamma\,(0.8Ws)^2 (Ch + Bh) H}{AX \times g} \quad (7)$$

where *AX* is the cross-sectional area of the bystander, *H* is bystander height, *Ch* is crop height, *Bh* is boom height above crop.

The scale correction factor γ, for impact parameter, has estimated mean value 1.386. This was found to give a reasonable match between wind tunnel measurements and field data, particularly for *P* > 1.0, as shown in Fig. 5. In the BREAM2-IP model, we use simulations from the uncertainty distribution of γ.

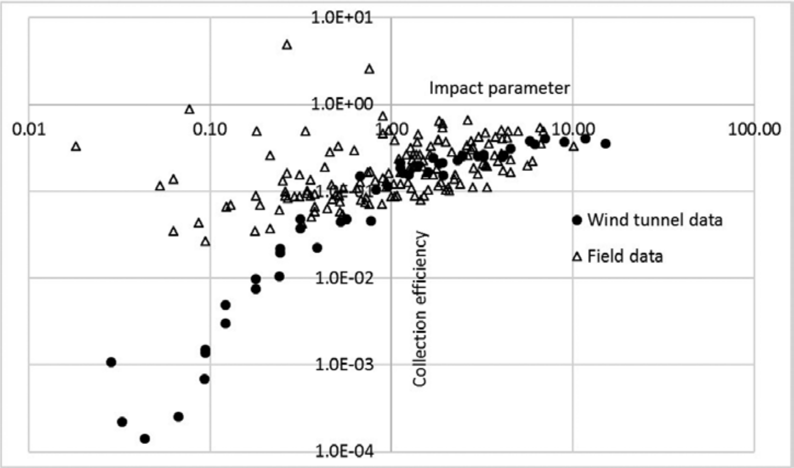

Figure 5. Comparison of the relationship between measured collection efficiency and impact parameter for wind tunnel data using equation (6) and that estimated for field data using equation (7) with the mean value of $\gamma = 1.386$.

Table 1. Settings for wind tunnel measurements.

Collector	Wind speed, m s^{-1}	Distance downwind of the nozzles, m
0.4 m cylinder	1.5	7
0.4 m cylinder	5.5	7
0.4 m cylinder	1.5	3
0.4 m cylinder	5.5	3
0.225 m cylinder	3	7
0.225 m cylinder	3	3
0.11 m cylinder	5.5	7
0.11 m cylinder	5.5	3
Airborne spray lines	1.5	7
Airborne spray lines	3	7
Airborne spray lines	5.5	7
Airborne spray lines	1.5	3
Airborne spray lines	3	3
Airborne spray lines	5.5	3

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. The field variability will be addressed through the use of distributions of inputs for wind speed, wind direction, boom height, and γ.

Comparison of model performance

The four criteria for evaluating model performance are shown in Table 2. BREAM2-IP has the smallest RMSE and RMSRE. It also has RMSSE closest to 1 and narrowest expected width of the 95% uncertainty interval. The simple BREAM includes wider 95% credible intervals, but the RMSSE is only around 0.5 which suggests that overall the simulated variation is too large relative to the observed errors. As seen in Fig. 6, the accuracy of the BREAM is good for the highest measurements but tends to overestimate the other measured values. This explains why BREAM has smaller RMSE but larger RMSRE than BREAM2. The BREAM output distributions are wider than the other models. The BREAM2 and BREAM2-IP models are seen to match the measured values more closely and give reasonable estimates for low or high measurements. For the lowest measurements, BREAM2 tends to overestimate, whereas BREAM2-IP underestimates the true values. BREAM2-IP has lower errors than BREAM2. Repeating this exercise with a different random seed produced only minor changes in the second or third decimal place and did not alter the relative rankings of the methods.

Table 2. Summaries of model performance for predicting observed dermal exposure values.

Model fit criterion	BREAM (R code); full dataset	BREAM2	BREAM2-IP
RMSE	0.210	0.359	0.277
RMSRE	2.250	1.879	0.790
RMSSE	0.565	0.705	0.845
Width of 95% CI	1.378	1.250	0.960

Discussion

Two different methods of predicting bystander contamination from airborne spray have been developed and incorporated into BREAM. The mechanistic approach based on an impact parameter suggests that collection efficiency depends upon wind speed, boom and crop height, distance downwind, and size of the bystander. The statistical approach identified wind speed, crop height, bystander height, and distance downwind as being important factors. It is likely that the field data were too variable and did not have a wide enough range for each variable to identify clearly the significant parameters, but there is some consistency between the two approaches. In Materials and methods, Measurement of collection efficiency under controlled conditions, it was explained how the spray VMD was used to calculate a representative impact parameter. The true impact parameter is more variable than this, and this could also partly explain why the model underestimates variation.

Some further statistical analyses were undertaken to identify which approach is the most appropriate. BREAM2-IP demonstrated better statistical properties based on the four criteria used and the available field data (Table 2).

Implications for regulatory exposure assessments

Using BREAM2-IP in the same way 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 3.

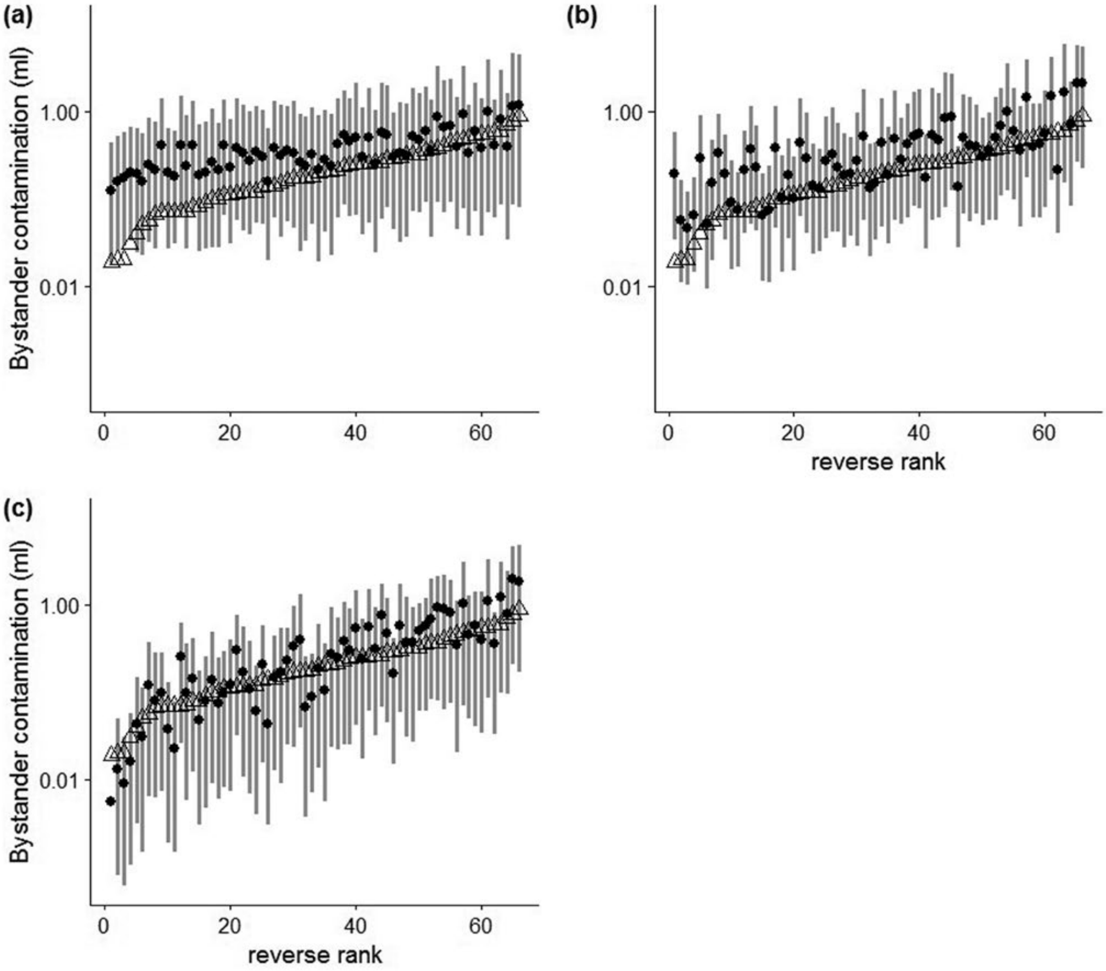

Figure 6. Cross-validation results for BREAM (a), BREAM2 (b), and BREAM2-IP (c). Black circles are model estimates, and grey bars are the corresponding intervals (2.5–97.5% of the simulated output distribution). Triangles are the measured values and have been ordered from low to high.

Table 3. Comparison of EFSA guidance exposure values (BREAM) with the corresponding values calculated by the new models BREAM2 and BREAM2-IP. Units are ml spray liquid per person. Number of simulations was 100 000.

		BREAM (EFSA calculator)	BREAM (including extended dataset)	BREAM2	BREAM2-IP
Adult	Median	0.22	0.25	0.21	0.16
	75th percentile	0.47	0.44	0.32	0.28
	95th percentile	1.21	0.98	0.58	0.55
Child	Median	0.18	0.18	0.12	0.12
	75th percentile	0.33	0.33	0.18	0.20
	95th percentile	0.74	0.74	0.32	0.37

Conclusions

An evaluation of the component of BREAM that relates bystander contamination to airborne spray suggests that the model potentially overestimates the variability (and therefore the higher percentiles) of the bystander contamination distribution. Including more information related to the spray conditions was shown to more accurately reflect the true variation.

The underlying mechanisms involved in determining the collection efficiency of the human body have been explored. A wind tunnel experiment was designed to evaluate the collection efficiency of objects in a drifting spray plume and tested using wind speeds, droplet sizes, and object sizes appropriate to bystanders exposed to spray drift.

The experimental results showed that a single relationship based on an impact parameter, similar to that proposed by May and Clifford (1967), can be used to define the collection efficiency of cylinders. It is hypothesized that this is also likely to be a good description of a bystander exposed to spray drift.

Some empirical fitting of data was required, however, to establish an equation for the impact parameter relevant to a bystander that is 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. This is likely to be as a result of a more accurate representation of the relationship between airborne spray and exposure and the variability due to wind turbulence and boom height fluctuations.

An alternative approach, of improving the regression equation between airborne spray and bystander exposure through further analysis (BREAM2), also gave improvements in exposure predictions as well as lower values for 75th and 95th percentiles, but the improvements were not as good as those from BREAM2-IP. Note that BREAM2-IP can give higher 75th and 95th percentiles than BREAM under some circumstances. BREAM gives high values for these percentiles for a wide range of conditions, but in the cross-validation results, these do not appear to be as realistic.

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. The variability relating to exposure is then derived from the distributions of model inputs for boom height, wind speed, and wind direction and from uncertainty in the impact factor.

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Conflict of Interest

C.J.K. works for Bayer AG. The authors declare no other conflict of interest relating to the material presented in this article. Its contents, including any opinions and/or conclusions expressed, are solely those of the authors.

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