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Summary

In the EU-FP7-BROWSE project (Bystanders, Residents, Operators and WorkerS Exposure models for plant protection products) spray drift data measured in the Netherlands and the UK for orchard spraying are combined to develop a probabilistic empirical model of bystander and resident exposure to spray drift. The model requires data relating to airborne spray to determine dermal and inhaled exposure, and relating to ground deposits, to determine indirect dermal exposure to contaminated ground. The available data can discriminate between full leaf (BBCH 74–92), the intermediate periods (BBCH 61–73 and 93–0) and the dormant (BBCH 0–60) period. For the BROWSE model, reference curves are defined for axial and cross-flow fan sprayers for ground deposit and airborne drift for 0–1 m and 0–2 m heights above ground as functions of distance downwind.

Key words: Spray drift, airborne drift, drift reduction, bystander risk, sprayer type

Introduction

In the EU-BROWSE project (Bystanders, Residents, Operators and WorkerS Exposure models for plant protection products; EU-FP7 project 265307), work is being undertaken to improve and extend existing models of human exposure to the agricultural use of pesticides, and to develop new models where none currently exists. The existing model of bystander exposure to spray drift from orchard applications is based on a single set of empirical data (Lloyd *et al.*, 1987). Similar work relating to bystander exposure to spray drift from boom sprayers showed that the exposure estimate was potentially underestimated as application practices have changed significantly (Butler Ellis *et al*., 2010) and therefore a new model was required. A study of orchard spraying practices in the UK (Defra, 2011) suggested that changes in orchard spraying practice (in the UK at least) were not as great, but it is still recognised that the single dataset is not ideal for an exposure model as it cannot take into account the different sprayer types (cross flow and axial fan), crop growth stages, distances between the sprayer and the bystander or resident, and other application, crop and environmental factors, and particularly drift reduction technology. Therefore, as a component of the BROWSE project, a new model of exposure of bystanders and residents to spray drift from orchard applications is being developed. Unlike for boom sprayers, there is no existing orchard spray drift model that can readily be used in a regulatory framework, so the new model is again empirical, but based on a large database of spray drift data measured in the Netherlands and the UK.

Bystander and resident exposure to spray drift requires knowledge of both airborne spray (to determine potential dermal and inhalation exposure) and ground deposits (to determine post-application exposure to contaminated ground). Data from the Netherlands is from measurements of airborne spray and ground deposits made in a series of experiments between 1990 and 2011 to a similar protocol, and includes a reference technique (based on a very fine spray) and drift reduction techniques. Data from the UK is from airborne spray measurements between1997–1999 (Cross *et al*., 2001*a*,*b*, 2003) using an axial fan sprayer (Hardi) with Very Fine spray quality nozzles focussing on the effect of spray volume and air assistance level in different growth stages of the apple trees. Due to the large number of measurements made with a very fine 'reference' spray it was possible to separate the data into the two sprayer types (axial fan and cross flow) and three growth stages. Discrimination between growth stages was based on the BBCH code for pome fruit development (BBCH, 2001) during the year distinguished between the periods full leaf (BBCH 74–92), the intermediate periods (BBCH 61–73 and 93–0) and the dormant (BBCH 0–60) period. While there is a substantial database available, it is insufficient to discriminate further, and therefore effects of other factors such as wind speed, sprayer speed and airflow and orchard structure cannot be included explicitly in the model, but are implicit in the variability of the data. This variability will be captured in the model and will contribute to determining a distribution of possible exposures in the probabilistic model.

The BROWSE bystander scenario currently considers a bystander located between 2 and 20 m from the treated area, and at heights up to 1.0 m for children, and up to 2.0 m for adults. Ground deposit data was obtained in the Netherlands at distances between 1.5 and 25 m from the centre of the last tree row, and is therefore appropriate to use directly in the model. However, airborne data was obtained at a single distance only: 7.5 m in the Netherlands and around 2.5 m in the UK from the centre of the last tree row. A technique for extrapolating these measurements to other distances is therefore required, and this has been based on a further analysis of the data obtained by Michielsen *et al.* (1997). There are other significant differences in the protocols used for obtaining data from the UK and The Netherlands, and additional data processing to take account of these differences has been considered, but is not described in this paper. Spray drift deposition (% of sprayed volume per unit area) on soil surface and airborne spray drift distributions up to 20 m downwind of the orchard are generated for the reference spray techniques; cross-flow fan and axial fan sprayer for fruit crop spraying for three growth periods during the season. These reference curves will be the basis for determining the spray drift deposition and airborne spray drift in the BROWSE software package for bystander exposure during fruit crop spraying. From these curves the bystander exposure can also be estimated for spray drift reducing technologies from the drift reducing classes 50%, 75%, 90% and 95% (ISO22369, 2006; Zande *et al*., 2013) as they can be presented relative to the spray drift curves of the reference spray technique in the different tree development periods during the year.

Work is continuing under the BROWSE project and it is possible that there will be further changes to the model before it is finalised. This paper captures the current plans for the development of a model of bystander and resident exposure to orchard spray drift, and the methodology for establishing airborne spray and ground deposits to use in determining exposures for a reference spraying condition.

Materials and Methods

Spray drift data are analysed for spraying an orchard with a cross-flow fan sprayer originating from spray drift measurements performed in the Netherlands and with an axial fan sprayer based on spray drift measurements done in the UK and in The Netherlands.

Cross-flow fan sprayer

Spray drift measurements in the Netherlands were carried out according to the ISO standard (ISO 22866; 2006) adapted for the situation in the Netherlands (ground deposits, ditch, and surface water area next to the sprayed field) following the Dutch protocol (CIW, 2003). Apple orchards were sprayed with a solution containing the fluorescent dye Brilliant Sulpho Flavine (BSF) and a non-ionic surfactant (Agral) to the spray agent. Spray drift deposition was measured using collectors (synthetic cloths; Camfil CM360 or Technofil TF-290) which were placed at several distances from the centre of the last tree row on ground surface (1.5 m up to 25 m) on the downwind edge of the orchard. At 7.5 m distance from the last tree row collectors (Siebauer Abtrifftkollektoren) were fit to vertical lines up to 10 m height to collect airborne spray drift. The spray drift was measured by quantifying the BSF deposition on the collectors. In the laboratory the collectors were washed with deionised water and the concentration of the tracer was quantified using a spectrophotometer (Perkin Elmer LS30). The measured fluorescent tracer on the collectors was expressed as µL cm^{-2} collector surface and as % of applied spray volume.

The reference technique for orchard spraying in the Netherlands is a cross-flow fan sprayer (Munckhof), equipped with Albuz ATR lilac nozzles (Huijsmans *et al*., 1997), which at 7 bar spray pressure produces a Very Fine spray quality (Southcombe *et al*., 1997). The experiments were carried out from early (dormant) to late growth stages (full leaf, leaf fall) of the trees.

In the early growth stages (developing foliage), air assistance was supplied with low gear settings for the fan. In the fully developed foliage stage, experiments were carried out with high gear fan settings. In total 316 spray drift measurements of the reference sprayer were analysed with 144 in the full leaf stage (BBCH 74–92), 140 in the dormant stage (BBCH 0–60) and 32 in the intermediate (BBCH 61–73, 93–0) period. Average weather conditions during measurements were average wind speeds of 2.3–2.9 m s^{-1} at 0.5 m above tree height, average temperature of 17°C and an average wind angle perpendicular to the tree row direction of 6–13°.

Field measurements were performed to quantify the effect of drift reducing techniques and are always measured in parallel with the drift situation of the reference technique (Zande *et al*., 2013). The data of the reference technique in these measurements is used to determine a general spray drift curve for spray deposition on soil surface up to 25 m from the last tree row and an airborne spray drift curve with height at 7.5 m distance from the last tree row.

Axial fan sprayer

In the UK in-tree spray deposition and spray drift measurements (1997–1999) were made (Cross *et al*., 2001*a,b*, 2003) using an axial fan sprayer (Hardi TC1082) equipped with on both sides four hollow cone nozzles (Albuz ATR orange, green, brown) having a Very Fine to Fine spray quality (Southcombe *et al*., 1997). Focus was on the effect of spray volume and air assistance level in different growth stages of the apple trees (359 measurements) and potential airborne spray drift at 2-3 m distance from the last tree (5 m from spray track). Spray pressures used were 5 bar, 12 bar and 24 bar at a driving speed around 6 km/h applying spray volumes between 60 L ha^{-1} and 780 L ha^{-1}. Air assistance settings varied between low, medium and full air, having respectively air outlet speeds of 7.7 m s^{-1}, 14.1 m s^{-1} and 21.2 m s^{-1} (4.1, 7.5, 11.3 m^3 s^{-}). Tree height varied between 1.3 m and 3 m with a row distance between 4 m and 5.5 m and a tree spacing of 2 m to 3.5 m. Spray drift was measured as the amount passing through a single tree row following a single spray pass spraying on both sides of the sprayer the tree rows from one side. Spray drift deposition was measured on 10 m high polythene tubing lines (SIMS; diameter 1.98 mm) attached to 10 m high supports. After spraying the collectors were stored and analysed in parts of 1 m in height. EDTA chelates of metals were used as spray tracers (manganese, zinc, strontium, copper).

The UK data with an axial fan sprayer includes only airborne spray measurements, and there is a relatively small amount (75) of axial flan data from the Netherlands. However, comparative measurements have been performed comparing a Munckhof cross-flow fan orchard sprayer and a similar Munckhof axial fan orchard sprayer without the cross-flow air distribution box on top of the axial fan (Wenneker *et al*., 2008, 2009). The Munckhof axial fan orchard sprayer was on both sides equipped with four hollow cone nozzle types. Nozzle types used were the Albuz ATR lilac and yellow, both operated at 7 bar spray pressure, a driving speed of 6.7 km h^{-1}, applying a spray volume of respectively 90 L ha^{-1} and 180 L ha^{-1}. Air setting was low air in the dormant situation and full air in the full leaf situation. From these comparative measurements it was shown that the spray drift deposition on soil surface downwind of the orchard was similar for the cross-flow fan sprayer as for the axial fan sprayer. The spray drift deposition on soil surface of the cross-flow fan sprayer is therefore combined with those of the axial fan sprayer and used as a reference for the axial fan sprayer. Airborne spray drift differed between the two sprayer types and is therefore analysed separately for the two sprayer types.

Average weather conditions during the UK and NL axial fan measurements were an average wind speed of 3.1–6.3 m s^{-1} at 10 m height and average temperature was 14–20°C. Wind direction was for the NL drift measurements with the axial fan sprayer on average 12° from perpendicular to the tree row direction and from a wider range of directions for the UK measurements.

Results

Cross-flow fan sprayer

Spray drift deposition downwind of field

For the cross-flow fan sprayer, mean drift deposition on the soil surface is presented in Fig. 1. At 5 m distance from the last tree row spray drift deposition on soil surface was 11% in the full leaf, 15% in the intermediate and 23% in the dormant period. Spray drift deposition decreases with distance from the orchard. From the mean spray drift deposition data, exponential functions with distance were fitted for the dormant (BBCH 0–60), intermediate (BBCH 61–73, 93–0) and full leaf (BBCH 74–92) situation. The functions and its parameters for the three growth stages are:

Dormant: $y = 38.797e^{-0.104x}$
Intermediate: $y = 26.928e^{-0.124x}$
Full leaf: $y = 19.036e^{-0.118x}$

With y = spray drift deposition (% of sprayed volume) at distance × m from the last tree row.

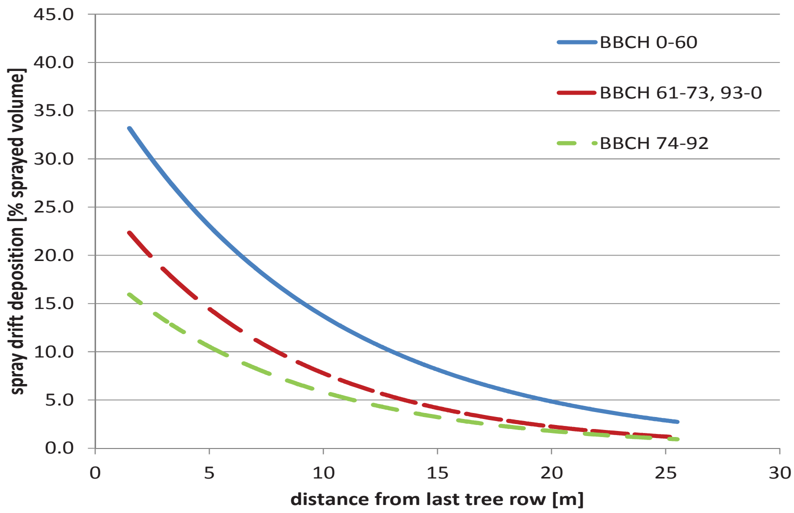

Fig. 1. Average spray drift deposition (% of sprayed volume per unit area) downwind of the sprayed orchard for the reference sprayer at dormant (BBCH 0–60), intermediate (BBCH 61–73, 93–0) and full leaf (BBCH 74–92) periods (apple).

From these fitted spray deposition curves the mean spray drift deposition is calculated for the distances up to 60 m from the last tree row for the dormant, intermediate and full leaf situation spraying an orchard with a cross-flow fan orchard sprayer (Table 1). In order to capture the variability in the data of Table 1, these average curves are not used directly in the BROWSE model, but the underlying data is used to generate a distribution of curves which can be sampled to determine a distribution of deposits at any location between 2 and 20 m.

Table 1. *Estimated average spray drift deposition (% of sprayed volume) at different distances from the last tree row spraying an orchard in the dormant, intermediate and full leaf situation with a cross-flow fan sprayer*

	Distance from last tree row [m]										
	5	10	15	20	25	30	35	40	45	50	60
Dormant	23.1	13.7	8.2	4.8	2.9	1.7	1.0	0.6	0.36	0.21	0.08
Intermediate	14.5	7.8	4.2	2.3	1.2	0.7	0.35	0.19	0.10	0.05	0.02
Full leaf	10.6	5.8	3.2	1.8	1.0	0.6	0.31	0.17	0.09	0.05	0.02

Airborne spray drift

Mean airborne spray drift at 7.5 m distance from the last tree row for the reference cross-flow fan spray technique for fruit orchard spraying (24 m wide strip) is presented in Fig. 2. Maximum airborne spray drift was 19% of applied volume at 2 m height in the full leaf period, 27% at 1 m height in the intermediate, and 53% at 1 m height in the dormant period. Only data up to 2.0 m height is used in the BROWSE model.

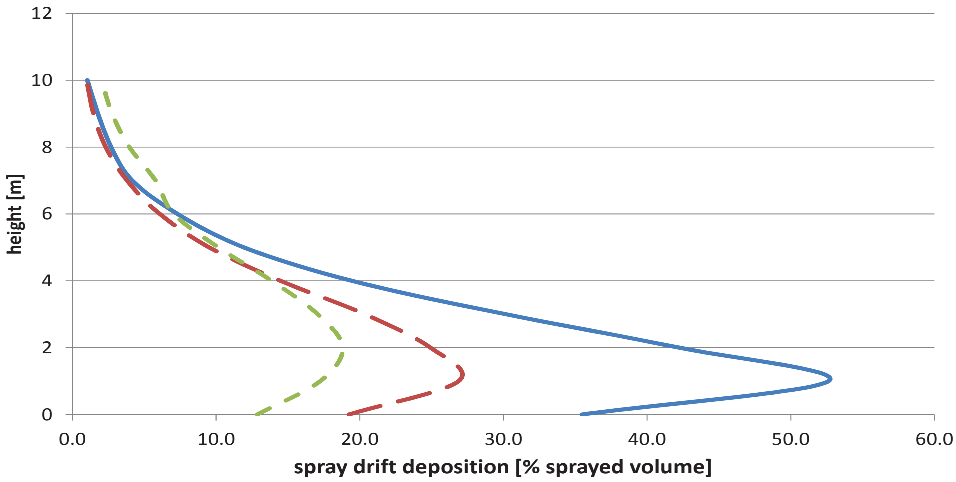

Fig. 2. Mean airborne spray drift at 7.5 m distance downwind of the sprayed orchard from the last tree row for the reference sprayer at dormant (BBCH 0–60), intermediate (BBCH 61–73, 93–0) and full leaf (BBCH 74–92) periods (apple).

Axial fan sprayer

Spray drift deposition downwind of field

As spray deposition on soil surface downwind of the sprayed orchard for the axial fan spraying is generated from 75 axial fan measurements and joined with the cross-flow fan measurements (Fig. 1) results are very similar as for the cross-flow fan sprayer. At 5 m distance from the last tree row spray drift deposition on soil surface was 12% in the full leaf, 16% in the intermediate and 23% in the dormant period. The functions and its parameters for the three growth stages for the axial fan sprayer are:

Dormant: $y = 38.755e^{-0.109x}$

Intermediate: $y = 30.371e^{-0.126x}$

Full leaf: $y = 20.848e^{-0.115x}$

With y = spray drift deposition (% of sprayed volume) at distance × m from the last tree row.

Airborne spray drift

The UK measurements (357) were made with an axial fan sprayer spraying a single path between two rows of an orchard. The measurements were distributed over the periods dormant (53 in April), intermediate (53 in May) and full leaf (251 in June, July, September). In The Netherlands, 75 measurements were made in the dormant (22 measurements in April), intermediate (14 measurements in May) and full leaf period (39 measurements in October).

The airborne spray drift data of the measurements in the UK and NL are combined (432 measurements) and presented in Fig. 3. In the lower 2 m height where exposure risk occurs for bystanders averaged airborne spray drift, at 3–7.5 m from the last tree row, is maximal at 0.750 m height and is in the dormant period 52%, 44% in the intermediate period and 31% in the full leaf period. Airborne spray drift is at these heights for the axial fan sprayer similar to those of the cross-flow fan sprayer in the dormant period but higher in the intermediate and full leaf period.

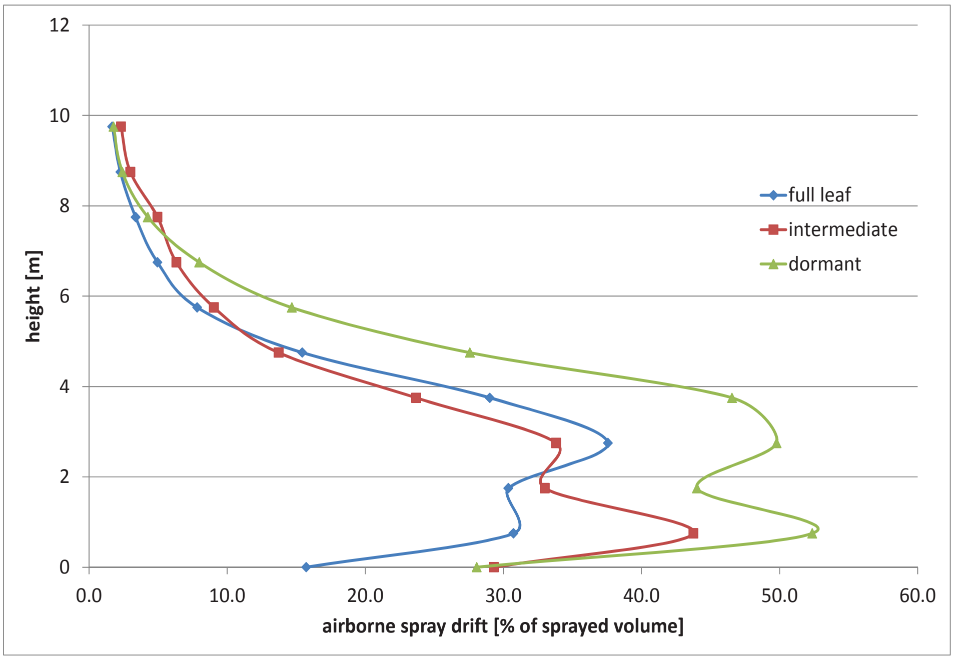

Fig. 3. Averaged airborne spray drift (% of sprayed volume) 7.5 m downwind of the sprayed orchard from the last tree row for different UK and NL axial fan spray techniques in the dormant (April), intermediate (May) and full leaf (June–October) periods (apple).

Discussion

The extrapolation of airborne spray drift at 7.5 m measuring distance (Figs 2 and 3) to different distances can be based on results of individual tree row sprayings with a cross-flow fan sprayer (Michielsen *et al*., 2007). There is no equivalent data for an axial fan sprayer, and so the same relationship is assumed for both sprayer types. The relative airborne spray at different distances from the last tree row can be obtained from this data for dormant and full leaf situations, and is shown in Table 2. It is assumed that the effect of the n^{th} row spraying is similar as if the collector pole was at a similar distance (+7.5 m) from the last tree row. For the intermediate period, a similar table was created from the average values of dormant and full leaf. This resulted in airborne spray drift height-distance matrices for the dormant period, the intermediate period and for the full leaf period. From these airborne spray drift distributions the spray drift in the bottom 0–2 m height was calculated as the potential spray drift deposition on an adult person standing downwind at different distances of a sprayed orchard. Airborne spray drift distributions of the spray drift in the bottom 0–1 m height was calculated as the potential spray drift deposition on a child.

Average airborne spray drift with distance

From the averaged values of airborne spray drift with distance, exponential curves [1] can be fitted for the airborne spray drift between 0–1 m (for children) and 0–2 m height (for adults) between 2 and 20 m from the last tree row for the dormant, intermediate and full leaf situation spraying an orchard with each sprayer type (Tables 3 and 4).

$$y = a.e^{b.x} \quad [1]$$

With y = spray drift deposition at certain height (% of sprayed volume) at distance x m from the last tree row.

Table 2. *Relative airborne spray deposition at different distances from the measured distribution at 7.5 m from the last tree row and up to 2 m height based on individual row (path) sprayings in the dormant situation and the full leaf situation(from Michielsen* et al.*, 2007)*

		Distance from last tree row [m]									
Dormant		7.5	10.5	13.5	16.5	19.5	22.5	25.5	28.5	31.5	34.5	37.5
Height [m]	path	1-1	2-2	3	4	5	6	7	8	9	10	11
0		1	0.860	0.443	0.246	0.150	0.102	0.075	0.054	0.037	0.023	0.010
1		1	0.888	0.555	0.354	0.226	0.152	0.105	0.071	0.047	0.027	0.012
2		1	0.908	0.637	0.453	0.295	0.197	0.138	0.093	0.063	0.038	0.017
Full leaf												
0		1	0.704	0.314	0.209	0.134	0.091	0.068	0.047	0.029	0.015	0.005
1		1	0.796	0.409	0.270	0.180	0.125	0.095	0.068	0.044	0.024	0.009
2		1	0.841	0.488	0.325	0.214	0.153	0.118	0.086	0.055	0.031	0.012

Table 3. *Parameters of the exponential functions for the airborne spray drift at heights 0–1 m and 0–2 m for a cross-flow fan spraying in the dormant, intermediate and full leaf stage of the fruit trees*

	0–1 m		0–2 m	
	a	b	a	b
Dormant	155.86	-0.145	155.58	-0.141
Intermediate	77.974	-0.147	80.632	-0.142
Full leaf	48.678	-0.150	52.567	-0.144

Table 4. *Parameters of the exponential functions for the airborne spray drift at heights 0–1 m and 0–2 m for an axial fan spraying in the dormant, intermediate and full leaf stage of the fruit trees*

	0–1 m		0–2 m	
	a	b	a	b
Dormant	143.49	-0.145	149.46	-0.140
Intermediate	123.68	-0.147	120.38	-0.143
Full leaf	74.87	-0.148	82.505	-0.143

These curves can be used to extrapolate the measured data at 7.5 m, shown in Figs 2 and 3 to different distances, as given in Table 5 for cross flow and axial fan sprayers.

At 5 m distance airborne spray drift for the cross-flow fan sprayer for the 0–2 m height air layer is 77% in the dormant, 40% in the intermediate and 25% in the full leaf situation. In the dormant situation airborne spray drift is about three times higher than in the full leaf season. At 5 m distance airborne spray drift for the axial fan sprayer for the 0–2 m height air layer is 74% in the dormant, 59% in the intermediate and 40% in the full leaf situation. Airborne spray drift is in the dormant situation around two times higher than in the full leaf season. For the axial fan sprayer calculated airborne spray drift deposition is in the dormant situation almost similar as for the cross-flow fan sprayer. For the intermediate and full-leaf situation airborne spray drift is for the axial fan sprayer around 1.5 times higher as for the cross-flow fan sprayer.

Table 5. *Estimated average airborne spray drift (% of sprayed volume) in the bottom 0–2 m layer at different distances from the last tree row spraying an orchard in the dormant, intermediate and full leaf situation with an cross-flow fan sprayer and an axial fan sprayer*

Average airborne spray drift lower 0–2 m							Distance from last tree row [m]				
Axial fan	5	10	15	20	25	30	35	40	45	50	60
Dormant	74.2	36.9	18.3	9.1	4.5	2.2	1.1	0.6	0.3	0.14	0.03
Intermediate	58.9	28.8	14.1	6.9	3.4	1.6	0.8	0.4	0.2	0.09	0.02
Full leaf	40.4	19.7	9.7	4.7	2.3	1.1	0.6	0.3	0.1	0.06	0.02
Cross-flow fan											
Dormant	76.9	38.0	18.8	9.3	4.6	2.3	1.1	0.6	0.3	0.13	0.03
Intermediate	39.6	19.5	9.6	4.7	2.3	1.1	0.6	0.3	0.14	0.07	0.02
Full leaf	25.6	12.5	6.1	3.0	1.4	0.7	0.3	0.17	0.08	0.04	0.01

Conclusions

An analysis of existing spray drift data in the UK and The Netherlands is being used to develop a new model of bystander and resident exposure to spray drift from orchard applications. This involves a number of steps, which include combining two separate datasets, selecting data relevant to bystander exposure that can be the basis for a reference exposure and developing a relationship between airborne spray and distance downwind.

The analysis has shown that, whereas spray drift deposition at edge of field distance (e.g. 5 m distance from last tree row) on soil surface ranges from 11% in the full leaf situation to 23% in the dormant situation of the fruit trees, it ranges from 25% to 77% in these stage for airborne spray drift. Airborne spray drift at the height relevant to bystanders is 2.5–3 times higher than spray drift deposition on soil surface. This is related to the air assistance on orchard sprayers which results in the spray blowing through the tree canopy. These figures make it clear that it is important to know more about airborne spray drift in the estimation of exposure of persons around sprayed orchards.

The presented database and reference curves are further processed and used as a basis for the BROWSE model for calculating the exposure risk of bystanders and residents, in a similar way to that for boom sprayer applications following the BREAM model (Kennedy *et al.*, 2010). Collector effects in measured airborne spray drift and the transfer function to bystanders is further analysed (Butler Ellis *et al.*, 2014). A further expansion of the database and spray drift analysis for both on soil deposition as airborne spray drift is emphasised to make spray drift data more robust. More specific measuring data are also needed to provide a better relationship between airborne spray drift and distance form the last tree row of the orchard.

Acknowledgement

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