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SID 5 Research Project Final Report

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Project identification

1. Defra Project code: PS2024
2. Project title: Options for the development of a model for evaluation of bystander and resident exposures to pesticides used in orchard, hop and bush fruit application
3. Contractor organisation(s): The Arable Group
   Silsoe Spray Applications Unit
4. Total Defra project costs (agreed fixed price): £ 44597
5. Project: start date 01/06/2010
   end date 31/03/2011

6. It is Defra's intention to publish this form.
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Executive Summary

7. The executive summary must not exceed 2 sides in total of A4 and should be understandable to the intelligent non-scientist. It should cover the main objectives, methods and findings of the research, together with any other significant events and options for new work.

The project investigated current practice in tree, hop and bush fruit spraying and management and review the current scientific knowledge of spray drift from broadcast air-assisted sprayers used for foliar spraying of these crops. The aim was to propose an appropriate modelling and experimental approach to the development of a new exposure assessment for bystanders and residents.

A survey was conducted, largely by telephone, of ten growers spread over the southern part of the UK where the majority of fruit plantations are. A series of questions, relating to the plantations, the pesticide application equipment, and the practice of the spray operator where asked and answers recorded. The findings were incorporated into excel spreadsheets so that some broad conclusions could be drawn. No statistical analysis was conducted because the sample is too small and not appropriately selected, being based primarily on growers already known to East Malling Research.

The total area that the survey covered was 379 ha, just over 1% of the total area of fruit and orchards in 2010. While the sample is clearly small, it is considered to be representative of the range of current UK growers and therefore provides useful information in evaluating applicability of the current risk assessment and determining appropriate scenarios for future model development

There were 20 sprayers reported, ten of which were axial fan machines, the majority of which were used in orchards. There were four ducted cross-flow machines, and one each of a number of other more specialist machines, including purpose-constructed and hand-held air-assisted. Axial fan sprayers are still likely to be the most common design of sprayer in use for fruit spraying.

Specific questions were asked about the factors that could influence bystander and resident exposure. It is estimated that around 30% of the area covered by the survey could be associated with some risk to people, either from footpaths crossing or around the plantation, adjacent roads and nearby residences or other public land, suggesting that it is an issue that most growers will have to consider.

The farms were not specifically selected for their proximity to residences or other factors that might influence the presence or otherwise of bystanders and residents. Therefore, if we assume that these farms are representative of those around the country growing fruit crops, there seems little doubt that there is potential for exposure of bystanders and residences from pesticides used in orchard and fruit plantations.

The situations where risks are likely to be highest are

(a) from use of footpaths crossing plantations
(b) from residential property adjacent to plantations.

The distance from a sprayer to a bystander on a footpath could be very short; however, the behaviour of the operator, if he sees the walker in good time, could ensure that spraying is stopped while the path is in use. This makes it difficult to estimate a minimum distance between sprayer and bystander, although it is likely to be something comparable to the row spacing or the headland width, and distances between 2 and 10 m would be appropriate

The review of modelling approaches was undertaken by Dr P J Walklate. The approaches that were reviewed ranged from the simplest form of model based on a fully explicit specification of the spray drift distribution to research models that represent an implicit specification of the spray drift distribution via the numerical solution of the equations of motion for spray droplets in the atmosphere. In addition, recent model developments aimed at efficient dosage of orchard spraying products could be further developed to include drift mitigation. In particular, it is envisaged that the PACE web page for dose adjustment could be adapted to give a risk estimate for bystander drift exposure based on user inputs.

While modelling approaches are increasingly seen as valuable tools in risk assessments and risk mitigation, there is a need to ensure that the data on which models are based are reliable and representative, and that there are sufficient data available for model validation. There is, therefore, a requirement for model developers to either obtain new data or to have access to existing data that is appropriate.

While the data relating to bystander exposure is very limited, and no new data has been added to that produced by Lloyd *et al*, some of the original dataset on which the existing bystander exposure assessment is based is probably still relevant to current application practice, although not sufficiently comprehensive to cover the necessary range of scenarios. The changes in application practice and nozzle design that have occurred in boom spraying do not seem to be as great with orchard spraying.

The location of the bystander relative to the orchard is one factor that might need revisiting. While 8 m downwind might be a reasonable distance to consider for orchards, it probably could not be considered worst case. The effect of orchard structure and season was not taken account of in the Lloyd et al dataset, and so this is also a factor that might need to be explored in future experimental work.

There is a wide range of airborne spray drift data referred to in the open literature. In all cases, however, the data was not obtained for the purposes of bystander exposure assessment, and some alternative analysis to that reported is likely to be needed to provide the information necessary to either extrapolate to bystander exposure or for validating a predictive spray drift model.

Whatever modelling approach is taken, there will be a requirement for some new data relating bystander exposure to airborne drift, whether the airborne drift is derived from empirical data or model predictions. This can be compared with the data obtained by Butler Ellis *et al* (2010) and if the relationship is not significantly different from boom sprayer data, the combined data set can be used to map airborne spray onto bystander contamination. If this is not the case, however, a larger data set will be required to adequately describe the relationship for orchard sprayers.

Project Report to Defra

8. As a guide this report should be no longer than 20 sides of A4. This report is to provide Defra with details of the outputs of the research project for internal purposes; to meet the terms of the contract; and to allow Defra to publish details of the outputs to meet Environmental Information Regulation or Freedom of Information obligations. This short report to Defra does not preclude contractors from also seeking to publish a full, formal scientific report/paper in an appropriate scientific or other journal/publication. Indeed, Defra actively encourages such publications as part of the contract terms. The report to Defra should include:

- the scientific objectives as set out in the contract;
- the extent to which the objectives set out in the contract have been met;
- details of methods used and the results obtained, including statistical analysis (if appropriate);
- a discussion of the results and their reliability;
- the main implications of the findings;
- possible future work; and
- any action resulting from the research (e.g. IP, Knowledge Transfer).

Project objectives

The project investigated current practice in tree, hop and bush fruit spraying and management, and to review the current scientific knowledge of spray drift from broadcast air-assisted sprayers used for foliar spraying of these crops. The aim was to propose an appropriate modelling and experimental approach to the development of a new exposure assessment for bystanders and residents.

Specific objectives are:

1. An informal survey of growers to establish relevant information about (a) their application machinery and the way it is used and (b) the layout of the orchards, hop gardens and bush fruit plantations;
2. Use of available mapping systems to determine bystander scenarios and resident proximity;
3. A review of modelling approaches for spray drift from broadcast air-assisted sprayers;
4. A review of orchard, hop and fruit plantation spray drift data and bystander contamination data that is available;
5. An analysis of the options for development of a bystander and resident exposure model for orchards, hop gardens and bush fruit plantations.

1. Informal survey of growers

A survey was conducted, largely by telephone, of ten growers spread over the southern part of the UK where the majority of fruit plantations are.

A series of questions, relating to the plantations, the pesticide application equipment, and the practice of the spray operator were asked and answers recorded. The forms are given in appendix 1. The findings were incorporated into excel spreadsheets so that some broad conclusions could be drawn. No statistical analysis was conducted because the sample is too small and not appropriately selected, being based primarily on growers already known to East Malling Research.

The approximate location of the ten farms covered by the survey is shown in Fig. 1. The majority were in the south east of England, with three in Gloucestershire/Herefordshire and one in East Anglia.

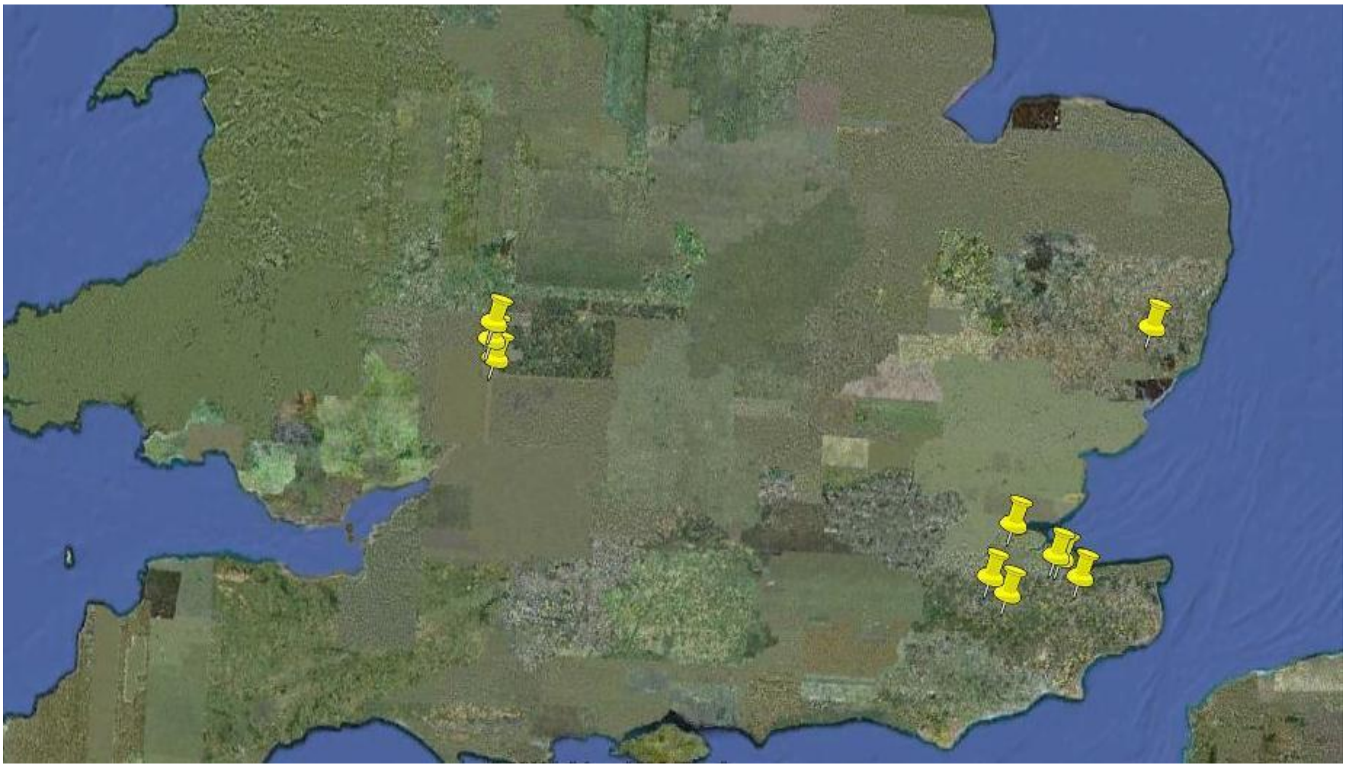

Figure 1. Location of the ten farms surveyed shown in Google Earth.

1.1 Survey Findings

1.1.1 Plantation details

Details of the crops covered in the survey are given in Tables 1 and 2.

Table 1. Tree plantations

Crop	Apple	Apple cider	Apple culinary	Pears	Plum	Cherry
No. plantations	30	2	14	24	10	5
No. beds	3	0	0	1	0	0
Area min (ha)	0.6	1.5	1.57	1	0.5	1.8
Area max (ha)	8	1.6	13.4	9.24	4.5	3.04
Area average (ha)	3.4	1.6	4.8	4.0	2.0	2.6
Total area (ha)	102.5	3.1	66.8	95.1	20.2	13.0
Age min (years)	1	12	9	3	1.5	2.5
Age max (years)	23	15	44	70	18	20
Age average (years)	9.1	13.5	23.0	31.0	10.0	8.7

Table 2. Other fruit plantations

Crop	Hops	Raspberry	Blackberry	Blackcurrant	Blueberry
No. plantations	6	9	2	10	1
No. beds	0	0	0	0	0
Area min (ha)	1.22	1.4	0.3	1.4	3
Area max (ha)	3.5	6	2	5.6	3
Area average (ha)	2.3	3.2	1.2	3.1	3.0
Total area (ha)	13.7	28.6	2.3	30.7	3.0
Age min (years)	3	1	4	3	1
Age max (years)	15	3	4	12	1
Age average (years)	7.7	2.3	4.0	7.8	1.0

The total area that the survey covered was 379 ha, just over 1% of the total area of fruit and orchards in 2010 (approximately 30,000 ha (1)). While the sample is clearly small, it is considered to be representative of the range of current UK growers and therefore provides useful information in evaluating applicability of the current risk assessment and determining appropriate scenarios for future model development

Further details about the plantations (including row spacing, plant spacing and crop height) are contained in Appendix 2 where collated details of the findings can be found.

1.1.2 Spraying equipment

There were 20 sprayers reported, ten of which were axial fan machines, the majority of which were used in orchards. There were four ducted cross-flow machines, and one each of a number of other more specialist machines, including purpose-constructed and hand-held air-assisted. Axial fan sprayers are still likely to be the most common design of sprayer in use for fruit spraying.

The mean age of the sprayers was 7.5 years, with a range between 1 and 26 years. There were five sprayers aged 2 years or less, indicating that there is a modest amount of investment in new machinery. All of these newer sprayers were axial fan machines, suggesting that there is no obvious trend to move away from this technique for fruit spraying.

There was a wide range of volumes used in spray applications, between 100 and 1000 l/ha, with forward speeds between 3 and 8.5 km/h.

The most common nozzle design was the hollow cone, with Albuz the most common nozzle manufacturer. The nozzle size (output) was also very variable, with the highest volumes generated by using an “05” size, and the smallest an “01” size.

Pressures were relatively high – from 3 to 12 bar for hollow cone nozzles but lower for flat fan nozzles. Spray qualities were indicated as being from very fine to medium.

The height of the spray plume was estimated to be between 2.5 and 5 m. Most growers aim to match plume height to crop height, although there are some that do not. Similarly the dose is matched to crop height in many cases, since growers use a constant concentration and switching off nozzles reduces dose.

1.1.3 Risk factors

Specific questions were asked about the factors that could influence bystander and resident exposure. It is estimated that around 30% of the area covered by the survey could be associated with some risk to people, either from footpaths crossing or around the plantation, adjacent roads and nearby residences or other public land, suggesting that it is an issue that most growers will have to consider.

Screening of adjacent properties or roads is relatively common, but less so for footpaths.

A scoring system was devised to assess how busy paths and roads were, shown in Table 3. The median score each for paths, roads and residential properties was 5 (frequent – a few people per day), indicating that there is a reasonable probability of people being nearby when spraying occurs, and that growers are aware of this.

The residential properties identified by growers as adjacent to their plantations were generally one or two houses. A caravan site and a gypsy caravan were noted, which might be more than averagely vulnerable because residents might spend more time than average outdoors.

The distances between the location of the bystanders or residents and the edge of the orchard were not possible to establish without detailed studies of location maps. However, it is likely that footpaths around the field will be separated from the sprayer by a row of trees or by the headland. Row widths varied from 1.5 m to 7.3 m. Headlands varied from 0 to 20 m, with a mean of around 5 m. Distances that should be considered in an exposure assessment for bystanders should probably, therefore, be similar to those considered for boom sprayers, i.e. two to ten metres.

Residential property is likely to be at a greater distance than this, but resident exposure over the long term is primarily due to vapour inhalation and the BREAM project showed that airborne vapour concentrations were relatively insensitive to distances compared with airborne spray, and therefore an approximate distance of 10 m is likely to be sufficient.

1.2 Summary of survey conclusions

While the sample size was very small, and there was no sample selection methodology employed, the farms were not specifically selected for their proximity to residences or other factors that might influence the presence or otherwise of bystanders and residence. Therefore, if we assume that these farms are representative of those around the country growing fruit crops, there seems little doubt that there is potential for exposure of bystanders and residences from pesticides used in orchard and fruit plantations.

The situations where risks are likely to be highest are

(a) from use of footpaths crossing plantations
(b) from residential property adjacent to plantations.

The distance from a sprayer to a bystander on a footpath could be very short; however, the behaviour of the operator, if he sees the walker in good time, could ensure that spraying is stopped while the path is in use. This makes it difficult to estimate a minimum distance between sprayer and bystander, although it is likely to be something comparable to the row spacing or the headland width, and distances between 2 and 10 m would be appropriate

3. Review of modelling approaches for spray drift from broadcast air-assisted sprayers

The review of modelling approaches was undertaken by Dr P J Walklate and is reproduced in full in Appendix 3, and summarised here.

Various drift models have been developed during the last twenty years for orchard spraying. These models have been concerned with the exposure of different objects on/above the ground. The review is limited to spray drift of pesticide during orchard spraying so that the drift of the volatile component of pesticide after spray application is not considered.

The approaches that are reviewed range from the simplest form of model based on a fully explicit specification of the spray drift distribution, such as Ganzelmeier et al., (1995) to research models that represent an implicit specification of the spray drift distribution via the numerical solution of the equations of motion for spray droplets in the atmosphere such as Walklate (1992).

A number of models are based on computational fluid dynamics packages. This approach was considered during the BREAM project, but rejected for three main reasons:

- The expertise needed to run such models is significant – they are more useful as research tools than as regulatory models which need to be used by a wide range of people who are unlikely to be modelling experts
- The time taken to run such models can be extremely long (many hours, rather than a few minutes for the droplet tracking approach). This is a significant limitation for regulatory use.
- They do not lend themselves to probabilistic modelling – repeated runs with a distribution of inputs is out of the question.

There are, however, some advantages which may be particularly useful when developing an orchard spray drift model. The ability to model accurately the 'source' term – i.e. the spray and the airflows that are emitted from the sprayer – limits the accuracy of the predicted drift, yet is a crucial factor. The Silsoe spray drift model that underpins the BREAM model is still being developed to include a reliable parameterisation of sprays that can take account of different nozzle sizes and designs. In principle, the use of CFD could be valuable in describing the source, although the degree to which this is reliable will depend on the software package chosen.

The approach taken by Walklate (1992) was to use experimental data close to the sprayer to define the source and use random-walk modelling to extrapolate downwind.

Existing models predict only airborne spray. It is possible to adapt their output by using a correction to account for typical drift deposit on a bystander (or resident) similar to that undertaken in the BREAM project. A small number of drift trials would confirm the output from the model with extreme orchard structures for "low density" and "standard density" orchards using drift collectors of similar dimensions to human targets.

Measurements of drift from orchard spraying already exist for UK growing practices (Walklate, 2000a) based on standardised passive drift collecting lines. The studies made by SRI and EMR between 1997 and 2000 also include suitable canopy structure measurements, albeit, at 5m from the sprayer. However, this data could be used with the orchard sprayer drift model (Walklate, 1992) to generate the drift distribution beyond 5m.
Recent model developments aimed at efficient dosage of orchard spraying products (Walklate et al., 2011) could be further developed to include drift mitigation. In particular, it is envisaged that the PACE web page for dose adjustment could be adapted to give a risk estimate for bystander drift exposure based on user inputs.

4. A review of orchard, hop and fruit plantation spray drift data and bystander contamination data that is available

4.1 Introduction

While modelling approaches are increasingly seen as valuable tools in risk assessments and risk mitigation, there is a need to ensure that the data on which models are based are reliable and representative, and that there are sufficient data available for model validation. There is, therefore, a requirement for model developers to either obtain new data or to have access to existing data that is appropriate.

Human exposure to pesticide spray drift arises from direct inhalation of spray, direct dermal contamination of spray, both of which occur during the application when the spray is airborne, and indirectly from surfaces contaminated by sedimenting spray drift, contact with which can occur at any time following the application. The highest exposures are likely to occur during the application, and airborne spray is therefore an important parameter to determine.

Drift of sprays from agricultural and horticultural treatments has been studied for many years, and it would be expected that in the literature there would be a wealth of data available for development and validations of models. However, because of the cost of such trials, the majority have been focused on specific aspects of drift, meaning that not all the necessary information is available to extrapolate data to provide estimates of human exposure.

In particular, recent efforts have focused on improving deposits on tree foliage, or reducing losses to water, or possibly both, which has resulted in published data emphasising differences between application technique or formulation, rather than absolute measurements of airborne concentration or deposits. There are many factors which will influence spray drift and therefore a very large dataset is needed to ensure that the range of possible scenarios is covered. As well as all the machine variables, such as air flow characteristics, nozzle design, and operating parameters, there are variables relating to the orchard structure itself (tree height/volume and spacing), the meteorology and the wider landscape (windbreaks and screening). There are also bystander or resident behaviour factors – such as the location of the person relative to the orchard – that are significantly more complicated than with arable boom spraying.

The BREAM model uses a prediction of airborne spray combined with a relationship describing a human collection efficiency (albeit with large uncertainties) to determine bystander dermal exposure. A similar relationship would be expected for orchard spraying, although the relationship would not necessarily be the same. There were difficulties in the BREAM project in reconciling different datasets, and it was hypothesised that crop height might be an important factor. Clearly, the crop height is a major difference between orchard and arable applications, in addition to the important differences in the application technique.

4.2 Bystander exposure data

The original data obtained by Lloyd *et al* (1987) remains the largest set of measurements relating to bystander exposure from orchard applications. This covered three different nozzle designs and a range of meteorological conditions, but only one orchard structure at one time during the season. Screening or windbreaks were not included, and the number of bystander positions was limited. As with the similar work carried out for boom sprayers, the airborne spray over the height of the bystander could not be determined from the data so that it would not be possible to establish the 'human collection efficiency' for orchard or fruit spraying.

Bozdogan *et al* (2008) made measurements of bystander exposure from application to strawberry plantations: while they did not use a standard boom sprayer, the equipment had more in common with boom spraying than with airblast spraying and therefore results are not applicable to the types of machinery and crops relevant to those encountered in our survey.

Vercruysse and Steurbaut (2001) made measurements of operator exposure, but only made estimates of possible bystander exposure from orchard spraying, but this was based on ground deposits of spray as determined by Ganzelmeier *et al* (1995), and assuming 100% collection efficiency. While the use of ground deposits is likely to underestimate the airborne fluxes by an order of magnitude, the collection efficiency is likely to be too high by at least an order of magnitude and a brief analysis suggests that their estimate of bystander exposure was considerably higher (by a factor of around four) than that measured by Lloyd *et al*. This demonstrates the danger of extrapolating measurements of ground deposits to inappropriate situations.

Measurements of airborne spray near to an apple orchard in the USA were made using high volume air samplers (Marshall Clark *et al*, 1991), both during and after the application and the data used to estimate dermal and inhalation exposures for bystanders. The height of the samplers was not given, and no meteorological data was included. A technique for calculating human exposure (Draper *et al*, 1981) from the measured data combined with some other assumptions was used to estimate exposure to three different active ingredients at a distance of 150 ft from the treated area. Although it is difficult to compare with other data, it seems likely that the lack of an appropriate 'collector efficiency' factor included in the calculation again leads to an over-estimate of dermal exposure.

4.3 Spray drift data

There are some major datasets that have been obtained which, theoretically at least, could be used to develop an improved bystander exposure model. However, the range of distances involved was not always appropriate to our likely requirements (particularly for data from the USA) and frequently only ground deposits are given, which would require significant extrapolation (and some assumptions) to be able to estimate airborne fluxes.

4.3.1 Measurements of airborne spray

The Washington orchard spray drift study (Tsai, 2007) made measurements of airborne spray for four applications over two days in a single orchard. Airborne spray was sampled with medium volume air samplers at distances of 9 – 40 m and high volume samplers at 18.4 and 61 m from the first tree row. The height of the samplers was not given. The applications were made with an axial fan airblast sprayer with a range of nozzle sizes, but operated at a relatively low pressure compared with that used by the growers in our survey. The data might therefore have some relevance to the scenarios we are likely to need to model, although might not represent a worst case.

Derksen *et al* (2007) made measurements of airborne spray at 8 m at a range of heights above the ground, using non-standard collectors (mesh screens). High volume air samplers were positioned at two heights (1 and 3 m) and five distances (8 to 128 m). Applications were made with an axial fan sprayer, with a range of nozzles, in a single orchard. Zhu *et al* (2006) made similar measurements in a nursery orchard over a growing season, at distances of 15 to 90 m, also with the mesh screens. While the results are presented as $\mu l/cm^2$, which would be valuable for model development, the collection efficiency of the screen is not described and there would be concerns that it would not be comparable with other more commonly-used sampling devices such as 2 mm lines.

A number of other papers by the same authors suggest that there might be available a reasonable dataset that could be used to provide information about factors influencing airborne spray concentrations and assist with model development and validation.

An alternative approach to collecting spray moving off-target was used by Balsari *et al* (2005). Measurements of airborne spray appeared to have been made relatively close to the orchard, but the data does not seem to have been published.

Cross, Walklate and colleagues published a number of papers that refer to an extensive set of data, which includes airborne spray at 5 m downwind. (e.g. Cross *et al*, 2001a, b, 2003) The data published is analysed in such a way that it is not possible to determine absolute airborne concentrations or fluxes without reverting to the original data. Walklate (1992) refers to other unpublished data and Richardson et al (2004) has some data relating to the effect of windbreaks on drift. The work undertaken by this team also included characterising the orchard structure using Lidar techniques, and it is possible that this could be used in a potential exposure model to incorporate the effect of orchard structure on exposure (see Appendix 3).

The US Spray drift task force has an experimental dataset (2) on which its orchard drift model is based. While this was aimed at predicting ground deposits, measurements of airborne spray were made for apple, almond, pecan and vine plantations. However, limited information is available in the public domain, because of proprietorial interests, but it is possible that this could be made available. Published data relates only to relative drift, not absolute measurements, and no information is given about meteorology or equipment.

Van de Zande (personal communication) has also an extensive dataset. This is currently being reviewed for the BROWSE project (3) and is not yet available. Examples of published work include Wenneker et al (2008), although this focussed solely on ground deposits, and more recently a methodology for extrapolating airborne drift measurements to estimate bystander exposure was outlined (van de Zande, 2010). Much of the data relates to cross-flow sprayers, less common in the UK than the Netherlands, but does also include some data obtained with axial fan sprayers.

4.3.2 Measurements of ground deposits

Ganzelmeier *et al* (1995) produced a comprehensive drift dataset relating to orchards, fruit and hops, and ground deposit data has been catalogued and widely used in a range of regulatory models. Airborne spray was also measured, but not, however, published.

In South Africa, Schulz *et al* (2001) made ground deposit measurements up to 15 m downwind for high volume applications to very large trees, and found deposits consistent with those measured by Ganzelmeier *et al* (1995).

Capri *et al* (2005) considered ground deposits on a landscape scale for the assessment of the potential contamination of surface water from vineyard applications in four trials. The distances downwind were not clear, and the application was made with chlorpyrifos, rather than an inert tracer. Work in the BREAM project showed that active ingredients can behave differently from tracers, particularly when there is significant volatility as is the case with chlorpyrifos. While this is important not to ignore in exposure assessments, and there are clearly additional mechanisms that reduce the quantity of deposited drift, these will be dependent on the chemical properties of the active ingredient and cannot be extrapolated to other active ingredients. The BREAM project concluded that a tier 1 exposure assessment should be based on data obtained with inert tracers, as this will be a worst case. Current models of spray drift do not take into account any influence of chemical properties (apart from potentially the indirect effect on droplet size) and are therefore unlikely to be as successful at predicting absolute levels of drift with plant protection products as they are with specifically-chosen tracer chemicals. Meli *et al* (2003) concluded that their own measurements made with chlorpyrifos-methyl were significantly lower than the Ganzelmeier *et al* (1995) data.

There are a number of other publications that, while not providing the detailed data likely to be needed for developing or validating an orchard drift model, show the relative effect on drift of different developments in application technology. Examples include Koch and Weisser (2000) who tested sensors and control systems that detect and switch the spray on and off as an individual tree is passed, Godyn *et al* (2008) who investigated different fan arrangements on a sprayer, Doruchowski and Holownicki (2000) also looked at on-off sensors as well as shields for capturing spray that would otherwise be lost. While many of these developments could have a significant effect on bystander exposure, there is no evidence of such techniques being taken up by UK growers as yet.

4.4 Conclusions from the review of drift data

While the data relating to bystander exposure is very limited, and no new data has been added to that produced by Lloyd et al, some of the original dataset on which the existing bystander exposure assessment is based is probably still relevant to current application practice, although not sufficiently comprehensive to cover the necessary range of scenarios. The changes in application practice and nozzle design that have occurred in boom spraying do not seem to be as great with orchard spraying.

The location of the bystander relative to the orchard is one factor that might need revisiting. While 8 m downwind, measured from the last tree row, might be a reasonable distance to consider for orchards, it probably could not be considered worst case, although the bystander might in fact be considerably closer to the sprayer when it was operating outside the last tree row. The effect of orchard structure and season was not taken account of in the Lloyd et al dataset, and so this is also a factor that might need to be explored in future experimental work.

There is a wide range of airborne spray drift data referred to in the open literature, particularly that obtained by van de Zande and colleagues in the Netherlands, Walklate, Cross and colleagues in the UK and Derksen, Zhu and colleagues in the USA. In all cases, however, the data was not obtained for the purposes of bystander exposure assessment, and some alternative analysis to that reported is likely to be needed to provide the information necessary to either extrapolate to bystander exposure in the manner of van de Zande (2010) or for validating a predictive spray drift model. In the situations where the work was undertaken some years ago, the ability to retrieve the original data for re-analysis might be limited.

It is rare that airborne measurements are made without also measuring ground deposits, and therefore the additional data relating only to ground deposits is unlikely to be useful except for scenarios where there is no relevant airborne data.

5. An analysis of the options for development of a bystander and resident exposure model for orchards, hop gardens and bush fruit plantations.

There are a number of options available for the development of an improved model of bystander exposure to pesticide drift from orchard and fruit applications, from use of experimental data sets to sophisticated CFD models. The most appropriate route to take, however, depends on a number of considerations, not all of which relate to scientific questions, including:

- The resources (budget and timescale) for model development;
- The type and range of scenarios that need to be included, such as
  - Bystander location and behaviour;
  - Crop type and structure;
  - Machinery used and operating conditions;
- The ease of use for the risk assessor and degree of flexibility needed;
- The degree of precaution/conservatism required.

The BROWSE project (3) is currently grappling with some of these questions for bystander exposure from a wide range of applications, including orchards, and it will be instructive to incorporate the findings into any proposals for future developments. Because there are insufficient resources available for development of a mechanistic model, the BROWSE project is likely to use empirical data as the basis of its bystander exposure model using the methodology proposed by van de Zande (2010) but incorporating a bystander collection efficacy relationship in the same way as Butler Ellis *et al* (2010). The limitation to this approach relates to the availability of relevant data and is likely to result in restrictions on the scenarios that can be included. For this reason, orchard spraying is likely to be the main scenario to be addressed, with perhaps some extrapolation to vines and hops. The lack of data relating to other fruit crops will have to be addressed by some further extrapolation, which will necessarily involve greater uncertainties.

The data available to the BROWSE project is likely to be weighted towards cross-flow sprayers because of the input from the Netherlands. While there are a number of cross-flow sprayers used in the UK, the most common machinery type is still the axial fan sprayer and therefore data relating to this type of sprayer will also be required. The majority of the studies identified in section 4.3 related to axial fan sprayers, but the most comprehensive and relevant dataset is that produced in the UK by Walklate, Cross and co-workers. It would be advantageous to ensure that this data could be made available to both the BROWSE project and for future developments in the UK.

It is likely that the exposure models developed in BROWSE will adopt a modular approach so that should a more sophisticated model of orchard drift be developed, it could be slotted into the BROWSE model, either directly or potentially through the use of an emulator. However, BROWSE recognises the need for a harmonised approach for exposure assessment across the EU and so any change to the BROWSE model will need to be agreed at EU level.

Whatever modelling approach is needed, there will be a requirement for some new data relating bystander exposure to airborne drift, whether the airborne drift is derived from empirical data or model predictions. This can be compared with the data obtained by Butler Ellis *et al* (2010) and if the relationship is not significantly different from boom sprayer data, the combined data set can be used to map airborne spray onto bystander contamination. If this is not the case, however, a larger data set will be required to adequately describe the relationship for orchard sprayers.

References to published material

9. This section should be used to record links (hypertext links where possible) or references to other published material generated by, or relating to this project.

(1)
http://archive.defra.gov.uk/evidence/statistics/foodfarm/landuselivestock/junesurvey/documents/England-timeseries.xls

(2)
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Appendix 1

Survey of fruit spraying by EMR October 2010 – Jan 2011

Farm form: One to be completed for each farm

Farm and contact details	
Business name	
Address	
Contact person	
Office phone	
Mobile phone	
Email address	

General crop and sprayer details				
Crop	Area grown (ha)	Broadcast sprayers		No. of sprayers
		Type	Make/model	

General farm policy for avoiding bystander spray contamination	
Perceived worst bystander risks	
Farm workers	
Residents	
Public	
Avoidance of growing?	
Buffer zones?	
Windbreaks?	
Notification?	
Time of spraying?	
Weather conditions?	
Produce assurance scheme?	
Scheme requirements re bystanders?	

Survey of fruit spraying by EMR October 2010 – Jan 2011

General crop form: One table below to be completed for each crop spcies on each farm

Farm and contact details	
Business name	
Contact person	

Crop no. 1	
Crop	
No. of plantations	
Protected or open field?	
Typical no. foliar spray rounds	
Time of season (start – end)	
No. of plantations with public road or footpath through or round	
No. of plantations next to private property	

Survey of fruit spraying by EMR October 2010 – Jan 2011

Individual crop form: One table below to be completed for each individual crop on each farm where there is a significant additional risk of bystander exposure

Farm and contact details	
Business name	
Contact person	

Risk crop 1	
Field name	
Crop	
Variety	
Location (NGR)	
Area (ha)	
Age (years)	
Width of headland (m)	
Row spacing (m)	
Plant spacing in row (m)	
Canopy row height (m)	
Footpath present?	
Length through field (m)	
Length round field (m)	
Frequency of use (persons/season)	
Notes	
Road or bridleway present?	
Length through field (m)	
Length round field (m)	
Frequency of use (persons/season)	
Notes	
Adjacent residential property?	
Type (house, garden, car park, business etc)	
Length of boundary (m)	
Frequency occupied by bystanders	
Notes	
Other bystander risks ?	

Survey of fruit spraying by EMR October 2010 – Jan 2011

Sprayer form: One table below to be completed for each sprayer

Farm and contact details	
Business name	
Contact person	

Sprayer no. 1	
Type	
Make/model	
Any modifications	
Age (years)	
RDS?	
Crops sprayed	
Typical operating conditions	
Volume (l/ha)	
Nozzle	
Pressure	
Spray quality	
No. of nozzles	
Spray plume height (m)	
Speed (kmph)	
Sprayer adjustment to crop?	
Dose rate?	
Volume rate?	
Spray plume height?	
Fan speed?	
Forward speed?	
PACE used?	
Other dose adjust method?	

Appendix 2

Crop	Apple	Apple cider	Apple culinary	Blackberry	Blackcurrant	Blueberry	Cherry	Hops	Pears	Plum	Raspberry
No. plantations	30	2	14	2	10	1	5	6	24	10	9
No. beds	3	0	0	0	0	0	0	0	1	0	0
Area min (ha)	0.6	1.5	1.57	0.3	1.4	3	1.8	1.22	1	0.5	1.4
Area max (ha)	8	1.6	13.4	2	5.6	3	3.04	3.5	9.24	4.5	6
Area average (ha)	3.4	1.6	4.8	1.2	3.1	3.0	2.6	2.3	4.0	2.0	3.2
Total area (ha)	102.5	3.1	66.8	2.3	30.7	3.0	13.0	13.7	95.1	20.2	28.6
Age min (years)	1	12	9	4	3	1	2.5	3	3	1.5	1
Age max (years)	23	15	44	4	12	1	20	15	70	18	3
Age average (years)	9.1	13.5	23.0	4.0	7.8	1.0	8.7	7.7	31.0	10.0	2.3
Width of head land min (m)	3.0	8.0	3.0	5.0	2.0	0.0	4.0	0.0	2.0	3.5	5.0
Width of head land max (m)	15.0	8.0	9.0	20.0	9.0	0.0	10.0	8.0	6.0	8.0	7.0
Width of head land Average (m)	5.0	8.0	4.1	9.0	6.4	0.0	4.9	4.2	4.1	6.2	5.8
Row spacing min (m)	3.3	5.4	3.0	2.0	3.2	2.2	3.8	1.5	2.8	3.5	2.2
Row spacing max (m)	4.3	5.5	7.3	2.0	3.6	2.2	5.4	2.8	6.6	6.0	2.8
Row spacing Average (m)	3.8	5.5	5.5	2.0	3.4	2.2	4.7	2.4	4.3	4.5	2.4
distance between beds centers(m)	7.1		4.7						10.5		
width of bed (m)	3.7		1.8						4.5		
Plant spacing min (m)	0.8	2.3	1.5	0.5	0.2	0.5	2.0	0.5	1.0	1.3	0.3
Plant spacing max (m)	2.1	2.7	7.3	0.5	30.0	0.5	5.4	1.2	5.5	4.8	0.7
Plant spacing average (m)	1.5	2.5	3.5	0.5	6.3	0.5	3.5	1.0	3.2	2.2	0.5
Canopy row height min (m)	1.5	5.0	0.2	1.8	0.5	1.2	1.8	2.4	1.5	2.2	2.0
Canopy row height max (m)	3.0	6.0	2.5	1.8	2.0	1.2	5.0	5.4	3.5	3.5	2.5

Crop	Apple	Apple cider	Apple culinary	Blackberry	Blackcurrant	Blueberry	Cherry	Hops	Pears	Plum	Raspberry
Canopy row height average (m)	2.3	5.5	2.0	1.8	1.2	1.2	3.2	4.6	2.5	2.8	2.3
Paths											
% risk by area surveyed	56.4	0.0	29.6	0.0	9.4	0.0	0.0	1.9	46.3	1.0	6.8
area of risk	57.8	0.0	19.7	0.0	2.9	0.0	0.0	0.3	44.1	0.2	1.9
Area of crop with paths	55.0	0.0	44.3	0.3	30.7	0.0	0.0	13.7	48.7	5.0	23.8
Total no. plantations with paths	16	0	8	1	10	0	0	6	12	3	7
No. with paths through	7	0	1	0	0	0	0	1	2	3	0
No. with paths around	10	0	7	1	10	0	0	5	11	3	7
Total length of paths through (m)	1552	0	337	0	0	0	0	100	552	630	0
Total length of paths around (m)	2872	0	2757	120	1353	0	0	1105	2365	600	1290
Mean length of paths through (m)	222	0	337	0	0	0	0	100	276	210	0
Mean length of paths around (m)	287	0	394	120	135	0	0	221	215	200	184
No paths screened	4	0	5	0	4	0	0	1	2	0	3
% paths screened	25.0	0.0	62.5	0.0	40.0	0.0	0.0	16.7	16.7	0.0	42.9
Mean hieght of screen (m)	3.8	0.0	4.1	0.0	10.4	0.0	0.0	9.0	4.3	0.0	9.8
Min height of screen (m)	3	0	0	0	0	0	0	0	0	0	2
Max height of screen (m)	5	0	5	0	30	0	0	9	5	0	40
Roads/bridleways											
% risk by area surveyed	66.3	0.1	19.7	0.0	1.1	0.1	1.3	0.6	70.2	3.1	3.2
Area of crop with roads/bridleways (ha)	64.7	3.1	29.5	0.0	3.7	3.0	10.0	4.3	73.9	15.1	11.2

Crop	Apple	Apple cider	Apple culinary	Blackberry	Blackcurrant	Blueberry	Cherry	Hops	Pears	Plum	Raspberry
No. with roads	19	2	7	0	2	1	4	2	20	16	3
No. with roads through	0	0	1	0	0	0	0	0	0	0	0
No. with roads around	19	2	7	0	2	1	4	2	19	10	3
Total length of roads through (m)	0	0	180	0	0	0	0	0	0	0	0
Total length of roads around (m)	5096	145	2227	0	330	10	596	240	4601	2733	540
Mean length of roads through (m)	0	0	180	0	0	0	0	0	0	0	0
Mean length of roads around (m)	268.2	72.5	318.1	0.0	165.0	10.0	149.0	120.0	242.2	273.3	180.0
No. roads screened	15	1	6	0	2	0	2	2	18	7	3
% roads screened	78.9	50.0	85.7	0.0	100.0	0.0	50.0	100.0	90.0	43.8	100.0
Mean hieght of screen (m)	4.2	5.3	2.8	0.0	12.3	0.0	9.0	4.8	5.0	7.7	5.0
Min height of screen (m)	0.5	0	0	0	0	0	0	0	0	0	4
Max height of screen (m)	20	4.5	4	0	20	0	10	5	20	30	6
Property											
% risk by area surveyed	51.3	0.1	11.3	0.0	0.7	0.1	1.4	0.6	61.5	1.7	4.0
Area at risk	50.1	3.1	16.9	0.3	2.3	3.0	10.4	4.3	64.7	8.4	14.1
No. of fields with properties	16	2	4	1	1	1	4	2	14	4	6
No. of properties	55	2	112	1	1	1	17	9	40	5	15
Total length of boundaries (m)	1321	30	425	40	60	50	640	83	1051	296	780
Mean length of boundaries (m)	24.0	15.0	3.8	40.0	60.0	50.0	37.6	9.2	26.3	59.2	52.0
Min length of boundry (m)	28	10	0	0	0	50	0	0	0	0	20
Max length of boundry (m)	252	20	350	40	60	50	250	63	210	200	400

Crop	Apple	Apple cider	Apple culinary	Blackberry	Blackcurrant	Blueberry	Cherry	Hops	Pears	Plum	Raspberry
No. of fields adjacent to residential	49	2	4	1	1	0	4	2	9	4	6
No. of fields adjacent to pickers	2	0	0	0	0	0	0	0	1	0	0
No. of fields adjacent to buisness	1	0	0	0	0	0	0	0	1	0	0
No. of fields adjacent to farm buildings	0	0	0	0	0	0	0	0	3	0	0
No. of fields adjacent to other	0	0	0	0	0	1	0	0	0	0	0
No. of fields adjacent to no properties	14	0	10	1	9	0	1	4	10	6	0
% properties screened	68.8	0.0	25.0	0.0	100.0	0.0	0.0	0.0	42.9	50.0	33.3
screened	11	0	1	0	1	0	0	0	6	2	2
Mean screen height (m)	3.2	2.0	5.3	2.5	3.0	3.5	0.8	1.4	8.7	12.1	24.8
Min screen height (m)	1.5	0	0	0	0	3.5	0	0	0	0	1
Max screen height (m)	3	1.5	2	1	3	3.5	8	8	15	5	10

Appendix 3
Orchard Bystander and Resident Exposure Assessment Model

By P J Walklate

Objective

To review pesticide spray drift models that could be adapted or make a significant contribution to bystander and resident exposure assessments for orchard spraying in the UK.

Summary

Various drift models have been developed during the last twenty years for orchard spraying. These models have been concerned with the exposure of different objects on/above the ground. The review is limited to spray drift of pesticide during orchard spraying so that the drift of the volatile component of pesticide after spray application is not considered.

The approaches that are reviewed here range from the simplest form of model based on a fully explicit specification of the spray drift distribution (ex. Gamzelmeier et al., 1995) or similar with specialised user interface software (ex AgDRIFT®; Golla et al.,2002; Praat & Woodward 2008; Bozon et al., 2008) to research models that represent an implicit specification of the spray drift distribution via the numerical solution of the equations of motion for spray droplets in the atmosphere (Walklate, 1992; Xu et al., 1997; Xu et al., 1998; DaSilva et al., 2006; Delele et al., 2005; Delele et al., 2007; Endalew et al., 2010a; Endalew et al., 2010b; Endalew et al., 2010c; Endalew et al., 2010d; Chahine et al., 2010) .

It is possible to adapt the output of all these models by using a correction to account for typical drift deposit on a bystander (or resident) which may be different from the drift deposit on typical standard collectors that have been used for model validation purposes (i.e. horizontal paper sheets or Petri dishes, vertical mounted plastic lines or string). Some further research will be needed to develop a bystander and resident exposure assessment model (BREAM) for orchard spraying; in particular, for drift exposure at distances less than 30 m from the sprayer where the correction for different standard drift collectors is expected to vary with distance.

A small number of drift trials would confirm the output from BREAM with extreme orchard structures for “low density” and “standard density” orchards using drift collectors of similar dimensions to human targets.

Measurements of drift from orchard spraying already exist for UK growing practices (Walklate, 2000a) based on standardise drift collector line. The measurements made by CSL (now FERA) which expand on earlier orchard drift measurements (Lloyd et al., 1989) have limited use because no assessment of canopy structure exists to support this data for developing BREAM. The studies made by SRI and EMR between 1997 and 2000 do include suitable canopy structure measurements, albeit, at 5m from the sprayer. However, this data could be used with the orchard sprayer drift model (Walklate, 1992) to generate the drift distribution beyond 5m.

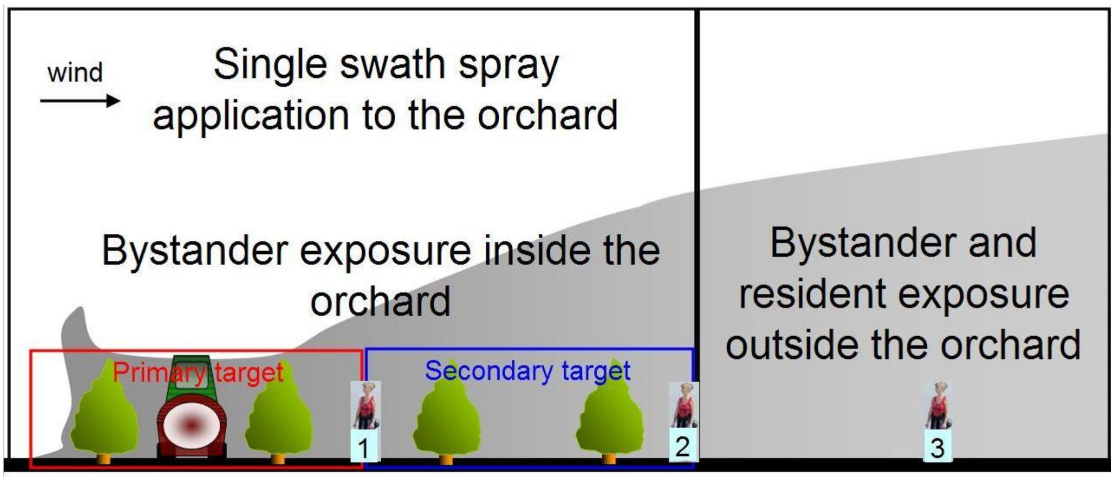
Recent model developments aimed at efficient dosage of orchard spraying products (Walklate et al., 2011) could be further developed to include drift mitigation. In particular, it is envisaged that the PACE web page for dose adjustment could be adapted to give a risk estimate for bystander drift exposure based on user inputs.

1. Introduction

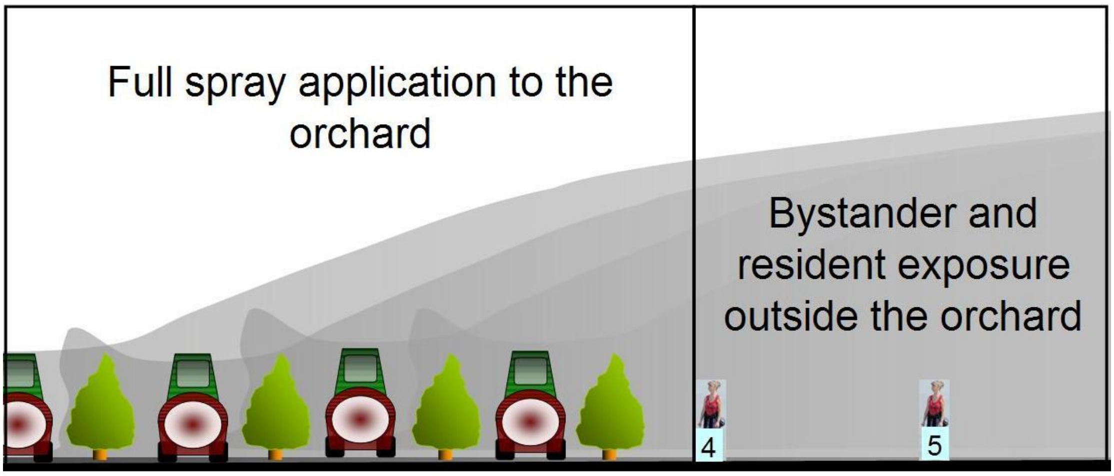
1.1 The problem

The majority of pesticide applications to commercial bush and tree fruit orchards in the UK (excluding a relatively small number of herbicide applications) are made using broadcast air-assisted sprayers. This type of sprayer uses an air compressor (ex. axial fans, squirrel cage blowers, etc) to produce air jets that control the direction and distance of spray droplet transport between the point of spray generation (i.e. close to the exit from the nozzles on the side of the sprayer and normally below the top of the canopy) and the primary target (i.e. tree-rows closest to the sprayer shown in Fig. 1a).

As a consequence of orchard spraying with a wide range of practical conditions, a variable proportion of the sprayer output is transported beyond the primary target where it represents a drift contamination risks to bystanders everywhere in space and residents outside the orchard (Matthews et al., 2003).



a. Single swath spray application



b. Multiple swath spray application and aggregation of the drift plume

Fig.1. Spray drift plumes from single (a.) and multiple (b.) swath application of pesticide. Each figure represents the range of positions for estimating exposure scenarios for bystanders inside the orchard, residents and bystanders outside the orchard.

1.2 Primary target for spray application

The normal spray application is made by treating the tree-rows on either side of the sprayer. The nearest tree-rows represent the “primary target” for which the sprayer controls are adjusted to deliver the target dose (Fig 1a). Each tree-row is usually sprayed from the avenues on both sides (Fig.1b). However, there are some spray application conditions that give rise to significant deposit on the “secondary target” (i.e. the blue boundary shown in Fig 1a).

1.3 Spray drift

For the purpose of this review the fraction of airborne spray that is transported beyond the primary target is regarded as spray drift because it has the potential to contaminate bystanders everywhere in space. The definition of spray drift, previously used to describe the potential exposure of objects beyond the orchard boundary (SDTF, 1991), is too restrictive to be adopted for used in this review.

1.4 Bystander and resident exposure to spray drift

The types of spray drift exposure relevant to bystanders and residents at the time of spraying are: direct dermal exposure, inhalation exposure and indirect dermal exposure (Zande et al., 2010). Dermal and inhalation exposure have typically been modelled on the airborne spray flux captured by standardised vertical line collectors (sampling the lower few metres of the atmospheric boundary-layer) and indirect dermal exposure has been modelled on ground surface collectors. The ratio of these standard drift measurements (vertical collector deposit / ground collector deposit) vary with distance from the sprayer (0-30m for typical UK spraying conditions) where the fall velocity of airborne droplets change rapidly relative to the local horizontal velocity (Walklate, 1992). However, at greater distances from the sprayer this ratio becomes constant in ideal conditions (i.e. where drift collectors efficiency is high with Stokes’ number significantly greater than 1).

Based on local Stokes’ number consideration the dermal exposure of a human bystander can be reduced compared with the exposure of standardised (small diameter) line collectors, assuming collectors are not saturated. However, the converse of this may be more representative for inhalation exposure of humans.

2. Drift model type

This review considers two general types of drift model. The first type of model (2.1) is aimed at a broad range of users who wish to make a rapid assessment of exposure to pesticide drift based on minimum input. Some of these models have the potential to be developed to support risk assessment beyond the worst-case or the first tier of a risk assessment system. The second type of model (2.2) is aimed at research users where there is a need to make some further developments.

2.1 Explicit Drift Distribution Models (EDDM)

Typically, this type of model is highly empirical though some are based on simplified theoretical distribution of airborne drift flux with distance from the sprayer. Close to the edge of the orchard or where it is protected by windbreaks the simplest decay profiles (ex. exponential and power law decay functions) are inappropriate within the shelter zone (i.e. typically horizontal distances less than two time the canopy or windbreak height - Walklate, 2000b).

Spray drift is, by convention, expressed as the ratio of the local drift flux to the ground applied dose rate. This is suitable for boom spraying where the drift can be related to label dose (usually expressed as the ground area dose rate). However, it may be less suitable in the future if the use of ground area applied dose rate is superseded by some other method of dose expression (Walklate et al., 2011).

The effect of aggregation due to multiple tree-row exposure (illustrated in Fig. 1b) is usually fixed by the protocols that have been used to generate the drift data before construction of the models (Ganzelmeier et al., 1995; AgDRIFT®; Kaul et al., 2004; Gil et al., 2007; Gil et al., 2008; Zande et al., 2010). However, the AgDRIFT® model enables the effect of variable swath applications to be simulated.

The simplest form of this model (Ganzelmeier et al., 1995) represents measurements of ground deposit outside the orchard where spray has been applied to five rows of trees upwind of the orchard boundary. In this case the 95th percentile of ground deposit from spray drift is used to represent worst-case at different distances from the edge of the sprayed orchard.

Subsequent developments of this type of model have included different types of user interface to simplify data presentation. The simplest example of this type of development is “AgDRIFT® ”. This software generates a set of windows forms to give the user some flexibility to access the model output appropriate to: different fruit orchard types and sprayer types. Other examples of specialised user interfaces have favoured the use of Geographic Information Systems (GIS) (France - Bozon et al., 2008; Germany - Golla et al., 2002; New Zealand - Praat & Woodward, 2008).

2.2 Mechanistic Research Models (MRM)

This type of model typically determines the turbulent motion of spray droplets (as time dependent or time averaged sets of numerical values for spray droplet velocity) and from this information the drift deposit distribution is determined by suitable numerical manipulation and integration. The models usually involve a lower level of empiricism than EDDM’s and this typically involve the modelling of unknown turbulent correlations that appear in the conservation equations of momentum for spray droplets. An example of this type of model was developed by Walklate (1992) to predict the effects of atmospheric dispersion downwind of an orchard sprayer, beyond the primary target zone where the sprayer air-jets are dissipated by the local interactions with the crop and the surrounding air. This model uses initial distribution measurements of spray volume with height and droplet size to start the solution procedure which predicts the ensemble averaged distribution of airborne spray and subsequent deposit on drift collectors.

More recent trends for this type of model development have become ambitious with regards to making use of sprayer outlet conditions (air velocity and spray droplet size distributions) by solving the equations of air and spray droplet motion within the primary target zone. To do this these models use commercially available Computational Fluid Dynamics (CFD) systems to determine the motion of the turbulent air and spray droplets (Xu et al., 1997; Xu et al., 1998; DaSilva et al., 2006; Delele et al., 2005; Delele et al., 2007; Endalew et al., 2010a; Endalew et al., 2010b; Endalew et al., 2010c; Endalew et al., 2010d). These models have the potential to quantify spray drift everywhere beyond the point of spray atomisation, though the extent of the solution is limited by the spatial resolution required. In general the need for high spatial resolution is desirable to limit the effects of poor numerical approximation, but high spatial resolution also increases the computation time. This aspect of using CFD systems is still, very much, a heuristic process and relies on user expertise.

These models also require detailed geometry of the crop canopy structure to accurately represent probabilistic capture of spray droplet. The applications have, so far, been restricted to the simplest types of orchard structure (i.e. pre-blossom orchard). Further work is required to establish models of orchard canopies at full-leaf development where airflow/crop interactions are important within the primary target zone.

The development of these models has helped identify important simplifications to describe spray drift as a result of the interactions between: spray droplets, atmospheric wind, sprayer air jets and orchard structure.

The output from these models gives the greatest flexibility to account for both single swath (Fig 1 a) and multiple swath (Fig, 1b) applications. In practice, however, this degree of sophistication may be unnecessary for assessing the drift contamination risks to bystanders and residents outside any treated orchard with 5 or more tree-rows (Ganzelmeier et al., 1995). Within the treated orchard where a bystander may move after initial contamination from a single swath application (i.e. Fig 1a ref. point 1-3), it may be necessary to use single swath models to examine other exposure scenarios.

3. Review of model developments country-by-country

3.1 Belgium

A commercially available CFD system (i.e. CFX-11 from ANSYS, Inc, Canonsburg, PA, USA) has been used to solve the governing turbulent conservation equations for air and spray droplet motion to enable spray drift distribution to be predicted (Delele et al., 2007; Endalew et al 2010a). This approach has been successfully used to compare the relative performance of different orchard sprayer designs (Endalew et al 2010d) for applications to a single pre-blossom pear orchard (Endalew et al 2009a; Endalew et al 2009b; Endalew et al 2010b).

This research has involved significant validation of airflow within the primary target zone (Endalew et al 2010c). The prediction of drift for higher-density post-blossom orchards is more complex than for low-density pre-blossom orchards and appropriate model validation has yet to be published. Additional model development may also be necessary to account for other effects of high velocity air flows in high-density canopies (ex: shattering of larger droplets and force compliant effects of foliage).

3.2 France

Model development in France has focussed on the use of commercial CFD systems to predict sprayer airflow interaction with the canopy in the primary target zone (DaSilva et al., 2002; DaSilva et al., 2006). This approach, based on the time averaged forms of the equations of motion, has now been abandoned in favour of large eddy simulation using a three dimensional non-hydrostatic meteorological model (i.e. ARPS developed by the Center for Analysis and Prediction of Storms at the University of Oklahama) to simulate time dependent interactions between atmospheric air flows, sprayer air-jets and vineyard canopies (Chahine et al., 2010). This type of modelling is more complex than CFD solution of the time averaged equations of motion. Detailed simulation of air-jet interactions with atmospheric canopy flow started in 2010.

An EDDM based multiple-regression data-fitting model has been developed to obtain an explicit description of some key scaling effects of the primary target zone. This approach used statistical and so called “fuzzy inference” methods to analyse spray loss measurements in artificial vineyards (Gil et al 2008; Gil et al 2007).

In addition to this a Gaussian plume based EDDM is being developed for use with GIS to facilitate prediction of spray drift from vineyards, taking into account local topography (Bozon et al., 2008; Mohammadi & Brun, 2007).

3.3 Germany

German spray drift research has produced various EDDM’s to represent the 95th percentile values of ground deposit from the spray drift cloud. The main use of these models has been the assessment of terrestrial and aquatic exposure from pesticide use in agriculture. However, with some further development these models could be corrected to enable prediction of bystander exposure.

The German EDDM’s of interest here represents different groups of data based on the application of pesticide to different horticultural structures: fruit orchards, hops and vineyards (Ganzelmeier et al., 1995). The “fruit orchard” data groups is of principal interest and this has been subdivided into two growth-stage ranges (i.e. for “early” and “late” growing season results) to quantify the effects of foliar density variation. The two EDDM’s are shown in Fig.2. These results are considered to be relevant to some broadcast air-assisted spraying conditions for tree and bush fruits grown in the UK. Furthermore, the German EDDM’s have been widely used by regulators in other countries around the world because they can be easily understood and can be easily adapted to different spraying practices by using local drift measurements. Also, German EDDM’s have been used as the basis for developing a risk assessment system based on GIS technology (Golla et al., 2002).

SAS® multiple regression software has been used to analyse the sensitivity of drift deposit to additional physical parameters that have been recorded within the German data set (Kaul et al., 2004). This analysis showed the greatest sensitivity of drift at 5m from the boundary of the application area could be attributed to the following parameter: gaps in the foliage (50% increased drift for an increase in the optical transmission of the crop canopy from 30% to 85%), hours since sunrise (45% increased drift for delaying the application from 6 to 13 hours after sunrise) and droplet size (20% reduced drift for increased VMD from 200 – 300 µm VMD).

3.4 Netherlands

Dutch research (Zande et al., 2010) has recently established EDDM’s based on the average values of ground deposit and airborne drift (Fig. 3). Airborne drift values based on 0-3m vertical collectors were used to estimate drift exposure of bystanders and residents at a range of distances between 5m and 50m from the boundary of the sprayed field. It has not been possible to establish enough crop structure information for suitable alignment with the structures represented by EDDM’s of Germany (Fig 2) and USA (Fig. 6).

The Dutch research is very much aimed at establishing drift mitigation based on the use of low drift nozzles (Zande et al 2008). This work also recognised the cross-flow fan type sprayer as the basis for a local standard to better represent Dutch practices rather than the German practices based on the axial fan sprayer.

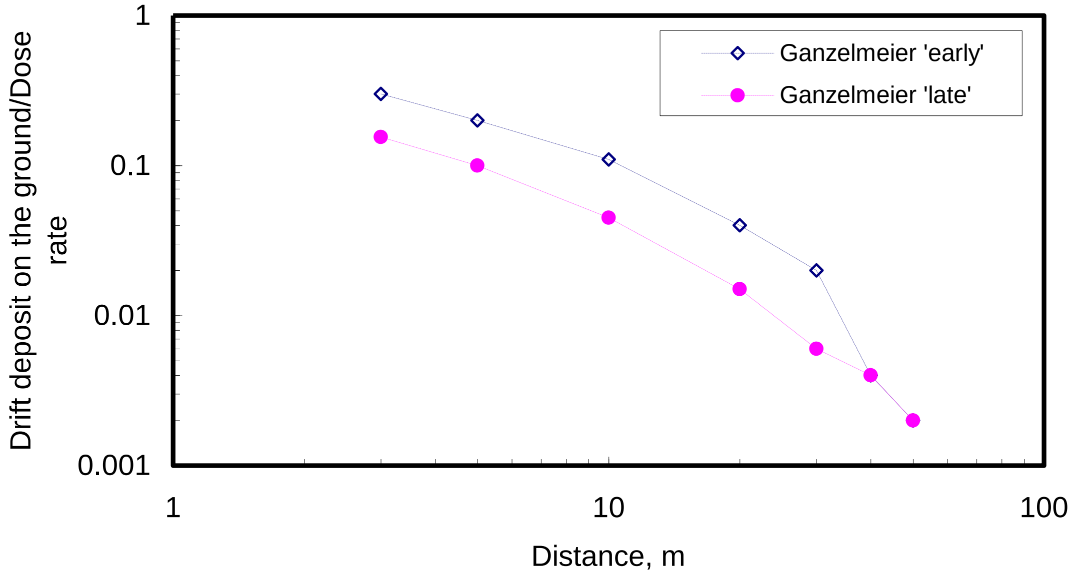


Fig. 2. The EDDM models of German “Fruit crops”. This is based on ground deposit measurements at distances beyond the spray application orchard. The results show the effects of two different growth stages (i.e. ‘early’ & ‘late’).

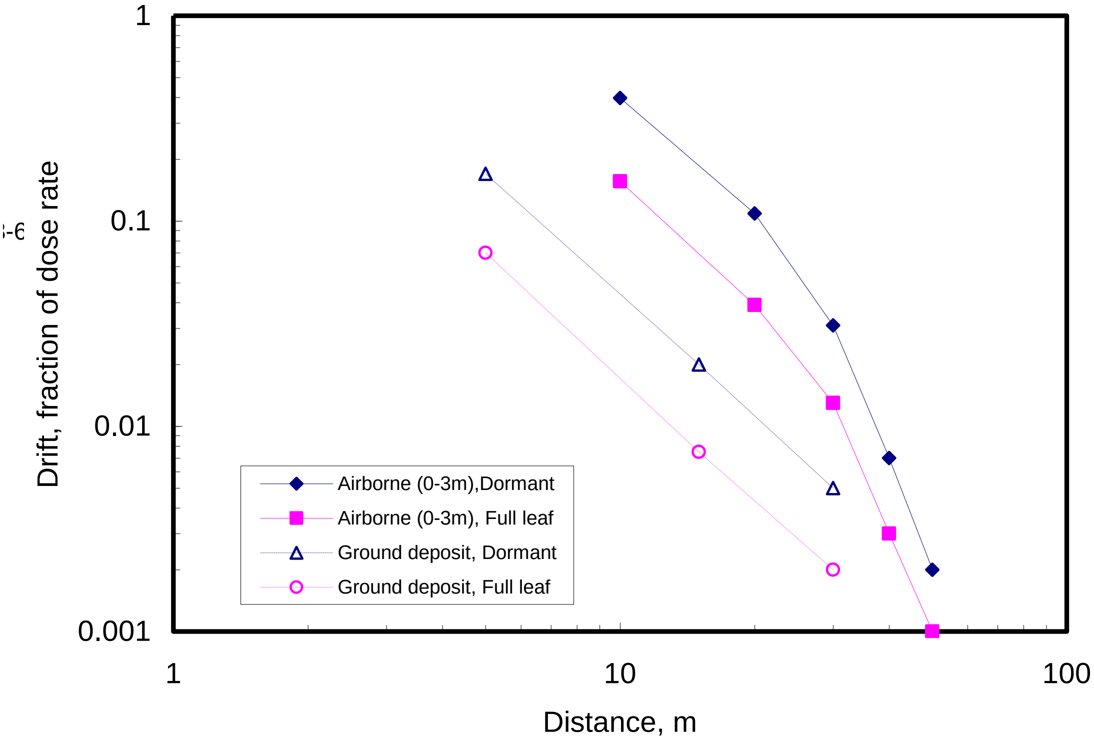


Fig. 3. A comparison between the EDDM’s used the Netherlands. The distance on the horizontal axis is measured from a reference at the edge of the spray application orchard. The results also show the effects of two different growth stages.

3.5 New Zealand

Cumulative Agrichemical Residue Tracking (CART) is a web-based Graphical Interface that has been designed to help pesticide users assess potential hazards from spray drift (Praat & Woodward 2008). The pilot scheme was developed for commercial avocado orchards where concern has been raised because tall commercial orchards may not be well targeted by existing equipment and some key pesticides have high toxicity.

AGDISP (available from Harold Thistle USDA Forest Service, Morgantown, WV26505) has been adapted to predict downwind droplet deposit distribution; although this model makes no claim to simulate the initial drift plume from an orchard sprayer. Furthermore, the AGDISP output was modified for droplet capture by typical shelterbelts for commercial orchards (Raupach et al., 2001).

The pilot CART system lacked the necessary models to extend its use for predicting drift from all types of commercial crops grown in NZ, including: ground crops, orchards and vineyards. New research has been recently commissioned (6 year project) to increase the range of crop spraying applications (email: Andrew Hewitt 23/09/10).

3.6 UK

The random-walk spray drift model (Walklate, 1992) was specifically developed for orchard spraying applications. The model however requires initial conditions to represent the vertical drift profiles of airborne spray on the down-wind edge of the primary target (Fig 1a). This was considered to be a limitation of this type of model in 1992 because of the limited availability of drift measurements and therefore subsequent model development moved in favour of using commercial CFD systems to solving for spray transport within the primary target zone.

The CFD code called CFX v4.1 (available from AEA Technology) was used to model the spray transport from the point of spray generation through the primary target zone (Xu et al., 1997; Xu et al., 1998). This type of modelling helped identify important simplifications to describe spray drift and deposit as a result of the interactions between: spray droplets, atmospheric wind, sprayer air jets and orchard structure.

The UK research on orchard spraying shifted focused towards developing practical methods of improving the efficiency of target deposit after 2000 (Walklate, 2000). This resulted in the development of PACE which involved a probabilistic model of spray transport within the canopy based on the analogy with optical transmission (Walklate et al, 2011). This model can be also be adapted to quantify drift exposure at the downwind edge of the primary target zone. Within the orchard canopy this approach would use the cumulative transmission probability to predict the drift based on LiDAR system measurements (Walklate et al., 2002). There is now a large database of these measurements that can be used to support this. In addition there are some 54 spray target exposure trials each with six drift profiles measurements at 5m from the sprayer (Walklate et al., 2000). An example is shown in Fig. 4 to represent the range of drift distribution measurements (vertical profiles at 5m from the sprayer) for “Standard” and “Low” density orchards.

The results (Fig 4) could be used with the random-walk model (Walklate, 1992) to calculate EDDM’s for the full range of exposure distances beyond the sprayer.

It is envisaged that it would be possible to make this research available to growers in the form of an extension to the PACE webpage to link with drift mitigation based on dose adjustment. Fig. 5 shows the relationship between dose adjustment for constant mean deposit (vertical axis) and the ratio of tree height to row-spacing (horizontal axis). Furthermore, it has been shown that the slope of data represented in this way can be linked to the interception probability of spray deposit which is simplified in the PACE scheme by using standardised orchard density class names (i.e “Standard density” and “Low Density”). The possible alignment between drift exposure at 5m from the sprayer centre-line (i.e. “Low drift” and “High drift”) and PACE orchard density classification is shown on the RHS of Fig.5. The orchard structures that represent the EDDM’s of Germany and US SDTF are also compared with UK orchards on this figure. In addition the range of data with initial drift profile suitable for use with the random-walk drift model (Walklate, 1992) is also shown.

Finally, there are drift measurements of windbreaks at various growth stages (Walklate, 2000b) that could be used to adapt the shelter belt model (Raupach, 2001). This model is similar to the spray transmission model used by PACE, but includes the effects of low particle velocity which reduces the capture efficiency of the windbreak and increases the length of the particle path due to the effect of droplet meander.

3.7 USA

American research (SDTF, 1999) has established EDDM’s based on average ground deposit measurements for a range of selected spraying scenarios (i.e. Commercial fruit orchards: “grapes”, “apple”, “almond”, “orange”, “grapefruit”, “small grapefruit”, “pecans” and “dormant apples”). Some addition spraying scenarios were included to quantify the effect of alternatives to the standard axial fan sprayer (i.e. “wrap-around” sprayer on grapes and “mist blower” on grapefruit). The SDTF EDDM’s may be generated using the AgDRIFT® modelling system (available from Harold Thistle at the USDA Forest Service, Morgantown, WV 26505).

Fig. 6 compares the output from AgDRIFT® (version 2.0.05) for apples orchards with measurements (Teske et al., 1999). Unfortunately, this version of AgDRIFT® gives drift values that do not appear to agree with the original drift data based on the treatment of trees on the three ‘outside’ rows of the orchard. The error has been reported to Harold Thistle (email 21/12/2010).

This research concluded that spray droplet size is one of the most important factors affecting spray drift, in general agreement with a wide range of other practical studies that have concentrated on the use of low drift nozzles for drift mitigation purposes. However, canopy structure was found to be an equally significant factor contributing to the variability of spray drift. Furthermore, the interaction between canopy structure and atmospheric wind speed was seen to be important for pre-blossom spraying (ex. “dormant apple” applications) due to low wind shelter, but less important for post-blossom spraying due to high wind shelter.

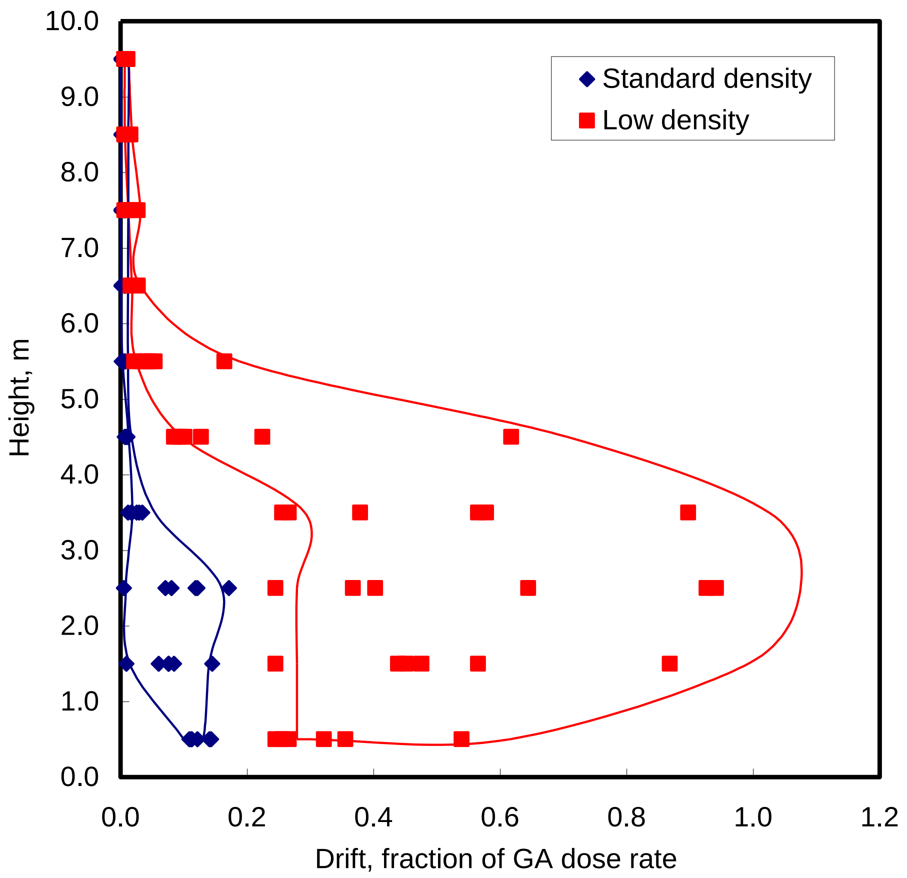


Fig. 4 The variation of airborne drift (fraction of the ground area applied dose rate) with height for PACE "Standard density" and "Low density" orchards.

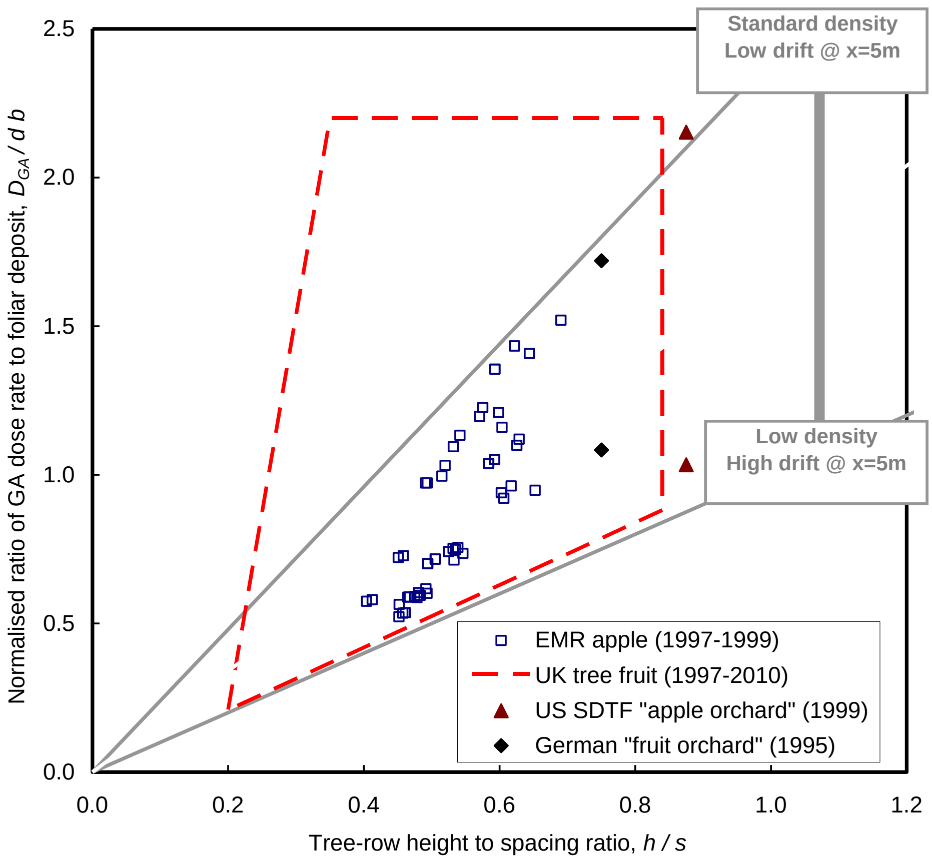


Fig.5. PACE orchard density classification and an alignment with a proposed drift classification at 5m from the sprayer centre-line.

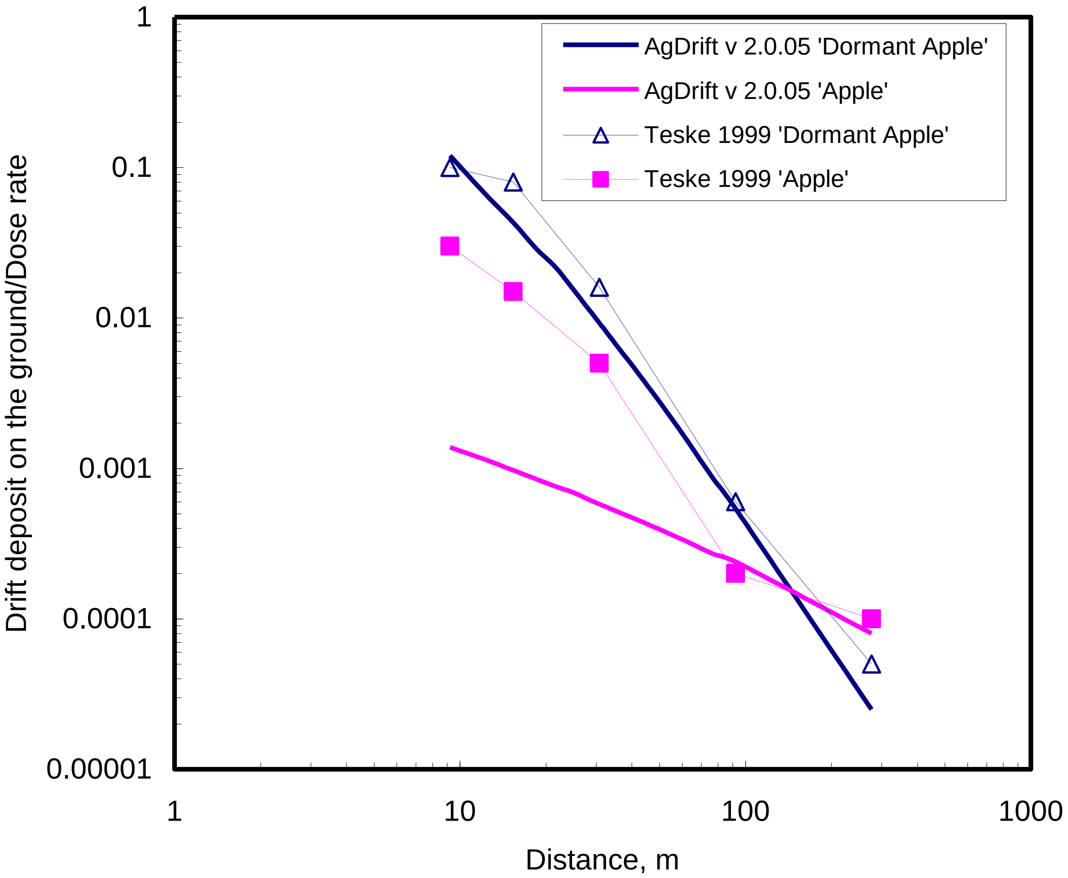


Fig. 6. The US SDTF EDDM's for apple orchards based on ground deposit at distances beyond the spray application orchard. The results show the effects of two different growth stages for 'Dormant Apple' and 'Apple' at full-leaf.

4. Final remarks

It is possible to adapt the output of all the EDDM's shown in this review by using a correction to account for typical drift deposit on bystanders (or residents) which may be different from the drift deposit on typical standard collectors that have been used for model validation purposes (i.e horizontal paper sheets or Petri dishes, vertical mounted plastic lines or string). Further research will be needed to develop this type of drift model for bystanders and residents; in particular, for drift exposure at distances less than 30 m from the sprayer where the correction for different standard drift collectors is expected to vary with distance.

A small number of drift trials could be used to confirm the output of this type of drift model for extreme orchard structures (i.e. "low density" and "standard density") and using drift collectors of similar dimensions to humans.

The SID 3 made reference to specific assessments of the drift models covered by this review and these have been included in Table 1.

Table 1. Assessment of models in accordance with the criteria listed in the original SID 3 document in Section 3a -3e. The % validation (columns 4 & 5) is a subjective assessment of the state of completeness of development to produce a model for drift exposure of bystander and residents. Probabilistic output represented by the letter "P" in column 7 refers to the possibilities of attributing the variability of drift to environmental factors in addition to the effect of distance from the sprayer.

Country	Reference	3a Approach taken	3b. Validation (BREAM)	3b. Validation (non-BREAM)	3c. Software	3d. Probabilistic output	3e. Regulator or Expert user
Belgium	Endalew et al., 2010	MRM		50%	CFX+	P	E
France	DaSilva et al., 2006	MRM		25%	CFX+		E
France	Chahine et al., 2010	MRM		10%	ARPS	P	E
France	Gil et al., 2008	EDDM		35%	B*	P	E
France	Bozon et al., 2008	EDDM		20%	B*		R
Germany	Ganzelmeier et al., 1995	EDDM		80%			R
Germany	Kaul et al., 2004	EDDM		80%	SAS	P	E
Germany	Golla et al., 2002	EDDM		80%	ATKIS		R
Netherlands	Zande et al., 2010	EDDM	50%				R
NZ	Praat & Woodward, 2008	EDDM		25%	CART		R
UK	Walklate, 1992	MRM		40%	B*	P	E
UK	Xu et al., 1998	MRM		25%	CFX+		E
USA	SDTF, 1999	EDDM		70%	AgDRIFT		R

* Bespoke software; + Bespoke modifications to commercial software systems

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