Novel field data for exposure of bystanders and residents towards spray drift during application of plant protection products in orchards

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Abstract

Exposure to pesticide spray drift during the application of plant protection products (PPP) in orchards poses potential health risks to bystanders and residents. To address this concern, this study aimed to gather novel field data on exposure to spray drift in orchards. The research was conducted by the Julius Kuehn-Institute (JKI), the Federal Office of Consumer Protection and Food Safety (BVL), and the German Federal Institute for Risk Assessment (BfR). From 2018 to 2021, the method for conducting the field trials and analysis was implemented. The data from multiple series of performed field trials conducted between 2021 and 2022 allowed for collecting data on potential dermal exposure (PDE), inhalation exposure, and ground sediment. The trials considered various distances from the treatment area and drift-reducing techniques. Adult and child mannequins were used to simulate bystanders' exposure, and petri dishes were used to measure ground sediment. The results showed that drift reduction settings (75% drift reduction) considerably reduced exposure levels on the mannequins. Furthermore, a strong correlation between PDE values for adults and children located next to each other at the same distance was observed. This finding suggests a possibility to convert exposure results from adult to child mannequins. The study produced realistic exposure data for bystanders and residents next to a treated area. It contributes to a better understanding of exposure risks from PPP application and includes data for different distances and spray drift reducing technique. If taken into account for further development of the current risk assessment models, new risk management options for the safe application of PPP, including buffer strips or application of drift reducing systems, might be available in near future.

Keywords Non-dietary risk assessment · Exposure · Orchard · 3-D drift · Residents · Bystander · Plant protection products

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1 Introduction

Drift during the application of pesticides does not only affect the environment. Uninvolved humans such as bystanders (walkers, sportsmen, etc.) or residents can unintendedly be exposed to spray drift, which might result in a potential health risk. Since 2016, the risk assessment for PPP of exposure for operators, workers, residents and bystanders has been carried out according to the internationally harmonised EFSA model (EFSA 2014). In 2014, due to the lack of appropriate exposure study data, the collection of experimental data on spray drift exposure in high crops was strongly recommended. This request to provide new data was repeated in the revised guideline, which was published recently (EFSA 2022).

For arable crops, many data have already been collected and models have been created. Matthews and Hamey (2003) showed that bystander exposure is related to the proportion of droplets in a spray mist that remain in the air. Glass (2006) presented a method to measure bystander exposure. The data published and discussed by Glass et al. (2010) and Butler Ellis et al. (2010) provided the data basis to develop the exposure assessment model BREAM (Kennedy et al. 2012).

The exposure model for high crops such as viticulture and orchards is based on rather old data from the 1980s (Lloyd et al. 1987). Exposure data for different distances from the treatment area and drift-reducing techniques were not considered in the data set by Lloyd et al. (1987). In addition, the data available did not cover exposure of children, so these data were extrapolated based on the different body surface area of adults and children.

To address some of the identified gaps, the European Crop Protection Association (ECPA now CropLife Europe) started a project in 2015 to measure spray exposure at distances of 5 m, 10 m, and 15 m when applying pesticides in viticulture and orchards (HSE 2021). Until recently, this data has not been made available for the models commonly used in risk assessment for the application of PPP.

Since 2016, the BVL has been funding field studies conducted by the JKI-Institute for Application Techniques in Plant Protection as a project partner. The aim was to establish the methodology within the German authorities, and thus independently generate new data that can later be used for basic regulatory decisions and for the further development of the exposure model. As mentioned, so far the data sets currently available contain gaps. Therefore, options for refinements in risk assessment like specific drift mitigation measures (i.e. effects of different buffer sizes and drift-reducing technique) are not available within the regulatory framework. By closing these gaps, a larger portfolio of risk mitigation measures could be used in future to ensure the use of pesticides. The project is economically independent and without the contribution of any industry partners or grants. The following project parameters were considered during the design of the field studies:

- collecting drift data with and without drift-reducing technique (75%),
- including distances of 3 m, 5 m, and 10 m,
- including application in early and late stages in orchards (with low and high density of leaf wall).
- taking care of a high predictive power and robustness based on data from a sufficiently high number of experiments. This will result in reliable exposure estimates that are close to reality and facilitate acceptance of the dataset and subsequent model development.

The present research was conducted in 2 different steps. First, appropriately sensitive methods for measuring 3D-drift using a fluorescent dye (pyranine) were developed from 2018 to 2021 to quantify small amounts of the dye on mannequins equipped with dosimeters under field trial conditions (Ahrens et al. 2023). In a second time period from 2021−2022, several field trials were conducted in orchards to collect realistic and statistically valid exposure data. The development of the methodology comprised:

- the comparison of different technical options (wind tunnel *vs.* open field trials).
- the development of different collector systems and including suitable materials for exposure measurement.
- the improvement of field recovery and sensitivity of laboratory analysis.

Gaining exposure data for high crops in the wind tunnel at the JKI failed, because lack of reproducible results using e.g. different collectors. Therefore, the methodological work was concentrated on field trials according to the frame of the JKI-guideline 7−1.5 for the measurement of direct drift with sprayers in the fields (JKI 2013). This guideline is identical to the ISO 22866:2005 standard (2005) in many ways. In some sectors, such as the weather conditions, the JKI-guideline is stricter.

2 Materials and methods

Between September 2021 and October 2022, 6 series of field trials were conducted at different locations (Table 1). Each series contained 8 runs. For each series, 4 runs were performed without drift reduction technique, and 4 with drift reduction technique (75% drift reduction). Within a series, the runs were conducted in randomised order.

2.1 Collectors

All field trials were conducted using small and tall mannequins with a height of 110 and 175 cm to collect exposure data for children and adults. To measure the potential dermal exposure (PDE), the mannequins had to be covered with appropriate material.

Protective coveralls (Tyvek 500 Xpert, DuPont, size L, 17,050 cm² surface) made of Tyvek® material were chosen for the trials. Since there was no small coverall available for children, the coverall (Tyvek 500 Xpert, DuPont, size S) had to be tailored smaller (6,968 cm² surface). For that, a welding machine, a sewing machine, and a self-made pattern were used. The sleeves were cut to T-shirt length during preparation to simplify the procedure on the field.

Table 1 General information on the experimental series and samples

Series	1	2	3	4	5	6
Location	Braunschweig	Braunschweig	Braunschweig	Braunschweig	Jork	Braunschweig
Timing	Sept. 2021	Nov. 2021	May 2022	June 2022	Sept. 2022	Sept. 2022
Crop situation	Low foliage density	Low foliage density	Low foliage density	Low foliage density	High foliage density	Low foliage density
Site specifics	Young orchard	Young orchard	Young orchard	Young orchard	Mature orchard	Young orchard
No. of runs (w / w/o drift reduction)	8 (4/4)	8 (4/4)	8 (4/4)	8 (4/4)	8 (4/4)	8 (4/4)
Replicates dermal exposure (per run/per run, distance and mannequin type)	144 (18/3)	144 (18/3)	144 (18/3)	144 (18/3)	144 (18/3)	144 (18/3)
Replicates ground deposits (per run/per run and distance)	240 (30/10)	240 (30/10)	240 (30/10)	240 (30/10)	240 (30/10)	240 (30/10)
Replicates air sampling pumps	72 (9/3) (adults only)	72 (9/3) (children only)	120 (15/5) (child & adult	120 (15/5) (child & adult	120 (15/5) (child & adult	120 (15/5) (child & adult
Aerosol collector filters	Nylon	Nylon	Fibreglass	Fibreglass	Fibreglass	Fibreglass

Fig. 1 Mannequins (adult/child) used for experiments dressed with coverall, gloves and plastic shoe covers

Double-sided tape was applied to the inner upper arm to attach the sleeves to the mannequins during the trials. Moreover, children's sleeves were also shortened. All coveralls were marked in advance with cutting lines at the position of the length of a typical shorts. This permitted the reproducible separation of different body parts with scissors on the field. Later, the body parts were analysed separately. For this reason, the results do not only show the total exposure but also its distribution on the head, torso, left and right arms as well as left and right legs. In contrast, for the children, the exposure on the legs was summarized. From series 3 onwards, this was done with the arms too.

Within the experimental setup, the mannequins were dressed in Tyvek® coveralls, nitrile gloves, and plastic shoe covers. The coveralls were put on the mannequins with the front side being at the back of the mannequins so that the faces of the mannequins were covered completely with the coverall hoods (Fig. 1). Additionally, 15 air sampling pumps (GilAir plus STP, Sensidyne) with a pump flow rate of 2 L/min have been used to measure inhalation exposure. The aerosol collector unit was equipped with nylon or fibreglass filters (Table 1). To measure 2D-drift - the ground sediment - petri dishes (Greiner BioOne) with a diameter of 14.5 cm were laid out.

For the determination of field recovery, spiked and blank samples of the collector materials were exposed to the same environmental conditions during the spray period of a trial, without being exposed to the spray liquid at least every second trial. Initially, small amounts (0.01 µg) were spiked. These small amounts could not be found in the laboratory, so the amounts were increased. Tank samples were taken every day of trials to determine the actual amount of fluorescent dye in the spray liquid. Table 2 summarises an overview of the materials and concentrations used.

2.2 Experimental setup

Figure 2 shows a sketch of the experimental setup. The spraying was carried out in orchards measuring 60 m in length and row widths of 3.50 m at 2 different locations. In Braunschweig, Germany (52°17'58.7"N 10°26'26.3"E), 5 series were performed in a young apple orchard (Fig. 3 left) with an interrupted leaf wall area of low density (early treatment). One series was conducted at the location of "Jork" (Esteburg Obstbauzentrum Jork), Germany (53°30'19.4"N 9°45'00.9"E), in an established orchard (Fig. 3 right) with a continuous leaf wall area of high density (late treatment).

Table 2 Overview preparation of field recovery samples

Series	1	2	3	4	5	6
Petri dishes low/high	0.01 µg/1 µg	1 µg/10 µg	1 µg/10 µg	1 µg/10 µg	1 µg/10 µg	1 µg/10 µg
Tyvek® low/high	0.01 µg/1 µg	1 µg/10 µg	1 µg/10 µg	1 µg/10 µg	1 µg/10 µg	1 µg/10 µg
Aerosol filters low/high[1]	0.01 µg/1 µg	0.1 µg/1 µg	0.1 µg/1 µg	0.1 µg/1 µg	1 µg/10 µg	1 µg/10 µg
Frequency	Each run	Each run	1st and 3rd run of each day	1st and 3rd run of each day	1st and 3rd run of each day	1st and 3rd run of each day
Time of spiking	Sept. 2, 2021	On field	On the day before	On the day before	On the day before	On the day before

[1] Nylon filters were used in series 1 and 2. Due to poor results, nylon filters were replaced by fibreglass filters. In response to the obtained results, the fortification level for fibreglass filters was adjusted after 2 series

Fig. 2 Experimental design of the exposure measurements for bystander in orchards
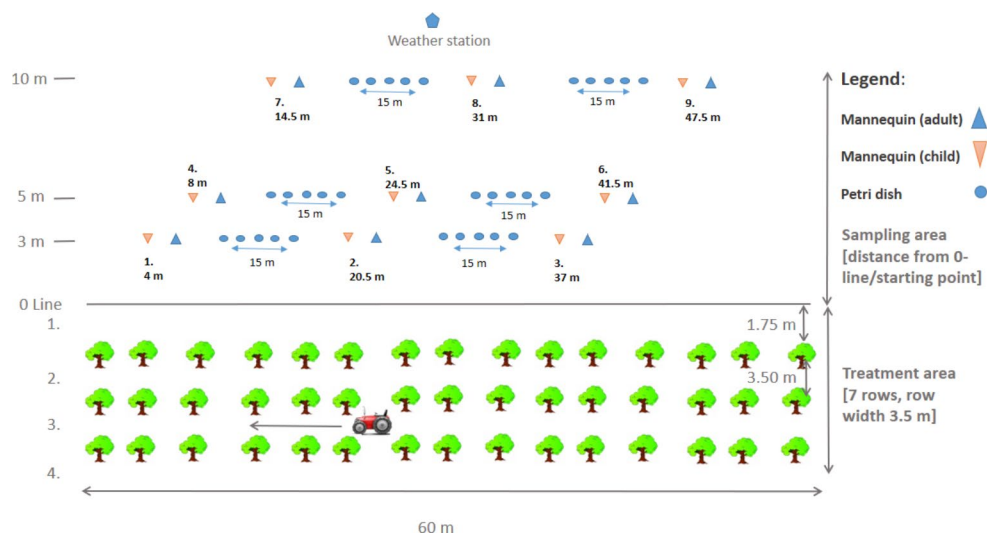
Fig. 3 Young orchard in Braunschweig (left) and mature orchard in Jork (right)

The sampling area downwind of both orchards was cut grassland. In Braunschweig, the rows of the orchard are aligned from south to north. On both sides, there is enough grassland to the west and east for the sampling area. This means that trials can be conducted when the wind blows from east or west. The orchard in Jork is oriented from west to east with a deviation of 12 degrees. The open space next to it is to the north, so the wind should blow roughly from the south for proper trial conditions.

The application took place using orchard sprayers KA32/1000 (Braunschweig) and NA32/1000 (Jork - both Wanner Maschinen GmbH) with an application rate of 400 L/ha, a concentration of 0.1% pyranine, a forward speed of 7 km/h with either ALBUZ ATR nozzles at a pressure of 10 bar (scenario without drift reduction) or IDK-90-015 nozzles at a pressure of 9 bar (75% drift reduction scenario). In total, 7 rows were treated in each trial. In Braunschweig, all rows were treated in the same direction because the sprayer had only one side air cover. In Jork, the treatments went back and forth. In the scenario without drift reduction in row 1, the nozzles and blower directing to the sampling area were switched off, in row 2–7, on both sides the nozzles and blower were switched on. The fan speed was 3000 rpm. In the second scenario with drift reduction (75%) in row 1,

the nozzles directing to the sampling area were switched off, in row 2–5 the blower directing to the sampling area was covered to prevent air flow in this direction, in row 6–7, on both sides the nozzles and blower were switched on. In this scenario, the fan speed was reduced to 2200 rpm.

The drift collectors were placed at 3 m, 5 m, and 10 m downwind of line 0, which is in accordance with ISO standard 22866 at a half-row distance from the outermost row (1.75 m). At each distance, 3 pairs (triplicates per distance and size) of child/adult mannequins with Tyvek®-coveralls were placed at an equal distance of 15 m between the pairs. 15 out of 18 mannequins were equipped with air sampling pumps with aerosol collectors. In the space between the mannequins, 5 petri dishes were laid out 1 m apart to collect ground deposits (10 replicates per distance). Each row had a horizontal offset of the collector positions compared to the other rows (Fig. 2) to avoid wind shadowing. In total, 18 mannequins (9 children, 9 adults), 15 air sampling pumps, and 30 petri dishes were positioned in the sampling area for each trial.

During each run, the weather conditions (temperature, humidity, wind speed and wind direction) were measured every second with a meteorological station (WENTO-IND, Lambrecht Meteo GmbH), which was placed approximately 15 m downwind of line 0 (i.e. behind the measurement area) at the centre of the field. Weather data were sent to a laptop located next to the field via WLAN, recorded electronically and used to verify that the runs were conducted under weather conditions meeting the general requirements for good agricultural practice and the requirements laid down in JKI guideline 7-1.5 (JKI 2013).

Before each trial, the mannequins were dressed in Tyvek® coveralls, nitrile gloves, plastic shoe covers, and an air sampling pump with a fresh filter in the aerosol collector. Since there were 18 mannequins but only 15 air sampling pumps available, the positioning of the pumps was changed systematically. The petri dishes were laid out. Generally, the distribution of the collectors and the dressing of the mannequins started at the distance of 3 m to avoid cross-contamination by stirring up dye from the grass from previous trials.

After the end of the application in a trial, there was a waiting time of 5 min to let all spray drift droplets deposit. Sample collection started at 10 m, as the lowest exposures are expected at this distance, thus reducing the potential for cross-contamination. The coveralls were cut into pieces along the cutting lines and packed into separate labelled plastic bags for transport, storage, and analysis. The filter in the aerosol collectors of the air sampling pumps were replaced with fresh ones and stored separately, too. Gloves and plastic shoe covers were discarded and replaced with new ones. Care was taken to ensure that no object touched the dye-contaminated ground, scissors were cleaned

regularly and people in the field wore disposable gloves to avoid cross-contamination. All samples were transported to the analytical laboratory at the JKI and stored in the dark at ambient temperature until analysis.

2.3 Laboratory analysis

The fluorescent dye was extracted from the collectors with deionised water. For extraction of ground sediment from petri dishes, 40 ml of deionised water was added and the collectors were stirred for 10 min on a rotating table at 65 rpm. This was done in order to wash the inner walls of the petri dishes completely. The filter elements of the air sampling pumps were placed in petri dishes with a diameter of 8 cm. They were wetted with 20 ml deionised water, and shaken on the table for 60 min. Each bag with a Tyvek®-coverall part was filled with 1500 ml deionised water, shaken by hand for 2 min, paused for 10 min, and shaken again shortly. After this preparation, the amount of pyranine in the washing water was analysed with a fluorometer RF-6000 (Shimadzu Duisburg, Germany). An excitation wavelength of 405 nm and an emission wavelength of 515 nm was used.

2.4 Data analysis

For the determination of the exposure of the dosimeters, a stock solution with a defined concentration was used as a reference. A calibration series was set up and measured for the quantitative determination of the amount of the substance of interest. For each value, 3 measurements were taken by the fluorometer and the arithmetic mean was calculated. A calibration curve was determined with linear regression. Using this calibration curve, the concentration of pyranine in the sample can be calculated from the fluorometer reading of the sample. The amount of spray on the collectors is determined by conversion. The ground sediment is calculated as a percentage compared to the application rate to compare the values with drift measurements from other studies. All values are corrected using the tank samples and field recovery. Since tests were carried out with and without drift-reducing settings (75% drift reduction), it can be determined whether the intended level of drift reduction was achieved. The drift reduction potential (DRP) is calculated from the difference between the 2 results divided by the value without drift reduction:

$$DRP\,(\%) = \frac{result_{without} - result_{with}}{result_{without}} \times 100$$

After determining the exposure values, the data analysis was carried out with R, version 4.2.0 (R Core Team 2022). Functions from the packages readxl (Wickham and Bryan 2022),

dplyr (Wickham et al. 2022), ggplot2 (Wickham 2016), ggh4sx (van den Brand 2023), ggpmisc (Aphalo 2022), rOstluft and rOstluft.plot (Allmen and Sintermann 2019a, b), and tidyR (Wickham and Girlich 2022) were used.

3 Results and discussion

3.1 Weather

Weather conditions were observed and recorded for all runs. For one run, the recording was not stored and for 3 runs, the data log was incomplete. Weather data for $2-3$ rows are missing. The air temperature ranged from 5.5 °C in November 2021 to 24.9 °C in September 2021. The average temperature was 14.5 °C with a standard deviation of 4.9 °C. The mean wind speed of the runs lay between 1.3 m/s and 4.6 m/s. Series 3 stood out with high wind speeds, but the mean value was <5 m/s, which is permitted by the JKI guideline. The mean wind direction ranged from $-34.1°$ to $40.5°$. According to ISO, no more than 10% of the wind speed measurements should be <1 m/s, and not $>30\%$ of the wind direction recordings should deviate $>45°$ from the downwind direction from the orchard to the measurement area. The mean wind direction should be between $-30°$ and $+30°$. In 4 runs, more than 10% of the wind speed measurements were <1 m/s. Since these values are mostly <1 m/s, they were kept in the present analysis. In 3 runs, the absolute mean direction is $>30°$, and in 2 runs $>30\%$ of the measurements were above 45°. For the first analysis, data from these runs were not sorted out. They can be checked later for significant discrepancies. Then, it can ultimately be decided whether the data should be considered for risk assessment or not. Figure 4 shows a graphical illustration of wind conditions per series.

3.2 Field recovery rates

For the lower fortification level of all materials, no measurements above LOD and LOQ could be quantified in the samples during the evaluation of the first series. The choice of the spiked quantity was too low. Therefore, the fortification levels were increased in the following series. In series 2, spiking was done at the field directly before the trials. But this procedure proved to be too impractical in conducting the trials. There was not enough space for so many samples, and it could not always be guaranteed that the preparation of the samples could be carried out without exposure to UV-radiation. From series 3 onwards, the samples were spiked on the evening/day before the trials, packed and stored in the dark after drying until they were laid out in the field, and also stored in the dark at a cool ambient temperature after the trials until they were analyzed. In addition, the fiberglass filters of the inhalation exposure were no longer laid out horizontally in Petri dishes, but vertically in collection heads to better simulate real trials. Table 3 shows an overview of the determined field recovery rates for all different materials. Tyvek® and Petri dishes showed good recovery rates. For nylon filters, a very low recovery rate with a large variability was found. For this reason, nylon filters were discarded and replaced with fiberglass filters.

Fig. 4 Depiction of wind conditions across all 6 series. The sector highlighted green or light green represents the preferred wind direction $\pm 30°$ or $\pm 45°$, respectively. For better comparability across the experiments, wind direction is given as degree deviation from the intended direction (perpendicular to driving direction). Wind speed is colour coded
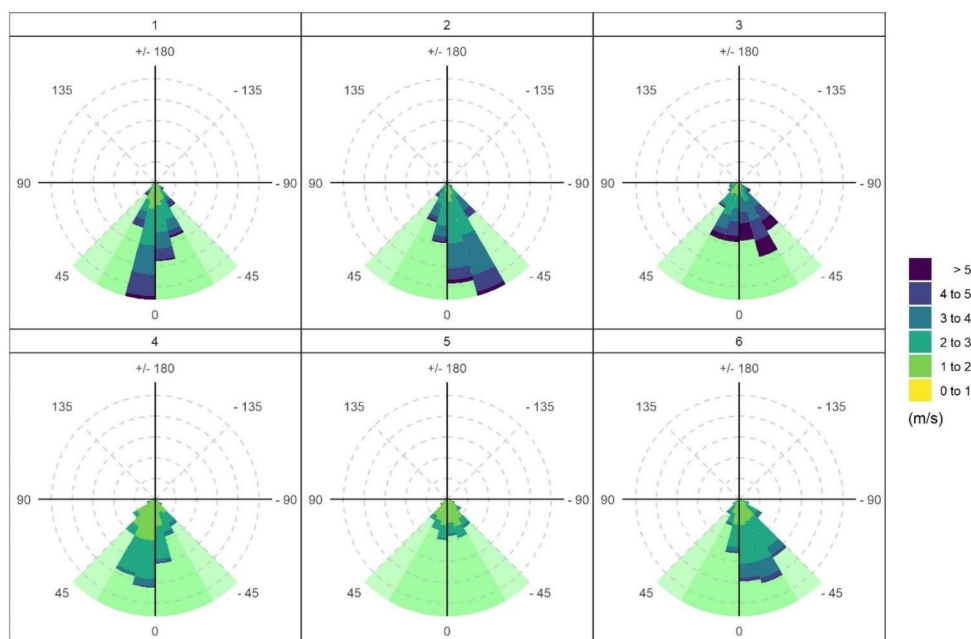
Table 3 Overview of determined field recovery rates for individual dosimeter

Material type	Low fortification level		High fortification level	
	Range	Mean	Range	Mean
Tyvek®	65 – 101%[1]	80% ± 10%[1]	68 – 96%[1]	87% ± 9%[1]
Nylon filter	4 – 54%	23% ± 17%	2 – 37%	10% ± 11%
Fibreglass filter[2]	21 – 57%[1]	42% ± 11%[1]	65 – 70%	67% ± 2%
Petri dishes	51 – 102%[1]	81% ± 13%[1]	68 – 98%[1]	88% ± 7%[1]

[1] Values clearly deviating from the average value were considered as outliers and disregarded

[2] Concentration ranges for the different levels of fortification changed during the course of experiments. Samples with 0.1 or 1 µg were summarised as low level

3.3 Potential dermal exposure

The potential dermal exposure (PDE) for the mannequins was calculated as the sum of the measured spray liquid on all body parts of the coveralls in ml on the total body surface (cf. Table 4 for the series in Braunschweig and Table 5 for the trials in Jork). The values decreased with the distance to the treatment area. The trials with drift reduction technique showed lower values than those without. The values of series 3 trials were more variable and higher than all other series due to strong winds. The PDE of series 5 in Jork was very low. Figure 5 shows boxplots of the PDE for adults and children and different drift reduction technique for the two trial sites. One can see the difference between the techniques. Furthermore, child mannequins (green boxplots) had lower exposure values than adult mannequins (blue boxplots), as expected. Both figures illustrate the same pattern: a decrease with increasing distance and an obvious effect of drift reduction setting. Despite that fact, the variation of data for one distance was widely spread and there were some outliers. This finding is regarded as quite normal for this kind of practical drift measurement in open field trials.

When comparing the two sprayer settings at the two locations with the drift reduction potential (DRP), at least 75% drift reduction was achieved in all series for the median and the 75th percentile (Tables 4 and 5). Across all series 1–6, the drift reduction potential calculated from median, 75th percentile and 95th percentile is more than 75%.
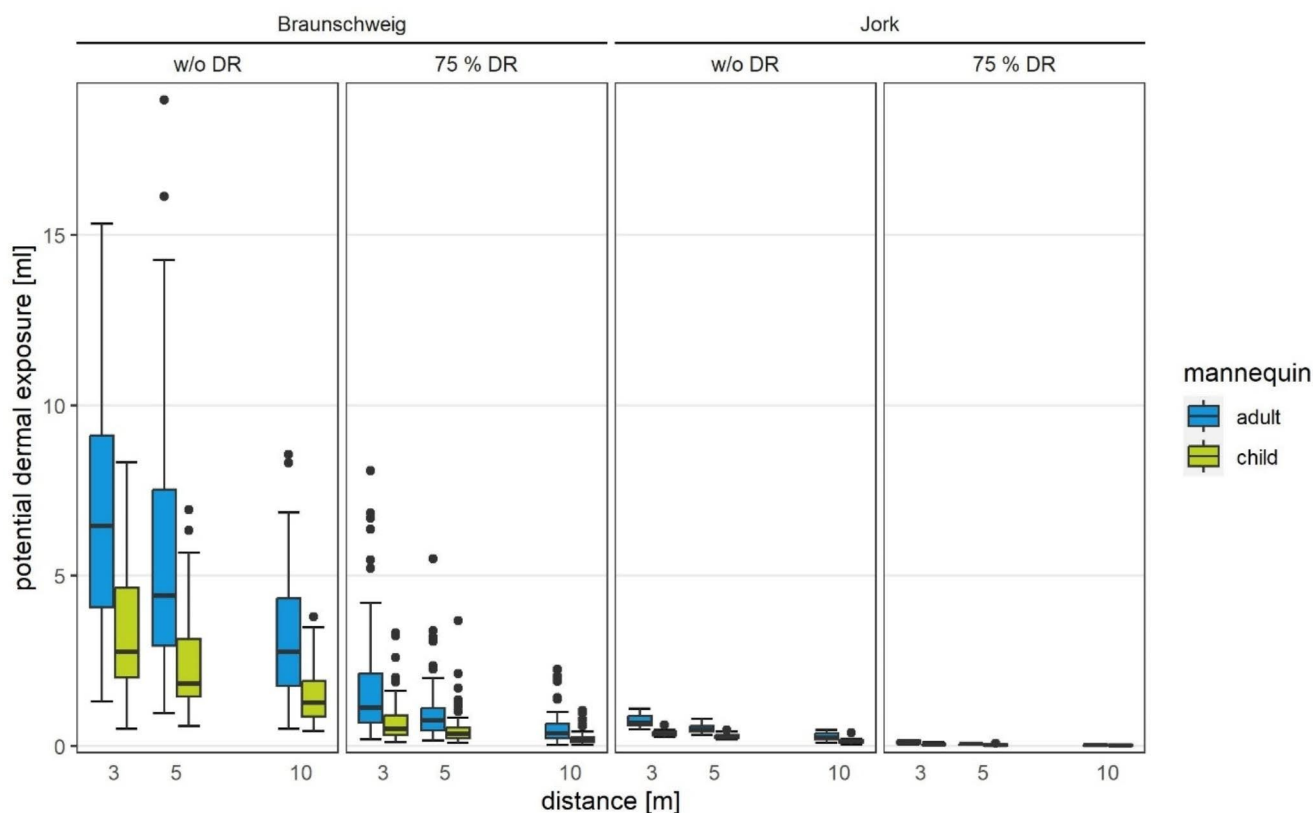
Comparing the results for adults with those for children, a strong correlation between the total potential dermal exposure for both groups could be seen. On average, about

Table 4 Potential dermal exposure of adult and child mannequins from all Braunschweig series given as median, 75th and 95th percentile for different distances and drift reduction setting. Drift reduction potential was calculated from median, 75th and 95th percentile values

	Distance [m]	Dermal exposure adult, w/o DR [µL]	Dermal exposure adult, 75% DR [µL]	Drift reduction [%]	Dermal exposure child, w/o DR [µL]	Dermal exposure child, 75% DR [µL]	Drift reduction [%]
Median	3	6 455	1 125	83	2 753	503	83
	5	4 410	751	83	1 828	356	83
	10	2 764	372	87	1 272	177	88
75th percentile	3	9 117	2 119	77	4 640	901	83
	5	7 528	1 107	85	3 145	529	84
	10	4 326	649	85	1 916	257	85
95th percentile	3	13 249	6 380	52	6 677	2 042	79
	5	14 052	3 071	78	5 174	1 369	84
	10	6 728	1 933	71	2 848	784	85

Table 5 Potential dermal exposure of adult and child mannequins from trials in Jork given as median, 75th and 95th percentile for different distances and drift reduction setting for series 5. Drift reduction potential was calculated from median, 75th and 95th percentile values

	Distance [m]	Dermal exposure adult, w/o DR [µL]	Dermal exposure adult, 75% DR [µL]	Drift reduction [%]	Dermal exposure child, w/o DR [µL]	Dermal exposure child, 75% DR [µL]	Drift reduction [%]
Median	3	687	90	87	379	44	88
	5	476	58	88	258	20	92
	10	243	26	89	127	13	90
75th percentile	3	874	154	82	418	62	85
	5	588	65	89	319	38	88
	10	368	40	89	172	20	88
95th percentile	3	1007	174	83	540	83	85
	5	796	87	89	444	59	87
	10	434	64	85	291	36	88

Fig. 5 Boxplots of potential dermal exposure on adults (blue) and children (green) in ml spray liquid on total body surface, 5 series in Braunschweig and one series in Jork. The boxes show the range of 50% of the data. The range is from the 25th to the 75th percentiles. The horizontal line in the boxes marks the median. The boundaries of the whiskers are based on 1.5 times the interquartile range (IQR: 75th percentile – 25th percentile). Observations outside this range are plotted as outliers

Table 6 Potential dermal exposure of adult and child mannequins and the proportion of child's PDE to adults PDE for trials in Braunschweig and Jork in % (calculated from median)

	Braunschweig				Jork			
	Distance [m]	Dermal exposure, adult [μL]	Dermal exposure, children [μL]	Proportion [%]	Distance [m]	Dermal exposure, adult [μL]	Dermal exposure, children [μL]	Proportion [%]
w/o DR	3	6.46	2.75	43	3	0.69	0.38	55
	5	4.41	1.83	41	5	0.48	0.26	54
	10	2.76	1.27	46	10	0.24	0.13	52
75% DR	3	1.13	0.50	45	3	0.09	0.04	49
	5	0.75	0.36	47	5	0.06	0.02	34
	10	0.37	0.18	48	10	0.03	0.01	52

45% of the spray liquid amount of adult mannequins was found on child mannequins. For both sprayer settings and all series, Table 6 shows the proportion of the median of the children's PDE to the adults' PDE in percent.

It seems feasible to scale the results for adult mannequins and child mannequins. The linear fit result based on data from adjacent adult and child mannequins was 0.442 with R^2 of 0.94. A factor of 0.5 could be derived as the worst case. The surface area of the child mannequins was < 41% of the adult mannequins. Following our findings, the extrapolation from adult data to children as published in the EFSA

Guidance underestimates children's exposure at a 5 m distance. A ratio of 0.3 was used in the EFSA model, based on body surface area figures. However, scaling by body surface might not be appropriate based on our data.

Regarding the data series from Braunschweig, the 75th and 95th percentile of dermal exposure of an adult at a distance of 5 m is 7.53 mL and 14.05 mL (Table 7), respectively, if no drift-reducing technology is used. These values are slightly higher than the numbers given in the EFSA guidance documents for exposure assessment (EFSA 2014, 2022), where the EFSA Working Group proposed 5.63 mL

and 12.9 mL as 75th and 95th percentile, respectively, for the risk assessment based on the study data by Lloyd et al. (1987). Disregarding series 3 with stronger winds the 75th and 95th percentile of dermal exposure of an adult at the distance of 5 m the values decrease to 6.30 mL and 9.09 mL.

Differences due to some uncertainties mentioned in the EFSA guidance document may arise (EFSA 2014, 2022), in particular bridging from 8 m distance (from the first tree row) to 5 m (from line 0). In addition, differences in the applied water volume and in leaf wall density of the orchard in the study by Lloyd et al. (1987) and the orchard in Braunschweig may have contributed to a different exposures (i.e. lower density of foliage is expected to lead to higher exposure; potential impact of water volume was not investigated systematically, yet and is part of a future project). This could explain why the 75th percentile of the current data set is higher than the number derived from the data set by Lloyd et al. (1987). In addition, the larger data set of the recent study may reduce the impact of outliers on the overall figures, which leads to a lower value for the 95th percentile.

In studies conducted and evaluated in the framework of project BROV (Bystander Resident Orchard Vineyard), drift data for orchards were collected as well. The exposure values (HSE 2021) were approximately 2- to 5-fold higher than the numbers from data of the current study (Table 7). This holds true for different distances and foliage densities. The notable differences in the data sets may partly be explained by differences in the crop situation (i.e. density of foliage at the early and/or late experiments). But it is very likely that other factors have an impact on the amount of spray drift as well. The most obvious difference between both sets of experiments is that the amount of water used in the BROV studies was significantly higher (app. 550 to 1 050 L/ha) than in the current study (app. 400 L/ha). Furthermore, the increase of water volume is accompanied by a decrease of

the driving speed. While the impact of differences in foliage wall density is obvious in both the available data sets from the current experiments and the BROV studies (HSE 2021), the effect of the water volume or driving speed on the spray drift remains elusive. The current models for risk assessment are based on the assumption that the exposure towards spray drift (i.e. amount of spray liquid per person) does not change with increasing or decreasing water volume (EFSA 2014, 2022). Thus, further studies are required to investigate if and how spray drift as well as exposure to PPP components is influenced by the water volume or other factors.

3.4 Inhalation exposure

Only the results of series 3–6 are presented due to the large variations in the first two series associated with low field recovery. The values were corrected with tank samples and field recovery but not converted to adult and child respiration rates, yet. Thus, in a first analysis, the values from the field can be considered without the different conversion factors for adults and children. Inhalation exposure values had to be strongly corrected due to weak field recovery. Figure 6 shows the results of 15 air sampling pumps (5 per distance) per run. The results show increased variability than potential dermal exposure. The effects of settings with and without drift reduction can also be seen. Since the values were not adjusted to the respiration rate of adults and children, but are presented with a flow rate of the air sampling pumps of 2 L/min, it can be seen that the values for adults and children are in the same ranges. Therefore, no distinction was made between adults and children (Table 8).

Table 7 Comparison dermal exposure: values of series in Braunschweig and Jork to values of the EFSA model (2014, 2022) and BROV Project (HSE 2021)

Trial/Data Source	Description		Adult, 3 m	Child, 3 m	Adult, 5 m	Child, 5 m	Adult, 10 m	Child, 10 m
			[mL spray/person]					
Braunschweig	Orchard, early	75th	9.12	4.64	7.53	3.14	4.33	1.92
		95th	13.25	6.68	14.05	5.17	6.73	2.85
	Orchard, early, 75% drift reduction	75th	2.12	0.90	1.11	0.53	0.65	0.26
		95th	2.50	1.17	1.40	0.72	0.77	0.33
Jork	Orchard, late	75th	0.87	0.42	0.59	0.32	0.37	0.17
		95th	1.01	0.54	0.80	0.44	0.43	0.29
	Orchard, late, 75% drift reduction	75th	0.15	0.06	0.07	0.04	0.04	0.02
		95th	0.17	0.08	0.09	0.06	0.06	0.04
EFSA / Lloyd et al. 1987	Orchard, no drift reduction	75th	N/A	N/A	5.63	1.69	5.63	1.69
		95th	N/A	N/A	12.69	3.87	12.69	3.87
BROV Project / HSE 2021	Orchard, early, no drift reduction	75th	N/A	N/A	16.67	5.96	9.55	3.75
		95th	N/A	N/A	34.12	7.67	14.58	4.77
	Orchard, late, no drift reduction	75th	N/A	N/A	3.00	0.90	1.81	0.65
		95th	N/A	N/A	5.93	1.52	3.43	1.00
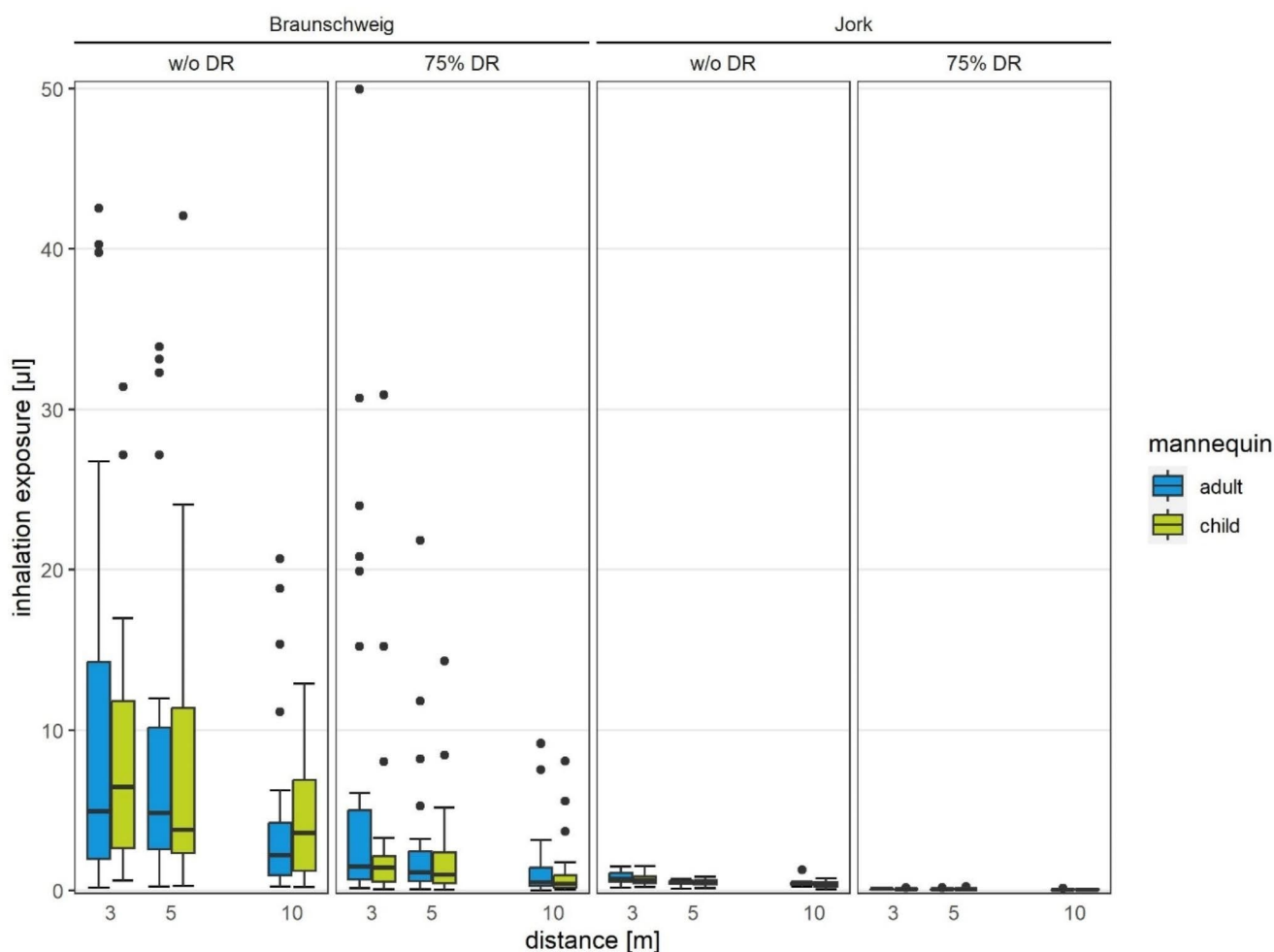
Fig. 6 Results air sampling pumps, series 3, 4 and 6 in Braunschweig and series 5 in Jork

Table 8 Inhalation exposure of all mannequins from series 3 − 6 at 2 locations given as median, 75th and 95th percentile for different distances and DR setting. Drift reduction potential was calculated from median, 75th and 95th percentile values

	Braunschweig				Jork		
	Distance [m]	Inhalation exposure, w/o DR [μL]	Inhalation exposure, 75% DR [μL]	Drift reduction [%]	Inhalation exposure, w/o DR [μL]	Inhalation exposure, 75% DR [μL]	Drift reduction [%]
Median	3	5.5	1.4	74	0.7	0.1	85
	5	4.1	1.1	73	0.5	0.1	86
	10	2.4	0.5	81	0.4	0.1	86
75th percentile	3	13.2	2.9	78	1.0	0.1	88
	5	10.4	2.5	76	0.6	0.1	86
	10	6.3	1.1	82	0.5	0.1	86
95th percentile	3	31.8	24.3	24	1.5	0.1	90
	5	32.3	8.6	73	0.8	0.2	80
	10	13.0	7.6	42	0.8	0.1	86

3.5 Ground deposit

Table 9 shows the median, the 75th, the 90th, and the 95th percentile of ground deposits in the petri dishes as a percentage of the application rate for both. The values from the series in Jork were very low. The reason for that is that the trials in Jork were carried out in a well-established mature orchard, whereas the trials in Braunschweig took place in a young orchard. In Jork, there was a strong foliage wall due to well-grown trees which is assumed to result in less drift

Table 9 Ground deposits measured at different distances from the zero-line in the different series. Values represent the median and the 90th percentile of all values obtained for the given distance. Values are given as 90th percentile and median for each location and setting. Drift reduction potential was calculated from 90th percentiles and median values for each location and distance

	Braunschweig				Jork			
	Distance [m]	Ground sediment, w/o DR [%]	Ground sediment, 75% DR [%]	Drift reduction [%]	Distance [m]	Ground sediment, w/o DR [%]	Ground sediment, 75% DR [%]	Drift reduction [%]
Median	3	34.7	8.2	76	3	7.7	1.0	87
	5	26.0	5.6	78	5	4.7	0.7	86
	10	14.0	2.1	85	10	3.2	0.2	93
75th percentile	3	39.6	13.3	34	3	10.3	1.8	17
	5	30.1	10.0	33	5	6.4	0.9	14
	10	17.3	3.3	19	10	3.8	0.4	11
90th percentile	3	46.7	18.2	61	3	12.5	2.3	81
	5	34.4	13.7	60	5	7.7	1.2	84
	10	20.8	5.8	72	10	4.5	0.5	89
95th percentile	3	50.6	21.5	43	3	12.7	2.5	19
	5	36.5	15.0	41	5	8.7	1.5	18
	10	23.8	6.7	28	10	4.5	0.6	13

exposure outside the area treated. The data of ground sediments confirm the results of dermal exposure.

4 Conclusion

In this study, 6 series with 8 runs each consisting of 3 replicates per run and distance (children and adult mannequins) or 10 replicates per run and distance (Petri dishes) were performed. For PDE, data were collected from 864 mannequins and 4392 body parts, for inhalation exposure 480 data points, and data from 1440 Petri dishes for ground sediment. Half of the data was gathered with drift reduction settings (75%), and the other half without drift reduction. This is an appropriate basis for risk assessment.

Results obtained from different series are comparable, with the exception of series 3 and 5. Series 3 suffered from unfavourable wind conditions in some runs, which resulted in higher variability, a trend for higher exposure and less drift reduction. Series 5 was conducted in a fully established orchard with a high density of foliage, which caused a strong reduction of spray drift, as opposed to the other series, which were conducted in an orchard with low density of foliage. While the overall effect of the density of foliage was confirmed by other independent studies (HSE 2021), the size effect needs to be verified. The data set covers some of the current gaps in the models used in non-dietary risk assessment. Unlike the data set by Lloyd et al. (1987), which is the basis for the risk assessment at present, the new data set provides dermal exposure figures for different distances and experimental data on the use of drift reducing technology. Now, data for distances of 3 m, 5 m, and 10 m are available. In addition, this study demonstrates that a sprayer setting

for obtaining 75% drift reduction for ground deposits is also suitable to achieve a similar reduction of dermal exposure for residents and bystanders. Hence, the data of this study offer new options for considering risk mitigation measures in the risk assessment for PPP. In addition, the novel data set also contains data on the exposure of children. This was of particular interest, because exposure to children was extrapolated based on adult data in the current model (EFSA 2014, 2022). Overall, results of the measurements are comparable to the numbers derived from the study by Lloyd et al. (1987). However, extrapolation of results obtained for an adult person to a child may underestimate exposure, if only the body surface area is considered for the calculation, as it was demonstrated by the pairwise comparison of the dermal exposure of child and adult samples across the whole series of experiments.

Future experiments may address further uncertainties and gaps, and could deliver data on higher levels of drift reduction (e.g. 90% or 95%) and the impact of the water volume on spray drift. In addition, verification of the drift-reducing effect of dense foliage is recommended. Trials in orchards with a drift reduction setting of 90% percent are planned. Trials will be conducted in different settings in vineyards. Different application rates or water volumes are of interest, too.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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