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Environmental, bystander and resident exposure from orchard applications using an agricultural unmanned aerial spraying system

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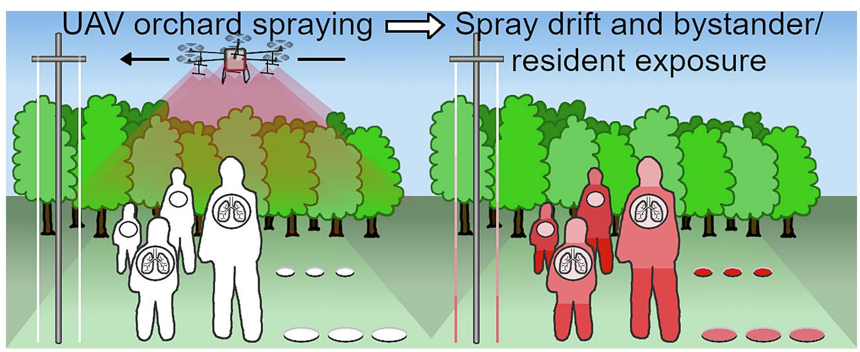
HIGHLIGHTS

- Drift and resident/bystander exposure resulting from UASS-assisted orchard applications were investigated in field trials.
- Deposition and exposure decrease as height and/or downwind distance increase.
- Compared to earlier UASS drift trials, spray drift is confined to rather short downwind distances.
- The results are covered by predictions of current EU and US regulatory models for ground and aerial applications.

GRAPHICAL ABSTRACT



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ABSTRACT

Unmanned aerial spraying systems (UASS), *i.e.*, unmanned aerial vehicles designed for pesticide applications, are widely used in East Asia and increasingly prevalent in other regions of the world, including North America and Europe. However, according to a recent report of the Organization for Economic Co-operation and Development, spray drift and exposure caused by these systems are not yet fully understood. In particular, there are at present no peer-reviewed reports on direct exposure of residents and bystanders to spray drift following UASS applications. This lack of data results in regulatory concerns with respect to the environment and human safety. The objective of this study was to quantify environmental, resident and bystander exposure following the application of a plant protection product to an orchard using a commercial UASS under field conditions. Using a fluorescent tracer, horizontal and vertical downwind drift data were collected and direct exposure of residents and bystanders located downwind the sprayed area to spray drift was quantified using display mannequins equipped with personal air sampling pumps. Spray drift and exposure inversely correlated with sampling height and downwind distance. Furthermore, drift and exposure were strongly influenced by wind speed and direction, albeit hardly affected by the growth stage of the trees. In addition, substantially less tracer was extracted from the filters of the air sampling pumps than from the coveralls worn by mannequins, suggesting that direct resident/bystander exposure to spray drift may predominantly occur *via* the dermal route. This report provides essential data on UASS spray drift potential that are relevant for environmental and health risk assessments related to these systems. The results are compared to predicted values of current regulatory models and previously reported field data on drift and exposure caused by different spraying equipment.

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1. Introduction

Unmanned aerial spraying systems (UASS), defined in the context of this work as unmanned aerial vehicles designed for spraying pesticides, are increasingly used throughout the world, in particular in East Asia (Xiongkui et al., 2017). As of March 2016, roughly 2800 unmanned helicopters were registered for operation in Japan alone, spraying 42 % of the country's rice paddies (FAO and ITU, 2018; Iost Filho et al., 2020). The 2020 statistics of the Chinese Agriculture Department indicates that almost 100,000 UASS were used to treat 66 million hectares that year (Yan et al., 2021). In other parts of the world, for example Germany, Switzerland and the United States, UASS are also increasingly deployed (Dubuis and Jaquerot, 2022; Rodriguez, 2021). The Organization for Economic Co-operation and Development (OECD) noted in a recent report that UASS promise to provide benefits compared to conventional ground-based methods, such as the reduction of operator exposure, improved applications in terrain not readily accessible with other equipment as well as the possibility for precise zone or spot application treatments (OECD, 2021). In turn, it is also pointed out that potential benefits of these systems cannot be realized without improving the available data, primarily with regard to drift, efficacy and exposure (OECD, 2021).

According to the U.S. Environmental Protection Agency (US EPA), spray or dust drift is defined as “the physical movement of pesticide droplets or particles through the air at the time of pesticide application or soon thereafter from the target site to any non- or off-target site” (US EPA and US EPA, 2001). Unintended drift of pesticide sprays may pose a risk to animals, plants and water bodies (Al Heidary et al., 2014; FOCUS, 2001; Hilz and Vermeer, 2013). In addition, it may lead to direct and indirect exposure of individuals that live and/or work in the vicinity of the treated area (“residents”) as well as individuals that spend a short time in proximity of a treated plot (“bystanders”) (EFSA, 2022; Martin et al., 2008). The extent of drift is affected by numerous variables, including environmental factors such as wind direction, wind speed, temperature, humidity and the presence of windbreaks in proximity of the sprayed area, and application parameters such as sprayer type, release height, nozzle type and operating pressure as well as the physico-chemical properties of the spray solution (Al Heidary et al., 2014; Butler Ellis et al., 2016; Fritz, 2006; Fritz et al., 2009; Hilz and Vermeer, 2013; Huang et al., 2023; Nuyttens et al., 2007a; Nuyttens et al., 2006a; Nuyttens et al., 2006b; Polveche et al., 2011; Wang et al., 2023; Wang et al., 2020). Additional variables affecting drift are specific to aerial application techniques, such as the nozzle location with respect to rotors, turbulences caused by multiple rotors, interaction of the downward-directed wind generated by the rotor(s) (downdraft) with foliage and/or ground and the effect of UASS design and operational parameters on potential downdraft (Herbst et al., 2020; OECD, 2021).

A number of field studies to assess off-target movement of droplets following UASS applications have been reported. Drift deposition onto horizontal surfaces, which is related to contamination of surface waters and exposure of residents and bystander, and/or airborne drift profiles related to contamination of vegetative structures at field boundaries and direct exposure of residents and bystanders have been studied (EFSA, 2022; FOCUS, 2001; ISO 22866, 2005). These experiments were performed at sites at which various crops were grown, including (artificial) rice (Chen et al., 2020; Huang et al., 2023; Xue et al., 2014), pineapple (Wang et al., 2018), cotton (Zhan et al., 2022), (artificial) vine (Brown and Giles, 2018; Delpuech et al., 2022; Wang et al., 2021; Wang et al., 2023), and peach (Li et al., 2022). Further trials were carried out in fields overgrown to a varying extent with weeds (Ahmad et al., 2022; Wang et al., 2020). Some of these studies also assessed operational parameters known to influence off-target movement of spray droplets in the context of aerial applications, such as droplet size (Chen et al., 2020; Huang et al., 2023; Wang et al., 2023; Wang et al., 2020), release height (Huang et al., 2023; Wang et al., 2018; Zhan et al., 2022) and flight velocity (Li et al., 2022). Reviews addressing drift of UASS have recently been published (Chen et al., 2021; Chen et al., 2022). To date, there are no peer-reviewed reports on direct exposure of residents and bystanders to spray drift as a consequence of UASS applications, albeit a recently published report of the French Agency for Food, Environmental and Occupational Health & Safety discusses preliminary results on the topic (ANSES, 2022).

As for drift as a result of pesticide applications using conventional tractor-mounted equipment, a wealth of data has been published. Specifically, the Federal Biological Research Centre for Agriculture and Forestry has published the results of a total of 119 spray drift trials performed in field crops, grapevine, fruit crops and hops (Ganzelmeier et al., 1995). These data have been complemented by the results of 122 additional trials in field and fruit crops and the combined dataset has been re-analyzed (Rautmann et al., 2001). In the European Union, the data generated by Ganzelmeier, Rautmann and co-workers are used to predict environmental concentration of pesticides in surface waters (EFSA et al., 2020; FOCUS, 2001). Along with predictions of the BREAM model (Kennedy et al., 2012), they are also used to estimate the exposure of residents and bystanders to surface deposits originating from off-target drift in the current EU risk assessment process (EFSA, 2022). Moreover, they are implemented in a model of the German Federal Institute for Risk Assessment to assess resident/bystander exposure (Martin et al., 2008). Extensive field trials to characterize drift from applications with ground hydraulic sprayers and orchard airblast sprayers have also been performed in the United States (Johnson, 1995a; Johnson, 1995b). The results of these trials have been implemented in the software AgDRIFT, which permits to model off-site deposition of pesticides due to spray drift and is used by the US EPA for terrestrial and aquatic assessments (Teske et al., 2002; Teske et al., 2003; US EPA, 2013). Further studies assessing drift caused by pesticide ground applications to various crops have been conducted in numerous countries, including Belgium (De Schampheleire et al., 2008; Nuyttens et al., 2007b), Colombia (García-Santos et al., 2016), France (Polveche et al., 2011), Italy (Meli et al., 2003), Spain (Torrent et al., 2017), Switzerland (Schweizer et al., 2013), the Netherlands (van de Zande et al., 2012; van de Zande et al., 2019; van de Zande et al., 2010), the United Kingdom (Cross et al., 2001a; Cross et al., 2001b) and the United States (Kasner et al., 2018; Kasner et al., 2020; Rathnayake et al., 2021). With regard to manned aerial applications, the results of a number of experimental studies have been reported (Bird et al., 1996; Bird et al., 2002; Butts et al., 2022; BVL, 2020; Hewitt et al., 2002; Viret et al., 2003; Woods et al., 2001). AgDRIFT allows to estimate downwind deposition from aerial applications using a modified version of the AGDISP model (Bilanin et al., 1989; Teske et al., 2002; Teske et al., 2003; Teske et al., 2019).

In the context of pesticide applications using conventional tractor-mounted equipment, there are also a number of reports on direct exposure of residents and bystanders to spray drift through deposition of drift droplets on the skin and/or inhalation. Specifically, Lloyd and co-workers have conducted trials in a field with arable crops and in an apple orchard in which off-target drift was collected on coveralls and self-breathing respirators worn by volunteers located in proximity to the field (Lloyd and Bell, 1983; Lloyd et al., 1987). In the European Union, the data collected in the framework of the orchard experiments as well as predictions according to the BREAM model are used to assess the direct exposure of residents and bystanders to drift droplets (EFSA, 2022; Kennedy et al., 2012; Lloyd et al., 1987). Additional field trials addressing direct resident and bystander exposure have been performed following applications to bare soil (Kasiotis et al., 2014), short grass (Butler Ellis et al., 2010; Glass et al., 2010), wheat (Butler Ellis et al., 2010; Kuster et al., 2021), grapevine (HSE, 2021; Mercier, 2020) as well as orchards (Butler Ellis et al., 2014; HSE, 2021). Further trials have been announced (Verpont et al., 2022). The European Food Safety Authority (EFSA) stated in a recent report that there is a high need for further data on resident/bystander exposure following orchard applications and that the associated concern is deemed high (EFSA, 2022).

The objective of this study was to quantify environmental, resident and bystander exposure due to spray drift caused by orchard treatments with a commercial UASS in order to address knowledge gaps that have recently been highlighted by the OECD (OECD, 2021). Based on the methodology described in the dedicated ISO standard 22866 (ISO 22866, 2005), deposition of spray droplets onto horizontal surfaces and airborne spray profiles were assessed downwind of a sprayed apple orchard. In addition, direct dermal and inhalation exposure of residents and bystanders to spray drift was quantified taking into account the above-mentioned ISO standard as well as relevant publications of EFSA and the OECD (EFSA, 2022; OECD, 1997; OECD, 2021). The collected data were compared to predictions of current regulatory models and previously reported field data on drift and exposure caused by different spraying equipment.

2. Material and methods

2.1. Study site

Field trials were conducted in an apple orchard located in Saint-Léonard, Switzerland (46.254° N, 7.437° E). In the orchard, the trunk-to-trunk distance in the same row was ~1.2 m and the inter-row spacing was ~4.0 m. During the first series of field trials performed in April 2022, trees were at the end of blossom and the development of foliage was incomplete (early treatment, BBCH 67) (Meier, 2018). The canopy height varied between 2.8 m and 3.2 m Based on the calculation method of the European and Mediterranean Plant Protection Organization, the tree row volume (TRV) and the leaf wall area (LWA) were estimated to be 11,472 m^3/ha and 14,850 m^2/ha, respectively (EPPO, 2021). Foliage was fully developed during the second series of field measurements, which were performed post-harvest in October 2022 (late treatment, BBCH 91) (Meier, 2018). The canopy height was 3.2 m, the TRV 15,960 m^3/ha and the LWA 16,015 m^2/ha (EPPO, 2021). The downwind detection area was grassland. Prior to the experiments, vegetation inside the detection area was cut to a maximum height of 7.5 cm in agreement with the stipulations laid out in the ISO standard 22866 (ISO 22866, 2005).

2.2. Application equipment

The UASS used was the six-rotor DJI Agras T30 (DJI Co., Ltd., Shenzhen, China). The weight without batteries and with an empty tank is 26.4 kg and the maximum take-off weight is 76.5 kg. The dimensions of the device with unfolded spraying arms are 2.86 m × 2.69 m × 0.79 m. It is equipped with a 30 L tank for the spraying liquid, which was dispensed *via* 16 downward-directed Teejet XR 11002 VK flat spray nozzles. The operational pressure was 1.2 bar. In general, these operational parameters are expected to result in "fine" and "medium" droplets according to the standard to measure and interpret spray quality from tips of the American Society of Agricultural and Biological Engineers (ASABE, 2020). With regard to the specific spraying liquid used herein (see Section 2.3), the droplet volume median diameter (VMD) of Teejet XR 11002 VK flat spray nozzles operated at 1.2 bar corresponds to 278 μm (Daniel Schneider, Syngenta Crop Protection AG, personal communication). Spray applications were conducted at a flight height of ~4.2 m above the ground, *i.e.*, ~1 m above the canopy, at a flight speed of 7.5 km/h (2.08 m/s) and at a nominal application rate of 140 L/ha. The swath width was approximately 4 m and corresponded to the inter-row spacing. These spray parameters were chosen because they reflect typical application practices of Swiss UASS service providers for orchard treatments. The drone was operated by DigitalRoots SA (Granges, Switzerland) and the spray track was followed in the satellite-assisted autopilot mode with a horizontal and vertical minimal hovering precision of ± 10 cm. Before the first measurement on April 27 and October 11, the nominal flow rate of 500 mL/min/nozzle was confirmed by measuring the actual volume sprayed within 60 s. Both field trials performed in April and those conducted in October were replicated four times.

2.3. Tracer material and additives

The fluorescent tracer benzoxazole, 2,2′-(2,5-thiophenediyl)bis[5-(1,1-dimethylethyl)- was used in all field trials. In order to mimic a typical plant protection product, it was formulated as a suspension concentrate at a nominal concentration of 500 g/L (trade name: Helios 500 SC, Syngenta Crop Protection AG, Basel, Switzerland). Helios 500 SC has been used in earlier efficacy and drift trials (Dubuis and Jaquerot, 2022; Schweizer et al., 2013; Viret et al., 2003; Vučajnk et al., 2018). The liquid used for spraying applications contained 0.3 % v/v Helios 500 SC, which corresponds to a nominal tracer concentration of 0.15 % w/v. Based on the directives given in the ISO standard 22866, a wetting agent was also added to the spraying liquid (0.02 % w/v Etalfix Pro, Syngenta Crop Protection AG, Basel, Switzerland).

2.4. Orchard treatment

Spray applications were performed on April 27–28, 2022 and October 11–12, 2022. The trial site is depicted in Fig. 1. The outermost 6 rows of the orchard were treated. The length of the sprayed area was 87 m and the width 24 m. The recently published OECD literature review on unmanned aerial spray systems in agriculture suggest to define the edge of an orchard (distance = 0 m) as half a swath from the downwind flight line (OECD, 2021). This definition was adopted in the context of the aerial treatments performed herein, where the downwind flight line of the UASS is equivalent to the imaginary line formed by the trunks of the outermost row of trees and a half-swath corresponds to 2 m in this trial. Before and after each field trial, a sample from the spraying liquid was taken directly from a nozzle to determine the actual tracer concentration, which was used in subsequent analysis of the results.

2.5. Collection of drift deposit and airborne drift

The collection of drift samples was performed in accordance with the ISO standard 22866 and the experimental set up is represented in Fig. 1. Sedimented spray drift was collected 0, 1, 3, 5, 10, 15, 20, 30 and 50 m downwind the sprayed area. For this purpose, a total of 4 laths per distance were placed parallel to the edge of the field. 5 Petri dishes (Fischerbrand™; Fischer Scientific) with a diameter of 8.8 cm serving as collectors were placed on each lath. Hence, the combined area of all collectors was 1216 cm^2 per distance. Airborne spray was collected 5 m downwind the edge of the field using a 6 m tall sampling tower with three vertical polypropylene strings with 2.5 mm diameter (mamutec AG, Sankt Gallen, Switzerland). Each string was cut into six 1 m long sections from the ground upwards to assess airborne drift at different heights. The sampling period ended 5 min after the end of the spraying application to ensure that spray drift droplets had deposited and was followed by sample collection. Similar waiting times were reported for earlier drift trials (Butts et al., 2022; Rathnayake et al., 2021).

2.6. Direct exposure of bystanders and residents to spray drift

The methodology of the direct drift exposure measurements was based on the whole body method and the personal sampling method described in the OECD guidance document for the conduct of studies of occupational exposure to pesticides during agricultural application (OECD, 1997). Briefly, display mannequins with a height of 175 cm and 110 cm, respectively, were used to represent adults or children. 3 mannequin pairs, each consisting of one adult and one child mannequins spaced by ~1 m, were placed 3 and 10 m downwind the sprayed area, respectively. 4 additional mannequin pairs were positioned at a downwind distance of 5 m. As shown in Fig. 1, the distance between two mannequin pairs located at the same downwind distance was >5 m and mannequin pairs were arranged in a staggered fashion to prevent "shadowing" effects. In order to collect spray drift leading to dermal exposure, they were dressed with loose fit 3M-4570 coveralls (3 M, Saint Paul, MN, USA) covering all body parts including the head. Child coveralls were small size adult coveralls with shortened arms and legs. To collect spray drift resulting in inhalation exposure, 3 adult and 3 child mannequins located a downwind distance of 3 m, 3 adult and 2 child mannequins located a downwind distance of 5 m and 2 adult and 2 child mannequins located at a downwind distance of 10 m were equipped with personal air-sampling pumps set to a flow rate of 5 L/min (GilAir Plus, Sensidyne®, St. Petersburg, FL, USA). A rubber tube was attached to the

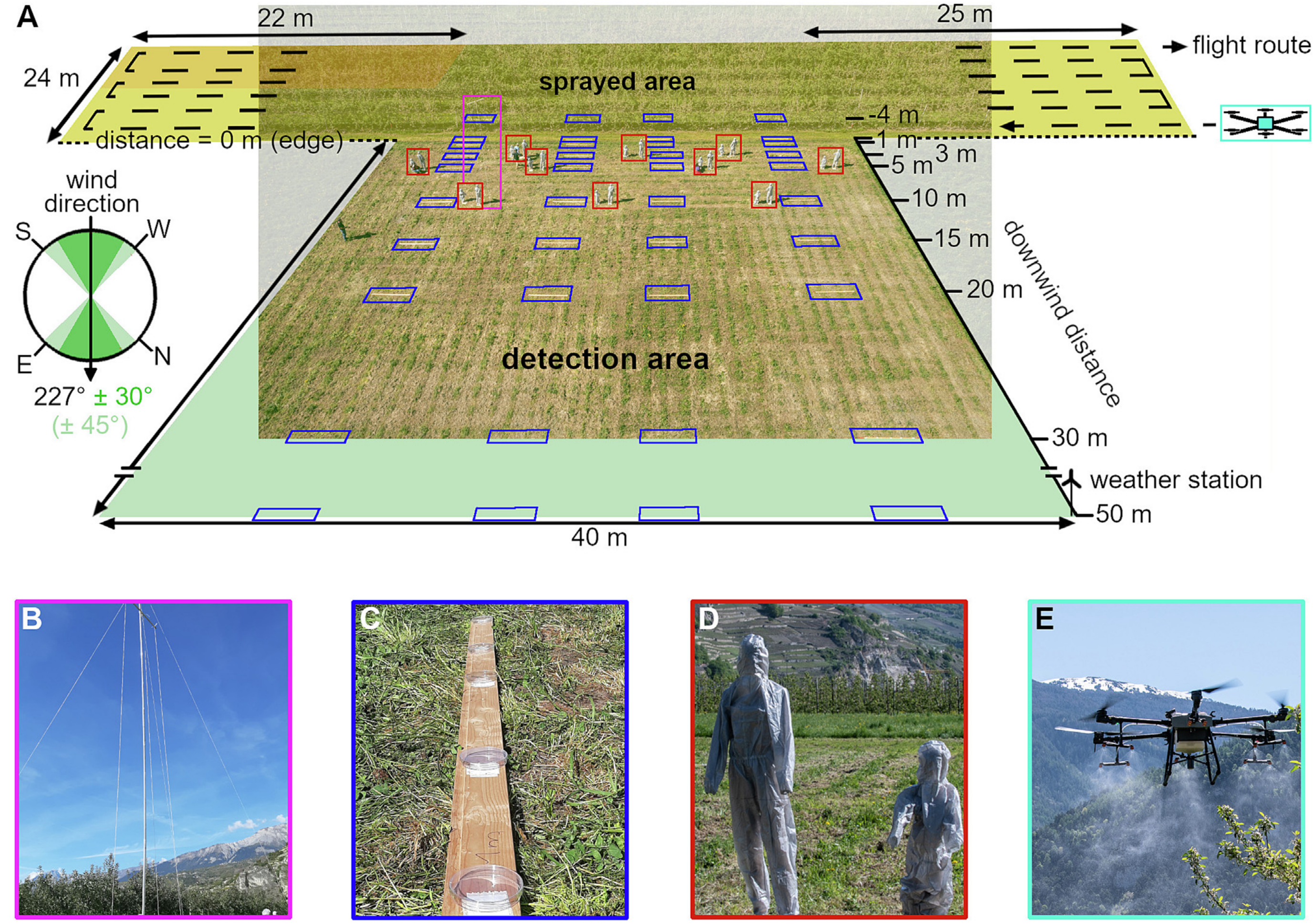

Fig. 1. Trial layout. A. Aerial photograph of the trial site overlaid with a schematic of the experimental design. The sprayed area corresponds to 6 rows of apple trees spreading out over ~24 m × ~87 m. It is represented in yellow and orange, though, the orange area was not treated in trials 5 and 6 (see Section 3.1). The downwind detection area is highlighted in green and extends over an area of 40 m × 50 m. The locations of the drift sampling tower, lats with Petri dishes and mannequins are indicated by purple, blue and red frames, respectively. At the trial site, the perpendicular of the spray track corresponds to a wind direction of 227°, which is indicated in the compass along with the acceptable mean wind directions and the range of wind directions that should represent at least 70 % of individual measurements. B. Picture of the drift sampling tower located 5 m downwind the sprayed area. C. Photograph of Petri dishes used to collect sedimented spray drift. D. Picture of mannequins representing adult or child bystanders and residents directly exposed to spray drift *via* the dermal and the inhalative route. E. Photograph of the six-rotor DJI Agras T30 used for spraying.

inlet of each pump with one end and the other end, which contained a cotton wool filter (50 mg ± 1 mg), was fixed to the side of the head-piece of the coverall such that ambient air was sampled from the breathing zone. The sampling period ended approximately 5 min after the end of the spraying application to ensure that spray drift droplets had deposited. Subsequently, coverall parts covering head, torso (chest and back including upper thigh groin level), upper limbs and lower limbs were collected separately. In addition, wool filters were collected from air-sampling pumps.

2.7. Sample handling, transport and storage

In general, samples were collected at decreasing distance from the sprayed area, *i.e.*, collection started 50 m downwind and was terminated 4 m upwind the edge of the field. To avoid contamination, disposable nitrile gloves (Unigloves®, Gillingham, UK) were worn and regularly changed during sample collection and samples corresponding to a specific body part of a specific mannequin, a specific downwind distance or height, respectively, were wrapped in individual bags labeled with identification numbers. All individually wrapped samples were transported to Agroscope, Changins, Switzerland, and stored in the dark at room temperature until further analysis.

2.8. Quantification of the collected tracer

The fluorescent marker was recovered from the different collectors using 2-propanol (99.6 % ACS, Acros Organics). To recover tracer material from Petri dishes, 10 mL of 2-propanol were added, followed by an incubation on a rotary plate for at least 10 min. Sections of monofilament string were soaked in 10 mL 2-propanol in Falcon tubes. The different coverall parts stored in individual plastic bags were soaked thoroughly in 100 mL 2-propanol (head) or 200 mL 2-propanol (upper and lower limbs, torso) for at least 10 min. Cotton wool filters were placed in Falcon tubes, followed by addition of 10 mL 2-propanol and incubation. After recovery, the tracer material was quantified by fluorimetry at an excitation wavelength of 375 nm and an emission wavelength of 435 nm (Fluorimeter 96, Syngenta Crop Protection AG, Basel, Switzerland) (Viret et al., 2003). Recovery efficiency was determined for the 3M-4570 coveralls used and ranged from 94.8 % to 98.7 %. The recovery efficiency of field samples was determined during the trials performed in October 2022 by spiking a 400 cm^2 piece of 3M-4570 coverall with 500 μL of spray liquid and measuring the amount recovered in the laboratory after transport and storage. The field recovery was 97.1 %.

2.9. Measurement of meteorological conditions

Wind velocity, wind direction, air temperature as well as relative humidity were monitored during the entire sampling period of each field trial at a sampling rate of 0.5 Hz. Wind speed and direction were detected at a height of 2.4 m using a WindSonic™ ultrasonic anemometer (Gill Instruments Limited, Hampshire, UK) connected to a weather station (Campbell Scientific, Logan, UT, USA), both of which were located within the sampling area at a downwind distance of 50 m.

2.10. Data analysis

Drift data (Section 2.5) were used to calculate height-dependent mean airborne drift and distance-dependent mean drift deposits for each trial. The latter further permitted to compute a cumulative projection along the decay curve to determine the distance corresponding to a cumulative drift deposit value of 90 % of the total amount of spray drift measured as described in the ISO standard 22844 (ISO 22866, 2005). Measurements of drift deposit in individual Petri dishes stemming from different trials were further used to compute the 50th, 77th and 90th inclusive percentiles at a given downward distance and crop growth stage by interpolation between adjacent values. In order to facilitate the comparison with other spray drift studies, all drift values were expressed as a percentage of the actual application rate (OECD, 2021).

Measurements of direct drift exposure using mannequins (Section 2.6) were characterized by small sample sizes of 3–4 per mannequin type, downwind distance and trial. For higher tier exposure assessments, EFSA stipulates that “exposure estimates should, as a default, be derived as the higher of: (a) (…) the distribution of measurements in the sample (…); or (b) a statistical estimate (…) for the theoretical population of measurements from which the sample was derived, under the assumption that this population has a log-normal distribution” (EFSA, 2022). To derive exposure percentile values from the distribution of measurements in the sample, adult and child exposure measurements performed at a certain downwind distance and crop growth stage were combined. As measurements of individual exposures for a given scenario are often log-normally distributed (EFSA PPR panel, 2010), they were fitted to a log-normal probability density function:

$$f(x) = \frac{1}{x\sigma\sqrt{2\pi}}\exp\left\{-\frac{(\ln(x)-\mu)^2}{2\sigma^2}\right\} \tag{1}$$

where x denotes the exposure expressed as a volume, μ is the location parameter and σ corresponds to the scale parameter. The respective cumulative distribution functions were used to derive the 50th, 75th and 95th percentiles.

Statistical estimates of the 75th and 95th were computed as:

$$\textit{percentile estimate} = \exp\left\{\bar{x} + t_{n-1,\alpha} * s * \sqrt{\frac{1}{n}}\right\} \tag{2}$$

Here, $\bar{x}$ and s are the arithmetic mean and the standard deviation of the natural logarithms of the exposure measurements, respectively, n denotes the sample size and $t_{n\text{-}1,\alpha}$ is the percentile of the t-distribution with n-1 degrees of freedom (EFSA, 2022).

Direct dermal and inhalation drift exposure data were expressed as volumes. To account for differences between the flow rate of the personal air sampling pumps and the actual inhalation rate of a person, inhalation exposure estimates were calculated based on hourly inhalation rates for acute exposures of 0.228 m^3/h per kg body weight (toddlers) and 0.053 m^3/h per kg body weight (adults) and body weights of 10 kg (toddlers) and 60 kg (adults), respectively (EFSA Scientific Committee, 2012; US EPA, 2011). These values are recommended in the recently published EFSA guidance on the assessment of exposure of operators, workers, residents and bystanders in risk assessment for plant protection products (EFSA, 2022).

All data analyses were performed using RStudio, R version 4.2.0. Specialized functions from the R libraries *dplyr* (Wickham et al., 2023), *ggplot2* (Wickham, 2016), *tidyverse* (Wickham et al., 2019), *showtext* and *MASS* (Venables and Ripley, 2002) were used.

3. Results

3.1. Unexpected events during field trials

Wind speed and direction during trials 1 and 3 conducted on April 27 and 28, 2022, respectively, as well as trial 7 done on October 12, 2022 did not fully comply with the stipulations of the ISO standard 22866. The deviations are discussed in Section 3.2. During trials 5 and 6, the outermost 22 m of the last three rows, which were located at upwind distance of 12 m or more, were not treated (Fig. 1A, highlighted in orange). As >90 % of spray drift deposit was confined within a downwind distance of <5 m, this deviation is thought to have a negligible impact on measured drift levels. Please see Section 3.4 for further details. Further deviations occurred during trials 5 and 6: (i) The spraying liquid was not diluted according to the experimental protocol, which resulted in an actual tracer concentration of 0.19 % (w/v) instead of the target concentration of 0.15 % (v/w), and (ii) the volume application rate was 150 L/ha instead of the target rate of 140 L/ha. In general, actual tracer concentration and actual application rates were accounted for in the analysis of the results, and hence, the impact of these deviations was considered minor. During all trials, a total of 24 Petri dishes, *i.e.*, 1.5 % of a total of 1600 drift deposit measurements, were blown off the laths during the spraying operation. The Petri dishes concerned were located at downwind distances of 0–5 m and excluded from further analysis. Finally, a total of three mannequins toppled over backwards during the sampling period, the possible impact of which is discussed in detail in Sections 3.5 and 3.6.

3.2. Meteorological conditions

Mean air temperatures were very similar during all trials performed in April and October 2022. They ranged from 18.8 °C to 22.4 °C with a standard deviation ≤0.2 °C. Considering mean relative humidity, which ranged from 29.7 % (trial 1, April 27, 2022) to 56.5 % (trial 8, October 12, 2022), mean wet bulb temperatures that take into account cooling due to evaporation were estimated to range from 9.9 °C (trial 1) to 15.4 °C (trial 8) (Stull, 2011). The mean wind velocity was at least 1.3 m/s (trials 1, 3 and 7) and did not exceed 3.0 m/s (trial 4), which corresponds to the legal threshold beyond which UASS operations are not permitted in Switzerland (FOCA, 2021). Mean wind directions did not deviate by >24° from the perpendicular to the spray track. These meteorological data comply with the stipulations of the ISO standard 22866, according to which temperatures between 5 °C and 35 °C, wind speeds ≥1 m/s and mean wind directions at 90° ± 30° to the spray tracks are acceptable (ISO 22866, 2005). According to the same document, no more than 10 % of wind speed measurements should be <1 m/s and no more than 30 % of wind direction measurements should be >45° from the perpendicular of the spray track (ISO 22866, 2005). As shown in Fig. 2, the meteorological conditions during trials 2, 4, 5, 6 and 8 complied with these criteria as well. In turn, 38.3 % of wind speed measurements during trial 1 were below the threshold with a concomitant variation in wind direction resulting in 56.8 % of values falling outside the permitted range. Deviations were particularly pronounced during treatment of the first tree row with weak winds almost parallel to the spray track (Fig. S1). During trial 3, 33.3 % of wind speed and 48.8 % of wind direction measurement did not comply with the above-mentioned criteria, albeit deviations were almost exclusively observed after complete treatment of the outermost rows contributing most to downwind drift (Fig. S1). Regarding trial 7, 28.8 % of wind speed measurements were below the threshold of 1 m/s, though, only 8.3 % of individual data points were below 0.75 m/s (Fig. S1).

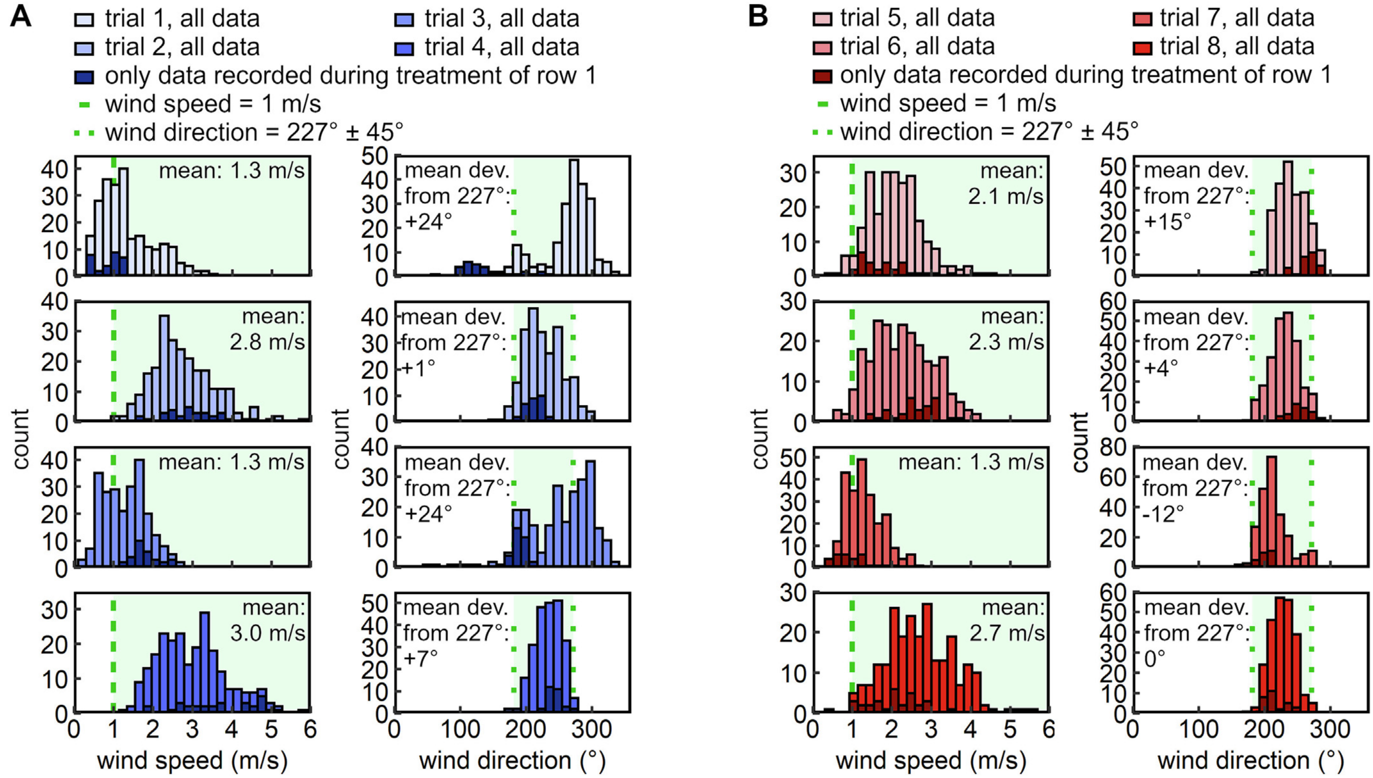

Fig. 2. Wind speed and direction during the field trials. A. Histograms showing the distribution of wind speed and wind direction data collected during field trials conducted in April 2022 (blossom, BBCH 67). B Histograms showing the wind data recorded in October 2022 (post-harvest, BBCH 91). Data that were recorded during the treatment of the first tree row neighboring the edge of the field are depicted in dark blue or dark red, respectively. Dashed lines indicate a wind speed of 1 m/s that should not be undercut by >10 % of individual measurements according to the ISO standard 22866 (ISO 22866, 2005). Dotted lines represent the wind directions perpendicular to the spray track ± 45° that constitute the range that should not be exceeded by >30 % of data points according to the ISO standard 22866 (ISO 22866, 2005).

3.3. Airborne drift

The results of airborne drift measurements conducted at the sampling tower located 5 m downwind are given in Fig. 3. They are indicative of the profile of the drift cloud resulting from the UASS operation. In general, airborne drift correlated negatively with sampling height and increased at higher wind speed. Very low airborne drift levels were observed with respect to trial 1, which reflects the substantial deviation from the range of acceptable wind conditions of standardized drift trials (ISO 22866, 2005). Airborne drift observed in trials 3 and 7 was similar to the data collected in trials 4 and 5, respectively, suggesting that the slight deviations from the meteorological acceptance criteria did not considerably impact airborne drift levels. Finally, airborne drift values did not approximate 0 % at a height of 5–6 m in trial 8, which may be due to turbulent and/or gusty wind conditions (Rathnayake et al., 2021).

3.4. Drift deposit

Fig. 4 shows ground deposition levels upwind and downwind the edge of the field in each trial, *i.e.*, both in-swath and drift measurements are represented. Each data point corresponds to the arithmetic mean of deposit values from individual Petri dishes, *i.e.*, 20 measurements per distance in most cases but not less than 12 when individual Petri dishes had to be excluded from further analysis (see also: Section 3.1). Mean deposition 4 m

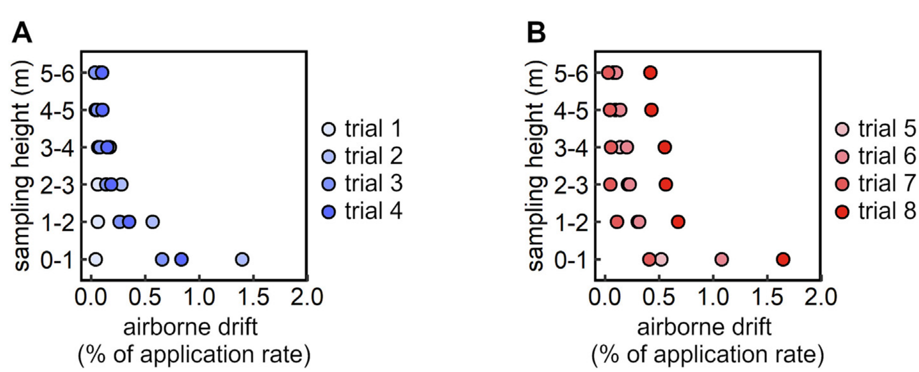

Fig. 3. Height-dependent mean airborne drift at a downwind distance of 5 m. A. Vertical drift data collected during field trials conducted in April 2022 (BBCH 67, blossom). B Data recorded in October 2022 (BBCH 91, post-harvest). Each dot corresponds to the arithmetic mean of three individual measurements, *i.e.*, the drift collected on a given portion of three different monofilament lines.

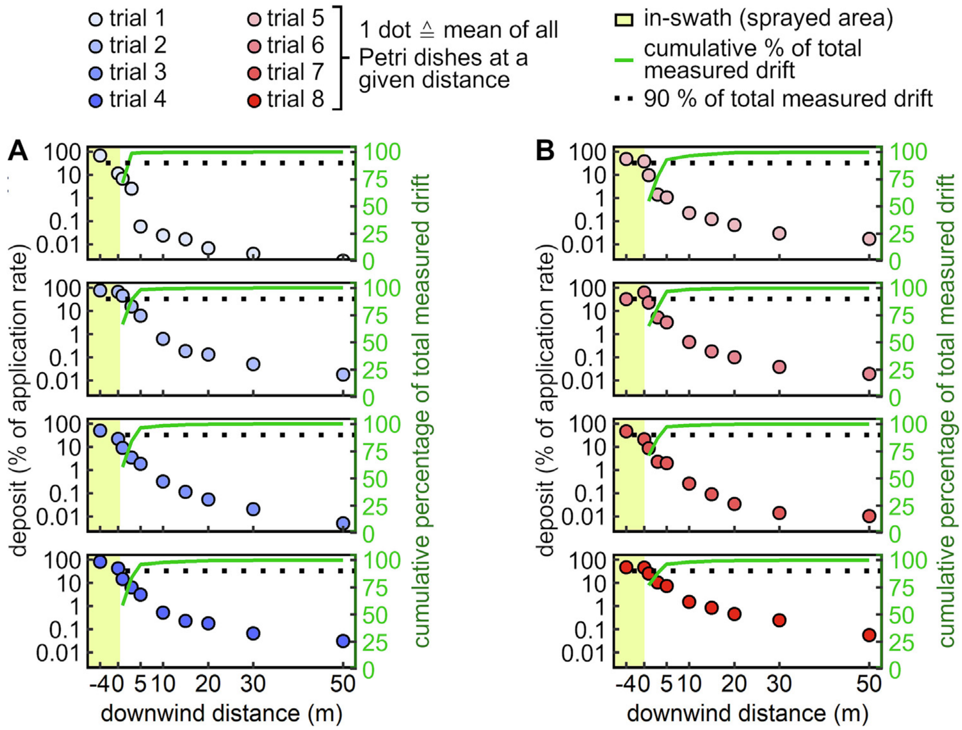

Fig. 4. Drift deposit at different downwind distances. A. Drift deposit data collected during field trials conducted in April 2022 (blossom, BBCH 67). B Data recorded in October 2022 (post-harvest, BBCH 91). Yellow swaths highlight negative downwind distances, *i.e.*, data points collected within the sprayed area. Green lines correspond to the cumulative projection of the measured drift values to determine the distance corresponding to a drift value of 90 % of the total amount of drift deposit measured. The 90 % threshold is indicated in each panel as a dotted line.

upwind the edge of the plot ranged from 31.5 % (trial 6) to 79.5 % (trial 4) of the actual application rate, which varied from 197.37 g tracer/ha (trial 1) to 284.36 g tracer/ha (trial 5). Deposition inside the treated plot was generally higher in the first series of field trials conducted prior to full development of foliage. Distance-dependent drift levels resembled a "slackened" exponential decay (Holterman et al., 2017), which decreased to values <0.1 % at the farthest downwind distance of 50 m. The cumulative projection of the measured drift values, a representation proposed in the ISO standard 22866, reveals that 90 % of the total amount of drift deposit measured deposited at downwind distances <5 m in trials 2–8. Conversely, the threshold of 90 % of total drift was reached at a downwind distance <3 m in trial 1 during which wind speed and direction significantly deviated from the stipulations of the ISO standard. This observation highlights the importance of wind conditions in drift trials.

For an in-depth analysis, the aggregated data collected in trials performed in April and October, respectively, were used to calculate mean drift deposit levels as well as 50th, 77th and 90th drift percentiles for early and late UASS treatments. As drift profiles observed in trial 1 proved markedly different from those observed in the other trials done in April (trials 2–4), the former were excluded from further analysis. Two representative plots depicting drift deposits at a downwind distance of 3 m along with the corresponding 50th, 77th and 90th percentiles are shown in Fig. 5. Analogous plots for all downwind distances investigated can be found in the Supplementary Information (Figs. S2 and S3). For all distances and growth stages, individual measurements spread over a wide range and followed a positively skewed distribution, with arithmetic means systematically higher than the corresponding 50th percentiles. Interestingly, 77th and 90th drift percentiles observed in trials conducted in April were in very good agreement with the corresponding percentiles derived from data collected in October (Fig. 6). As a consequence, distance-dependent arithmetic means and percentiles values were also calculated for the combined dataset (trials 2–8). All results are summarized in Table S1.

3.5. Direct dermal exposure to drift

Fig. 7 shows the relative dermal exposure of different body parts at a downwind distance of 3 m for early and late UASS treatments. The entire dataset is represented in Figs. S4 and S5. Based on the rationale provided in the previous section, the results of trial 1 were eliminated from the analysis. Dermal exposure measured with adult mannequins was most pronounced on the lower limbs (62/70 mannequins), followed by the torso and the arms, which displayed similar exposure levels. With regard to child mannequins, a trend was less evident, as the legs were the most exposed body part in 32 instances, followed by the torso (21 instances) and the arms (17 instances). In this context, it should be emphasized, however, that the surface areas of the coverall parts covering the legs and the torso were roughly equal in the case of adult mannequins, while they were not in the case of child mannequins. Specifically, the surface of the coverall region covering the torso was 1.39 ± 0.15 fold greater than that covering the lower limbs (mean ± standard deviation). This is in excellent agreement with default surface area values that are used within the European Union to assess the risks associated with biocides and pesticides, based on which the surface of a torso is expected to be 1.32 times greater than that of the legs in the case of a 6 to <12 year old child irrespective of gender (EFSA, 2022). Finally, the head was the least exposed part of the body in the combined adult/child mannequin dataset (135/140 instances).

From a risk assessment perspective, it is relevant to compute the potential dermal exposure, which corresponds to the maximum amount of tracer that could have come in contact with the skin. In the context of the present study, it is calculated as the sum of tracer detected on all body parts. The corresponding cumulative percentage plots of the potential dermal exposure data collected at a downwind distance of 3, 5 or 10 m are shown in Figs. 7, S4 and S5. Three data points stem from adult mannequins that toppled over backwards while the trial was on-going, possibly because of uneven ground and gusts. The corresponding dermal exposure values were not excluded from the dataset, as the adjacent child mannequins, which were located at a distance of ~1 m, displayed similar dermal exposure

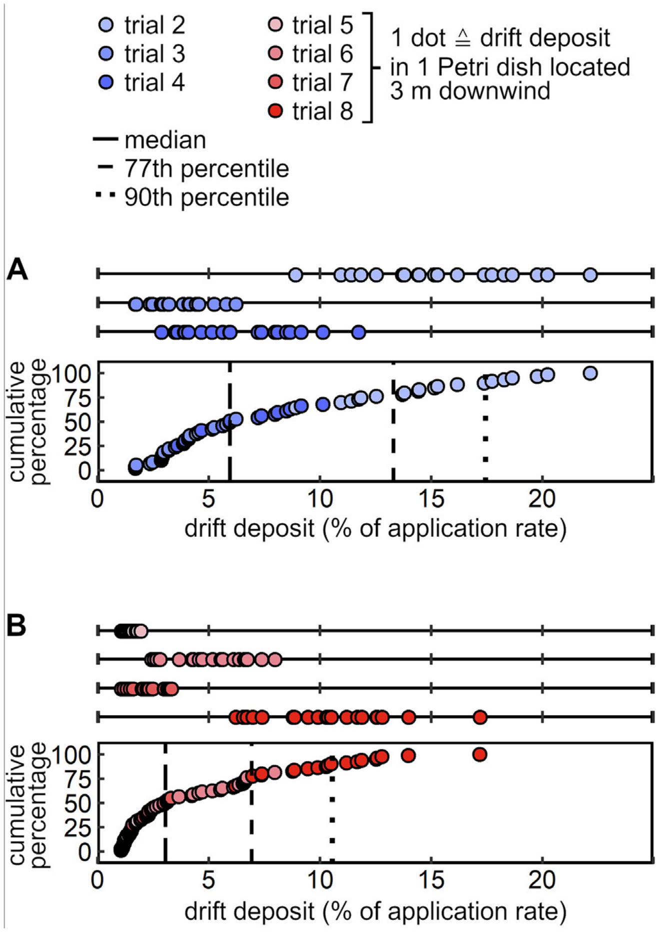

Fig. 5. Cumulative percentage graphs built from drift deposit values derived for individual Petri dishes, representative data collected at a downwind distance of 3 m. A Data collected during field trials conducted in April 2022 (blossom, BBCH 67). B Data recorded in October 2022 (post-harvest, BBCH 91). 1D dot plots above the cumulative percentage plots illustrate the scatter of drift deposit values observed within the same trial. Long dashed, dashed and dotted lines correspond to the median, 77th and 90th percentiles, respectively, all of whom were determined by interpolation between the two closest values. Analogous plots were computed for the entire range of downwind distances assessed and are shown in Figs. S2 and S3.

levels, suggesting that the incidents did not markedly influence the outcome of the measurements. Based on EFSA's stipulations for higher tier exposure assessments (EFSA, 2022), 50th, 75th and 95th percentiles were calculated for each crop growth stage, mannequin type and downwind distance from a log-normal fit to the data and 75th and 95th percentile values were further statistically estimated assuming a log-normal distribution of the sample. Statistical estimates were consistently higher than the corresponding percentiles derived from the fit. Both log-normal fits, 50th percentiles and the statistical estimates of the 75th and 95th percentiles are represented in Figs. 7, S4 and S5. Analogous analyses were performed for each body part and the results are represented in Figs. S6 and S7. Remarkably, 75th and 95th potential dermal exposure percentiles upon early and late treatment were virtually identical (Fig. 8), which corroborates the observations made for drift deposit levels (Fig. 6). As a consequence, dermal exposure descriptors were derived from the entire dataset (trials 2–8) as well. All results are recapitulated in Table S2 of the Supplementary Information.

3.6. Direct inhalation exposure to drift

Representative plots built from inhalation exposure data collected at a downwind distance of 3 m are given in Fig. 9. The entire dataset is represented in the Supplementary Information (Figs. S8 and S9). Log-normal fits are shown as well as 50th, 75th and 95th exposure percentiles that were calculated as described above. Based on the rationale provided in the preceding sections, data points stemming from fallen mannequins, which did not tangibly differ from the remaining measurements, were considered in the analysis, whereas those of trial 1 were not. In general, total direct inhalation exposure to spray drift was orders of magnitude below potential direct dermal exposure. The average amount of tracer was higher in filters from pumps attached to child mannequins than from those fixed to adult mannequins, albeit this difference was levelled out upon correcting for inhalation rates and body weights (Figs. 9, S8 and S9 depict the corrected data). In an analogous fashion as the drift deposit and direct dermal exposure levels, direct inhalation exposure declined at increasing downwind distance, albeit the 95th percentile estimate for child mannequins located 10 m downwind, which was derived from the data of the first trial series, was comparatively high. This is likely to be due to the way statistical percentile estimates were calculated, *i.e.*, a low sample size of 6 results in a substantial weight given to the standard deviation. Fig. 10 shows that the 75th and 95th inhalation exposure percentiles upon early and late treatment match reasonably. Comparison of percentiles exclusively computed from the log-normal fit, thereby excluding statistical estimates, improved the agreement of the two datasets (Fig. S10). All results are compiled in Table S2 of the Supplementary Information.

4. Discussion

Overall, both drift and exposure levels tailed off at increasing downwind distances and height. Distance-dependent decreases in drift deposit levels have been observed in earlier trials involving various crops for both UASS, manned agricultural aircrafts and tractor-mounted sprayers (Ahmad et al., 2022; Bird et al., 2002; Brown and Giles, 2018; Butts et al., 2022; Chen et al., 2020; De Schampheleire et al., 2008; Herbst et al., 2020; Huang et al., 2023; Li et al., 2022; Meli et al., 2003; Nuyttens et al., 2006a; Torrent et al., 2017; van de Zande et al., 2012; van de Zande et al., 2019; Wang et al., 2021; Wang et al., 2023; Wang et al., 2020;

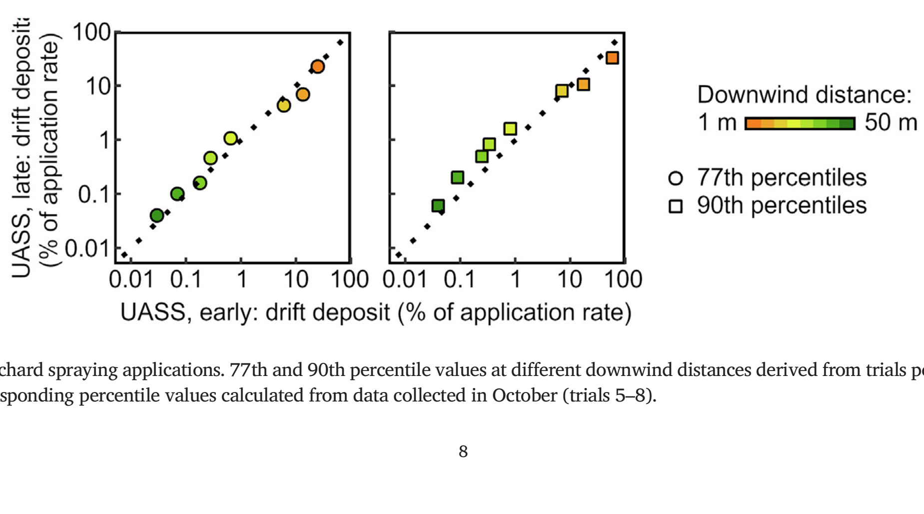

Fig. 6. Drift deposit upon orchard spraying applications. 77th and 90th percentile values at different downwind distances derived from trials performed in April (trials 2–4) are plotted against the corresponding percentile values calculated from data collected in October (trials 5–8).

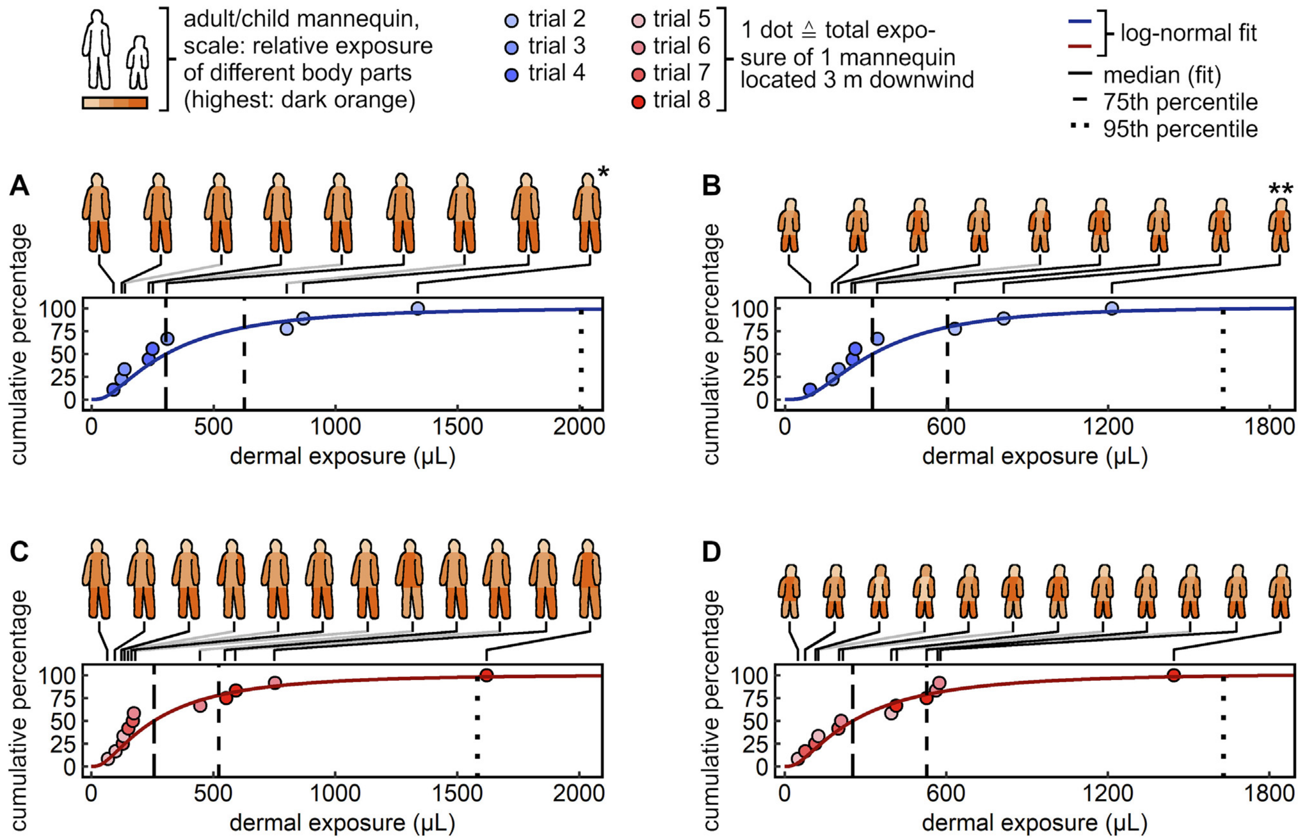

Fig. 7. Cumulative percentage graphs built from potential dermal exposure data estimated using adult and child mannequins dressed with 3M-4470 coveralls, representative data collected at a downwind distance of 3 m. A-B Data collected during field trials conducted in April 2022 (blossom, BBCH 67). C-D Data recorded in October 2022 (post-harvest, BBCH 91). Individual mannequins and the relative exposure of their different body parts are represented above each plot. Blue/red lines correspond to a cumulative representation of a log-normal fit to a histogram constructed from the respective dataset. Long dashed, dashed and dotted lines correspond to its median (log-normal fit), 75th and 95th percentiles (higher of log-normal fit and statistical estimate), respectively. The value from the adult mannequin that fell during the trial is highlighted with an asterisk, the value of the neighboring child mannequin with two asterisks.

Wang et al., 2018; Woods et al., 2001; Xue et al., 2014; Zhan et al., 2022). In a number of UASS drift trials, airborne drift has also been measured, unveiling vertical profiles that were qualitatively very similar to the one reported here (Herbst et al., 2020; Wang et al., 2021; Wang et al., 2023; Wang et al., 2020; Xue et al., 2014). This can be explained by fact that larger drift droplets have a higher mass than smaller drift droplets, and hence, tend to deposit at shorter downwind distances and on the lower fraction of the vertical drift detectors (Wang et al., 2020; Zimdahl, 2007). It should be noted, however, that vertical drift profiles with a maximum not located on the lowest fraction of the vertical collectors have been observed in drift trials performed with tractor-mounted orchard sprayers (Cross et al., 2001a; Cross et al., 2001b; Kasner et al., 2018; Kasner et al., 2020). Moreover, canopy growth stage has been reported to affect agrochemical drift and resident/bystander exposure following tractor-assisted orchard applications (Ganzelmeier et al., 1995; HSE, 2021; Polveche et al., 2011; Rathnayake et al., 2021; Rautmann et al., 2001; van de Zande et al., 2019; van de Zande et al., 2010), whereas such effects were not evident in in the present study despite marked differences in tree row volume. The possible reason for these differences is that cross-flow blowers and radial flow compressors typically used in orchard applications discharge spray liquid in an arc in the sideward and/or upward direction, whereas UASS, analogous to hydraulic boom sprayers, operate above the crop and discharge the spray liquid in a

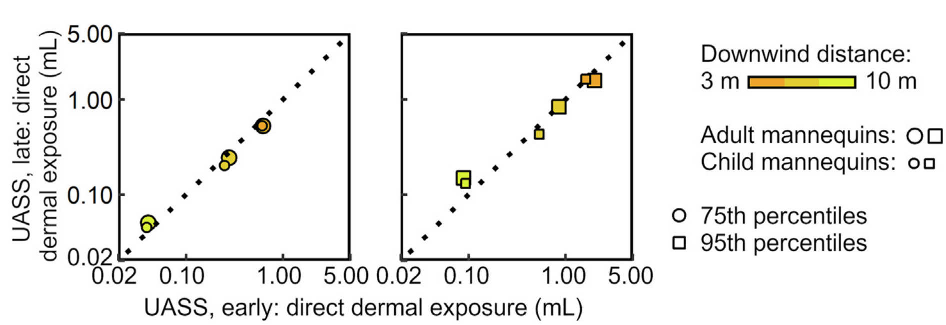

Fig. 8. Direct dermal bystander/resident exposure to spray drift following orchard spraying applications. 75th and 95th percentile values at different downwind distances derived from trials performed in April (trials 2–4) are plotted against the corresponding percentile values calculated from data collected in October (trials 5–8). Each exposure value corresponds to the higher of the log-normal fit and the corresponding statistical estimate.

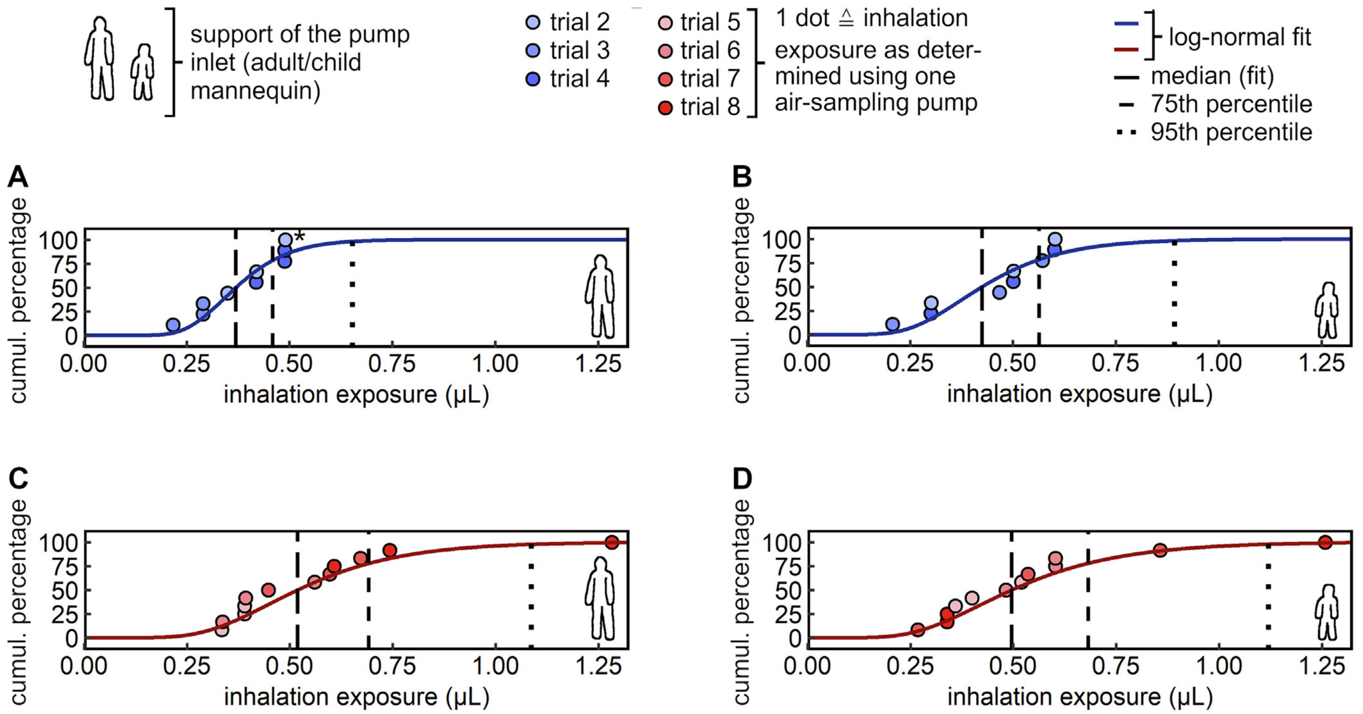

Fig. 9. Cumulative percentage graphs generated from inhalation exposure data estimated using adult and child mannequins equipped with personal air sampling pumps, representative data collected at a downwind distance of 3 m. A-B Data collected during field trials conducted in April 2022 (blossom, BBCH 67). C-D Data recorded in October 2022 (post-harvest, BBCH 91). Blue/red lines correspond to a cumulative representation of a log-normal fit to a histogram constructed from the respective dataset. Long dashed, dashed and dotted lines correspond to its median (log-normal fit), 75th and 95th percentiles (higher of log-normal fit and statistical estimate), respectively. The value derived for the adult mannequin that fell during the trial is highlighted with an asterisk.

downward-directed fashion. For hydraulic boom sprayers, drift levels have been reported to be unaffected by crop growth stage (Ganzelmeier et al., 1995; Rautmann et al., 2001).

In all trials conducted here, 90 % of total drift deposit as determined according to the method described in the ISO standard were consistently contained within a downwind distance of <5 m (ISO 22866, 2005). This value is rather low compared to those published in earlier reports: For a Z3 single-rotor UASS releasing a tracer over a rice paddy, 90 % of spray drift was observed within the first 8 m (Xue et al., 2014). The 90 % of the total drift locations ranged from 3.7 to 46.5 m for applications to a pineapple field with a single-rotor 3WQF120–12 (Wang et al., 2018). In a different study conducted in grassland with a P20 4-rotor UASS equipped with a rotary nozzle, the 90 % threshold was reached at a distance of 3.6–23.9 m (Wang et al., 2020). In a drift study performed in an almond orchard, the threshold was not reported, but calculated by the authors of the present work. It ranged from <3-<10 m depending on the flight speed of the 3WYD-4-22A quadcopter used. Wang and co-workers have tested three UASS equipped with hollow-cone or drift-reducing air-injection nozzles in trials involving artificial grapevines (Wang et al., 2021). They found that 90 % of spray drift were contained within a distance of 9.1–10.0 m (3WQF120-12 single-rotor UASS), 7.9–11.5 m (3WM6E-10 6-rotor UASS) and 11.7–13.6 m (3WM8A-20 8-rotor UASS). Brown and Giles reported that 82 % of total drift deposit generated by a Yamaha R-Max II single-rotor UASS following treatment of a full-leafed vineyard were contained within 7.5 m (Brown and Giles, 2018). Finally, Huang et al. assessed the influence of reduced flight height, increased droplet size and addition of non-ionic surfactant on drift caused by a DJI Agras T30 hexacopter (Huang et al., 2023), *i.e.*, the same UASS that was used in the present study. 90 % of spray drift was observed within the first 7.7–18.9 m downwind the artificial rice paddy treated. As UASS were not operated side-by-side, comparing these results is daunting due to differences in study methodology, droplet size distribution, crop characteristics and environmental conditions (Brown and Giles, 2018). Nonetheless, the rather narrow buffer zone containing most of the drift deposit observed herein was surprising because the release height of ~4.2 m was comparatively high, the droplet size distribution was medium (VMD = 278 μm) and wind speeds reached the

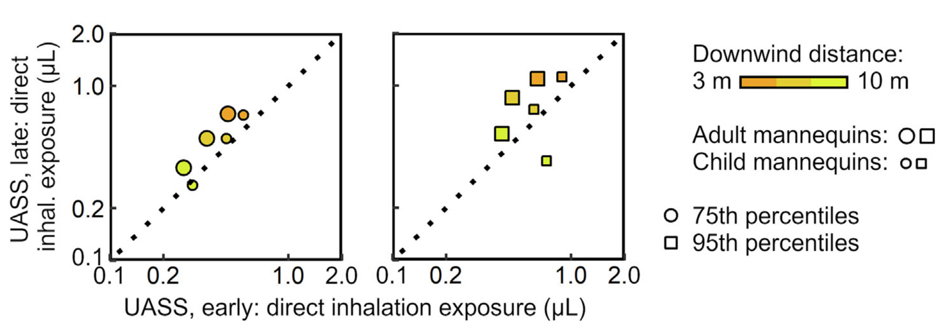

Fig. 10. Direct bystander/resident exposure *via* inhalation of spray drift following orchard spraying applications. 75th and 95th percentile values at different downwind distances derived from trials performed in April (trials 2–4) are plotted against the corresponding percentile values calculated from data collected in October (trials 5–8). Each exposure value corresponds to the higher of the log-normal fit and the corresponding statistical estimate.

maximum legal threshold for UASS operations in Switzerland. Both release height, droplet size distribution and wind speed are major known factors impacting drift in aerial pesticide applications (Butts et al., 2022; Huang et al., 2012; Huang et al., 2023; Wang et al., 2023). Scrutiny of the operational parameters in the above-mentioned UASS drift studies unveiled that most of the UASS flew at velocities of 3 m/s or more (Brown and Giles, 2018; Huang et al., 2023; Wang et al., 2020; Wang et al., 2018; Xue et al., 2014). Wen et al. demonstrated the occurrence of a spiral wake at the rear of the fuselage of a single-rotor aircraft when flight speeds exceeded 3 m/s in numeric simulations (Wen et al., 2018). This vortex has been referred to as a major factor affecting the drift of UASS (Chen et al., 2022) and may have contributed to the observed discrepancies between the findings reported here and the literature precedent. Indeed, increased far-field drift was observed in a recent field study as the flight speed of a 4-rotor UASS was increased from 1 m/s to 3 m/s (Li et al., 2022). Finally, it was also noted that not all UASS used in the above-mentioned studies were operated in the satellite-assisted autopilot mode. In our hands, manual UASS operation can lead to higher drift levels.

From a risk assessment perspective, it is critical to understand whether off-target movement of spray droplets caused by UASS is covered by predictions of existing regulatory models relating to conventional tractor-mounted equipment. Fig. 11A shows a comparison of the distance-dependent drift deposit values observed herein (trials 2–8) and reference values for orchard sprayers implemented in current regulatory models. Interestingly, the distance-dependent 90th percentile values derived from the Ganzelmeier-Rautmann dataset (Ganzelmeier et al., 1995; Rautmann et al., 2001), which have been implemented in the EU models to assess surface water and bystander exposure (EFSA et al., 2020; EFSA, 2022; FOCUS, 2001), are systematically higher than the corresponding percentiles computed from our UASS dataset. Similarly, 50th drift percentiles calculated in a tier I terrestrial assessment with AgDRIFT version 2.1.1 (Teske et al., 2002), a software used by the US EPA to assess the risk of pesticide drift to the environment (Rathnayake et al., 2021; US EPA, 2013), are consistently higher than the corresponding UASS drift percentiles. In this context, it should be stressed that the EU risk assessment process assumes that "early" treatments are performed at a dormant growth stage, *i.e.*, the underlying drift trials were performed in the absence of foliage (Ganzelmeier et al., 1995; Rautmann et al., 2001). The US risk assessment process makes the general assumption that orchard applications are made to sparse, young, dormant apple trees and disregards the actual timepoint of application (Rathnayake et al., 2021; Teske et al., 2002; Teske et al., 2003). In contrast, "early" treatments were done at blossom in the context of the present study, even though growth stage does not appear to have a significant effect on drift deposit levels generated by the specific UASS used (*vide supra*). The deposit levels observed were further compared to the results of drift trials conducted in an apple orchard with an axial fan sprayer equipped with different nozzles in April and October, as well as recently published findings from a total of 220 drift measurements in apple orchards before and after May 1 using a cross-flow fan sprayer (Polveche et al., 2011; van de Zande et al., 2019). It should be noted that in the spray drift deposition curves reported by van de Zande and co-workers, the edge of the field is located 3 m from the center of the last tree row (Ctgb, 2021), and thus, an offset of 1.5 m was incorporated to match the definition of the edge of the field used here. As citrus is an important tree crop, which differs from apple trees with regard to training system, tree architecture, leafiness, canopy penetrability as well as its evergreen condition (Meli et al., 2003; Torrent et al., 2017), the results of drift trials with an axial airblast sprayer that were performed in commercial clementine orchards located in Spain were included as well (Torrent et al., 2017). With the exception of one measurement reported by Polveche et al. (ATR yellow nozzles, late treatment, distance = 5 m, Δ = 0.34 %), all drift values reported in the above-mentioned studies were higher than the corresponding percentiles calculated from the data collected here. This also holds true for lower percentile values of the reference datasets (Fig. S11A). Overall, these findings demonstrate that the drift deposit levels observed for the specific UASS used are covered by current regulatory models relating to drift of orchard sprayers. They were also generally lower than those observed in experimental drift studies involving orchard sprayers. In this comparison, the inherent variability under field conditions is expected to be partially addressed by the large number of samples underlying the datasets. A side-by-side comparison of UASS and orchard sprayers would, however, be required to unambiguously clarify whether UASS can indeed be deemed superior to conventional orchard sprayers with regard to drift deposit.

Limited data exist with regard to direct resident/bystander exposure following orchard treatments with conventional tractor-mounted sprayers. The data that were reported by Lloyd et al. for a volumetric application rate of 470 L/ha are used in the European exposure assessment model to predict dermal and inhalation exposure at downwind distances of 5 and 10 m (EFSA, 2022), albeit it should be noted that they were recorded at a distance of 8 m from the outermost line of tree trunks (Lloyd et al., 1987). The model allows for the assessment of both early and late treatments (EFSA, 2022), even though no explicit mention of crop growth stage is made in the original report. The meteorological data included suggest that experiments were conducted in summer, and thus, foliar development likely was advanced (HSE, 2021; Lloyd et al., 1987). Extensive field trials in orchards at early (53 ≤ BBCH ≤ 57) and late (81 ≤ BBCH ≤ 91) growth stage were conducted in the "Bystander Resident Orchard Vineyard" (BROV) project, though, there was uncertainty regarding the actual application rate in some of these trials (HSE, 2021). Finally, Butler Ellis and co-workers performed field experiments to assess direct dermal resident/bystander exposure at application rates of 202 and 219 L/ha, respectively (Butler Ellis et al., 2014). As for the study of Lloyd et al., distances were reported from the last row of tree trunks. Fig. 11B and C show a comparison of the distance-dependent 95th dermal and inhalation exposure percentiles of the above-mentioned datasets and the corresponding percentiles of the present study, all of which were normalized to an application rate of 100 L/ha. Regarding the data of Lloyd et al., the comparison shown reproduces the way the data are presently used in the European regulatory process, *i.e.*, downwind distances of 5 and 10 m as well as early and late treatments are considered. As for the dataset of the BROV project, the means of the reported application rates for early/late treatments were used for normalization. With respect to the dataset of Butler Ellis and co-workers, dermal exposure percentiles relating to downwind distances of 5 and 10 m were statistically estimated (see Section 2.10). To partly account for the difference in the way the edge of the field was defined, they are plotted against the corresponding percentiles pertaining to downwind distance of 3 and 5 m, respectively. Overall, the comparison shows that resident/bystander exposure levels observed for the specific UASS used are covered by the current EU regulatory model to assess resident/bystander exposure following orchard treatments with conventional tractor-mounted equipment. Moreover, direct exposure of residents/bystanders observed here was not substantially dissimilar from direct exposure in earlier trials with tractor-based equipment at downwind distances of 3 and 5 m. It was consistently lower at a downwind distance of 10 m. Comparison of the 75th exposure percentiles yields very similar results (Figs. S11B and S11C). As for drift deposit, a side-by-side comparison of UASS and orchard sprayers would, however, be required to unambiguously clarify whether the UASS cause less resident/bystander exposure than orchard sprayers, especially at higher downwind distances.

With regard to downwind deposition caused by pesticide applications involving manned aircrafts, the US EPA uses a modified version of the AGDISP algorithm implemented in the AgDRIFT software (Bilanin et al., 1989; Teske et al., 2002; Teske et al., 2019). A number of assumptions are made in tier I assessments, *i.e.*, treatment is performed with an Air Tractor AT-401 fixed-wing aircraft with a swath width of ~18.3 m, release height is ~3 m and the wind speed is 4.47 m/s (Teske et al., 2003; US EPA, 2013). The model has been shown to provide reasonable estimations of drift deposits, albeit underpredictions in the near-field and overprediction in the far-field have been precedented (Bird et al., 2002; Butts et al., 2022). Fig. 11D (left panel) depicts a comparison of distance-dependent drift deposit levels as determined in a tier I assessment using AgDRIFT version 2.1.1 assuming a fine to medium drop size distribution and the

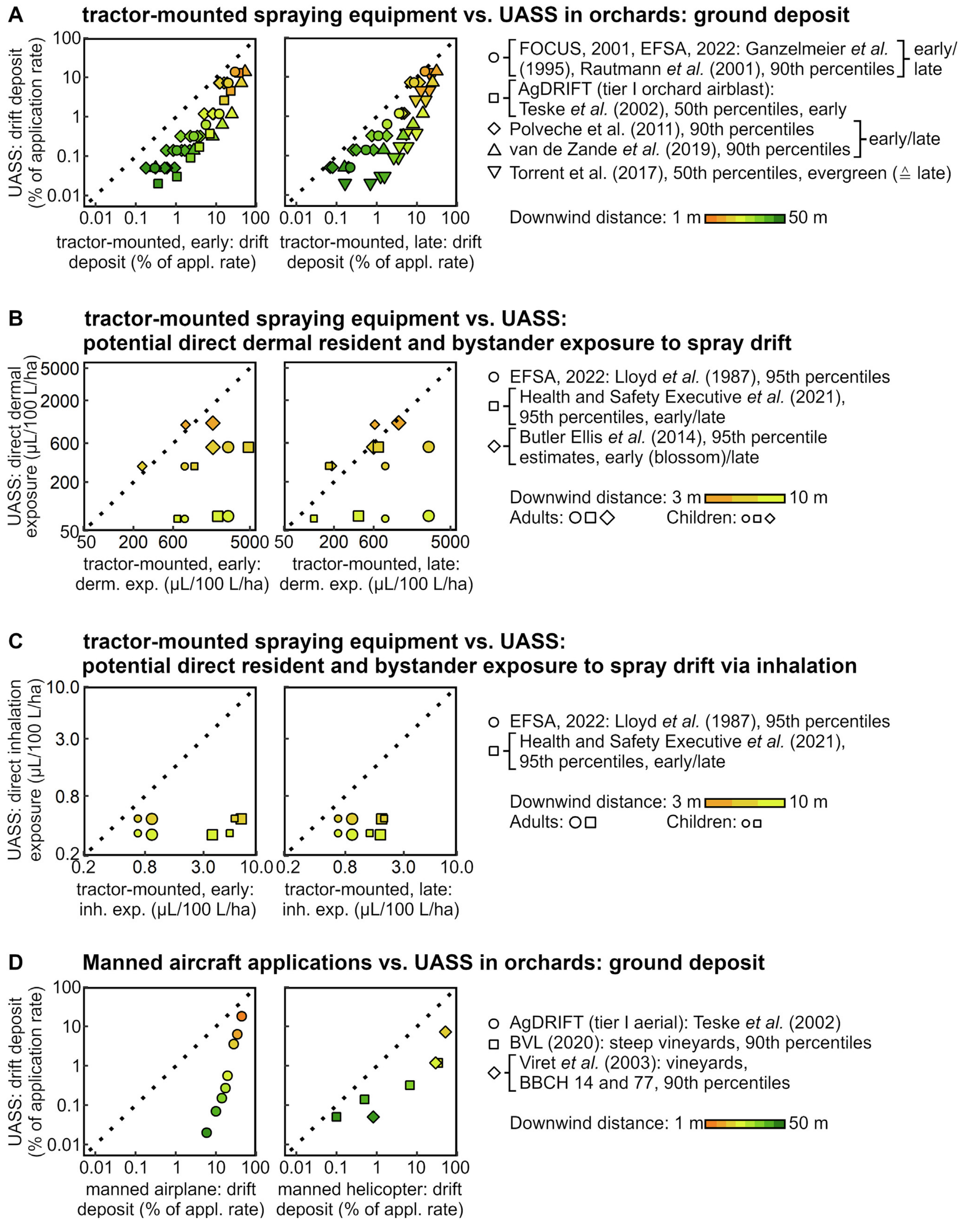

Fig. 11. Comparison of the findings with published and predicted data.

corresponding mean drift values calculated in the present study. The latter are greatly exceeded, especially at increasing downwind distances, where the difference amounts to almost three orders of magnitude. These results highlight that existing regulatory models relating to aerial applications have not been validated for UASS. In this context, it is interesting to note that the ability of AGDISP combined with CHARM (comprehensive hierarchical aeromechanics rotorcraft model) to predict drift and deposition of spray released from UASS has recently been assessed (Teske et al., 2018). Finally, the 90th drift percentiles of the German reference dataset to assess manned helicopter spraying operations in steep vineyards are consistently higher than the corresponding percentiles of the UASS trials conducted here (Fig. 11D, right panel) (BVL, 2020). Very similar results are obtained when the data of Viret and co-workers are used for comparison (Viret et al., 2003).

5. Conclusion

In this study, environmental, resident and bystander exposure following orchard treatments with a six-rotor DJI Agras T30 UASS was investigated. For this purpose, horizontal and vertical downwind drift data were collected according to the ISO standard 22866. In the same experiments, exposure of residents/bystanders located downwind the treated area was quantified using display mannequins equipped with personal air sampling pumps. Spray drift and exposure generally decreased at increasing height and downwind distances. Even though 90 % of spray drift was consistently contained within a downwind distance of <5 m, absolute drift and exposure values were strongly influenced by wind speed and direction. In turn, the growth stage of the crop hardly influenced drift and exposure levels. Finally, direct dermal exposure defined as the deposition of droplets on coveralls worn by mannequins was much more pronounced than exposure through inhalation, *i.e.*, droplet deposition on the filters of the air sampling pumps. This suggests that direct resident/bystander exposure to spray drift may predominantly occur *via* the dermal route.

Drift levels tailing off at increasing downwind distances and height have been reported in earlier trials involving downward-directed spraying equipment in general and UASS in particular. However, the 90 % of total drift location observed for the DJI Agras T30 used here is lower than most of those observed in previous drift trials with UASS conducted in orchards and other crops. This may in part be due to operational parameters such as flight speed and the lack of a satellite-assisted autopilot mode. Measured drift deposit and exposure values are consistently below the reference values implemented in models currently used to predict surface water contamination and resident/bystander exposure in the EU. Furthermore, measured drift values are also systematically lower than the results of tier I terrestrial and aerial assessments performed with the AgDRIFT model used by the US EPA. Further comparison with experimental data suggests that the specific UASS used may compare favorably to orchard sprayers and manned aircrafts in terms of off-target movement of spray droplets. To unambiguously clarify whether UASS can indeed be deemed superior with regard to drift deposit and/or resident/bystander exposure, a side-by-side comparison with conventional orchard sprayers/manned aircrafts would, however, be required.

Overall, the dataset is anticipated to be useful to identifying how the risks associated by UASS differ from those of conventional methods. It extends the existing data on drift and exposure generated by UASS that could eventually prove useful in validating models such as AGDISP and BREAM for UASS applications, and hence, facilitate regulatory decision-making.

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CRediT authorship contribution statement

Pierre-Henri Dubuis: Conceptualization, Methodology, Investigation, Data curation, Writing – review & editing, Supervision, Project administration. **Michel Droz:** Conceptualization, Validation, Investigation, Data curation, Writing – review & editing. **Aurélie Melgar:** Investigation. **Ursina A. Zürcher:** Conceptualization, Writing – review & editing, Project administration. **Jürg A. Zarn:** Writing – review & editing. **Katia Gindro:** Writing – review & editing. **Sebastian L.B. König:** Conceptualization, Methodology, Formal analysis, Data curation, Writing – original draft, Visualization, Supervision, Project administration.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Ahmad, F., et al., 2022. Comparison of water sensitive paper and glass strip sampling approaches to access spray deposit by UAV sprayers. Agronomy 12, 1302. https://doi.org/10.3390/agronomy12061302.

Al, Heidary M., et al., 2014. Influence of spray characteristics on potential spray drift of field crop sprayers: a literature review. Crop Prot. 63, 120–130. https://doi.org/10.1016/j.cropro.2014.05.006.

ANSES, 2022. Note d'appui scientifique et technique de l'Agence nationale de sécurité sanitaire de l'alimentation, de l'environnement et du travail relative à « l'expérimentation de l'utilisation de drones pour la pulvérisation de produits phytopharmaceutiques», saisine 2022-AST-0026.

ASABE, 2020. The American Society of Agricultural and Biological Engineers: Spray Nozzle Classification by Droplet Spectra, S.572.3.

Bilanin, A.J., et al., 1989. AGDISP, the aircraft spray dispersion model, code development and experimental validation. Trans. ASABE 32, 327–334. https://doi.org/10.13031/2013.31005.

Bird, S.L., et al., 1996. Off-target deposition of pesticides from agricultural aerial spray applications. J. Environ. Qual. 25, 1095–1104. https://doi.org/10.2134/jeq1996.00472425002500050024x.

Bird, S.L., et al., 2002. Evaluation of the AgDISP aerial spray algorithms in the AgDRIFT model. Environ. Toxicol. Chem. 21, 672–681. https://doi.org/10.1002/etc.5620210328.

Brown, C.R., Giles, D.K., 2018. Measurement of pesticide drift from unmanned aerial vehicle application to a vineyard. Trans. ASABE 61, 1539–1546. https://doi.org/10.13031/trans.12672.

Butler Ellis, M.C., et al., 2016. Novel spray adjuvants to decrease spray drift. Asp. Appl. Biol. 132, 257–263.

Butler Ellis, M.C., et al., 2014. Bystander and resident exposure to spray drift from orchard applications: field measurements, including a comparison of spray drift collectors. Asp. Appl. Biol. 122, 187–194.

Butler Ellis, M.C., et al., 2010. Bystander exposure to pesticide spray drift: new data for model development and validation. Biosyst. Engin. 107, 162–168. https://doi.org/10.1016/j.biosystemseng.2010.05.017.

Butts, T.R., et al., 2022. Herbicide spray drift from ground and aerial applications: implications for potential pollinator foraging sources. Sci. Rep. 12, 18017.

BVL, 2020. Sechste Bekanntmachung über die Abdrifteckwerte, die bei der Prüfung und Zulassung/Genehmigung von Pflanzenschutzmitteln herangezogen werden (BVL 20/02/05).

Chen, H., et al., 2021. Review of agricultural spraying technologies for plant protection using unmanned aerial vehicle (UAV). Int. J. Agric. Biol. Eng. 14, 38–49. https://doi.org/10.25165/j.ijabe.20211401.5714.

Chen, P., et al., 2022. Characteristics of unmanned aerial spraying systems and related spray drift. Front. Plant Sci. 13, 870956. https://doi.org/10.3389/fpls.2022.870956.

Chen, S., et al., 2020. Effect of droplet size parameters on droplet deposition and drift of aerial spraying by using plant protection UAV. Agronomy 10, 195. https://doi.org/10.3390/agronomy10020195.
Cross, J.V., et al., 2001a. Spray deposits and losses in different sized apple trees from an axial fan orchard sprayer: 1. Effects of spray liquid flow rate. Crop Prot. 20, 13–30. https://doi.org/10.1016/S0261-2194(00)00046-6.
Cross, J.V., et al., 2001b. Spray deposits and losses in different sized apple trees from an axial fan orchard sprayer: 2. Effects of spray quality. Crop Prot. 20, 333–343. https://doi.org/10.1016/S0261-2194(00)00163-0.
Ctgb, 2021. Chapter 6: fate and behaviour in the environment; behaviour in surface water and sediment, version 2.6. Evaluation Manual for the Authorisation of Plant Protection Products and Biocides According to Regulation (EC) No 1107/2009, NL Part, Plant Protection Products. August 2021.
De Schampheleire, M., et al., 2008. Spray drift measurements to evaluate the Belgian drift mitigation measures in field crops. Crop Prot. 27, 577–589. https://doi.org/10.1016/j.cropro.2007.08.017.
Delpuech, X., et al., 2022. Evaluation of aerial drift during drone spraying of an artificial vineyard. IVES Technical Review Vine & Wine 1-2 https://doi.org/10.20870/IVES-TR.2022.7212.
Dubuis, P.-H., Jaquerot, A., 2022. Evaluation of the performance of drone treatments to control downy and powdery mildew in grapevines. BIO Web Conf. 50, 01006. https://doi.org/10.1051/bioconf/20225001006.
EFSA, 2022. Non dietary exposure to plant protection products: state of the art and perspectives.
EFSA, et al., 2020. Scientific report of EFSA on the 'repair action' of the FOCUS surface water scenarios. EFSA J. 18, 6119. https://doi.org/10.2903/j.efsa.2020.6119.
EFSA, 2022. Guidance on the assessment of exposure of operators, workers, residents and bystanders in risk assessment of plant protection products. EFSA Journal 20, 7032. https://doi.org/10.2903/j.efsa.2022.7032.
EFSA PPR panel, 2010. Scientific opinion on preparation of a guidance document on pesticide exposure assessment for workers, operators, bystanders and residents. EFSA Journal 8, 1501. https://doi.org/10.2903/j.efsa.2010.1501.
EFSA Scientific Committee, 2012. Guidance on selected default values to be used by the EFSA scientific committee, scientific panels and units in the absence of actual measured data. EFSA J. 10, 2579. https://doi.org/10.2903/j.efsa.2012.2579.
EPPO, 2021. Dose expression for plant protection products, EPPO general standard PP 1/239 (3). EPPO Bull. 51, 10–33. https://doi.org/10.1111/epp.12704.
FAO, ITU, 2018. E-agriculture in Action: Drones for Agriculture.
FOCA, 2021. Application for a Permit to Operate Aircraft for Spreading Substances From the Air, ISS 2 / REV 0 / 20.01.2021.
FOCUS, 2001. FOCUS Surface Water Scenarios in the EU Evaluation Process Under 91/414/EEC, SANCO/4802/2001-rev.2Final. May 2003.
Fritz, B.K., 2006. Meteorological effects on deposition and drift of aerially applied sprays. Trans. ASABE 49, 1295–1301. https://doi.org/10.13031/2013.22038.
Fritz, B.K., et al., 2009. Effects of spray mixtures on droplet size under aerial application conditions and implications on drift. Appl. Eng. Agricul. 26, 21–29. https://doi.org/10.13031/2013.22038.
Ganzelmeier, H., et al., 1995. Studies on the spray drift of plant protection products. Mitteilungen aus der BBA für Land-und Forstwirtschaft Berlin-Dahlem. 305, pp. 1–110.
García-Santos, G., et al., 2016. Drift from the use of hand-held knapsack pesticide sprayers in Boyacá (Colombian Andes). J. Agric. Food Chem. 64, 3990–3998. https://doi.org/10.1021/acs.jafc.5b03772.
Glass, C.R., et al., 2010. Generation of field data for bystander exposure and spray drift with arable sprayers. Asp. Appl. Biol. 99, 271–276.
Herbst, A., et al., 2020. The influence of unmanned agricultural aircraft system design on spray drift. J. Kult. 72, 1–11. https://doi.org/10.5073/JfK.2020.01.01.
Hewitt, A.J., et al., 2002. Development of the spray drift task force database for aerial applications. Environ. Toxicol. Chem. 21, 648–658. https://doi.org/10.1002/etc.5620210326.
Hilz, E., Vermeer, A.W.P., 2013. Spray drift review: the extent to which a formulation can contribute to spray drift. Crop Prot. 44, 75–83. https://doi.org/10.1016/j.cropro.2012.10.020.
Holterman, H.J., et al., 2017. An empirical model based on phenological growth stage predicting pesticide spray drift in pome fruit orchards. Biosyst. Engin. 154, 46–61. https://doi.org/10.1016/j.biosystemseng.2016.08.016.
HSE, 2021. Proposals for New Spray Drift Exposure Values in Orchard and Vineyards for Residents and Bystanders.
Huang, Y., et al., 2012. Optimizing selection of controllable variables to minimize downwind drift from aerially applied sprays. Appl. Eng. Agricul. 28, 307–314. https://doi.org/10.13031/2013.41487.
Huang, Z., et al., 2023. Field evaluation of spray drift and nontargeted soybean injury from unmanned aerial spraying system herbicide application under acceptable operation conditions. Pest Manag. Sci. 79, 1140–1153. https://doi.org/10.1002/ps.7285.
Iost Filho, F.H., et al., 2020. Drones: innovative technology for use in precision pest management. J. Econ. Entomol. 113, 1. https://doi.org/10.1093/jee/toz268.
ISO 22866, 2005. Equipment for Crop Protection - Methods for Field Measurement of Spray Drift.
Johnson, D.R., 1995. Drift from applications with ground hydraulic sprayers: integration and summary of 1992 and 1993 field studies, study no. I94-001. EPA MRID No. 43508001 https://github.com/tidyverse/dplyr.
Johnson, D.R., 1995. Drift from orchard airblast applications: integration and summary of 1993 and 1994 field drift studies, study no. I95-004. EPA MRID no. 439925701.
Kasiotis, K.M., et al., 2014. Spray drift reduction under southern European conditions: a pilot study in the ecopest project in Greece. Sci. Total Environ. 479–480, 132–137. https://doi.org/10.1016/j.scitotenv.2014.01.088.
Kasner, E.J., et al., 2018. Spray drift from a conventional axial fan airblast sprayer in a modern orchard work environment. Ann. Work Expos. Health 62, 1134–1146. https://doi.org/10.1093/annweh/wxy082.
Kasner, E.J., et al., 2020. Spray drift from three airblast sprayer technologies in a modern orchard work environment. Ann. Work Expos. Health 64, 25–37. https://doi.org/10.1093/annweh/wxz080.
Kennedy, M.C., et al., 2012. BREAM: a probabilistic bystander and resident exposure assessment model of spray drift from an agricultural boom sprayer. Comput. Electron. Agr. 88, 63–71. https://doi.org/10.1016/j.compag.2012.07.004.
Kuster, C.J., et al., 2021. Measurements of the dermal exposure to bystanders from direct off-crop drift during the application of plant protection products. Ann. Appl. Biol. 179, 123–133. https://doi.org/10.1111/aab.12686.
Li, L., et al., 2022. Effect of flight velocity on droplet deposition and drift of combined pesticides sprayed using an unmanned aerial vehicle sprayer in a peach orchard. Front. Plant Sci. 13, 981494. https://doi.org/10.3389/fpls.2022.981494.
Lloyd, G.A., Bell, G.J., 1983. Hydraulic nozzles: comparative spray drift study. MAFF Report, London, UK.
Lloyd, G.A., et al., 1987. Orchard sprayers: comparative operator exposure and spray drift study. MAFF Report, London, UK.
Martin, S., et al., 2008. Guidance for exposure and risk evaluation for bystanders and residents exposed to plant protection products during and after application. J. Verbr. Lebensm. 3, 272–281. https://doi.org/10.1007/s00003-008-0361-5.
Meier, U., 2018. Growth Stages of Mono- and Dicotyledonous Plants: BBCH Monograph, Quedlinburg, Germany.
Meli, S., et al., 2003. Studies on pesticide spray drift in a Mediterranean citrus area. Agronomie 23, 667–672. https://doi.org/10.1051/agro:2003044.
Mercier, T., 2020. Direct dermal and inhalation exposure of bystanders and residents during vine foliar application using sprayer equipment fitted with an anti-drift device: a comparison between measured exposure levels and existing exposure models. J. Verbrauch. Lebensm. 15, 219–227. https://doi.org/10.1007/s00003-020-01274-1.
Nuyttens, D., et al., 2007a. Effect of nozzle type, size and pressure on spray droplet characteristics. Biosyst. Engin. 97, 333–345. https://doi.org/10.1016/j.biosystemseng.2007.03.001.
Nuyttens, D., et al., 2007b. The influence of operator-controlled variables on spray drift from field crop sprayers. Trans. ASABE 50, 1129–1140. https://doi.org/10.13031/2013.23622.
Nuyttens, D., et al., 2006a. Experimental study of factors influencing the risk of drift from field sprayers, part 1: meteorological conditions. Asp. Appl. Biol. 77, 1–8.
Nuyttens, D., et al., 2006b. Experimental study of factors influencing the risk of drift from field sprayers, part 2: spray application technique. Asp. Appl. Biol. 77, 1–8.
OECD, 1997. Guidance Document for the Conduct of Studies of Occupational Exposure to Pesticides During Agricultural Application.
OECD, 2021. Report on the State of the Knowledge – Literature Review on Unmanned Aerial Spray Systems in Agriculture.
Polveche, V., et al., 2011. Effects of Nozzle Types, Windbreak and Vegetation Stage on Drift Performance Issued Froman Orchard Sprayer.
Rathnayake, A.P., et al., 2021. Downwind spray drift assessment for airblast sprayer applications in a modern apple orchard system. Trans. ASABE 64, 601–613. https://doi.org/10.13031/trans.14324.
Rautmann, D., et al., 2001. New Basic Drift Values in the Authorisation Procedure for Plant Protection Products.
Rodriguez, R., 2021. Agricultural aerial application with unmanned aircraft systems: current regulatory framework and analysis of operators in the United States. Trans. ASABE 64, 1475–1481. https://doi.org/10.13031/trans.14331.
Schweizer, S., et al., 2013. Abdrift - Reduzierende Massnahmen im Praxisversuch. Agrar. Schweiz 4, 470–477.
Stull, R., 2011. Wet-bulb temperature from relative humidity and air temperature. J. Appl. Meteorol. Climatol. 50, 2267–2269. https://doi.org/10.1175/JAMC-D-11-0143.1.
Teske, M.E., et al., 2002. AgDrift®: a model for estimating near-field spray drift from aerial applications. Environ. Toxicol. Chem. 21, 659–671. https://doi.org/10.1002/etc.5620210327.
Teske, M.E., et al., 2003. A user's guide for AgDRIFT® 2.0.07: a tiered approach for the assessment of spray drift of pesticides. Continuum Dynamics Report (01-01).
Teske, M.E., et al., 2019. Modeling aerially applied sprays: an update to AGDISP model development. Trans. ASABE 62, 343–354. https://doi.org/10.13031/trans.13129.
Teske, M.E., et al., 2018. Prediction of aerial spray release from UAVs. Trans. ASABE 61, 909–918. https://doi.org/10.13031/trans.12701.
Torrent, X., et al., 2017. Comparison between standard and drift reducing nozzles for pesticide application in citrus: part I. Effects on wind tunnel and field spray drift. Crop Prot. 96, 130–143. https://doi.org/10.1016/j.cropro.2017.02.001.
US EPA, US EPA, 2001. Pesticide Registration (PR) Notice 2001-X Draft: Spray and Dust Drift Label Statement forPesticide Products.
US EPA, 2011. Exposure Factors Handbook, EPA/600/R-09/052F. National Center for Environmental Assessment, Washington, DC.
US EPA, 2013. Guidance on Modeling Offsite Deposition of Pesticides Via Spray Drift for Ecological andDrinking Water Assessments (Draft for Comment).
van de Zande, J.C., et al., 2012. Spray drift for the assessment of exposure of aquatic organisms to plant protection products in the Netherlands, Part 1: Field crops and downward spraying. WUR-PRI Report 419. Wageningen UR Plant Research International.
van de Zande, J.C., et al., 2019. Spray drift for the assessment of exposure of aquatic organisms to plant protection products in the Netherlands; Part 2: Sideways and upward sprayed fruit and tree crops. Wageningen Research, Report WPR-564.
van de Zande, J.C., et al., 2010. Risk estimation of bystander and residential exposure from orchard spraying based on measured spray drift data. Asp. Appl. Biol. 99, 149–156.
Venables, W.N., Ripley, B.D., 2002. Book Modern Applied Statistics With S. 4th ed. Springer, New York.

Verpont, F., et al., 2022. How to conciliate application of plant protection products and protection of bystanders - CAPRIV: a French collaborative project. Asp. Appl. Biol. 147, 307–313.

Viret, O., et al., 2003. Comparison of spray deposits and efficacy against powdery mildew of aerial and ground-based spraying equipment in viticulture. Crop Prot. 22, 1023–1032. https://doi.org/10.1016/S0261-2194(03)00119-4.

Vučajnk, F., et al., 2018. Head and leaf fungicide deposit on winter wheat, deoxynivalenol content and yield parameters as affected by different nozzle types. Cereal Res. Commun. 46, 321–332. https://doi.org/10.1556/0806.46.2018.13.

Wang, C., et al., 2021. Assessment of spray deposition, drift and mass balance from unmanned aerial vehicle sprayer using an artificial vineyard. Sci. Total Environ. 777, 146181. https://doi.org/10.1016/j.scitotenv.2021.146181.

Wang, C., et al., 2023. Comparison between drift test bench and other techniques in spray drift evaluation of an eight-rotor unmanned aerial spraying system: the influence of meteorological parameters and nozzle types. Agronomy 13, 270. https://doi.org/10.3390/agronomy13010270.

Wang, G., et al., 2020. Field evaluation of spray drift and environmental impact using an agricultural unmanned aerial vehicle (UAV) sprayer. Sci. Total Environ. 737, 139793. https://doi.org/10.1016/j.scitotenv.2020.139793.

Wang, J., et al., 2018. Drift and deposition of pesticide applied by UAV on pineapple plants under different meteorological conditions. Int. J. Agric. Biol. Eng. 11, 5–12. https://doi.org/10.25165/j.ijabe.20181106.4038.

Wen, S., et al., 2018. Influence of wing tip vortex on drift of single rotor plant protection unmanned aerial vehicle. Trans. Chin. Soc. Agric. Mach. 49, 127–137. https://doi.org/10.6041/j.issn.1000-1298.2018.08.015.

Wickham, H., 2016. ggplot2: Elegant Graphics for Data Analysis. 2nd ed. Springer-Verlag, New York.

Wickham, H., et al., 2019. Welcome to the tidyverse. J. Open Source Softw. 4, 1686. https://doi.org/10.21105/joss.01686.

Wickham, H., et al., 2023. dplyr: A Grammar of Data Manipulation. https://github.com/tidyverse/dplyr https://dplyr.tidyverse.org.

Woods, N., et al., 2001. Spray drift of pesticides arising from aerial application in cotton. J. Environ. Qual. 30, 697–701. https://doi.org/10.2134/jeq2001.303697x.

Xiongkui, H., et al., 2017. Recent development of unmanned aerial vehicle for plant protection in East Asia int. J. Agric. Biol. Eng. 10, 18–30. https://doi.org/10.3965/j.ijabe.20171003.3248.

Xue, X.Y., et al., 2014. Drift and deposition of ultra-low altitude and low volume application in paddy field. Int. J. Agric. Biol. Eng. 7, 23–28. https://doi.org/10.3965/j.ijabe.20140704.003.

Yan, X., et al., 2021. Minimizing occupational exposure to pesticide and increasing control efficacy of pests by unmanned aerial vehicle application on cowpea. Appl. Sci. 11, 9579. https://doi.org/10.3390/app11209579.

Zhan, Y., et al., 2022. Influence of the downwash airflow distribution characteristics of a plant protection UAV on spray deposit distribution. Biosyst. Eng. 216, 32–45. https://doi.org/10.1016/j.biosystemseng.2022.01.016.

Zimdahl, R.L., 2007. Herbicides and plants. Fundamental of Weed Science. Academic Press, San Diego, pp. 417–443.