

Original Article

Spray Drift from a Conventional Axial Fan Airblast Sprayer in a Modern Orchard Work Environment

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Abstract

Pesticide spray drift represents an important cause of crop damage and farmworker illness, especially among orchard workers. We drew upon exposure characteristics from known human illness cases to design a series of six spray trials that measured drift from a conventional axial fan airblast sprayer operating in a modern orchard work environment. Polyester line drift samples ($n = 270$; 45 per trial) were suspended on 15 vertical masts downwind of foliar applications of zinc, molybdenum, and copper micronutrient tracers. Samples were analyzed using inductively coupled plasma mass spectrometry and resulting masses were normalized by sprayer tank mix concentration to create tracer-based drift volume levels. Mixed-effects modeling described these levels in the context of spatial variability and buffers designed to protect workers from drift exposure. Field-based measurements showed evidence of drift up to 52 m downwind, which is approximately 1.7 times greater than the 30 m (100 ft) 'Application Exclusion Zone' defined for airblast sprayers by the United States Environmental Protection Agency Worker Protection Standard. When stratified by near (5 m), mid (26 m), and far (52 m) distances, geometric means and standard deviations for drift levels were 257 (1.8), 52 (2.0), and 20 (2.3) μl , respectively. Fixed effect model coefficients showed that higher wind speed [0.53; 95% confidence interval (CI): 0.35, 0.70] and sampling height (0.16; 95% CI: 0.11, 0.20) were positively associated with drift; increasing downwind distance (-0.05 ; 95% CI: -0.06 , -0.04) was negatively associated with drift. Random effects showed large within-location variability, but relatively few systematic changes for individual locations across spray trials after accounting for wind speed, height, and distance. Our study findings demonstrate that buffers may offer drift exposure protection to orchard workers from airblast spraying. Variables such as orchard architecture, sampling height, and wind speed should be included in the evaluation and mitigation of risks from drift exposure. Data from our study may prove useful for estimating potential exposure and validating orchard-based bystander exposure models.

Keywords: airblast sprayer; application exclusion zone; drift; exposure assessment—mixed models; orchard; passive sampling; pesticide exposure; pesticide spraying

Introduction

Spray drift is described as the off-target movement of droplets, irrespective of active ingredient, during or shortly after the time of pesticide application (Drewes et al., 1990; USEPA, 1990; Miller, 2014). Spray drift—hereafter referred to as ‘drift’ and distinct from movement by volatilization or windborne dust particles—represents an important cause of crop damage and farmworker illness resulting from agricultural applications (Felsot et al., 2010; Lee et al., 2011). It is a public health concern in the Pacific Northwest, especially among orchard workers (WADOH, 2013; WADOH, 2017). We drew upon exposure characteristics from known human illness cases to design a series of spray trials that measured drift from a conventional axial fan airblast (AFA) sprayer operating in a modern orchard. Our trials placed a grid of field targets in an orchard work environment during a simulated drift event, an incident when one or more humans are exposed to pesticide drift (Lee et al., 2011).

Method of application, droplet size, and meteorological conditions are key factors that influence drift (Murray and Vaughan, 1970; Thistle, 2004; Felsot et al., 2010; USEPA, 2016a). The AFA sprayer has been a standard tool for tree fruit pesticide application since its rapid and wide scale adoption in the 1950s (Fox et al., 2008; Matthews et al., 2014a). Over time, orchard management practices have greatly reduced tree height and canopy volume. As a result, conventional AFA output no longer matches modern canopies and thereby increases drift potential (Landers, 2011; Cross et al., 2013). Spraying finer droplets promotes good crop coverage, but it competes with the need for coarser droplets that reduce drift potential (ASABE, 2013). At a release height of 3 m, coarse droplets typically settle out within seconds due to gravitational force (deposition drift), whereas fine droplets can remain suspended for minutes or hours and be carried greater distances by the wind (airborne drift) (Matthews et al., 2014b; Miller, 2014). The deposition fraction of drift can be collected on horizontal surfaces by gravitational settling and the airborne fraction can be collected on vertical surfaces by interception or impaction (Hinds, 1999). Meteorological conditions modify the effect of droplet size and release height on drift potential. Higher wind speeds result in more drift at greater distances (Nuyttens et al., 2005). Larger fluctuations in wind direction increase the unpredictability of

droplet travel direction and the amount of dilution due to atmospheric turbulence (Thistle, 2004).

Regulatory agencies attempt to protect pollinators, sensitive crops, bodies of water, and humans by mitigating drift using the above factors. Some pesticide labels specify acceptable wind speeds or buffer zones during application (USEPA, 2001; LERAP, 2002; De Schamphelre et al., 2007; EFSA, 2014). In the UK, aquatic buffer requirements vary by sprayer type, applied dose, and the presence of windbreaks (LERAP, 2002). In the USA, the federal Worker Protection Standard (WPS) includes an ‘Application Exclusion Zone’ (AEZ), a buffer that moves with active application equipment that ‘must be free of all persons other than appropriately trained and equipped handlers’ (USEPA, 2016b). An AEZ of 30 meters (m) or 100 feet (ft) is required for aerial, airblast, fumigant, smoke, mist, and fog applications and also for any other application methods that produce droplets having a volume median diameter less than 294 microns (USEPA, 2016b).

A growing body of research about sampling techniques (Donkersely and Nuyttens, 2011), spray mass balance (Jensen and Olesen, 2014), and experimental spray trials (Holterman et al., 2017) indicates sustained interest in characterizing orchard drift. Foliar application of elements (i.e. micronutrients) has long been recognized as a means for crop nutrition (Boynton, 1954; WSU, 2017a). Conveniently, experimental trials can be designed to apply multiple metal salt solutions to a single field sample, recovered through acid extraction, and then analyzed in a sensitive inductively coupled plasma mass spectrometry (ICP-MS) procedure (Foqué et al., 2014). For example, micronutrient tracers have been used in previous orchard-based drift field studies (Travis et al., 1985; Murray et al., 2000). Databases of such field studies are being developed to model orchard drift (Bonds et al., 2016; Holterman et al., 2017), including bystander exposure (Cunha et al., 2012; Van de Zande et al., 2014; Kennedy and Butler Ellis, 2017). Two models—the Bystander and Resident Exposure Assessment Model (BREAM) and Bystanders, Residents, Operators, and WorkerS Exposure (BROWSE)—were created to improve regulatory drift exposure and risk assessment in the European Union (Butler Ellis et al., 2010; Butler Ellis et al., 2017a,b). BROWSE model developers have called for more orchard-based experiments to support a wider range of drift distances, better describe the relationship

between airborne spray and bystander exposure, and provide data for model validation (Butler Ellis et al., 2017a).

Volunteers and mannequins have been used in drift studies to estimate potential dermal exposure by measuring deposits on coveralls (Butler Ellis et al., 2010; Butler Ellis et al., 2014). Such studies have addressed crucial components of human exposure, including collection efficiency (Butler Ellis et al., 2018). Yet, spatiotemporal aspects of orchard work environments known to result in drift-related illnesses have not been evaluated. For example, Calvert et al. (2015) describe a scenario in which an airblast application to pear trees drifted on 20 workers who were tying branches of cherry trees at distances from 9 to >107 m (30 to >350 ft) away. Orchard drift sampling usually occurs in flat areas downwind of one or a few sprayer passes, but no studies have simulated longer spray periods with sampling in downwind tree canopies more representative of orchard worker exposure scenarios.

The purpose of this study was to characterize the magnitude and spatial variability of drift levels in an orchard work environment during longer spray periods. Our secondary goals were: (i) to evaluate drift in the context of buffers designed to prevent bystander exposure and (ii) to develop methods for comparing the drift potential of different application technologies in future studies.

Methods

Figure 1 provides an overview of our methods. Briefly, three micronutrient tracers—zinc (Zn), molybdenum (Mo), and copper (Cu)—were applied by an AFA sprayer to the same 0.4 hectare (1 acre) orchard block of trees at full canopy on 6 days: 1–2 July 2015; 10 June, 2016; and 28–30 September 2016. Each spray trial, which consisted of one tracer application to the block on a single day, involved the downwind collection of drift samples on two different matrices suspended from 6 m vertical masts. Samples were analyzed for metals in a laboratory and then used to build a mixed-effects model.

All field studies took place at a Washington State University (WSU) research orchard situated in a river valley that oriented the wind prevailingly from the north (Supplementary Figure S1 in the Supplementary Material, available at *Annals of Work Exposures and Health* online). Three varieties of apple trees were planted in rows along a north–south axis, trained to trellises, and had columnar-shaped canopies that reached approximately 3.5 m (11.5 ft) tall (Supplementary Figures S2–S3 in the Supplementary Material, available at *Annals of Work Exposures and Health* online). The study site was bordered by open flat land to the north, other orchard blocks to the east and south, and a small private service road with no traffic to the west.

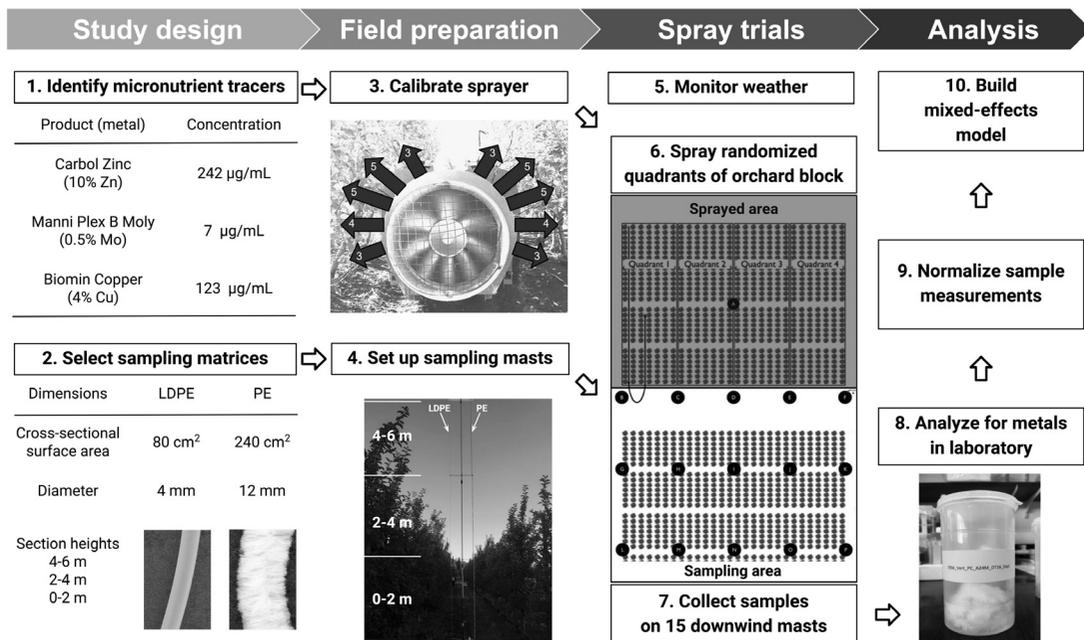


Figure 1. Overview of methods used in study. Drift levels were measured with passive sampling matrices consisting of low-density polyethylene (LDPE) and polyester (PE) lines.

Study design

Micronutrient tracers

Our trials utilized the efficiency of applying multiple metal salt solutions to a single target by adapting micronutrient tracer field sampling methods described by Cross et al. (2001a) and ICP-MS lab methods described by Zabkiewicz et al. (2008). Before each trial, the sprayer tank was flushed with cleaner (sodium tripolyphosphate and sodium carbonate) and then triple-rinsed. The certified applicator mixed, loaded, and applied label-recommended concentrations for one of three water soluble micronutrient product mixes: *Carbol™ Zinc* (10% Zn; 2.5 ml/l; 32 oz/100 gal), *Manni-Plex® B Moly* (0.5% Mo; 1.3 ml/l; 16 oz/100 gal), and *BioMin® Copper* (4% Cu; 2.5 ml/l; 32 oz/100 gal). The sprayer tank was allowed to mechanically agitate for at least 5 minutes (min) until the solution was thoroughly mixed. Bulk tank mix and water source samples were collected in 180 ml (6 oz) polyethylene containers before spraying began.

Sampling matrices

Two different matrices were deployed to compare their relative drift sampling strengths: low-density polyethylene (LDPE) line for its uniform surface area and polyester (PE) line for having a high collection efficiency similar to pipe cleaners (Gilbert and Bell, 1988; Miller et al., 1989; Davis et al., 1993; Miller, 2014). The LDPE line was tubing with an outer diameter of 4 mm (0.16 in) (*Dynalon*; Rochester, NY; product #1248). The PE line was PE pile with wireless cotton core and a diameter of 12 mm (0.47 in) (*Hewitt and Booth*; Huddersfield, UK). We used pairwise scatter plots to investigate whether PE lines captured higher drift levels than LDPE lines after adjusting for cross sectional area.

Field preparation

Sprayer calibration

An AFA sprayer (*Rears Pak-Blast-100*) was calibrated to apply a liquid volume of 935 l/ha (100 gal/ac), which is commonly listed on pesticide labels as a volume per area goal for tree fruit applications. Expected volume output was calculated using parameters for orchard row width (3 m; 10 ft); tree spacing (0.9 m; 3 ft); tractor speed (1.3 m/s; 3.0 mph); boom type (curved); system operating pressure (14 bar; 205 psi); and nozzle type (steel, hollow cone, *TeeJet*), number (10), size (two D3, two D4, four D5, all with 25 cores), and arrangement (Hoheisel, 2016; Turbo-Mist, 2017). The field team calibrated tractor speed and sprayer system pressure, inserted new stainless steel nozzles, adjusted sprayer airflow direction into the tree canopy, and compared expected versus observed nozzle volumetric flow rates to ensure accurate

nozzle output (Hoheisel, 2016). Nozzle and pressure settings were used to find theoretical droplet sizes, which were 110–125 µm and fit into the ‘fine’ droplet classification category (ASABE, 2013; TeeJet, 2014). The sprayer was outfitted with a global positioning system to verify the sprayer route and spray start and stop times to the nearest minute for each quadrant.

Sampling masts

Fifteen 6 m (20 ft) vertical target masts were set up between tree rows in a sampling area that was downwind of the area to be sprayed. Each mast had collocated LDPE and PE line matrices suspended in a vertical plane with crossbars at 2, 4, and 6 m (Supplementary Figure S4 in the Supplementary Material, available at *Annals of Work Exposures and Health* online).

Spray trials

Weather conditions

Local meteorological measurements followed applicable protocols from the American Society of Agricultural and Biological Engineers (ASABE) and the International Organization for Standardization (ISO) (ASABE, 2004; ISO, 2005). Wind speed, wind direction, air temperature, and relative humidity were recorded at two locations on opposite sides of the study site.

A permanent on-site station (WSU AgWeatherNet) was located approximately 70 m (230 ft) west of the nearest corner of the sprayed block with instruments that were approximately 2 m (about 6 ft) above the ground. Data were collected with a 0.2 Hz sampling frequency by a data logger (*Campbell Scientific CR-1000*; Logan, UT), processed as 15-min averages, and downloaded from an online portal (Pierce and Elliott, 2008; WSU, 2015). The wind speed sensor (*Met One Model 014A*; Grants Pass, OR) was a three-cup anemometer. The wind direction sensor (*Met One Model 024A*; Grants Pass, OR) was a wind vane that reported one of eight categories [four cardinal (N-E-S-W) and four ordinal (NE-SE-SW-NW)]. Temperature and relative humidity (*Campbell Scientific Rotronic HC2S3 Model 107*; Logan, UT) data were also available (WSU, 2015; WSU, 2017b).

A second, temporary station was placed approximately 190 m (623 ft) northeast of the nearest corner of the sprayed block. Data were collected with a 0.1 Hz sampling frequency by a data logger (*Campbell Scientific CR-1000*; Logan, UT), processed as 1-min averages, and downloaded to a laptop. Measurements were taken at two different heights. At 3 m (10 ft), there was a three-cup anemometer with a wind vane (*Met One Model 034B*; Grants Pass, OR) and temperature probe (*Campbell Scientific Model 109*; Logan, UT). At

10 m (33 ft), there was a three-axis ultrasonic anemometer (*RM Young Model 81000V*; Traverse City, MI) and a temperature and relative humidity probe (*Campbell Scientific Model HMP45C-L*; Logan, UT). The temporary meteorological station measured wind direction in azimuth degrees.

Only spray trials that met ISO meteorological data quality standards for drift sampling were included: samples were replicated at least three times in similar wind conditions, wind speeds were at least 1.0 m/s (2.2 mph), mean wind direction was at $90^\circ \pm 30^\circ$ to the downwind edge of the sprayed area (i.e. wind rose direction $\geq 330^\circ$ or $\leq 30^\circ$), and temperatures were 5–35°C (41–95°F) (ISO, 2005).

Randomized quadrant spraying

Application start timing decisions were based on the most recent 15-min average meteorological measurements for wind speed, wind direction, and temperature. A block of 28 tree rows was divided into four quadrants of approximately seven rows each (Fig. 2). Quadrant spray order was randomized to mitigate the effect of changing environmental conditions across spray trials. A certified applicator sprayed each row in serpentine fashion with nozzles open on both sides of the sprayer as it traveled between every row. Nozzles were turned off during turns. The outward facing half of outside rows was not sprayed.

Sample collection

We followed applicable ISO drift sampling guidelines by establishing a coordinate reference system with an array of samples, measuring all distances from the downwind edge of the sprayed area, and setting up vertical target masts for air-assisted orchard sprayers (ISO, 2005). Drift samples were taken in an adjacent orchard block at different distances and heights relevant to farmworker activities (e.g. harvesting, pruning, or thinning on the ground or a ladder). Three rows of five vertical masts were arranged 5 m (16 ft, Masts B-F), 26 m (85 ft, Masts G-K), and 52 m (171 ft, Masts L-P) downwind of the sprayed block (Fig. 2). Reference samples were also collected in the middle of the sprayed block (Mast A) and 200 m (656 ft) upwind (Mast Q). To understand the vertical drift profile for each spray trial, continuous lines were cut into discrete sections (2 m; 7 ft) and stored in separate collection bottles at ambient temperature (ISO, 2005).

Analysis

Laboratory metals analysis

Samples were submitted to the DEOHS Environmental Health Laboratory (EHL) in Seattle and analyzed for micronutrient tracer mass. Aliquots of the sprayer bulk

tank and water source samples were prepared using microwave assisted digestion (open vessel, ramp to 90°C in 10 min and hold for 20 min) and then diluted with deionized water to final concentration of 10% HNO₃, 6% HCl, and 10 ppb terbium (Tb) recovery standard. Bulk samples were digested because of precipitation and apparent microbial growth in some sample containers. To all other samples, 10% HNO₃ with 10 ppb Tb was added. The extraction and digestion solutions were analyzed by ICP-MS based on Method 6020a Rev.1 2007 from United States Environmental Protection Agency (USEPA) (USEPA, 1998). A minimum of three matrix blanks were analyzed with each batch of samples to quantify and correct for mean blank background metal levels.

Samples with resulting negative values were considered below the limit of blank (LOB), or the concentration found when replicates of a blank sample containing no analyte were tested (Armbruster and Pry, 2008). The limit of quantitation (LOQ) was determined by multiplying the standard deviation (SD) of the matrix blanks by 3. We explored both substitution (e.g. $\frac{LOQ}{\sqrt{2}}$) and imputation techniques for samples below the LOQ, but any gains made by these methods did not compare to using the log-normally (ln) distributed raw lab values themselves (Succop et al., 2004). As such, we included sample measurements that were below LOQ but above LOB. Measurements below LOB ($n = 4$) were excluded.

Sample measurement normalization

Laboratory values were normalized by dividing the mass per sample (M_{sample} in μg per 2 m section of PE line) by the concentration of the tracer in the tank mix (C_{tank} in $\mu\text{g}/\text{ml}$) (Cross et al., 2001b). This allowed comparison of corresponding normalized values (in μl) for different spray trials in a way that eliminated micronutrient effects, which we defined as differences in concentration due to label mixing instructions or sampling variability. Normalized results were reported as drift levels, or volume tank equivalents (V_{drift}) deposited on each sample, giving a convenient interpretation shown by the following worked example:

$$V_{drift} = \frac{M_{sample}}{C_{tank}} = \frac{0.871\mu\text{g}}{11.4\frac{\mu\text{g}}{\text{ml}}} = 0.0764\text{ml} = 76.4\mu\text{l}$$

Mixed-effects model

Data were managed and analyzed with R v.3.3.3 (R Core Team, 2017) using the following packages:

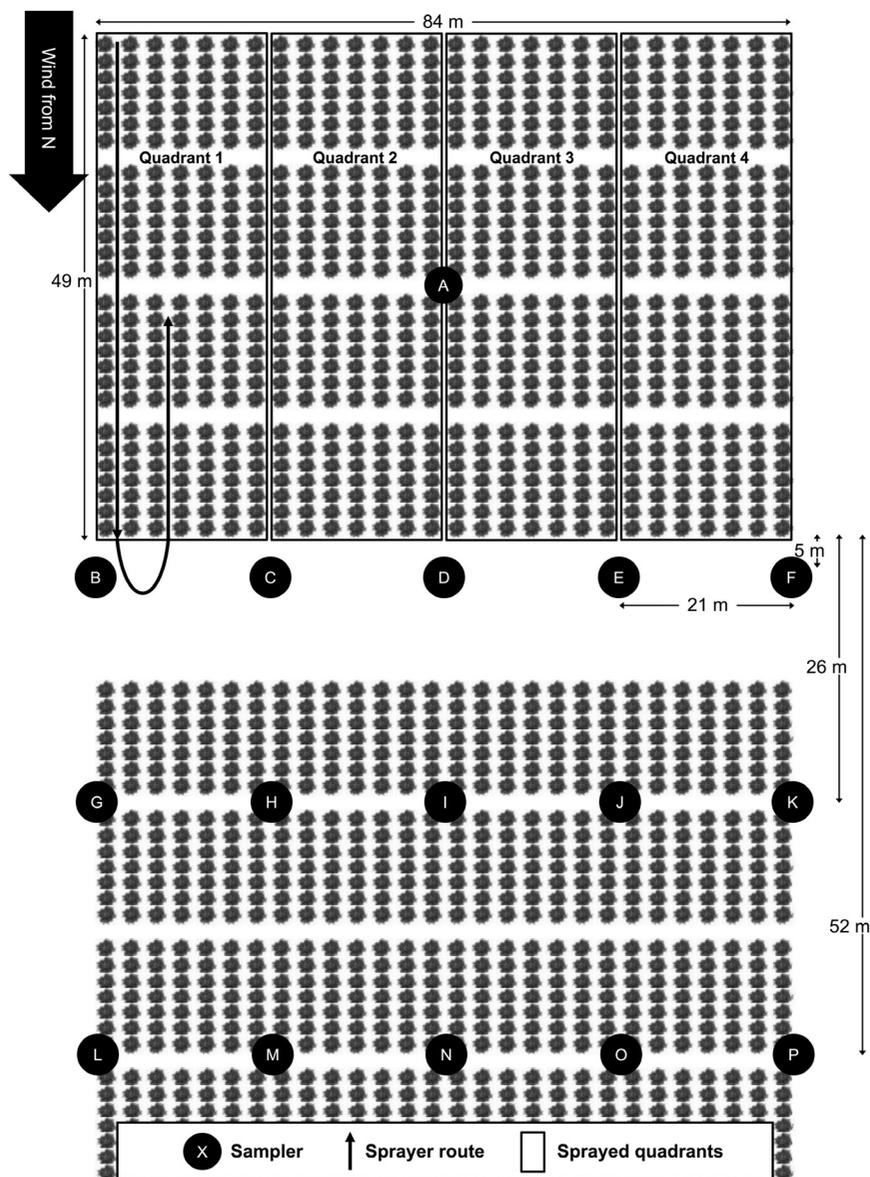


Figure 2. Relative locations of sprayed and sampling blocks with prevailing wind from the north. Sprayed block was divided into four quadrants and sprayed in a randomized order by the axial fan airblast sprayer. Drift sample locations were Masts B-P organized in a grid downwind of the sprayed block. Reference sample locations were Mast A (middle of the sprayed area) and Mast Q (not pictured; 200 m upwind).

ggplot2, knitr, lme4, lubridate, reshape, and rstudio (Wickham, 2007; Wickham, 2009; Grolemund and Wickham, 2011; RStudio Team, 2012; Bates et al., 2015; Xie, 2017). We produced tables of arithmetic and geometric means (AM; GM) and standard deviations (ASD; GSD), scatter plots, box plots, and heat maps.

Linear mixed-effects modeling fit by restricted maximum likelihood was used to assess the significance of

downwind distance, height, and wind speed in explaining variations of drift level ($\ln\text{-}\mu\text{l}$) by location, as measured on PE line [$n = 270$ (samples), $k = 15$ (locations), $l = 6$ (spray trials)]. The model was generated using the lmer function in the R package lme4, with continuous measures of distance, height, and wind speed as fixed effects and categorical location as a random effect. To estimate their impact on within- and between-location

variance components, we reran the model without fixed effects. We assumed a ln distribution for drift level and a normal distribution for all other parameters. Model significance was reported at the $\alpha = 0.05$ level.

Results

Weather conditions

Overall meteorological conditions were relatively similar across spray trials and measurement intervals (Table 1). Spraying typically occurred between 8:00 AM and approximately noon. The duration was longer in September 2016 because three sprayers were used each day compared to only two in July 2015 and June 2016. Results for 1-min averages were not available from 1–2 July 2015 due to a malfunctioning data logger.

Average wind speeds at 2 m elevation were within USEPA's drift-reducing wind recommendations of 3–10 mph (USEPA, 2001). The 15-min wind speed measurements taken 70 m west of the sprayed block at a height of 2 m ranged from 2.9 to 4.0 m/s (6.4–8.9 mph); 1-min measurements taken 190 m northeast at a height of 10 m ranged from 3.4 to 4.7 m/s (7.6–10.5 mph). As expected, wind direction was almost exclusively from a northerly direction. The 2 m station always averaged $\pm 20^\circ$ from true north. The 10 m station once averaged -48° (northwest) on 10 June 2016, but otherwise no more than approximately $\pm 20^\circ$ from true north (Supplementary Figure S5 in the Supplementary Material, available at *Annals of Work Exposures and Health* online).

Temperatures in July 2015 were 10–15°C higher than spray days in early summer or fall, but still within the acceptable range of temperatures for drift sampling. Inclusion of temperature, humidity, and 1-min (instead

of 15-min) wind data as fixed effects in secondary models did not impact study findings.

Sample collection

Samples ($n = 459$) were collected over six spray days (Supplementary Table S1 in the Supplementary Material, available at *Annals of Work Exposures and Health* online). During each of the first three spray days, 102 line samples (3 PE and 3 LDPE from 17 masts) were collected. Only PE samples ($n = 51$) were collected during the last three spray days. After demonstrating that the cross sectional area adjusted deposits from 1 July 2015 were highly correlated (Fig. 3, $R^2 = 0.81$), LDPE samples collected on 2 July 2015 and 10 June 2016 were not analyzed and LDPE samples were not collected on 28–30 September 2016. The intercept in Fig. 3 demonstrates that PE line collected 0.072 $\mu\text{l}/\text{cm}^2$ more than LDPE line, on average. Over the entire study, a total of 306 PE samples (51 from each of the six spray days) were collected and analyzed. There were 270 drift samples (Masts B-P) and 36 reference samples (Masts A and Q).

Laboratory metals analysis

Reporting limits for Zn, Mo, and Cu sampling with LDPE (LOB: 0.1, 0.001, 0.01 μg ; LOQ: 0.2, 0.005, 0.04 μg) and PE (LOB: 3, 0.03, 0.7 μg ; LOQ: 8, 0.08, and 2 μg) were low enough to avoid substantial data censoring (Supplementary Table S2 in the Supplementary Material, available at *Annals of Work Exposures and Health* online). With the exception of four PE Zn measurements from 52 m downwind, all drift samples were above LOB and therefore included in the statistical analysis. LDPE spike recovery efficiencies for Zn, Mo, and Cu from the July 2015 sample analysis batch were 91, 87, and 90%. PE spike recovery efficiencies for Zn, Mo, and Cu from

Table 1. Summary of meteorological data collected during each spray day.

Spray day	Time	Duration ^a (min)	Temp ^b (°C)	Wind speed (m/s) ^c AM (ASD)	Wind direction (°) ^c AM (ASD)
1 July 2015	10:41–12:13	92	32.4	3.3 (0.3); - -	360 (0.0); - -
2 July 2015	10:15–11:21	66	31.6	4.0 (0.3); - -	360 (0.0); - -
10 June 2016	10:44–12:08	84	19.3	3.7 (1.5); 4.7 (2.0)	340 (0.6); 312 (0.5)
28 September 2016	09:34–11:35	121	18.9	4.0 (0.2); 4.4 (1.1)	360 (0.0); 338 (0.2)
29 September 2016	08:50–10:42	112	16.0	2.9 (0.2); 3.4 (0.9)	12 (0.4); 343 (0.2)
30 September 2016	08:20–10:07	107	15.5	3.2 (0.2); 3.7 (1.0)	360 (0.0); 340 (0.2)

^aDuration was longer in September 2016 because three sprayers were used each day compared to only two sprayers in July 2015 and June 2016.

^bArithmetic mean (AM) for 15-min temperature measurements.

^cAM and standard deviation (ASD) for wind measurements. 15-min data to the left of each semicolon and 1-min data to the right. Data are reported from two locations: (i) 15-min averages from a wind cup anemometer located 70 m west of the sprayed block at 2 m elevation and (ii) 1-min averages from an ultrasonic anemometer located 190 m northeast of the sprayed block at 10 m elevation. Wind speed was measured in m/s and wind direction in azimuth degrees, where 0° or 360° represents wind from the north. Only 15-min data were available for 1–2 July 2015.

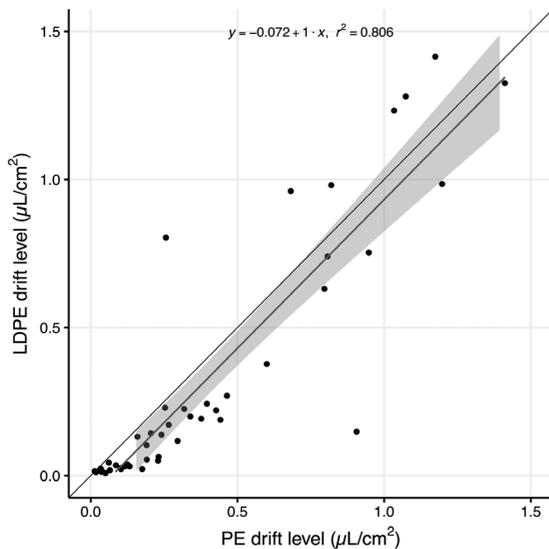


Figure 3. Tracer-based drift volume level collected on collocated polyester (PE) and low-density polyethylene (LDPE) lines, adjusted for cross sectional area, July 2015. Paired PE and LDPE drift levels were correlated ($R^2 = 0.81$), with PE collecting $0.072 \mu\text{L}/\text{cm}^2$ more than LDPE, on average.

July 2015, June 2016, and September 2016 were 102–115, 82–101, and 92–108% (Supplementary Table S3 in the Supplementary Material, available at *Annals of Work Exposures and Health* online). Mean tank mix concentrations for Zn, Mo, and Cu across all AFA trials were 242, 7, and 123 $\mu\text{g}/\text{ml}$, respectively (Fig. 1; Supplementary Table S1 in the Supplementary Material, available at *Annals of Work Exposures and Health* online). Mean Zn, Mo, and Cu background concentrations in the water source as a percentage of tank mix concentrations were 0.056, 0.0077, and 0.00038%, respectively.

Mixed-effects model

Summary statistics indicate evidence of drift at distances up to 52 m downwind. Tracer-based drift volume levels for reference PE samples taken in the middle of the sprayed area (Mast A, $n = 18$) and 200 m upwind (Mast Q, $n = 18$) had GMs and GSDs of 1079 (2.3) and 10 (1.9) μl , respectively (Supplementary Table S4 in the Supplementary Material, available at *Annals of Work Exposures and Health* online).

Among 270 PE drift samples, 266 (98.5%) were above LOB (Table 2). The four values below LOB were 52 m downwind and at the 0–2 m mast height sections. The GM (GSD) for all drift levels was 66 (3.6) μl . When stratified by near (5 m), mid (26 m), and far (52 m) downwind distances, drift levels were 257 (1.8), 52 (2.0), and 20 (2.3) μl , respectively. When stratified by

high (4–6 m), medium (2–4 m), and low (0–2 m) vertical heights, drift levels were 89 (2.5), 65 (3.4), and 51 (4.8) μl , respectively. When stratified by downwind distance and height, drift levels decreased with height at near distances, but increased with height at mid and far distances. As expected, the data were ln distributed. Subsequent analysis was on ln-transformed drift levels.

Table 3 provides point estimates and 95% confidence intervals for the mixed-effects model. Increasing distance was significantly associated with a decrease in drift level (-0.05 ; 95% CI: $-0.06, -0.04$; $P < 0.001$). This coefficient represents a -0.05 change in ln- μl drift volume per m distance. Higher height (0.16; 95% CI: 0.11, 0.20; $P < 0.001$) and wind speed (0.53; 95% CI: 0.35, 0.70; $P < 0.001$) were significantly associated with an increase in drift level. These coefficients represent a 0.16 change in ln- μl drift volume per m height and a 0.53 change in ln- μl drift volume per m/s, respectively.

More of the remaining variance was within-location ($0.378, \frac{0.378}{0.093 + 0.378} \times 100 = 80.2\%$) than between-location (0.093; 19.8%). Distance, height, and wind speed impacted the between-location variance component (1.206–0.093; 92% reduction) considerably, but did not greatly alter the within-location component (0.499–0.378; 24% reduction). This difference in percent reduction suggests that there were relatively few systematic changes for individual locations across spray trials.

Discussion

This study characterized spray drift in an orchard work environment and developed a method for comparing the drift potential of different application technologies. We report tracer-based drift volume level, a useful metric that describes the tank mix volume equivalent intercepted by vertical sampling lines or drift as a percent of the applied tank volume. After adjusting for cross sectional area, we found that fibrous PE lines collected $0.072 \mu\text{l}/\text{cm}^2$ more than collocated smooth LDPE lines, on average. We propose that this difference was due mainly to a higher collection efficiency via interception and impaction of smaller aerosols throughout the PE line matrix and, to a lesser extent, gravitational settling of larger aerosols on horizontal fibers.

A unique design feature of this study was that it drew from spatiotemporal characteristics of actual farmworker illness scenarios. Instead of spraying one or a few tree rows, our trials included repeated sprays in a 28-row orchard block. Other studies have measured airborne drift using vertical masts, but this was the first time a grid of such masts was used to characterize

Table 2. Summary statistics^a for tracer-based drift volume level (μl) collected on polyester line sampling matrices from axial fan airblast spray trials.

Sample	<LOB	N	AM	ASD	GM	GSD
Total drift samples	4	266	136	179	66	3.6
Downwind distance ^b						
Near (5 m)	0	90	310	216	257	1.8
Mid (26 m)	0	90	66	42	52	2.0
Far (52 m)	4	86	28	24	20	2.3
Vertical height ^c						
High (4–6 m)	0	90	134	145	89	2.5
Medium (2–4 m)	0	90	132	190	65	3.4
Low (0–2 m)	4	86	142	201	49	4.8
Near (5 m) distance at height						
High (4–6 m)	0	30	266	183	222	1.8
Medium (2–4 m)	0	30	310	244	252	1.9
Low (0–2 m)	0	30	354	215	304	1.8
Mid (26 m) distance at height						
High (4–6 m)	0	30	90	47	77	1.8
Medium (2–4 m)	0	30	63	35	53	1.8
Low (0–2 m)	0	30	44	29	35	2.0
Far (52 m) distance at height ^d						
High (4–6 m)	0	30	47	26	41	1.8
Medium (2–4 m)	0	30	25	16	20	1.9
Low (0–2 m)	4	26	11	6	9	1.8

^aListed by limit of blank (LOB), number of measurements (N), arithmetic mean (AM), arithmetic standard deviation (ASD), geometric mean (GM), and geometric standard deviation (GSD). N is reflective of each micronutrient tracer analyzed via inductively coupled plasma mass spectrometry (ICP-MS).

^bAs shown in Fig. 1, downwind sampling rows were at distances of 5 (Near), 26 (Mid), and 52 (Far) m from the southern edge of the sprayed area. These correspond to Masts B-F (Near), G-K (Mid), and L-P (Far).

^cSampling heights were categorized in terms of 2 m polyester (PE) line sections taken at 4–6 m (High), 2–4 m (Medium), and 0–2 m (Low) above the ground.

^dAM (and GM) for High, Medium, and Low heights at Far distances were 3.9 (3.7), 1.5 (1.7), and 1.6 (1.3) times greater than background levels measured at the upwind reference location (Mast Q). See Supplementary Table S4 (available at *Annals of Work Exposures and Health* online) for reference location values. All measurements were corrected for lab matrix blank values.

Table 3. Coefficients for determinants of drift from axial fan airblast spray trials^a.

Fixed effects	Model estimate (95% CI)	SE	P-value
Intercept	3.17 (2.48, 3.87)	0.36	<0.001
Distance (m)	-0.05 (-0.06, -0.04)	0.01	<0.001
Height (m)	0.16 (0.11, 0.20)	0.23	<0.001
Wind speed (m/s)	0.53 (0.35, 0.70)	0.09	<0.001
Variance components ^b	Random and fixed effects included	Only random effect included	
Within-location (Residual)	0.378 (80.2%)	0.499 (29.3%)	
Between-location (Intercept)	0.093 (19.8%)	1.206 (70.7%)	
Total variance	0.471 (100%)	1.705 (100%)	

^aThere were 266 tracer-based drift volume levels (ln- μL) measured on polyester lines at 15 downwind locations in six spray trials.

^bWhen the fixed effects were dropped from the model, within-location variance was 0.499 (29.3%) and between-location variance was 1.206 (70.7%). Fixed effects impacted the between-location component of the variance (1.206–0.093; 92% reduction) considerably, but did not alter the within-location component of variance (0.499–0.378; 24% reduction) as much. The difference between these models suggests that there were relatively few systematic changes for individual locations across spray trials.

the variability of drift levels in a downwind orchard block. We used a mixed-effects model to investigate the relationship between orchard work environment

characteristics and between- and within-location variance components of drift levels, enabling future development of similar exposure groupings for orchard workers.

'Tree canyon effects', akin to urban street canyon effects (Sini et al., 1996), may isolate components of wind flow below the canopy where orchard workers are often located. Using an orchard spray drift model and light detection and ranging (LIDAR), Tsai (2007) demonstrated the complex movement of within-canopy spray, which can escape the end of tree rows as drift when aligned with wind direction.

Study results highlight the importance of differentiating buffers not only by sprayer type and distance, but also by wind speed, orchard architecture, and sampling height (e.g. workers on the ground or on ladders). As expected, drift levels decayed with downwind distance (Table 2). Drift was measured up to 52 m downwind, which is approximately 1.7 times greater than the 30 m (100 ft) AEZ buffer for orchard sprayers defined by the Worker Protection Standard (USEPA, 2016b). Based on this standard, the first two rows of our sampling area should have been free of all persons other than appropriately trained and equipped handlers when the sprayer was at the southern edge of the sprayed block (USEPA, 2016b). As distance from the sprayed block increased, vertical profiles indicated more deposition on the highest line section (4–6 m) relative to lower sections. GM drift levels for high (4–6 m), medium (2–4 m), and low (0–2 m) heights at far (52 m) distances were 3.7, 1.7, and 1.3 times greater than background levels measured at the reference samples 200 m upwind.

Our findings are largely consistent with other orchard-based field studies. A recent meta analysis of spray drift sampling found that 4.4% of total pesticide applied was measured between 0 and 5 m downwind of fully leafed orchards (Donkersley and Nuyttens, 2011). In our study, we estimate that 1.7% $\left(\frac{0.000310\text{l} \times 21,000}{378\text{l}} \times 100\right)$ of the total volume applied was measurable 5 m downwind; this percentage is based on an AM drift level of 0.000310 l (310 μl) measured 5 m downwind from an applied volume of 378 l during each trial and a vertical sampling field surface area (504 m² = 84 m wide by 6 m tall) that was 21,000 times larger than the PE line cross sectional area (0.024 m²; 240 cm²). At 5 m downwind, Cross et al. (2001a) measured normalized spray deposits on 0–4 m sections of vertical sampling lines that were two to five times greater than those on 4–6 m sections.

We observed deposits that were 1.2 $\left(\frac{354}{0.5(310 + 266)}\right)$ times greater, on average. Fox et al. (1993) reported that deposits on floss decreased with height at 7.5 m downwind, but were more uniform across all heights at 15, 30, and 60 m downwind. Butler Ellis et al. (2014) reported that average bystander exposures were higher

when wind was directed along orchard rows and that bystander exposure showed a high level of variability.

There are several limitations to this study. First, it modeled values from stationary area sampling instead of workers. Potential exposure estimates are not provided because we have not addressed the relationship between PE lines and a human body. Though outside the scope of this paper, we believe such work is possible by using, for example, measured drift volume levels, product label mixing instructions, and publicly available statistical data about human factors used to assess exposure. Second, data were collected in one orchard and may not be representative of other planting systems or sprayer configurations, such as adapted airflow or different nozzles (Khot et al., 2012). Also, tree row orientation in the sprayed block was parallel to the prevailing wind direction as opposed to perpendicular, which is required by some protocols (ASABE, 2004; ISO, 2005). Third, although the field team followed detailed standard operating procedures for prespray sample setup and post-spray sample harvesting, some sample surfaces contacted gloved hands, tree leaves, or the ground; however, inclusion or exclusion of these potentially contaminated samples ($n = 12$; 4%) did not change our findings.

We recommend vertical passive sampling with PE lines and micronutrient tracers in future assessments of orchard drift. Drift levels measured by highly efficient, nonuniform surfaces such as PE lines could be used to estimate potential worker exposure and validate other models such as BROWSE (Butler Ellis et al., 2017a,b). As part of our larger study, we found that optical particle counters, despite limitations that do not allow for analysis of chemical composition or detection of particles with diameters smaller than 0.5 μm , can detect drift plumes and finer time-resolved data on aerosol levels (Blanco et al., 2017). This approach may hold promise for real-time monitoring of human exposure during drift events. To better understand how orchard drift dynamics contribute to environmental and occupational exposures, it would be ideal to take measurements from actual workers involved in actual drift events. Such studies would require equipping orchardists and orchard workers with low-cost and easy-to-use sensors such as on-site meteorological stations and direct-reading particle counters to identify when drift reaches a level of concern for human exposure.

Conclusions

Our study measured tracer-based drift volume levels from a conventional AFA sprayer in a modern orchard. The field site proved to be ideal for the spray trials because it adhered to applicable drift sampling standards. Vertical PE

lines captured greater drift levels than LDPE lines. Buffers are likely to offer drift exposure protection to orchard workers near an active AFA sprayer. However, drift was measured well beyond the USEPA 'Application Exclusion Zone' buffer. Buffers for airblast applications could be further defined by factors such as worker location, wind speed, and features of orchard architecture such as tree canopy shape, height, and density. Data from our study may prove useful for estimating potential orchard worker exposure and validating bystander drift exposure models.

Supplementary Data

Supplementary data are available at *Annals of Work Exposures and Health* online.

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Conflict of Interest

The authors declare no conflict of interest relating to the material presented in this article. Its contents, including any opinions and/or conclusions expressed, are solely those of the authors.

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