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Original Article

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Spray Drift from Three Airblast Sprayer Technologies in a Modern Orchard Work Environment

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Abstract

Pesticide spray drift represents an important exposure pathway that may cause illness among orchard workers. To strike a balance between improving spray coverage and reducing drift, new sprayer technologies are being marketed for use in modern tree canopies to replace conventional axial fan airblast (AFA) sprayers that have been used widely since the 1950s. We designed a series of spray trials that used mixed-effects modeling to compare tracer-based drift volume levels for old and new sprayer technologies in an orchard work environment. Building on a smaller study of 6 trials (168 tree rows) that collected polyester line drift samples (n = 270 measurements) suspended on 15 vertical masts downwind of an AFA sprayer application, this study included 9 additional comparison trials (252 tree rows; n = 405 measurements) for 2 airblast tower sprayers: the directed air tower (DAT) and the multi-headed fan tower (MFT). Field-based measurements at mid (26 m) and far (52 m) distances showed that the DAT and MFT sprayers had 4–15 and 35–37% less drift than the AFA. After controlling for downwind distance, sampling height, and wind speed, model results indicated that the MFT [–35%; 95% confidence interval (CI): –22 and –49%; $P < 0.001$] significantly reduced drift levels compared to the AFA, but the DAT did not (–7%; 95% CI: –19 and 6%; $P = 0.29$). Tower sprayers appear to be a promising means by which to decrease drift levels through shorter nozzle-to-tree canopy distances and more horizontally directed aerosols that escape the tree canopy to a lesser extent. Substitution of these new technologies for AFA sprayers is likely to reduce the frequency and magnitude of pesticide drift exposures and associated illnesses. These findings, especially for the MFT, may fit United States Environmental Protection Agency's Drift Reduction Technology (DRT) one-star rating of 25–50% reduction. An 'AFA buyback' incentive program could be developed to stimulate wider adoption of new drift-reducing spray technologies. However, improved sprayer technologies alone do not eliminate drift. Applicator training, including proper sprayer calibration and maintenance, and application exclusion zones (AEZs) can also contribute to minimizing the risks of drift exposure. With regard to testing DRTs and establishing AEZs, our study findings demonstrate the need to define the impact of airblast sprayer type, orchard architecture, sampling height, and wind speed.

Keywords: airblast sprayer; drift; drift reduction technology; engineering controls; exposure assessment—mixed models; pesticide spraying

Introduction

Modern agricultural practices designed to protect the food supply can include the use of pesticides that may pose health risks to unintended targets. Off-target pesticide spray drift is a potential exposure pathway for farmworkers and bystanders alike (Lee *et al.*, 2011). In the Pacific Northwest, orchard workers are recognized as a population particularly susceptible to pesticide drift exposure and the illnesses that may result (WADOH, 2013, 2017; Calvert *et al.*, 2015).

Unlike sprayer technologies used in other crops, the conventional axial fan airblast (AFA) orchard sprayer has remained largely unmodified since the basic design was widely adopted in the 1950s (Fox *et al.*, 2008). Studies have reported that 45% or more of applied amounts can be lost to the ground and off-target drift, depending on factors such as meteorological conditions, spray droplet size, and orchard architecture (Steiner, 1969; Herrington *et al.*, 1981; Raisigl *et al.*, 1991; Vercruysse *et al.*, 1999). The combination of widespread AFA sprayer use, reduced tree height and canopy volume of modern orchards, and documented spray loss has made the search for better technologies a top priority for equipment manufacturers and agricultural engineers. More advanced systems aim to strike a balance between improving spray coverage and reducing drift (e.g. canopy sensors, spray recapture, directed deposition, targeted sprayers, and solid set canopy delivery systems) (Nuyttens, 2007; Landers *et al.*, 2017; Sinha *et al.*, 2019). The tree fruit industry is actively promoting new and emerging agricultural spray technologies with improved efficacy, providing us with the opportunity to evaluate these technologies in the context of drift levels in a modern orchard work environment.

Regulatory agencies promote drift reduction technology (DRT) by creating online databases that pesticide applicators can search for spray equipment that has received official low-drift star ratings. Both the United Kingdom Safety Executive (LERAP, 2002, 2018) and United States Environmental Protection Agency (USEPA, 2014) keep such databases to encourage 'manufacture, marketing, and use of spray technologies scientifically verified to significantly reduce pesticide drift' (USEPA, 2017a). For example, USEPA uses ratings of one, two, three, or four stars for technologies that reduce drift 25–49, 50–74, 75–89, and 90+%, respectively, compared to standard technologies (USEPA, 2017b). However, no airblast sprayers currently have the scientific verification needed for inclusion in the USEPA program.

Previous studies have compared different orchard sprayer technologies using controlled indoor laboratory experiments and computational fluid dynamics. For example, Dekeyser *et al.* (2013, 2014) assessed spray nozzles, liquid distribution, air streams, within-tree deposition quality, and off-target losses to the ground. Yet, few studies have attempted such comparisons in outdoor field experiments. Derksen *et al.* (1995), Hendrickx *et al.* (2012), and Duga *et al.* (2015) compared in-canopy deposition of orchard sprayers in field experiments, but none of these studies included downwind sampling.

The purpose of this study was to quantify the drift potential of two tower sprayers compared to a conventional airblast sprayer. Our central hypothesis was that the three sprayers would generate different source plumes and therefore different drift levels at downwind receptor locations. We expected that the tower sprayers would have lower drift levels due to: (i) shorter nozzle-to-tree canopy travel distances for sprayed aerosols and (ii) a lower likelihood of these aerosols escaping above the tree canopy.

Methods

Study design

Three micronutrient tracers—zinc (Zn), molybdenum (Mo), and copper (Cu)—were applied separately by each of the three sprayers to the same apple orchard block (0.4 ha; 1 acre) during July 2015, June 2016, and September 2016. The trials utilized the efficiency of applying multiple metal salt solutions [Carbol™ Zinc (10% Zn; 2.5 ml l^{-1}; 32 oz/100 gal), Manni-Plex® B Moly (0.5% Mo; 1.3 ml l^{-1}; 16 oz/100 gal), and Biomin® Copper (4% Cu; 2.5 ml l^{-1}; 32 oz/100 gal) to a single target by adapting the field sampling methods of Cross *et al.* (2001) and ICP-MS lab methods described by Zabkiewicz *et al.* (2008). Spray days consisted of two or three spray trials, each of which involved one application technology spraying a single micronutrient to the orchard block (Table 1). In order to provide a fair comparison across the three sprayers, we subdivided the orchard block into four quadrants of approximately seven tree rows each (Fig. 1). Rows in each quadrant were sprayed in serpentine fashion along the orchard's north–south axis. On every spray day, quadrant spray order was randomized and each application technology sprayed one quadrant before moving to another quadrant. For example, Quadrant 3 was sprayed with AFA, DAT, and MFT before Quadrant 2 was sprayed with the same sprayers. The relatively short spray periods that resulted (6–8 min per sprayer) minimized the potential for changes in environmental conditions (e.g. wind speed and/or direction) to affect the comparison. For example, all three sprayers conducted applications within a 20- to 25-min period during which wind conditions were unlikely to change drastically. Each sprayer carried a global positioning system (GPS) to verify the route and spray times by quadrant (Kasner *et al.*, 2018). In total, there were 15 sprayer trials: 6 AFA, 5 DAT, and 4 MFT (Supplementary Table S1, available at *Annals of Work Exposures and Health* online).

Sprayer calibration

As with most orchard sprayers, the AFA (Rears Pak-Blast-100), DAT (Turbo Mist Tower Model 30P), and MFT (Quantum Mist Tower 2000) had modifiable features to customize sprayer output for a particular canopy. We used micronutrient product label instructions and knowledge of common practices to select a liquid spray volume output of 935 l ha^{-1} (100 gal ac^{-1}) and to produce spray droplet sizes classified as fine-to-very fine (ASABE, 2013; TeeJet, 2014). As indicated in Table 2, sprayer features and settings were optimized to match orchard row width (3 m; 10 ft), tree spacing (0.9 m; 3 ft), tree height (3.5 m; 11.5 ft), and canopy shape (columnar) (Hoheisel, 2016; Turbo-Mist, 2017). Our field team, which included a certified private applicator, calibrated settings for each sprayer's volumetric air flow rate, liquid spray nozzles, system speed, and operating pressure (Table 2). Only one setting for each sprayer parameter was used across all trials. These 'optimized' sprayer settings were selected based on in-field consultation with an agricultural extension expert who developed the calibration procedures (Hoheisel, 2016).

Table 1. Summary of data collected and analysed from 15 spray trials for AFA, DAT, and MFT sprayers.

Spray day	Spray trial[a]	Tank concentration[b] (µg ml^{-1})	PE line samples[c]	
			<LOB	Drift measurements
01-Jul-15	AFA-Zn	247	0	45
	DAT-Mo	7.37	0	45
02-Jul-15	AFA-Mo	7.04	0	45
	DAT-Zn	160	2	43
10-Jun-16	AFA-Zn	222	4	41
	MFT-Mo	9.57	0	45
28-Sep-16	AFA-Zn	258	0	45
	DAT-Cu	87.1	0	45
	MFT-Mo	11.4	0	45
29-Sep-16	AFA-Mo	6.74	0	45
	DAT-Zn	297	0	45
	MFT-Cu	129	0	45
30-Sep-16	AFA-Cu	123	0	45
	DAT-Mo	7.06	0	45
	MFT-Zn	381	0	45
Subtotal	6 AFA		4	266
	5 DAT		2	223
	4 MFT		0	180
Total	15 trials		6	669

[a]Each spray trial consisted of one sprayer-micronutrient combination. Zn, Mo, and Cu micronutrients were used in each sprayer at least once.

[b]CV for each tracer was computed by dividing standard deviation of tank concentration by mean tank concentration: 74/261 = 0.28 (Zn, n = 6), 1.9/8.2 = 0.23 (Mo, n = 6), and 23/113 = 0.20 (Cu, n = 3).

[c]We collected 45 PE line samples (3 different heights in 15 locations) on each spray day (n = 6) for a total of 270 PE line samples. This resulted in 669 drift volume measurements based on micronutrient deposits that were above the LOB. Does not include reference samples collected from Masts A and Q.

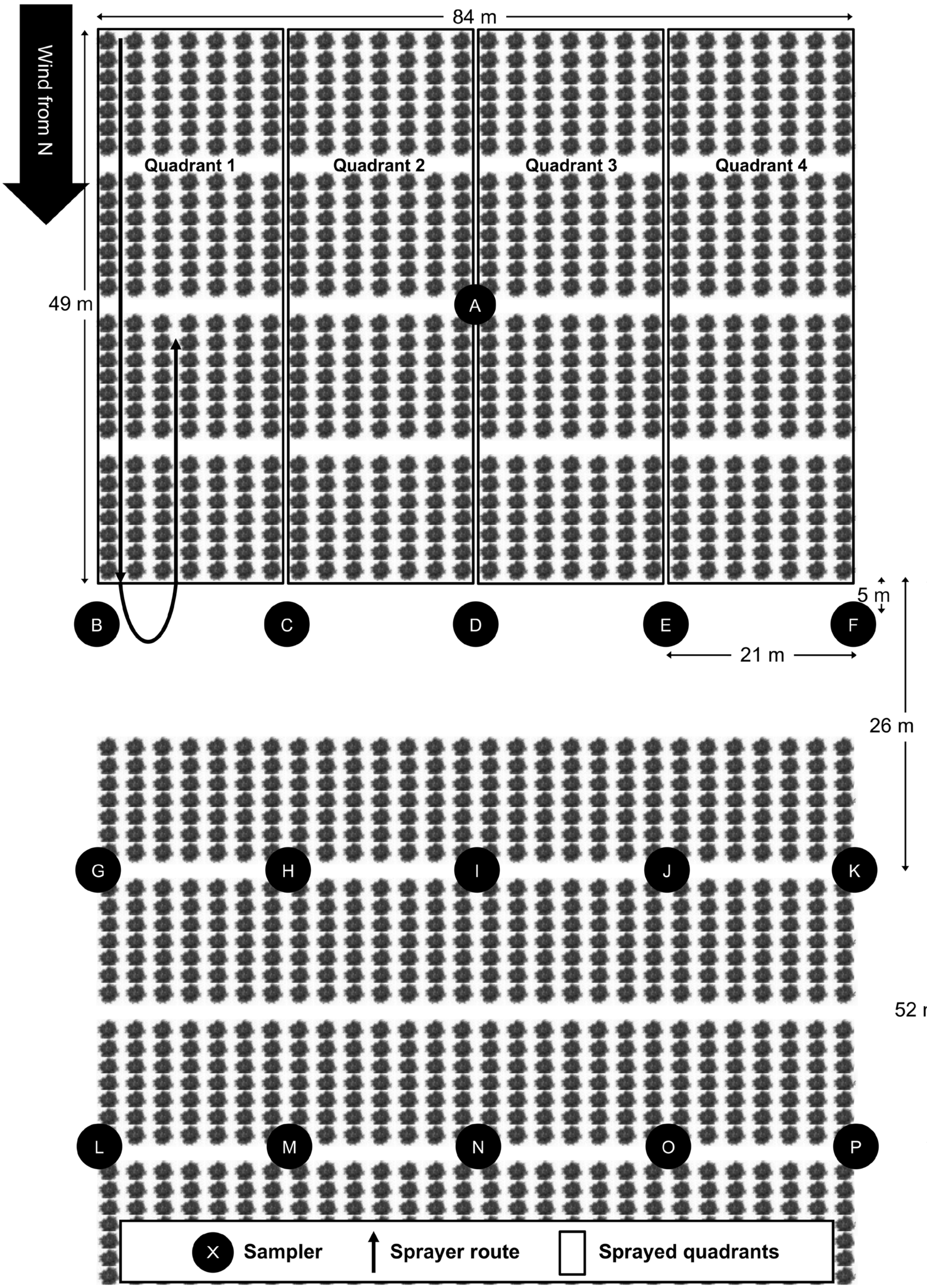

Figure 1. Relative locations of sprayed and sampling blocks with prevailing wind from the north. Sprayed block was divided into four quadrants and sprayed in a randomized order by the three sprayers. Drift sample locations were Masts B–P organized in a grid downwind of the sprayed block. Reference sample locations were Mast A (middle of the sprayed area) and Mast Q (not pictured; 200 m upwind). Reproduced with permission (Kasner *et al.*, 2018).

Fan(s)

The sprayers in this study used fans to move large volumes of air to assist spray nozzles (i.e. air assisted sprayers) with canopy deposition (Khot *et al.*, 2012; Matthews *et al.*, 2014a). The AFA and DAT each had one rear-facing axial fan with diameters of 71 and 76 cm. The MFT had six 50 cm axial fans mounted on the tower (three fans per side). Fan speed settings and volumetric air flow rates on the AFA, DAT, and MFT were estimated to fall within normal ranges of 1835–3700 revolutions min^{-1} and 566–850 m^3 min^{-1}, which were not measured but based on values reported in the technical manuals for each sprayer.

Nozzles

New spray nozzles (*TeeJet*) were inserted into all sprayers and then tested to compare expected versus observed liquid volumetric flow rates (i.e. expected values from nozzle technical manual versus observed values measured in the field with a digital flow meter). We used an online calculator (Turbo-Mist, 2017) to determine the volume output for each sprayer. Some nozzles were closed on each sprayer to match the tree canopy and achieve the desired spray volume and droplet size. The AFA had 10 open nozzles (5 per tree canopy side), the DAT had 22 open nozzles (11 per side), and each of the 6 MFT fan heads had 6 nozzles for a total of 36 open nozzles (18 per side). Stainless steel disc-core nozzles (*TeeJet*) were on the AFA and DAT and ceramic one-piece nozzles (*TeeJet*) were on the MFT. All nozzles created the same hollow-cone shaped spray pattern.

System

As measured from the top nozzle, boom heights for the AFA, DAT, and MFT sprayers were approximately 1.2, 2.7, and 3.7 m, respectively. The combination of nozzle and system operating pressure settings determined expected volume median diameter (VMD) for spray droplets. VMD expresses the value where 50% of the total volume of liquid sprayed consists of droplets with diameters larger than the median value and 50% with smaller diameters (Matthews *et al.*, 2014b). When AFA, DAT, and MFT system pressures were set to 14, 7, and 7 bar, theoretical VMDs were approximately 106–116 (fine), 125–130 (fine), and 61–105 µm (very fine), respectively (ASABE, 2013; TeeJet, 2014). The MFT had an automatic rate controller, a device found on some new spray technologies designed to provide a consistent application volume by adjusting operating pressure based on sprayer travel speed (Deveau, 2016). To maintain constant pressure and reduce variability due to the MFT rate controller, travel speed was fixed at 1.3 m s^{-1} for all sprayers in the study. Travel speed was checked with a full sprayer tank in the same field where applications took place. A path of known distance (30.5 m; 100 ft) was marked with stakes and a stopwatch was used to record the time it took for the tractor plus sprayer rig to pass from one stake to the next. This was repeated

Table 2. Comparison of sprayer settings for orchard study site.

Sprayer features and settings[a]	AFA	DAT	MFT
Liquid volume applied per area (l ha^{-1})	935	935	935
Fan(s)			
Number on sprayer	1	1	6
Diameter (cm)	71	76	50
Volumetric air flow rate (m^3 min^{-1})	566–850	566–850	566–850
Nozzles			
Number per side	5	11	18
Type (*n*)	D3 (2); D4 (1); D5 (2)	D3 (11)	VK-4 (6); VK-8 (12)
Core size	25	25	–
System			
Boom height (m)	1.2	2.7	3.7
Travel speed (m s^{-1})	1.3	1.3	1.3
Operating pressure (bar)	14	7	7
Spray droplets			
Theoretical VMD (µm) range[b]	106–116	125–130	61–105
Size classification	Fine	Fine	Very fine

[a]More information about nozzles and droplet size classifications can be found in the TeeJet technical catalog and ASABE standard 572.1. l ha^{-1}, liters per hectare; VMD measured in micrometers.

[b]Values were not measured. They were estimated from ASABE 572.1 or related fitted curves based on nozzle and pressure settings for this study.

three times for each sprayer and then checked against GPS speed estimates.

Sample collection and laboratory analysis

A detailed description of our meteorological and field data collection methods, which conformed to applicable standards (ASABE, 2004; ISO, 2005), is described in a previous publication (Kasner *et al.*, 2018) and summarized here.

Wind speed, wind direction, air temperature, and relative humidity were measured by two different on-site meteorological stations (WSU, 2015, 2017). A permanent on-site weather station (AgWeatherNet) located 70 m (230 ft) west of the sprayed block had instruments 2 m (6 ft) above ground that collected data at 0.2 Hz and then processed as 15-min averages. A second, temporary station located 190 m (623 ft) northeast of the sprayed block had instruments at 3 m (10 ft) and 10 m (33 ft) above ground that collected data at 0.1 Hz and then processed as 1-min averages.

Aerosols containing the micronutrients deposited on drift samples placed at near (5 m), mid (26 m), and far (52 m) distances downwind (Fig. 1). Each drift sample consisted of a 2 m section of polyester (PE) line suspended vertically at low (0–2 m), medium (2–4 m), or high (4–6 m) heights from one of fifteen vertical masts. Drift samples were analysed through inductively coupled plasma mass spectrometry (ICP-MS). These laboratory values were normalized by dividing the mass per sample (µg) by the concentration of the tracer in the tank mix (µg ml^{-1}) to indicate drift levels, or volume tank equivalents (µl) deposited on each sample by each sprayer.

Video footage

Three video cameras recorded the spray trials. Camera #1 (Supplementary Figure S1, available at *Annals of Work Exposures and Health* online) was located in the sampling area with an aerial view of the sprayed area from approximately 26 m downwind and 6 m above the ground, near Mast I (Fig. 1). Camera #2 (Supplementary Figure S2, available at *Annals of Work Exposures and Health* online) was located approximately 10 m from the western edge between the sprayed and sampling fields, with a side view of the sprayers. Camera #3 (Supplementary Figure S3, available at *Annals of Work Exposures and Health* online) was positioned on the sprayer's tractor facing backwards during the spray trial.

Statistical analysis

Data were managed and analysed with R v. 3.3.3 (R Core Team, 2017) using the ggplot2, knitr, lme4, lubridate, reshape, and rstudio packages (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 and standard deviations, scatter plots, and heat maps.

Because there were repeated measures at 15 individual locations (proxy for individual workers), we used a mixed-effects model to characterize drift potential based on several factors. We expanded our previously developed AFA drift model (Kasner *et al.*, 2018) to include a term for sprayer type that used AFA as the reference category and estimated the impact of different tower sprayers on drift levels. The expanded model thus demonstrated the drift-reducing performance of the DAT and MFT sprayers relative to the AFA reference sprayer.

The expanded linear mixed-effects model was fit by restricted maximum likelihood to assess the significance of continuous measures of downwind distance, height, wind speed, and categorical sprayer type (fixed effects) in explaining drift level and its variation (ln-µl) by location category (random effect) [n = 669 (sample measurements), k = 15 (locations), l = 15 (spray trials)]. Distance and wind speed were selected *a priori* as key determinants of drift based on previous modeling efforts. Height was included to investigate the impact of sampling for airborne drift (fine droplets that remain suspended for minutes or hours and carried greater distances by the wind) instead of deposition drift (coarse droplets that settle out within seconds due to gravitational force). With the exception of location, all covariates were treated as fixed effects and interpreted like other linear model covariates to describe observable variation due to systematic group-level differences. Location was treated as a random effect to describe variation due to individual differences and was interpreted as the percent of remaining variation that was attributable to within-location versus between-location. We assumed a ln-distribution for drift level, a normal distribution for all other parameters, and the default assumed covariance structure of the lmer function (Bates *et al.*, 2015). Model significance was reported at the α = 0.05 level. We also reran the model without fixed effects to estimate their impact on within-location and between-location variance components.

Some spray days included only two sprayers (i.e. July 2015 and June 2016) due to logistical constraints, so we also reran the original model using only data collected during days in which all three sprayers were deployed (i.e. September 2016, n = 405 measurements). This ensured comparisons under the most practically equivalent environmental conditions for all sprayers. Additionally, we ran a secondary model to explore the impact of adding temperature and relative humidity as fixed effects to the original model, which were not included *a priori* because wind speed was thought to be more variable than temperature or humidity during short spray intervals.

Results

Weather conditions

Meteorological data indicated conditions were relatively similar across sprayers and trials (Supplementary Tables S1 and S2, available at *Annals of Work Exposures and Health* online). Average wind speeds at 2 m elevation were within USEPA's drift-reducing wind recommendations of 1.3–4.5 m s^{-1} (3–10 mph) (USEPA, 2001). Mean 15-min wind speed measurements were 3.4–3.5 m s^{-1} and almost exclusively from the north. Mean temperature and relative humidity were 21.5°C and 43%, respectively. No MFT spraying occurred in July 2015, which was a hotter and less humid month than either June or September 2016. As such, AFA and DAT trials had higher mean temperatures and lower mean relative humidity compared to MFT trials.

Sample analysis

A total of 669 tracer-based drift volume level measurements were available from 270 PE line samples collected in 15 spray trials (Table 1). Six measurements (0.9% of 669) were excluded because they fell below the limit of the blank (LOB), which was defined as the concentration found when replicates of a blank sample containing no analyte were tested (Armbruster and Pry, 2008; Kasner *et al.*, 2018). Reporting limits for Zn, Mo, and Cu were 3, 0.03, and 0.7 µg, respectively (Kasner *et al.*, 2018). The coefficients of variation (CV) for Zn, Mo, and Cu tank concentrations across all trials were 28, 23, and 20%, respectively.

Comparison of drift levels between sprayers

In agreement with our previous study (Kasner *et al.*, 2018), there was this at distances up to 52 m downwind for all sprayers ($n = 669$). Video footage from the field also confirmed this (Supplementary Videos, available at *Annals of Work Exposures and Health* online). The geometric mean (GM) and geometric standard deviation (GSD) for all drift levels were 58 µl (3.8) (Table 3). Those for AFA, DAT, and MFT sprayers were 66 µl (3.6), 60 µl (3.7), and 45 µl (4.3), respectively. When restricted to data collected at distances farther than 25 m downwind, the same trend was observed across sprayers. At 26 m, AFA, DAT, and MFT were 52 µl (2.0), 50 µl (1.8), and 33 µl (2.3), respectively. At 52 m, they were 20 µl (2.3), 17 µl (2.5), and 13 µl (2.8). By this metric, the MFT had 35–37% (e.g. $1 - \frac{33}{52} \times 100 = 37\%$ for samples at 26 m) less drift measured by volume than the AFA at mid and far field distances. Similarly, the DAT sprayer had 4–15% less than the AFA at the same distances. As expected, a large difference (more than 2-fold) between arithmetic and geometric means for drift levels from each sprayer was indicative of ln-distribution. Subsequent analysis was on ln-transformed drift levels.

Drift levels for all sprayers decreased with height at near distances, but increased with height at mid and far distances. In Fig. 2, the locally weighted smoothing curve suggests that the MFT was less drift prone than the AFA. Differences between DAT and AFA performance were present but not statistically significant. The trend of decreasing drift level with distance (i.e. drift decay curve) was more pronounced for low versus high sampling heights across all sprayers.

Model results

When compared to the AFA, MFT sprayer type was significantly associated with a decrease in drift level (−0.35; 95% CI: −0.49, −0.22; $P < 0.001$), but DAT sprayer type was not (−0.07; 95% CI: −0.19, 0.06; $P = 0.29$) (Table 4). Increasing distance was significantly associated with a decrease in drift level (−0.06; 95% CI: −0.07, −0.05; $P < 0.001$). This coefficient represents a −0.06 change in ln-µl drift volume per m distance. Higher height (0.13; 95% CI: 0.10, 0.16; $P < 0.001$) and wind speed (0.28; 95% CI: 0.16, 0.40; $P < 0.001$) were significantly associated with an increase in drift level. These coefficients represent a 0.13 change in ln-µl drift volume per m height and a 0.28 change in ln-µl drift volume per m s^{-1}, respectively. Similar to our AFA-only model (Kasner *et al.*, 2018), more of the remaining variance was within-location (79.5%) than between-location (20.5%), but the opposite was true when all fixed effects were dropped from the model (30.4% versus 69.6%).

When the original model was restricted to days in which all three sprayers were used, MFT sprayer type was still significantly associated with a decrease in drift level (−0.28; 95% CI: −0.42, −0.14); $P < 0.001$) and DAT was not (−0.10; 95% CI: −0.24, 0.04; $P = 0.18$). The secondary model showed that inclusion of temperature and relative humidity also did not change how the sprayers performed relative to each other. MFT sprayer type was still significantly associated with a decrease in drift level (−0.30; 95% CI: −0.45, −0.17; $P < 0.001$) and DAT was not (−0.06; 95% CI: −0.19, 0.06; $P = 0.35$). Temperature (0.06; 95% CI: 0.01, 0.11; $P = 0.01$) and relative humidity (0.05; 95% CI: 0.01, 0.09; $P = 0.01$)

Table 3. Summary statistics[a] for tracer-based drift volume level (µl) collected on PE line sampling matrices downwind[b] from AFA, DAT, and MFT spray trials.[c]

Sample	<LOB	*N*	AM	ASD	GM	GSD
Total drift samples	6	669	128	172	58	3.8
AFA sprayer	4	266	136	179	66	3.6
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
DAT sprayer	2	223	129	169	60	3.7
Near (5 m)	0	75	300	197	247	1.9
Mid (26 m)	0	75	59	37	50	1.8
Far (52 m)	2	73	25	25	17	2.5
MFT sprayer	0	180	114	166	45	4.3
Near (5 m)	0	60	276	203	200	2.5
Mid (26 m)	0	60	44	32	33	2.3
Far (52 m)	0	60	21	19	13	2.8

[a]Listed by limit of blank (LOB), number of measurements (*N*), arithmetic mean (AM), arithmetic standard deviation (ASD), GM, and GSD. *N* is reflective of each micronutrient tracer analysed via ICP-MS.

[b]As 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).

[c]GM drift volume levels measured for AFA, DAT, and MFT sprayers at 52 m downwind were 2.0 (20/10), 3.4 (17/5), and 3.3 (13/4) times greater than background levels measured at the upwind reference location (Mast Q) (Supplementary Table S2, available at *Annals of Work Exposures and Health* online).

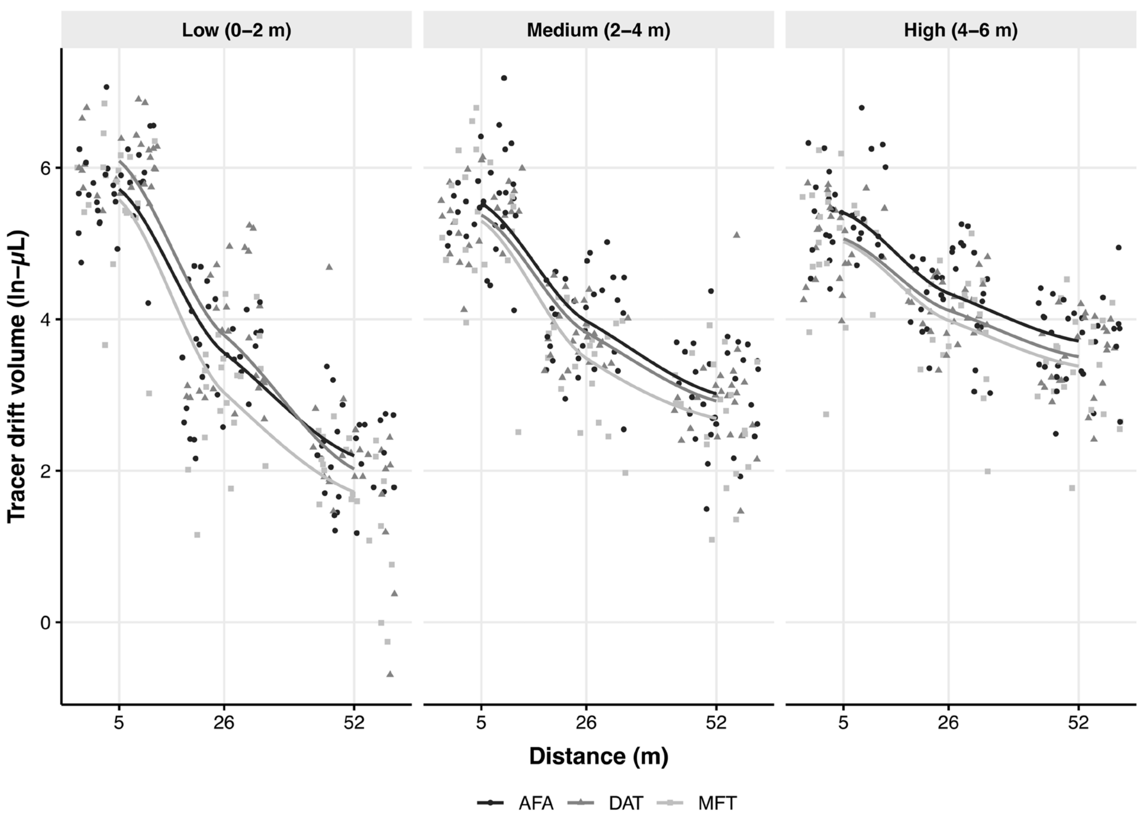

Figure 2. Tracer-based drift volume levels measured on 2 m sections of PE lines suspended at different heights (low, medium, and high) and distances (5, 26, and 52 m) downwind of the sprayed block. Smoothed lowess curves and points jittered along the *x*-axis are included to indicate differences between sprayers.

had small, positive associations with an increase in drift level.

Discussion

This study made side-by-side comparisons of the conventional AFA sprayer against more modern airblast tower sprayers based on tracer-based drift volume levels in an orchard work environment. We drew from spatiotemporal characteristics of farmworker illness scenarios (Lee *et al.*, 2011; Calvert *et al.*, 2015) and captured evidence with downwind drift samples and cameras (Supplementary Videos, available at *Annals of Work Exposures and Health* online). The randomized study design minimized the effect of changing environmental conditions on sprayer comparisons. With regard to testing DRTs and establishing AEZs to minimize the risks of drift exposure, our study findings demonstrate the need to define the impact of airblast sprayer type (e.g. AFA, DAT, or MFT), orchard architecture (e.g. methods that match a spray to the size, shape, and density of an orchard block), sampling height (e.g. workers on the ground or a ladder), and wind speed (e.g. ranges such as 0–2 or 2–4 m s^{-1}).

According to summary statistics, the DAT and MFT had 4–15% and 35–37% less drift measured by volume than the AFA at mid and far field distances. Model results indicated that, compared to the AFA sprayer, drift reduction was significantly different for the MFT but not the DAT. One possible explanation for the difference between tower sprayer performance is air flow face velocity. Although we estimated that the tower sprayers had similar total volumetric air flow rates, the DAT likely had a higher air face velocity, and therefore higher drift potential, due to narrow tower slots with a smaller total surface area than the six MFT fans. Compared to the AFA, these MFT drift reduction findings may fit into USEPA's DRT one-star category consisting of a 25–50% reduction. The voluntary USEPA DRT program is currently limited to protocols that test row and field crop application technologies, but it may expand to orchard crops in the future (USEPA, 2014, 2017a,b). Although a one-star rating is encouraging, it also suggests that more drift reduction may be possible by improved application technology (USEPA, 2014, 2017a,b). An 'AFA buyback' incentive program (similar to 'cash for clunkers' for automobiles) may stimulate wider adoption of newer drift-reducing spray technologies.

Previous studies have demonstrated the impact of spray technology on improved spray efficacy. Derksen *et al.* (1995) found that a more modern raised fan and nozzle manifold assembly produced a better vertical distribution of spray deposits than a conventional sprayer. Hendrickx *et al.* (2012) discovered that differences in spray deposit are due to not only sprayer characteristics but also canopy structure and tree architecture; compared to two modern sprayers, a conventional sprayer had lower total deposition on all tree canopies, which could have been attributable to higher volumetric air flow rates and more drift. Dekeyser *et al.* (2013, 2014) showed that sprayer design can cause major differences in air flow pattern, spray liquid distribution, and off-target

Table 4. Coefficients for determinants of drift from AFA, DAT, and MFT spray trials.[a]

Fixed effects[b]	Model estimate (95% CI)	SE	*P*-value
Intercept	4.21 (3.65, 4.76)	0.29	<0.001
DAT sprayer	−0.07 (−0.19, 0.06)	0.06	0.29
MFT sprayer	−0.35 (−0.49, −0.22)	0.07	<0.001
Distance (m)	−0.06 (−0.07, −0.05)	0.01	<0.001
Height (m)	0.13 (0.10, 0.16)	0.02	<0.001
Wind speed (m s^{-1})	0.28 (0.16, 0.40)	0.06	<0.001
Variance components[c]	Random and fixed effects included	Only random effect included	
Within-location (residual)	0.498 (79.5%)	0.581 (30.4%)	
Between-location (intercept)	0.128 (20.5%)	1.328 (69.6%)	
Total variance	0.626 (100%)	1.909 (100%)	

[a]There were 669 tracer-based drift volume levels (ln-μl) measured on PE lines at fifteen downwind locations in fifteen AFA, DAT, and MFT spray trials.
[b]AFA sprayer was the reference level for the 'sprayer' term in the model. Fixed effect estimates for DAT and MFT sprayers indicate drift-reducing performance compared to the AFA sprayer reference (i.e. larger negative values show greater drift reduction potential).
[c]When the fixed effects were dropped from the model, within-location variance was 0.581 (30.4%) and between-location variance was 1.328 (69.6%). Fixed effects impacted the between-location component of the variance (1.328–0.128, 90% reduction) considerably, but did not alter the within-location component of variance (0.581–0.498, 14% reduction) as much. The difference between these models suggests that there were relatively few systematic changes for individual locations across spray trials.

losses. Importantly, Dekeyser *et al.* (2013) found 'the limited means the grower has available to "tune" the air flow patterns from axial or cross-flow sprayers (gear settings, deflector, etc.) cannot significantly change the liquid distribution patterns'. Duga *et al.* (2015) indicate that precision spraying—a technique that uses sensors to adjust air assistance and spray flow rate based on canopy height, foliage density, and canopy width—is needed to reduce off-target losses through tree-specific spraying. In a nested study that utilized real-time monitors during the June and September 2016 spray trials, we found the same relative ranking of drift reduction potential for the three sprayer technologies (Blanco *et al.*, 2018). As more research investigates the impact of not only deposition drift but also airborne drift on bystander exposure, our findings should prove useful in regulatory risk assessment and modeling (Cunha *et al.*, 2012; EFSA 2014; Van de Zande 2014; Butler Ellis *et al.*, 2017a,b).

Limitations of this study mirrored some of those in our original study (Kasner *et al.*, 2018). First, we used stationary samples in controlled spray trials instead of mobile personal monitors on workers during actual drift events. We do not provide potential exposure estimates, but additional work in this area is possible with measured drift volume levels, product label mixing instructions, and statistical data about human factors used to assess exposure. Second, data from this study may not be representative of other planting systems or sprayer configurations. We tested commonly retailed sprayers with typical settings for a modern high-density orchard, which has become the dominant architecture for new orchards in the last few decades. Generally, a tower sprayer is less effective in a traditional canopy than a modern canopy due to inadequate spray coverage in the upper portion of tall trees and not fitting between tree rows with large spherical canopies. Future studies could compare other sprayers, such electrostatic or multi-row sprayers, and nozzles that produce spray patterns besides the customary hollow-cone shape. Relative to the DAT and MFT, higher pressure was needed on the AFA to achieve the same liquid volume output and droplets with similar VMDs. Third, our sampling field did not capture any spray drift plumes reaching higher than 6 m. Additionally, our careful attention to sprayer calibration may not be representative of everyday behavior and the levels could therefore be underestimates of drift levels in other settings.

Tower sprayers appear to be a promising means by which to decrease drift in modern orchards through shorter nozzle-to-tree canopy distances and more horizontally directed aerosols that escape the tree canopy to a lesser extent. New engineering controls alone did not eliminate drift, as evidenced by drift levels at distances up to 52 m downwind for all sprayers. This suggests the need for policy approaches that include more applicator training, proper sprayer calibration and maintenance, or more stringent application exclusion zones (AEZs) (USEPA, 2016).

Conclusions

Systematic evaluation of orchard sprayers is essential for developing recommendations about pesticide drift reduction. Our findings indicate that airblast tower sprayers, when compared to conventional AFA sprayers, are likely to reduce the frequency and magnitude of occupationally related pesticide drift exposures and illnesses. USEPA's DRT program or an 'AFA buyback' incentive program may stimulate wider adoption of new drift-reducing spray technologies. However, the newer sprayer technologies alone did not eliminate drift. This suggests the need for policy approaches that include more applicator training, proper sprayer calibration and maintenance, or more stringent AEZs. Our study findings demonstrate the impact of airblast sprayer type, orchard architecture, sampling height, and wind speed on drift levels in an orchard work environment. The field study site was ideal for the trials because it adhered to applicable standards and allowed us to compare multiple sprayers, but further testing with other planting systems and sprayers is needed.

Supplementary Data

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

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