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Real-Time Monitoring of Spray Drift from Three Different Orchard Sprayers

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HIGHLIGHTS

- Elevated particle levels at all sampling locations 16–74 m from spray applications.
- Significantly lower particle levels during tower than airblast sprayer applications.
- Significantly higher particle levels at closer distances and below the canopy.
- The EPA's application exclusion zone is likely not fully protective of drift.
- Real-time monitoring may be an effective, novel method of drift characterization.

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ABSTRACT

In Washington State, half of all pesticide-related illnesses in agriculture result from drift, the off-target movement of pesticides. Of these, a significant proportion involve workers on another farm and orchard airblast applications. We compared the spray drift exposure reduction potential of two modern tower sprayers – directed air tower (DAT) and multi-headed fan tower (MFT), in relation to a traditional axial fan airblast (AFA) sprayer. We employed real-time particle monitors (Dylos DC1100) during a randomized control trial of orchard spray applications. Sections of a field were randomly sprayed by three alternating spray technologies – AFA, DAT and MFT – while monitors sampled particulate matter above and below the canopy at various downwind locations in a neighboring field. Geometric mean particle mass concentrations (PMC) outside the intended spray area were elevated during all applications at all of our sampling distances (16–74 m, 51–244 ft). After adjusting for wind speed and sampling height, the 75th percentile (95% confidence interval) PMC level was significantly greater during spray events than background levels by 105 (93, 120) μg/m^3, 49 (45, 54) μg/m^3 and 26 (22, 31) μg/m^3 during AFA, DAT and MFT applications, respectively. Adjusted PMC levels were significantly different between all three sprayers. In this study, tower sprayers significantly reduced spray drift exposures in a neighboring orchard field when compared to the AFA sprayer, with the MFT sprayer producing the least drift; however these tower sprayers did do not fully eliminate drift.

1. Introduction

Pesticide drift, the off-target movement of pesticides, is a major source of human pesticide exposure, particularly among agricultural workers (Calvert et al., 2008; Lee et al., 2011). Pesticide exposures have been associated with a variety of acute and chronic illnesses (Jeyaratnam, 1990; Lee et al., 2011; Mostafalou and Abdollahi, 2013), involving neurological, psychiatric, developmental, reproductive and carcinogenic effects (Leslie and Koger, 2012). In Washington State, about half of pesticide-related illnesses in agriculture are a result of drift (WA DOH, 2013). Of these, a significant proportion involve exposure of workers on another farm (64%) and orchard airblast applications (51%) (WA DOH, 2013). Over the past decade or longer, the incidence of pesticide drift-related illness has not fallen from about 0.33 to 1.85 cases per 100,000 Washington residents.

Abbreviations: PMC, Particle Mass Concentration.

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Axial fan airblast (AFA) sprayers have been widely used in Washington tree fruit orchards since the 1950s (Fig. 1) (Fox et al., 2008). These sprayers were originally designed to propel pesticide droplets out radially onto the tree canopy, but modern changes in tree shape and reduced tree height have made this technology more likely to produce drift compared to decades ago due to a larger proportion of the spray reaching above the canopy (Matthews et al., 2014).

Some growers have begun moving away from airblast sprayers in an effort to improve application accuracy and reduce drift (Fox et al., 2008). Unlike airblast sprayers, tower sprayers spray horizontally into the tree canopy and may improve target deposition by about 30% (Landers et al., 2017; Zhu and Zondag, 2011). While airblast sprayers dominate the market, directed air tower (DAT) and multi-headed fan tower (MFT) sprayers are two of the more commonly retailed tower sprayers in the North Central District and the Yakima Valley of Washington State (Fig. 1).

The U.S. Environmental Protection Agency (US EPA) addresses pesticide drift through its Worker Protection Standard (WPS) Application Exclusion Zone (AEZ). The AEZ requires that the immediate area surrounding pesticide application equipment be free of individuals not properly trained or equipped to handle pesticides during an application (US EPA, 2016). The AEZ for airblast applications and other spray applications using fine or very fine size droplets (volume median diameter less than 294 μm) is 100 ft (30 m) (US EPA, 2016). Still, studies have found significantly higher pesticide drift and particulate matter (PM) levels past 100 ft during airblast applications relative to background concentrations (Blanco et al., 2018; Frank et al., 1994; Kasner et al., 2018; Salyani and Cromwell, 1992), suggesting that this current AEZ does not fully protect individuals from pesticide drift.

There are many important factors that affect spray drift other than distance. Most importantly is the initial droplet size since smaller particles will take longer to fall and travel further with turbulent winds (Klein et al., 2008). Droplets under 100 μm are thought to have high drift potential (Klein et al., 2008). Some other factors that affect drift include wind speed, sprayer type, canopy development (fully foliated versus dormant), air stability, relative humidity and temperature (Klein et al., 2008; Praat et al., 2000).

Though many studies have evaluated pesticide applicator, bystander and resident spray drift exposures (Alavanja et al., 1999; Butler Ellis et al., 2010, 2014; 2017b, 2017a; De Roos et al., 2005; Nuyttens, 2007; Stokes et al., 1995), to the best of our knowledge, none have focused on what comprises the majority of pesticide drift cases in dense orchard regions like Washington State – occupational exposures in neighboring fields (WA DOH, 2013).

Furthermore, while many studies have investigated how different application technologies affect target crop accuracy (Cunningham and Harden, 1998; Landers et al., 2017), few studies have investigated whether the implementation of these technologies actually lowers pesticide drift exposures. If found to be true, the use of these technologies could reduce pesticide drift exposures more effectively than other methods that have been difficult to implement, including pesticide application notification systems (Kasner et al., 2016).

Our recent study appears to be the only one that has used low-cost, real-time monitors (Dylos DC1100, Dylos Corporation) to characterize spray drift (Blanco et al., 2018). Validation studies using Dylos DC1100 have found high correlations between these relatively new real-time optical particle monitors and three well-characterized reference instruments: the Grimm 1.109 (Grimm Technologies Inc.), APS 3321 (TSI Inc.) and FMPS 3091 (TSI Inc.) (Manikonda et al., 2016). Similar findings have also been reported between the Dylos DC1700 (an updated monitor that uses the same sensor as the DC1100) and the DustTrak 8520, DustTrak II for $PM_{2.5}$, and Sidepak AM510 for $PM_{2.5}$ (TSI Inc.) (Holstius et al., 2014; Northcross et al., 2013; Semple et al., 2015).

This study was nested in a larger study that measured

Fig. 1. From left to right: Axial fan airblast (AFA), directed air tower (DAT) and multi-headed fan tower (MFT) sprayer.

micronutrient drift using accepted methods of passive sampling for spray drift characterization (Kasner et al., 2018). Our past work described a novel method of drift characterization using real-time particle monitors during AFA sprayer applications (Blanco et al., 2018). The purpose of this study was to characterize the spray drift potential of three airblast sprayers (AFA, MFT and DAT) in an effort to evaluate whether modern tower sprayers (MFT and DAT) have the potential to reduce occupational pesticide drift exposures at different locations in a neighboring orchard field.

2. Methods

2.1. Study design

We briefly summarize our study design, which has been described previously (Blanco et al., 2018; Kasner et al., 2018), and provide further details about the unique aspects of this particular study. This research took place during June and September of 2016 in a modern research orchard operated by Washington State University. Apple trees 3.5 m tall were trellised along rows that ran in a north-south direction and spaced 3 m apart. Prevailing winds from the north made it possible to sample for spray drift in a southern orchard block (a 0.4-ha, or 1-acre field).

An orchard block was divided into four quadrants that were each randomly sprayed with micronutrients by three alternating application technologies: AFA, DAT and MFT during a “spray event” (Fig. 2). Each day, the spray quadrant order was randomized, and the application technology order was rotated so that each technology had a day where it was the first to spray (Supplementary Information Table A1). A non-spray, washout period of

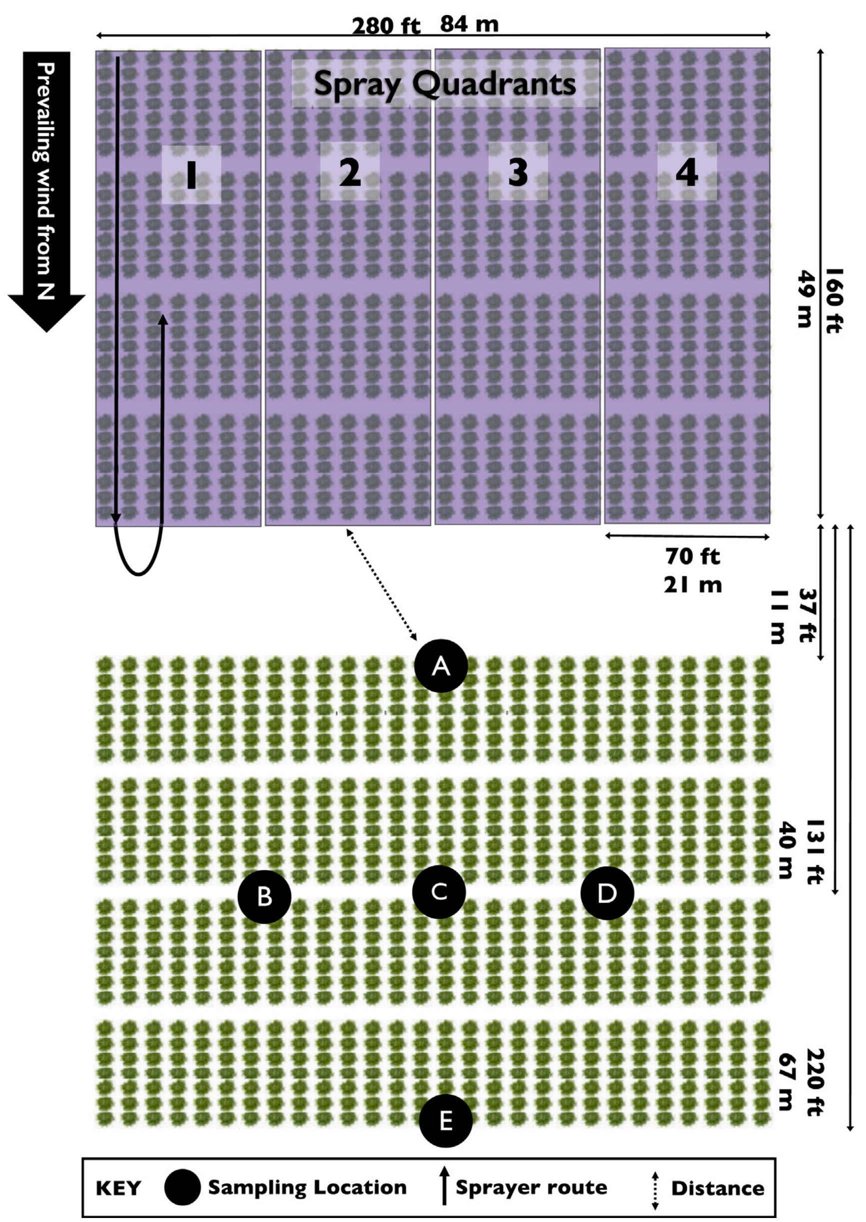

Fig. 2. Field diagram showing a northern orchard block (0.4 ha, 1 acre) consisting of four randomly sprayed quadrants, and an unsprayed southern block with ten Dylos monitors at five distinct locations, both above (6 m) and below (2 m) the canopy. Monitors collected 1-min particle number concentrations (PNC) of four bin sizes (0.5–1.0 μm, 1.0–2.5 μm, 2.5–10 μm, >10 μm) throughout a spray day. Monitor distance was measured as the length between a monitor and the central proximal edge of a spray quadrant. The dashed line shows an example of the distance measurement between monitors at location A and quadrant 2 (16 m). Figure is not to scale. Used with permission (Blanco et al., 2018).

approximately 2 min after each spray event was used to clear out any residual spray drift. Given that the average wind speeds in our study area sometimes approached 10 MPH (4.5 m/s), we used a conservative wind speed estimate of 5 MPH (2.2 m/s) and calculated that small particles being carried by the wind that had not yet deposited could travel up to 264 m within 2 min (2.2 m/s × 120 s), a distance much larger than our study field (116 m, Fig. 2). Each application technology sprayed all four quadrants during each sample day, except for the DAT sprayer which was not used on the first day. For example, on our second sampling day, Quadrant 2 was sprayed by the AFA sprayer, followed by the DAT sprayer and finally, the MFT sprayer. Quadrants 1, 3 and 4 were afterwards sprayed in the same order. On our third sampling day, the quadrant spray order was again randomized and this time, the DAT sprayer was the first to spray, followed by the MFT and AFA sprayer, etc. This design was intended to reduce environmental variability (e.g., wind speed, wind direction, temperature and relative humidity) between spray events since spraying occurred in the mornings when conditions were quickly changing (PennState, 2017), and an entire orchard block would have taken approximately 30 min to spray.

2.2. Equipment

All sprayers were calibrated to output 935 L/ha via hollow cone spray patterns while running at 1.3 m/s. These settings were in line with many pesticide labels which use 935 L/ha (100 gal/acre) as an application goal for low- and mid-volume applications in tree fruit (Midwest Fruit Workers Group, 2012; Quali-Pro, 2018; WSU, 2018). These settings were used to ensure that the AFA, DAT and MFT sprayers all produced fine droplet sizes between 110 and 125 μm, 125–130 μm and 61–105 μm, respectively. Agricultural application technologies often produce fine or very fine droplets to help improve target coverage, though these droplets are more drift prone than larger droplets. Sprayer settings are further detailed in the Supplementary Information (Table A2). The DAT and MFT sprayers had towers that were approximately 2.7 m and 3.7 m high, respectively. Spraying began between 8 a.m. and 10 a.m., as is typical for agriculture work, and ended around noon. A global positioning system (GPS) data logger was placed on each sprayer.

2.3. Sampling

Dylos DC1100 real-time monitors (concentration range per bin: 0–3,000,000 particles/ft^3, 10% coincidence loss) (Dylos Corporation, 2019) were mounted on poles at heights of 6 m (above canopy) and 2 m (below canopy) at five distinct locations in a neighboring southern block with their inlets facing towards the spray field (Fig. 2). Monitors were customized so that they recorded 1-min average particle number concentrations (PNC) of four (rather than two) PM size measurements (aerodynamic diameter greater than 0.5 μm, 1.0 μm, 2.5 μm and 10 μm). These ran from approximately an hour before the first spray event to an hour after the last spray event of the day and used a flow rate of 1700 cm^3/min. Two periods, the 15-min period preceding the first spray event of the day and the 15-min period following the last spray event of the day, were used as background controls.

An onsite meteorological station was used to monitor wind direction and wind speed (15-min average) at the beginning of each spray event to ensure that the wind was blowing towards the southern field (wind rose direction from 281 to 360° or 0–56°) and that the initial wind speed at the beginning of each spray event was within the US EPA's wind speed recommendations of 3–10 MPH (1.3–4.5 m/s) (US EPA, 2017). A second onsite meteorological station was used to gather more precise (1-min) observations of wind speed, wind direction, temperature and relative humidity throughout each spray event, though these data were not available to us until the end of each sampling period. The use of two meteorological stations followed protocols for the International Organization for Standardization (ISO) and the American Society of Agricultural (and Biological) Engineers (ASAE) (ASABE, 2004; ISO, 2005).

2.4. Data analysis

Onsite field measurements were used to calculate the distance between each Dylos monitor and the central proximal edge of each spray quadrant, as is conventional in the drift literature (Fig. 2) (ASABE, 2004; ISO, 2005). Sprayer GPS data were used to verify sprayer locations and spray times. Only the 1-min meteorological data that met our inclusion criteria was included in our analyses: wind speeds at least 1.0 m/s, air temperature 5–35 °C, relative humidity 0–100%, and wind blowing in 135° arc towards our sample field (wind rose direction from 281 to 360° or 0–56°). One-minute Dylos PNCs for each bin ($0.5\ \mu m \le b_1 < 1.0\ \mu m$, $1.0\ \mu m \le b_2 < 2.5\ \mu m$, $2.5\ \mu m \le b_3 < 10.0\ \mu m$, and $b_4 \ge 10.0\ \mu m$) were adjusted for changes in ambient PNC using a fifth percentile, 8-min rolling average of PNC (Blanco et al., 2018; Brantley et al., 2014; Bukowiecki et al., 2002). These adjusted 1-min PNCs for each bin (b) were converted to particle mass concentrations (PMC) using an assumed aerosol density (ρ) of 1 μg/m^3 and each bin's geometric mean diameter (d), except for the largest bin where the lowest size cut was used ($d_1 = 0.71$ μm, $d_2 = 1.58$ μm, $d_3 = 5.00$ μm and $d_4 = 10.00$ μm). All four bin PMCs were added to estimate a total 1-min average PMC (Blanco et al., 2018).

$$PMC_{Total} = \sum_{b=1}^{4} \left(PNC_b \ x \ \frac{\pi}{6} \ x \ d_b{}^3 \ x \ \rho \right)$$

Monitor distance measurements, spray times, and meteorological observations were merged with Dylos PNC data. For descriptive summaries of PMC levels, we categorized the data into three distances describing the proximity of a Dylos monitor to a spray quadrant: within the 100 ft AEZ (51 ft, 16 m) and outside of the 100 ft AEZ (111–168 ft, 34–51 m and 219–244 ft, 67–74 m). "Spray event samples" were defined as the total number of Dylos monitors for all of the spray events. For comparison purposes, "control period

Table 1
Environmental conditions during spray events (median and interquartile range).

Sprayer	Wind Speed		Wind Direction [degrees]	Temperature [C]	Relative Humidity [%]
	[MPH]	[m/s]			
AFA	8.7 (2.8)	3.9 (1.2)	335 (14)	16 (2.3)	50 (6)
DAT	9.0 (2.3)	4.0 (1.0)	339 (9.2)	16 (2.2)	50 (6)
MFT	9.4 (3.5)	4.2 (1.6)	330 (19)	17 (2.8)	49 (8)
Control	8.0 (3.5)	3.6 (1.6)	327 (46)	16 (3.3)	49 (15)

Note: Observations were from 1-min averages during spray events.
[a]Wind speeds are provided in imperial units, as regulations in the United States are expressed in these units.

Table 2
PMC levels above and below the canopy at various downwind locations from a spray quadrant.

Monitor Distance from Spray Quadrant	Samples[a]				GM (GSD)[b] [μg/m³]			
	AFA	DAT	MFT	Control	AFA	DAT	MFT	Control
Above the Canopy[c]	67	52	72	18	41 (3.2)	26 (2.2)	13 (3.1)	8.3 (1.7)
Within the 100 ft AEZ								
51 ft (16 m)	7	6	8	–	96 (1.6)	62 (1.4)	24 (2.2)	–
Outside the 100 ft AEZ								
111–168 ft (34–51 m)	39	30	42	–	40 (3.1)	25 (2.2)	11 (3.4)	–
219–244 ft (67–74 m)	21	16	22	–	31 (3.3)	22 (2.1)	12 (2.8)	–
Below the Canopy[d]	72	60	76	19	86 (3.6)	43 (2.9)	26 (3.9)	11.4 (1.8)
Within the 100 ft AEZ								
51 ft (16 m)	7	6	8	–	341 (2.1)	213 (1.6)	154 (1.9)	–
Outside the 100 ft AEZ								
111–168 ft (34–51 m)	45	36	48	–	97 (3.1)	44 (2.6)	24 (3.8)	–
219–244 ft (67–74 m)	20	18	20	–	41 (3.5)	24 (2.3)	14 (2.8)	–

[a] Spray event samples were defined as the total number of Dylos monitors during all of the spray events ($n_{AFA} = 15$, $n_{DAT} = 12$, $n_{MFT} = 16$). For comparison purposes, control period samples were defined as the total number of monitors (about 5 per height) during all sampling day (4) that collected non-spray, background observations. The number samples varied for different distances because quadrant position relative to the Dylos monitors (and thus the measured distance between the two) varied depending on what quadrant was being sprayed (e.g., Quadrant 1 vs Quadrant 2, Fig. 2).
[b] geometric mean (geometric standard deviation).
[c] from a sampling height of 6 m
[d] from a sampling height of 2 m

samples" were defined as the total number of monitors (about 5 per height) during all sampling days (4) that collected non-spray, background observations.

We calculated geometric means for descriptive statistics because we expected our data to be log-normal (see Supplementary Information Fig. A1). Moreover, we used quantile regression in our analyses, a semi-parametric technique that had several advantages compared to least-squares mean regression (Bradman et al., 2009; Cade and Noon, 2003). First, we did not have to assume the data were normally distributed and thus did not have to log-transform the data. Second, we were able to model higher quantiles of the concentration distribution (i.e., peak rather than mean concentration values). And third, quantile regression was more robust at handling extreme values, which we expected to observe. Other exposure assessment studies have used quantile regression to better understand the shape of the distribution curve (Bradman et al., 2009; Rydbeck et al., 2013; Schlink et al., 2010).

We performed quantile regression to predict the 75th percentile PMC (μg/m^3) using the following predictors: sprayer type (none - background, AFA, MFT or DAT; using dummy variables for AFA, MFT and DAT), sampling height (above or below the canopy; using a dummy variable for above the canopy) and wind speed (WS, m/s) such that:

$$Q_{\tau=0.75}(\mathrm{PMC}_{Total}) = \beta_0(\tau) + \beta_{AFA}(\tau)X_{AFA} + \beta_{DAT}(\tau)X_{DAT} + \beta_{MFT}(\tau)X_{MFT} + \beta_{Above}(\tau)X_{Above} + \beta_{WS}(\tau)X_{WS} \quad (1)$$

where Q is quantile regression using the τ^{th} quantile. The intercept represented the background PMC level at a sampling height below the canopy with no wind.

A restricted analysis looked at log PMC levels using the following predictors: monitor distance from spray quadrant (distance, m), sprayer type, sampling height and wind speed such that:

$$Log\ Q_{\tau=0.75}(\mathrm{PMC}_{Total}) = \beta_0(\tau) + \beta_{Distance}(\tau)X_{Distance} + \beta_{DAT}(\tau)X_{DAT} + \beta_{MFT}(\tau)X_{MFT} + \beta_{Above}(\tau)X_{Above} + \beta_{WS}(\tau)X_{WS} \quad (2)$$

We used dummy variables for the DAT and MFT sprayer type with the conventional AFA sprayer as the reference category in this model. This analysis was restricted to spray periods for which we had distance measurements and excluded control periods. PMC was log-transformed to model its multiplicative (rather than additive) growth at closer monitoring distances. The intercept in this model represented the 75th percentile PMC level for the AFA sprayer from a 0 m monitoring distance below the canopy and no wind.

Our previous work further describes this analysis (Blanco et al., 2018). All data were analyzed using R (RStudio 1.0.143 using R 3.3.1).

3. Results

3.1. Sample size

Ten Dylos monitors at five distinct locations, both above and below the canopy, collected samples throughout each spray event, with the following exceptions: 1) one monitor was not placed at location E below the canopy during the first spray day due to a protocol modification (there were 7 spray events on this day); and 2) two monitor batteries died before spraying started on the third day so we did not have data for locations B and D above the canopy (there were 12 spray events on this day). In addition, the first spray event as well as some additional 1-min observations were dropped from our analyses since the wind was not blowing towards our sample field (14% of the total observations). We thus had a total of 3776 1-min average PMC observations ($n_{AFA} = 1{,}028$, $n_{DAT} = 828$, $n_{MFT} = 1{,}071$, $n_{control} = 849$), or equivalently, 37 control periods and 399 spray event samples for 43 spray events ($n_{AFA} = 15$, $n_{DAT} = 12$, $n_{MFT} = 16$). Each spray event lasted an average (SD) of 7.1 (0.9) minutes. Supplementary Information Fig. A2 shows a time series plot of PMCs by sprayer type throughout a study day.

3.2. Environmental conditions

The 15-min median (interquartile range, IQR) wind speed at the beginning of each AFA, DAT and MFT sprayer event was 7.8 (1.2) MPH, 7.4 (2.5) MPH and 8.5 (2.5) MPH, respectively (Table 1). These results are presented in imperial units, as expressed in United States regulations. One-minute median wind speed, wind direction, temperature and relative humidity values were similar among all AFA, DAT and MFT sprayer events and control periods (Table 1).

3.3. Particle mass concentration levels

PMC levels in the orchard block downwind of the spray field were elevated relative to background levels for all sprayers and monitoring distances (51–244 ft, 16–74 m) - both within and outside of the US EPA's WPS AEZ of 100 ft (Table 2, Fig. 3). Closer distances and monitors below the canopy had the highest PMC levels. Generally, AFA sprayer events were associated with higher PMC levels than DAT sprayer events, followed by MFT sprayer events. We observed the lowest geometric mean (GM) PMC of 12 $\mu g/m^3$ during MFT sprayer applications when monitoring was done from our farthest distance of 219–244 ft (67–74 m) above the canopy. This concentration was 1.4 [(12 $\mu g/m^3$)/(8.3 $\mu g/m^3$)] times higher than the background GM PMC above the canopy. We observed the highest GM PMC of 341 $\mu g/m^3$ during AFA sprayer applications when monitoring was done from our closest distance of 51 ft (16 m) below the canopy. This concentration was 30 [(341 $\mu g/m^3$)/(11.4 $\mu g/m^3$)] times higher than the background GM PMC below the canopy.

After adjusting for wind speed and sampling height, the 75th percentile (95% confidence interval, 95% CI) PMC level was significantly greater during spray events than background levels by 105 (93, 120) $\mu g/m^3$ during AFA sprayer events, 49 (45, 54) $\mu g/m^3$ during DAT sprayer events and 26 (22, 31) $\mu g/m^3$ during MFT sprayer events (Table 3). The non-overlapping sprayer coefficient confidence intervals indicate that the 75th percentile PMC level was significantly lower during tower sprayer applications than AFA sprayer applications when we adjusted for sampling height and wind speed, with MFT sprayer applications being associated with the lowest levels. The 75th percentile (95% CI) PMC level was significantly higher below the canopy than above the canopy by 14 (−18, −10) $\mu g/m^3$, after adjusting for sprayer type and wind speed. These results are presented for the 50th percentile in the Supplementary Information (Table A3).

After adjusting for sampling height and wind speed, our restricted analyses showed that the 75th percentile (95% CI) PMC level significantly dropped by 2% (2%, 3%) for every additional meter away from a spray application (Table 4). These results were based on the 2843 1-min spray observations (n_{AFA} = 999, n_{DAT} = 806 and n_{MFT} = 1038).

4. Discussion

This study was the first to use real-time particle monitoring to

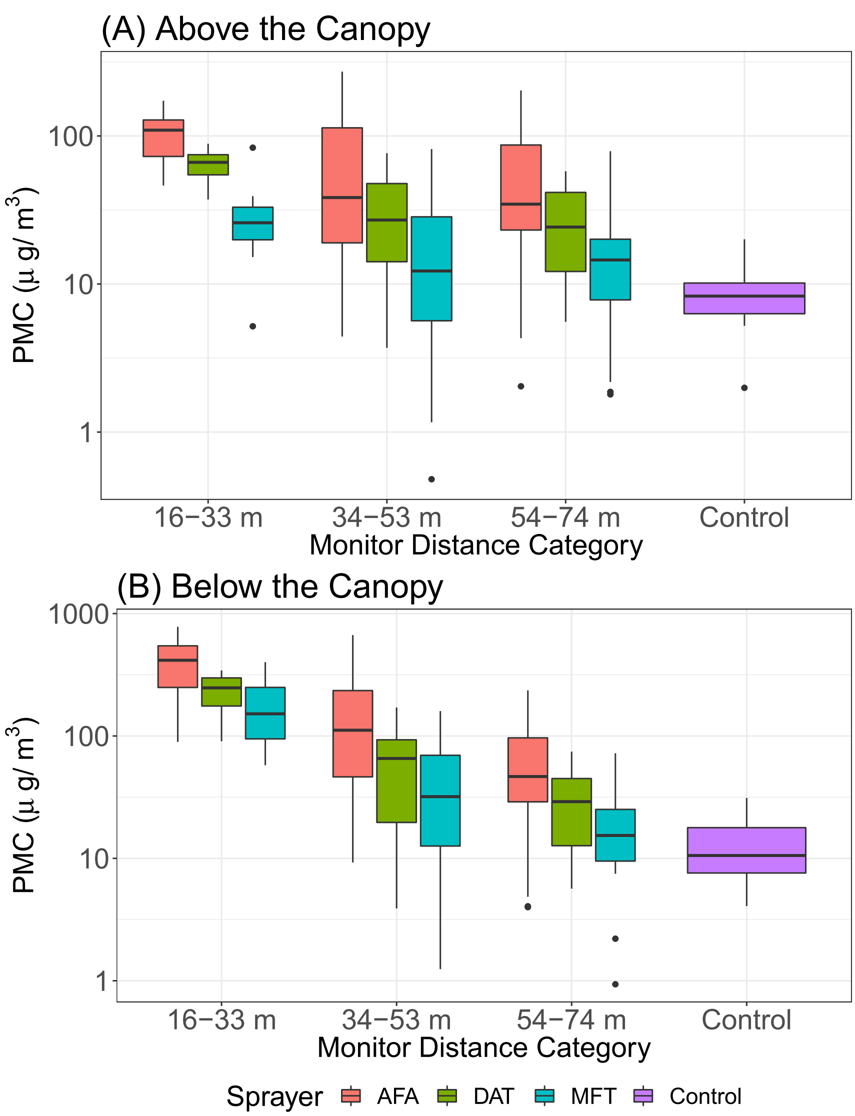

Fig. 3. PMC ($\mu g/m^3$) above (A) and below (B) the canopy with increasing monitor distance from the southern edge of a spray quadrant. Monitor distance categories were the same for all three sprayers (e.g. 16–33 m). PMC is on the log scale.

Table 3
Quantile regression of 75th percentile PMC (μg/m^3) by sprayer type, adjusting for sampling height and wind speed.

Covariate	Coefficient (95% CI)
(Intercept)	33 (27, 41)
AFA Sprayer	105 (93, 120)
DAT Sprayer	49 (45, 54)
MFT Sprayer	26 (22, 31)
Above Canopy	−14 (−18, −10)
Wind (m/s)	−3.2 (−4.7, −2.1)

Note: Results are based on 2927 1-min spray event and 849 1-min control observations. The intercept represents the background PMC level at a sampling height below the canopy with no wind. All covariates were statistically significant.

Table 4
Restricted quantile regression of 75th percentile log PMC (μg/m3) by downwind location from a spray quadrant, adjusting for sprayer type, sampling height and wind speed.

Covariate	Coefficient (95% CI)	Exponentiated Coefficient (95% CI)
(Intercept)	7.30 (7.03, 7.76)	1480 (1130, 2345)
Distance (m)	−0.02 (−0.03, −0.02)	0.98 (0.97, 0.98)
DAT Sprayer	−0.79 (−0.99, −0.60)	0.45 (0.37, 0.55)
MFT Sprayer	−1.14 (−1.34, −1.00)	0.32 (0.26, 0.37)
Above Canopy	−0.54 (−0.68, −0.40)	0.58 (0.51, 0.67)
Wind (m/s)	−0.25 (−0.34, −0.21)	0.78 (0.71, 0.81)

Note: Results are based on 2843 1-min spray observations. The intercept represents the 75th percentile log PMC level during an AFA sprayer event from a 0 m monitoring distance below the canopy and no wind. All covariates were statistically significant.

characterize elevations in PMC levels outside of a spray orchard using different types of application technologies. We were unable to find any published studies that have compared axial and tower sprayers based on downwind sampling in outdoor field experiments. Past studies that have compared orchard sprayer technologies have done so in indoor laboratory experiments (Dekeyser et al., 2014, 2013), or outdoor field experiments without wind sampling (Derksen and Gray, 1995; Duga et al., 2015; Hendrickx et al., 2012).

Our results suggest that tower sprayers may significantly reduce drift in neighboring orchard blocks when compared to traditional AFA sprayers, though differences exist between tower sprayers. The adjustable spray heads and smaller fans on the MFT sprayer were likely responsible for lower association with downwind PMC levels.

A finding of particular interest is that the higher PMC levels for all three sprayers occurred below the canopy. Drift-carrying wind is funneled between tree rows when it is below the canopy, but it more readily disperses and leads to lower pollutant concentrations when it is above the canopy. This is phenomenon has been commonly referred to as the street canyon effect (Kuo et al., 2015). Workers in neighboring fields who may perform the majority of their tasks below the canopy are thus at high risk of being drifted on, even when tower sprayers are used.

Relative to background levels, PMC levels were elevated for the three sprayers at all sampling distances. This suggests that the current AEZ may not be fully protective of spray drift exposure from conventional or tower airblast applications under our study conditions We used our restricted 75th percentile regression model (Table 4) to further investigate how far a receptor (below the canopy) would have to be located from a spray application before PMC levels were no longer be elevated above background level (Fig. 4). In

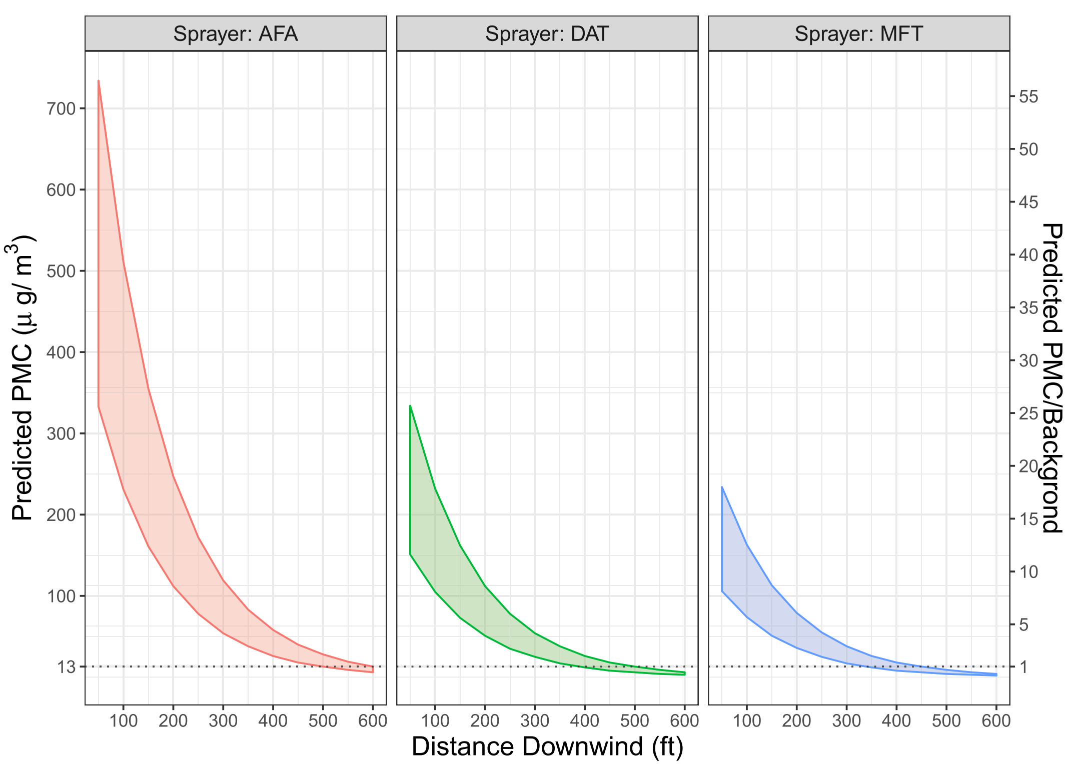

Fig. 4. Predictions of the 75th percentile PMC below the canopy for various distances and wind speeds outside of a spray field. Predictions were made from our restricted model (Table 4) using the US EPA's recommended spraying wind speeds of 3–10 MPH (1.3–4.5 m/s). The horizontal line represents the 75th percentile background concentration that was measured below the canopy during this study (13 μg/m^3). The y-axis on the right shows the predicted PMC values rescaled relative to the background level. An individual would have to be located a minimum of about 500–600 ft (152–183 m), 340–500 ft (104–152 m) and 340–450 ft (104–137 m) downwind of an AFA, DAT and MFT sprayer application, respectively, before their exposure level was comparable to the background level. At 100 ft (30 m) downwind, their predicted PMC exposure level would be between 230 and 510 μg/m^{232}, 110–230 μg/m^3 and 70–160 μg/m^3 during an AFA, DAT and MFT sprayer application, respectively. Higher PMC levels for any particular distance are associated with lower wind speeds (less dispersion).

our study, we observed a 75th percentile background PMC level below the canopy of 13 μg/m^3. Using the US EPA's recommended spraying wind speeds of 3–10 MPH (1.3–4.5 ms/) (US EPA, 2017), our model predicted that an individual would have to be located about 500–600 ft (152–183 m), 340–500 ft (104–152 m) and 340–450 ft (104–137 m) downwind of an AFA, DAT and MFT sprayer application, respectively, before the drift level would no longer be above the background level. These estimated distances are roughly 3–6 times the current 100 ft AEZ, providing evidence that this zone may not fully protect workers from pesticide drift under these conditions. In fact, an individual 100 ft downwind of an AFA, DAT or MFT sprayer application would have an estimated PMC exposure level between 230-510 μg/m^3, 110–230 μg/m^3 or 70–160 μg/m^3, respectively. This is roughly 6–39 times higher than the background level in this study.

Our study results were generally in agreement with the larger parent study in which passive sampling was done during the same spray events (Kasner et al., 2018), though the Dylos detected a larger difference between the DAT and AFA sprayer than did passive sampling. Gravimetric methods (i.e., passive sampling) are less sensitive than optical particle counters (i.e., Dylos) to smaller, lightweight particles (Lilienfeld, 1986). We have shown previously that Dylos monitors can be effective methods of drift characterization (Blanco et al., 2018; Kasner et al., 2018). Real-time instruments can be time and cost-effective methods for capturing a large number of samples, unlike traditional methods of drift sampling that are more time consuming and costly, and thus result in smaller sample sizes with limited variability. Furthermore, the minute-by-minute measurements provided by real-time instruments can be coupled with meteorological readings to better understand how changes in wind speed and direction impact drift, a limitation of passive sampling.

Our results are likely underestimates of the drift production and dispersion that occurs during a true pesticide application. First, we defined “distance” as the length between a monitor and the southern edge of a spray quadrant. Our distance measurements would have been greater had we used the measured length between a monitor and the central or northern edge of a spray quadrant, and this would have resulted in elevated PMC levels at further distances. Second, pesticide applicators may not perform calibrations as frequently as we did due to time constraints (Deveau, 2016). Third, while we used onsite meteorological station readings to determine when to start a spray application, pesticide applicators typically do not have access to such on-site data during a spray, and may not be able to measure wind speeds as accurately with handheld anemometers (Kasner, 2017). Finally, elevated PMC levels at all of our sampling locations indicate that we did not fully capture the edges of the drift plume in the downwind or crosswind direction, and that elevated drift levels likely occurred over a larger area.

There were several limitations to this study. First, this was not a study of actual exposures to agricultural workers during real-world pesticide applications Instead, it was an experiment designed to more efficiently and accurately measure potential drift exposures and associated factors. Second, Dylos monitors were calibrated by the manufacturer and not onsite. Past studies, however, have seen high correlations between the Dylos and other reference methods using this same technique (Holstius et al., 2014; Manikonda et al., 2016; Northcross et al., 2013; Semple et al., 2015). Moreover, similar to other instruments, the Dylos had a specific particle size range over which they reported concentrations. Particles smaller than 0.5 μm in diameter were not captured. Third, our monitors collected total ambient PM, and not strictly spray drift. Since spray periods had significantly higher PMC levels than non-spray periods, however, this difference can likely be attributed to spray drift. Finally, while many different types of new application technologies exist, we were unable to find a database listing the prevalence of each of these technologies. Our study compared two of the more common tower sprayers in the North Central District and Yakima Valley of Washington state during controlled spray trials. Future studies should investigate the degree to which other spray technologies may reduce pesticide drift exposures in practice.

5. Conclusions

This study found that using tower sprayers significantly reduced elevated PMC levels (drift) in neighboring orchard fields when compared to AFA sprayers. The MFT sprayer reduced PMC levels more effectively than the DAT sprayer. These findings suggest that the number of occupational pesticide drift-related illnesses could be reduced by shifting the agricultural industry and public health policy towards already-existing, modern spray technologies. It is important to note, however, that using either of the two tower sprayers did not completely eliminate elevated PMC levels at any of our sampling locations in the neighboring field (16–74 m, 51–244 ft). The US EPA's application exclusion zone of 100 ft for airblast applications and other spray applications using fine or very fine size droplets is not likely to be fully protective for occupational exposures to drift under field conditions similar to this study. Additional precautions thus need to be taken to fully protect workers in neighboring fields.

We believe that the results of this study are highly generalizable to different orchard structures and sprayer technologies. We used the most popular orchard sprayer (AFA) and two widely available tower sprayers (DAT and MFT) in the region. We calibrated sprayers to best fit our research orchard, though all three sprayers can be modified to match varying tree canopies.

An important next step involves gathering epidemiological evidence to determine whether the implementation of tower sprayers reduces the risk of pesticide drift illness. The findings from this study possible benefits from expanding the EPA's voluntary Drift Reduction Technology program (US EPA, 2018), as well as public health policies that support already-existing, modern spray technologies suitable for current canopy structures. Such developments could significantly reduce the number of occupational pesticide drift exposures among workers on neighboring farms.

Declarations of interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.chemosphere.2019.01.092.

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