Real-Time Particle Monitoring of Pesticide Drift from Two Different Orchard Sprayers

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Abstract

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Pesticide drift from agricultural spraying is a significant public health concern, affecting workers and surrounding communities. In Washington State, a majority of pesticide-related illnesses and application-related complaints involve drift. This study employed real-time particle monitors to characterize off-target spray drift during a series of orchard spray trials. The study was nested within a larger study that used micronutrients as tracers, and both active and passive sampling methods. Sections of an orchard block were randomly sprayed by alternating two orchard spray technologies – axial fan airblast (AFA) and multi-head fan tower (MFT) – while ten Dylos DC1100 Pro real-time particle counters sampled aerosols generated by the sprayers from various locations in a neighboring block, ranging from 0-122 meters (0-400 ft) downwind. Two meteorological stations collected wind speed, wind direction, temperature and relative humidity throughout the study period. Measurable aerosol drift levels were found at all downwind sampling locations for both sprayers. Significantly greater drift was associated with the AFA than the MFT sprayer below the canopy and at closer distances. Controlling for wind speed and height, the 75th drift percentiles were 123.5 and 43.3 $\mu g/m^3$ for the AFA and MFT sprayers respectively. Independent of sprayer type and wind speed, the 75th drift percentiles were 29.3 and 17.7 $\mu g/m^3$ above and below the canopy respectively. In a restricted analysis looking at spray periods and controlling for sprayer type, wind speed and height, every additional foot (0.305 m) away from the sprayer was associated with 0.1 $\mu g/m^3$ of reduced drift. These results were consistent with results determined by passive sampling methods. Our findings indicate that real-time particle monitoring for pesticide aerosols can serve as an accurate and relatively inexpensive approach to characterizing pesticide drift.

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Table of Contents

List of Figures

List of Tables

Acronyms and Definitions

AFA	Axial fan airblast sprayer: Name for conventional orchard sprayer without implements such as towers or multi-headed fans
CDC	Centers for Disease Control and Prevention
Drift	The movement of pesticide dust or droplets through the air at the time of application or soon after, to any site other than the area intended (US EPA). In this study, drift is measured with particle mass concentrations (PMC).
Drift Case	Meets the WA DOH and NIOSH case definition for an individual with a documented drift exposure. WA DOH: http://www.doh.wa.gov/AboutUs/ProgramsandServices/EnvironmentalPublicHealth/EnvironmentalPublicHealthSciences/Pesticides NIOSH: http://www.cdc.gov/niosh/topics/pesticides/case.html
Drift event	An incident in which one or more drift cases experienced exposure from a source
DRT	Drift Reduction Technology
Dylos	Dylos DC1100 real-time particle monitor
GM	Geometric Mean
IQR	Interquartile Range
ICP-MS	Inductively Coupled Plasma Mass Spectrometry
ISO	International Standards Organization
MFT	Multi-Headed Fan Tower Sprayer: Specific design for one of the study's tower sprayers with three propeller fans per side. Each fan is an axial fan that assists with blowing liquid aerosols toward a spray target
NIOSH	National Institute for Occupational Safety and Health
OSHA	Occupational Safety and Health Administration
OP	Organophosphate Pesticide
PM	Particulate matter
PMC	Particle Mass Concentration ($\mu g/m^3$). In this study, PMC represents ambient PM levels during the control period and also includes drift during spray periods.
PNASH	Pacific Northwest Agricultural Safety and Health Center
PNC	Particle Number Concentration
SD	Standard Deviation
Spray Day	A day in which pesticide (or micronutrient) spraying occurs; this may include several spray trials
Spray Event	The application of pesticide or micronutrient spray to an orchard quadrant
USDA	United States Department of Agriculture
US EPA	United States Environmental Protection Agency
UW	University of Washington
WPS	US EPA's Worker Protection Standard
WSDOH	Washington State Department of Health
WSDA	Washington State Department of Agriculture
WSU	Washington State University

Introduction

Farmworker exposures to pesticides lead to more chemically-related injuries and morbidities than any other workforce (Calvert et al., 2008). In Washington state, most pesticide-related illnesses and application-related complaints involve drift, making it a significant and growing public health concern for agricultural communities (WADOH, 2013). Drift can be considered primary or secondary. Primary drift is the movement of pesticide particles in air during or soon after an application to an unintended area (EPA, 2015). Secondary drift occurs after an application and can include the volatilization or resuspension of particles. This study has focused on primary drift.

Axial fan airblast sprayers (AFA) have been widely used in Washington tree fruit orchards since the 1950s. Over time, changes in tree shape and reduced heights have made these sprayers less accurate and more likely to spray above canopies, thus increasing their potential for drift. The U.S. Environmental Protection Agency (EPA) has revised the Worker Protection Standard (WPS) recently to reduce risks to human health from pesticide drift (US EPA 2016f). EPA has also developed a voluntary Drift-Reduction Technology Program aim to encourage the use of improved technologies (US EPA, 2016a). Nonetheless, new spray technologies can independently self-label themselves as drift-reducing without having any empirical evidence to support their claims. Further research is needed to investigate the true drift-reduction potential of new technologies when compared to commonly used AFA sprayers. To the best of our knowledge, there is currently limited research looking at the physical characteristics of pesticide drift over space and time. Additionally, while many studies have focused on pesticide applicator exposures, little to no research has been done on occupational drift exposures in neighboring areas. The purpose of this study was to characterize the primary drift produced by a traditional AFA and a modern multi-headed fan tower (MFT) sprayer in order to evaluate each technology's potential to cause occupational pesticide drift exposures in a neighboring orchard.

Public Health Relevance

Agricultural Workers

While pesticide drift can damage non-target crops, contaminate water sources, cause illegal residues in food and reduce application effectiveness, this paper focuses on drift as it relates to human exposures (Felsot et al., 2011). Rachel Carson was one of the first scientists to link pesticides to detrimental health effects in people and the environment (ACS, 2012). Since then, significant developments in research have brought into the public eye the severity of pesticide exposures. Pesticide handlers, agricultural workers and agricultural communities are particularly at risk of pesticide exposures. Because they handle more pesticides than any other workforce, agricultural workers have a particularly high risk of being drifted on (Penn State Extension, 2016). In an analysis from 1997 to 2000 on 500 pesticide poisonings among California farmworkers, 51% were related to pesticide drift (Reeves & Schafer, 2003). Moreover, in Washington from 2010 to 2011 there were 131 agricultural cases of pesticide-related illness, most involving orchard airblast applications and drift (WADOH, 2013)

Agricultural Communities

Agricultural communities, particularly children, are also susceptible to off-target drift. In a study looking at 2,593 cases of acute pesticide-related illnesses in schools between 1998 and 2002, 69% were from pesticide use in schools while the other 31% were from nearby farmland drift (Alarcon et al., 2005). Though the consequences of pesticide poisoning are better understood for adults than children, children are believed to be especially susceptible to pesticide toxicity because their nervous systems are still developing. In a review of prenatal and childhood exposure to pesticides and neurobehavioral development, children's exposures to pesticides were found to be associated with neurobehavioral development impairment (Jurewicz & Hanke, 2008). Pesticide exposures were associated with abnormal reflexes in newborns; difficulty with short-term memory tasks, increased reaction times, impaired mental development and other developmental problems in children; and mental and emotional problems in adolescents (Jurewicz & Hanke, 2008). In another study done on fifty-two school-aged children to investigate the long-term effects of acute organophosphate (OP) pesticide poisoning during infancy, researchers found deficits in the inhibitory motor control of children (Ware, Estesen, Cahill, Gerhardt, & Frost, 2014).

Exposure Routes

Individuals are most commonly exposed to pesticide drift through two routes of exposure: dermal and inhalation. Chemicals absorbed through the skin must pass through the epidermis or appendages and seven cell layers before entering the blood and lymph capillaries in the dermis (Lehman-McKeeman, 2010). The inhalation of pesticide drift is also possible with small particles. These are deposited on the nasal hairs, nasal mucosa, bronchi and bronchioles. Particles greater than 100 μm are deposited in the naso-pharyngeal region; particles between 10 μm and 100 μm are deposited in the upper airways; particles smaller than 10 μm can be further respired into the lower airways, alveolar ducts and sacs; and particles smaller than 1 μm can either be exhaled without absorption or deposited further down in the alveoli where they can lead to pneumocyte toxicity, inflammation and interstitial pulmonary fibrosis (Lehman-McKeeman, 2010).

Drift

Determinant Factors of Drift

Pesticide drift can be considered particulate matter (PM), which is defined by the EPA as an airborne mixture of solid particles and liquid droplets (US EPA, 2016d). PM can greatly range in size, shape, chemical composition and source (US EPA, 2016d). Drift is a function of many factors. The most important factor for drift is initial droplet size, which is dependent on a sprayer's nozzle type, pressure, angle and volume (Klein, Schulze, & Ogg, 2008) . When a solution leaves a spray nozzle at high speeds (often 60 ft/sec or more), air resistance breaks up the spray into finer aerosols (Klein et al., 2008). Larger, heavier droplets will maintain a downward velocity longer, making them more likely to hit the intended target, while smaller particles will take longer to fall and travel further with turbulent winds (Klein et al., 2008). Typically, spray droplets under 100 microns (um) will have a high potential for drift (Klein et al., 2008). As an example, falling ten feet in still air will take a 100 μm particle about eleven seconds, a 10 μm particle seventeen minutes, and a 1 μm particle 28 hours (Ross & Lembi, 1985). The longer a particle is in the air, the greater the potential for drift. Still, spray technologies and applicators prefer small droplets because they achieve better foliar coverage. Wind speed is also an important environmental determinant of drift, with higher winds making drift more possible. Other factors contributing to drift include the sprayer boom height, nozzle spacing, spray thickness, wind direction, air stability, relative humidity and temperature (Klein et al., 2008; US EPA, 2016c).

Drift Sampling Methods

Pesticide drift tests will typically treat an area and measure downwind deposition (e.g., sedimentation by drift falling to horizontal surfaces) or air-borne spray using passive and active sampling techniques (Matthews, Bateman, & Miller, 2014). Analytical techniques that directly measure an active ingredient or tracer in a spray mix (e.g., gas chromatography) are preferred because of their high accuracy and sensitivity (Ecobichon, 1999). These techniques, however, can be costly and require specialized equipment as well as technical expertise.

Various methods and surfaces have been used to passively sample for drift deposition from a spray area over distance. Artificial sampling surfaces include glass plates, mylar sheets, filter papers, aluminum foil and stainless steel plates (Ecobichon, 1999). Water and oil-sensitive cards also have been used to depict the spectrum of droplet size and deposition of drift droplets. Imaging equipment or manual analysis is afterwards used with this method to estimate the percent of spray captured, droplet concentration and droplet size using appropriate spread factors. Other methods of measuring drift include taking water samples to evaluate drift deposition in aquatic environments; and using pesticide-sensitive plants near application areas as drift indicators (Ecobichon, 1999).

Similar sampling layouts have been used to measure air-borne spray, but with different sampling media and in vertical orientations. High-efficiency, static media including pipe cleaners, cotton piping, woolen line collectors, cotton clothing on mannequins and hair curlers can be placed vertically to capture horizontally moving drift (Matthews et al., 2014).

Low and high-volume active air samplers have also been used to sample for average drift levels at various heights and distances from a spray source (Matthews et al., 2014). The Rotorod, for example, uses a rotating sampling surface that collects airborne particles (Ecobichon, 1999). Cascade impactors have additionally been used to measure drift droplet sizes (Ware et al., 2014).

Finally, some studies have used laser-based systems such as rapid acquisition Light Detection and Ranging (LIDAR) to measure a spray's droplet density and distance from the sampling instrument, though this research is limited (Gregorio et al., 2016; Tsai, 2007). Two-dimensional visualizations of the drift plume as it moves downwind are generated. In one of the first studies to use LIDAR, Gregorio et al. found a high coefficient of determination ($R^2 > 0.85$) when compared to horizontal deposition samplers, suggesting that this may be a practical and reliable alternative to passive sampling (2016). This instrument's difficulty quantifying particle numbers, technicality and high cost, however, have limited its use in drift studies.

Drift Research

Studies have documented agrochemicals moving off-target during spraying into adjacent areas as early as the 1950s when California vineyards saw significant yield losses from 2,4-Dichlorophenoxyacetic acid (2,4-D) drifting over from neighboring cereal crops (Akesson & Yates, 1964). Since then, studies have found distance from the source, wind direction and wind speed to be the most important predictors of pesticide residue (Barnes, Lavy, & Mattice, 1987; Richards et al., 2001). For example, in a study looking at organophosphorus pesticide drift in Washington state, higher pesticide concentrations were seen around the perimeter of orchard blocks than in the community during and after applications (Fenske et al., 2009). In other studies conducted from 1996-1999 on different ground applications and crops, similar results were found (Murray & Vaughan, 1970). With the analytical techniques available at the time, these studies were able to measure drift up to 100 meters downwind of a crop. Another study found that the deposited amounts decreased exponentially with distance (Carlsen, Spliid, & Svensmark, 2006). Still, drift has been measured miles from the source (Forster & Streloke, 2001).

Drift-Reducing Strategies

Research has looked at reducing drift by increasing droplet size through the use of specific nozzles, spray pressure and adjuvant mixtures (Felsot et al., 2011). Non-ionic colloidal and polyvinyl polymer drift retardant additives, for example, have been shown to reduce drift when used with hollow cone nozzles under high pressure (Guler, Zhu, Ozkan, Derksen, & Krause, 2006). Pre-orifice nozzles have also been shown to reduce drift on their own by creating a courser spray, though they may be more effective on non-boom sprayers (Felsot et al., 2011). Nonetheless, this method of drift-reduction may lead to reduced foliar coverage and product penetration.

Buffer zones have also been found to reduce non-target drift. A spray buffer zone is an area between a spray application and a non-target area meant to reduce drift (Stephenson, Ferris, Holland, & Nordberg, 2009; Unsworth et al., 2009). Drift may be further reduced when crop cover is used in buffer zones, though the type of foliar coverage plays an important role in its effectiveness (Felsot et al., 2011). Needlelike foliage, for example, has been shown to reduce drift by two to four times when compared to break leaves. Buffer zones, however, have limitations since it may be difficult to determine their ideal size, and they can reduce yields if they use arable land for the buffer.

Moreover, drift prediction models are used for regulatory risk assessment. Though there are many, the AgDRIFT® model for near-field data and AGDISP (Agricultural DISPersal) model for far-field data are common (Felsot et al., 2011). Both models, however, assume constant atmospheric conditions, flat terrain and no vegetative barriers, all of which affect drift (Felsot et al., 2011).

Real-Time Direct-Reading Instruments for Analyzing Airborne Particles

Aerosol sampling instruments traditionally collect particles that are afterwards analyzed using microscopic, gravimetric, or chemical methods (Chen & Pui, 2008). The development of more complex, direct-reading instruments that analyze samples internally now allows the user to see results immediately. Direct reading instruments can calculate particle size, aerosol number concentration, aerosol mass concentration, aerosol surface area concentration, particle number or mass size distribution, opacity and chemical composition (Chen & Pui, 2008). Direct-reading instruments that take repeated measurements in "real-time" are now also available, and can provide large sample sizes (Chen & Pui, 2008). Some precautions should be taken with direct-reading instruments since they tend to use indirect sensing and require regular calibration (Chen & Pui, 2008). For example, many instruments provide particle sizes, though these are usually derived from various particle properties including gravimetric, optical, aerodynamic and mechanical behavior (Chen & Pui, 2008).

Dylos Monitors

The Dylos DC1100 monitor has been reliably used and evaluated by past scientific studies (Jones et al., 2016). In a study comparing the low-cost sensor Dylos DC1100 (~$700) to a pDR-1200 (~$5,800) and a respirable sampler for gravimetric analysis, the Dylos was found to be a reasonable indicator of respirable particle concentrations (Jones et al., 2016). The Dylos particle number concentrations (PNC) were first converted to particle mass concentrations (PMC) using both a physical property method and a regression method before being compared to pDR-1200 and gravimetric analysis. The physical property method involved converting PNCs to PMCs using aerosol size and density estimates, while the regression model determined the best-fit linear model from a sample of Dylos PNCs and pDR-1200 PMCs. Dylos DC1100 PNCs were highly correlated to pDR-1200 PMCs (R^2=0.85). Strong linear relationships were also seen using both methods (slope: 0.75 – 1.08, R^2: 0.62-0.73).

High correlations have also been seen between the Dylos DC1100 and three well-characterized reference instruments: the Grim 1.109 (Grim Technologies), APS 3321 (TSI Inc.) and FMPS 3091 (TSI Inc.) (Manikonda, Zíková, Hopke, & Ferro, 2016). While measuring cigarette smoke (328 nm GM diameter:) and Arizona Test Dust (ATD) (~ 2.8 μm GM diameters), the Dylos monitors showed high correlations (cigarette smoke: R^2 = 0.87 -0.97; ATD: $R^2 \approx$ 0.75 – 0.95).

Other studies have also found strong correlations between the Dylos DC1700 (an updated Dylos monitor that uses the same sensor as the DC 1100) and the DustTrak 8520 (R^2=0.81-0.99), DustTrak II for $PM_{2.5}$ (R^2= 0.78), and TSI Sidepack AM510 (R^2= 0.86) (Holstius, Pillarisetti, Smith, & Seto, 2014; Semple, Ibrahim, Apsley, Steiner, & Turner, 2013).

As low-cost sensors, the Dylos monitors could be incorporated into occupational settings. Many Dylos monitors, for example, could be deployed to better estimate PM variation and warn workers of high exposure levels when additional ventilation or personal protective equipment may be required (Jones et al., 2016). These monitors could also be used as indicators to perform further analyses with more sophisticated instrumentation.

Airblast Sprayers

Pesticide spray is one of the most common application techniques used in agriculture (PSEE, 2015). In Washington State, airblast spraying has been widely used in tree fruit orchards since the 1950s (Courshee, 1959). Airblast sprayers use air and liquid to apply pesticide to a desired surface (VirginiaTech, 2014). Low-pressure nozzles deliver pesticide droplets into a fan's high-speed airstream that then propels droplets out radially, breaking them up into finer ones before reaching their target (VirginiaTech, 2014). Most are mounted on a trailer that is then pulled by a tractor, and can be directed to one or both sides of the sprayer, or through a nozzle (VirginiaTech, 2014). Their tanks can hold anywhere from 100 to 1,000 gallons and their stirring ability makes it possible for them to hold varying concentrations of a chemical (VirginiaTech, 2014). Their spray can cover an area up to 90 feet (27 meters) wide and 70 feet (21 meters) high (VirginiaTech, 2014).

Airblast sprayers have several advantages and disadvantages. They provide good surface coverage and penetration, have mechanical stirring capabilities, are high capacity, can spray both low and high volumes, and have low pump pressures (VirginiaTech, 2014). A significant limitation to airblast sprayers, however, is their high drift hazard. Airblast sprayer technologies have been slow to adapt and have become less accurate with the changing of orchard tree shape and the reduction in tree height. Traditional airblast sprayers are thus now more likely to spray above canopies, increasing their potential for drift. Some studies estimate that 45% of airblast spray misses the intended target, instead becoming drift or depositing at ground level (Keen, 2010; Reichard et al., 1979; Steiner, 1969).

The US EPA's Drift-Reduction Efforts

The EPA's Drift Reduction Technology Program

In the 1950s, pesticide drift was recognized and purposefully used. In some cases it was even described as an economical application technique (Courshee, 1959). This technique involved the release of insecticide spray above ground level where it was then allowed to deposit downwind (Courshee, 1959). Pesticide drift is no longer recognized as an application technique and is instead discouraged by the EPA. Their voluntary Drift Reduction Technology (DRT) Program aims to encourage the development drift-reducing technologies, and with time, shift the entire agricultural sector towards the use of these technologies (US EPA, 2016a). Manufacturers who are interested can follow EPA's technology testing protocols and submit their results to be evaluated by the EPA for its ability to reduce drift. These ratings can be used in that technology's labeling and advertising. In addition, pesticide applicators can easily look up these technologies in an online database. While this program is currently only for row and field crops, it is expected to cover orchards and vineyards in the near future (US EPA, 2016a).

Worker Protection Standard

The EPA's Worker Protection Standard (WPS) was implemented in order to protect agricultural workers and handlers from pesticide poisoning and injury (US EPA, 2016b). It requires that agricultural owners and employers protect workers from pesticide exposure, provide workers with training regarding pesticide safety and assist in the case of exposures (GPO, 2016; US EPA, 2016b). More specifically, workers must have access to pesticide labeling, which includes guidelines on drift reduction, pesticide use and emergency information; workers must be kept out of areas being treated with pesticides or from those that have REIs; those who do enter pesticide-treated areas must be well protected; workers must be notified of treated areas; handlers must have adequate PPE; workers must be provided with adequate decontamination supplies including water, soap and towels; and workers must receive emergency assistance in the form of transportation to a medical facility where they must provide information about the pesticides being used during the incident (GPO, 2016; US EPA, 2016b).

Before January, 2017, the EPA’s WPS acknowledged drift but did not include specific rules to protect workers or areas nearby (Bohme, 2015; US EPA, 2016f). Among other things, the recent revision implements stronger regulations against drift and increases protections for children. The change defines an Application Exclusion Zone (AEZ) of 100 feet (30 meters) in any direction from an airblast sprayer. Employers are required to evacuate all individuals from the AEZ or stop spraying.

It is unclear whether the EPA’s recent revision of their WPS will be enough to protect agricultural workers. Historically, farm workers have had fewer rights than workers in other industries (Bohme, 2015). It was not until 1987, for example, that agricultural employers were required to provide their workers with drinking water, hand-washing facilities and toilets (Bohme, 2015). The current adaptation of the WPS still does not cover workers or communities past 100 feet even if they are technically within the same orchard facility. Moreover, pesticide regulations may not be stringent enough. In Reeves and Schafer’s 2003 analysis of pesticide-related poisonings, 41% of all incidents were due to worker safety law violations. Such agricultural regulations that are poorly enforced are thus not alone an ideal method of controlling pesticide drift and they must be supported with other effective controls.

Multi-Headed Fan Tower Sprayers

Unlike airblast sprayers, tower sprayers spray horizontally and incline into the tree canopy, thus potentially allowing them to both reduce drift and improve uniform coverage with a finer mist (Fox, Derksen, Zhu, Brazee, & Svensson, 2008; Zhu & Zondag, 2011). For optimal drift reduction, the appropriate pressure, volume and droplet size should be adjusted to best fit tree size, shape and density (Fox et al., 2008). Currently popular on the market, the Quantum Mist’s Tower Mutli-Headed Fan Tower (MFT) Sprayer advertises its drift-reduction and improved overall spray efficiency (Croplands, 2016). This sprayer has three spray heads per side and these faces are adjustable to provide more precise application for varying orchard structures (Croplands, 2016). Compared to traditional airblast sprayers that have ten spray nozzles per side, this sprayer has 24 nozzles (Croplands, 2016). Greater coverage and faster travel speeds are advertised to lead to lower costs. Other than drift reduction, the advertised benefits of this sprayer include its ability to help lower fertilizer application, concentrated spraying, multiple row application capabilities and reduced water rates. Importantly, this sprayer does not specify the degree of drift reduction or provide empirical evidence to support its claims. Moreover, while the AFA sprayer costs roughly around $15,000, these types of alternative sprayers may cost $30-40,000 making them a larger investment (Hoheisel, 2016).

Research Limitations

More research is needed to better understand drift behavior and the areas that may be most affected by it. Though many studies have looked at pesticide drift in row crop applications, few have looked at fruit trees or used real-time monitoring. In Washington State, apple trees are the largest crop (WSDA, 2014). Moreover, while pesticide drift studies have collected total drift deposition, none have used real-time samplers to look at particle size distributions over time. It is thus unclear how well aggregate sampling models describe drift variability over time. Higher detectable drift concentrations are believed to occur soon after a spray application, but more precise empirical data does not currently exist to better support these claims. Finally, few studies have researched the true effectiveness of new technologies that self-label themselves as drift-reducing or compared these to commonly used traditional AFA sprayers. A new, “drift-reducing” technology currently common in Washington, and whose prevalence could increase as pesticide applicators begin to accept drift-reducing technologies, is the Quantum Mist’s MFT Sprayer. This sprayer is advertised to provide better coverage and higher spray efficiency through its adjustable spray heights and angles (Croplands, 2013).

Study Objectives

This study was nested in a larger study in which micronutrient drift from a traditional AFA and modern MFT sprayer was measured using accepted methods of passive and active sampling for drift characterization (Kasner, 2017). In this study, we used real-time particle monitors to further characterize the drift events of a traditional AFA and modern MFT sprayer spatiotemporally, an area of limited research. PMC represented ambient PM levels during the control period and also included drift during spray periods. Because this approach was novel, it had not been validated. Our central hypothesis was that these two sprayers would generate different drift plumes, with the MFT sprayer producing less overall drift than the AFA. This hypothesis was based on our larger study's preliminary data showing that other types of tower sprayers produce less drift than AFA sprayers (Kasner, 2017). This study had two specific aims:

Aim 1: Determine whether the modern MFT sprayer, when compared to the traditional AFA sprayer, reduces micronutrient tracer drift of liquid aerosols spatiotemporally. Our working hypothesis was that, as advertised, the ability of the MFT sprayer to release spray closer to the target surface would yield a more accurate spray and reduce drift potential, as measured by aerosol concentrations in a neighboring field.

> **Aim 1a:** Measure the aerosol concentrations associated with an AFA and MFT sprayer in a neighboring field above and below the canopy (two and six meters). Our hypothesis was that drift would be deposited from above the canopy, and thus greater concentrations would be seen above than below the canopy at any given location. In a neighboring field, the concentration above the canopy would be indicative of drift traveling downwind, while the mass concentration below the canopy would be indicative of potential worker exposures.
>
> **Aim 1b:** Quantify the aerosol concentrations associated with an AFA and MFT sprayer at various distances in a neighboring field. We tested the hypothesis that greater concentrations would be detected closer to the spray field, while lower concentrations would be detected further from the spray field as drift droplets fell and diminish in size over time.

Aim 2: Characterize the aerosol concentration patterns associated with an AFA and MFT sprayer over time in a neighboring orchard block. We hypothesized that higher concentrations would be seen for the AFA sprayer than for the MFT sprayer over time with peak concentrations for both occurring soon after the beginning of a spray event.

Methods

Study Design

This study was part of a larger study in which micronutrient drift was measured using accepted methods of passive and active sampling for drift characterization (Kasner, 2017). Research took place in Washington State University's (WSU) Sunrise Research Orchard near Rock Island, Washington where prevailing winds from the north made it possible to sample for drift southbound. A one-acre orchard block (28 tree rows) was divided into four quadrants that were randomly sprayed by alternating AFA and MFT sprayers so that each technology sprayed all four quadrants daily (Figure 9). Ten Dylos DC1100 Pro optical particle samplers collected real-time particle samples in a neighboring southern block. Samplers were placed above and below the canopy at five distinct locations in the shape of a cross. Two meteorological stations within the research orchard collected wind speed, wind direction, temperature and relative humidity throughout our study period.

Dylos particle number concentrations (PNC) over time were adjusted for background PM levels and converted to particle mass concentrations (PMC) over time. Meteorological data that met our inclusion criteria was synced with PMC values: wind speed 0-500 m/s; air temperature greater than 0˚C, relative humidity 0-100%; and wind blowing in a 135˚ arc southbound ($x > 281^\circ$ and $x < 56^\circ$). Moreover, only sprayer distances below 400 feet were synced with PMC values. This was the furthest possible distance between an active sprayer and our samplers (Figure 1). Larger values were assumed to be a GPS error.

Power
No empirical evidence of the true mean difference between the AFA and MFT sprayer exists since this research is novel. Still, some research suggests that an AFA sprayers may miss the intended target 40% (SD 3%) of the time while technologies with tower sprayers may reduce drift down to 10% (Duga et al., 2015; Lešnik, Stajnko, & Vajs, 2015). For each technology, we predicted a log-normal distribution in RStudio using the rlnorm function (AFA: mean = 40, SD =3; MFT: mean = 10, SD = 3; n=16 spray events per technology). We used these log-normal distributions to perform a 75th quantile regression for mass concentration from sprayer type. Our estimated power was 0.96 (standard error = 0.01). We will also consider two modifiers: distance from the sprayer and sampler height.

Preparation

Protocol
Dr. Richard Fenske was the principal investigator on this study. Our team also consisted of PhD Candidate Eddie Kasner, our field leader, many field team members and several other personnel who helped with logistics. We largely followed a field sampling method for micronutrient tracer spray drift developed by Pacific Northwest Agricultural Safety and Health (PNASH) in which metal tracers are sprayed by different technologies and the total mass of their drift is collected on media placed in a neighboring field. Instead of using media to sample for drift, however, this study used real-time optical particle counters to sample overall aerosols.

Final Details
In the weeks leading to our data collection we finalized logistics through regular meetings. All of our equipment including our Dylos particle monitors, meteorological station and GPS units were tested for reliability. To prepare the Dylos, we taped a temporary cap over the functional buttons to prevent these from being accidentally activated while sampling. We also wrapped them in plastic to protect them from spray, leaving their inlets, outlets and power buttons clear. A team training, including a mock run using

our field protocol, was conducted a week prior to our first sampling session (Figure 2 and Appendix I). We covered safety topics including heat exposure, working in teams and first aid training.

Field Work

We collected data during two sampling periods, June 10, 2016 and September 28-30, 2016 at WSU's Sunrise Research Orchard near Rock Island, WA (Figure 3). This orchard's geographical location within a gorge provided for predictable winds from the north that allowed us to spray a micronutrient solution and sample for drift in a southern orchard block. This rural location also helped assure us that we would not be measuring additional vehicle emissions. These dates were selected because apple trees would have similar full canopies (Figure 4).

Meteorological Stations

We set up a temporary meteorological station to track weather conditions (wind speed, wind direction, temperature and relative humidity) throughout our spray events (Figure 5 and Figure 6). We used this station in conjunction with a permanent, regularly-maintained, on-site station to ensure the accuracy of our data (WSU, 2017; Figure 7). The permanent, on-site station was two meters high, 70 meters (229 ft) from the nearest corner (southwest corner) of the sprayed block, and it took meteorological readings every 15 minutes. Our temporary station was 10 meters high, 190 meters (623 ft) from the nearest corner (northeast corner) of the sprayed block, and it took more precise, ten-second and one-minute measurements. The use of a second meteorological station followed applicable protocols for the International Organization for Standardization (ISO) and the American Society of Agricultural (and Biological) Engineers (ASE) (Kasner, 2017). Before each sample period in June and September, the temporary station's internal clock was manually synced with a laptop. At the end of each sampling period, the station's internal clock was rechecked to ensure it had not changed more than a few seconds.

Real-Time Particle Counters

We used Dylos DC1100 Pro optical particle samplers to measure PMCs over time (Figure 8). Samplers used a flow rate of 0.06 ft^3/min (1699 cm^3/min) and had several advantages over other air samplers. First, these instruments are small, lightweight, battery operated and provided us with aerosol concentrations every minute, making them practical field samplers for spatiotemporal work in agriculture, an area with limited research. Second, samplers measured particles in bin sizes of various aerodynamic diameters (µm) each minute: $0.5 \leq b_1 < 1.0$, $1.0 \leq b_2 < 2.5$, $2.5 \leq b_3 < 10.0$, $b_4 \geq 1.0$, which allowed us to more precisely characterize aerosol concentrations which were indicative of drift. Third, at about $700, this instrument is an affordable alternative to more sophisticated instrumentation.

Dylos Field Setup

Ten uniquely labeled Dylos particle monitors were fully charged overnight; their internal clocks were synchronized to standard time with a laptop; and their data histories were cleared before sampling. We set up the Dylos in a field south of our spray field with their inlets facing north towards the spray field (Figure 9 and Figure 10). Our micronutrient sprays began early in the morning, as is typical of agricultural work, and ended around noon. The goal was to characterize overall drift, drift decay over distance and drift above and below the canopy. To better characterize drift decay, we aligned samplers 6, 35 and 56 meters south of the spray field, measuring from the spray field's most southern tree (Samplers A, C and E). To more closely look at drift differences at different heights, two samplers, one at 2 meters and the other at six meters, were placed at each location. The two-meter (6.5 feet) samplers were meant to capture potential worker exposures to drift below the canopy while the six-meter (20 feet) samplers were meant to capture drift above the canopy that was still traveling. Additional samplers were placed 21 meters east and west of sampler C at two and six meters to better capture overall drift (Samplers B and D). Samplers ran from approximately an hour before the first spray of the day to an hour after the last spray of the day.

Spraying

We used an AFA and MFT sprayer to apply micronutrients to our spray field (Figure 11, Figure 12). Both sprayers were calibrated running at three miles per hour and outputting one hundred gallons per acre. The AFA sprayer used an operating pressure of 205 PSI while the MFT's automatic rate controller was calibrated to 100 PSI when traveling at 3 MPH (Table 1). Both sprayers had air velocities of 20,000 – 30,000 CFM. The AFA sprayer produced fine droplets ranging from 110-125 μm while the MFT sprayer produced very fine droplets ranging from 61 – 105 μm. The AFA used disc-core nozzles while the MFT used one-piece nozzles. Both created hollow cone spray patterns.

All vehicles were removed from the orchard blocks more than 30 minutes prior to spraying, and we ensured that no other vehicles were nearby. Each application device had a global positioning system (GPS) to help us determine the exact start and end times of each spray event since it was unsafe for the research team to be in the application area. A single certified pesticide applicator from Washington Tree Fruit Research Commission sprayed every application in a north-south direction.

The quadrant spray order was randomized, with both technologies alternating until each technology had sprayed all four orchard quadrants daily (Figure 13, Table 2). Alternate spraying was meant to limit potential meteorological variations between sprays. Sprayer order was switched daily. We calculated that two minutes between sprays would be ample time for drift to completely clear out given that the average wind speeds in the area are around 10 MPH (WSDA, 2014). This speed falls within the EPA's recommended drift reducing wind condition range of 3-10 (US EPA, 1995). As an estimate, in wind speeds of six MPH, we calculated that a 5 μm particle would travel at about 2.4 m/sec, the equivalent of 146 meters in one minute (Klein et al., 2008; WSDA, 2014). Since the distance from the northern edge of the spray field to the southern edge of the sample field was about 111 meters, similar wind speeds would easily clear any remaining drift within one minute (or between sprays).

Cameras

Three cameras were used to record our spray events. One camera was positioned on the southern edge of the sample field with an aerial view of both the spray and sample field; one camera was positioned between the spray and sample field on the western border; and one was positioned on the sprayers' tractor facing the spray (Figure 14 - Figure 16).

Data Analysis

Data Download

After each day, each Dylos particle data was downloaded to a text file using PuTTy software (beta 0.67). Meteorological data from the permanent stations was downloaded online after each day of spraying while data from the temporary station was collected at the end of the day on June 10th and September 30th. Values from both stations were compared for consistency, and only those that met our inclusion criteria were kept (wind speed 0-500 m/s; air temperature greater than 0˚C, relative humidity 0-100%; and wind blowing in a 135˚ arc southbound ($x > 281˚$ and $x < 56˚$)). Overall, about 15% of the data within our sample periods were dropped. Minute values from the cup anemometer (3 meters) were used for wind speed, temperature, relative humidity. The ultrasonic anemometer's ten-second wind direction values (10 meters) were used after being averaged out to one-minute summaries since they were unavailable from the cup anemometer. Sprayer GPS data were downloaded to kml files and Google Earth (v 7.1) was used to determine the start and stop time (rounded to the nearest minute) of each sprayer's spray event. One minute was added to the end of each spray event to capture any potential residual spray. Two individuals initially had 98% concordance when following these sprayers start and stop time methods, and full concordance after all discrepancies were discussed and a single value was agreed upon.

Data Preparation
All particle and meteorological data were imported to the RStudio statistical package (0.99.903 using R 3.3.1 GUI 1.68 Mavericks build) where they was merged and prepared for analysis. We used two fifteen-minute control periods each day to characterize natural ambient PM levels, one immediately before the first spray event and one immediately after the last spray event.

For each bin size ($0.5 \le b_1 < 1.0$, $1.0 \le b_2 < 2.5$, $2.5 \le b_3 < 10.0$, $b_4 \ge 1.0$), we calculated a "changing background" using a 5th percentile 8-minute rolling average of PNCs to adjust for changing ambient PM concentrations throughout our spray events. Changing backgrounds were subtracted from original PNCs to calculate adjusted PNCs for each bin and create flat baselines. Similar methods of background adjustment for real-time air quality sampling of moving sources have been used in other studies (Brantley et al., 2014; Bukowiecki et al., 2002).

Adjusted PNCs were converted from particles per hundredth of a cubic foot to particles per cubic meters; and aerosol density was converted from grams per cubic centimeter to micrograms per cubic meters (Table 3). The geometric mean diameter of each of the four bins was calculated since we expected the particle distribution to be log-normal, and this was converted from micrometers per particle to meters per particle. For each sample, each bin's PNC was converted to PMC by multiplying that bin's PNC by: pi/6, that bin's geometric mean diameter except for the largest bin where the lowest size cut was used (d_1 = 0.71e-6 m, d_2 = 1.58e-6 m, d_3 = 5.00e-6 μm or d_4 = 10.00e-6 m), and an assumed aerosol density of 1 $\mu g/m^3$ (Equation 1). All bin PMCs were added to estimate total PMC.

Distance Calculations
We measured the direct distance from the moving sprayer to each of our five sampling locations thirty seconds into each sample minute. These distances were categorized into one hundred-foot "zones" (0 to 100 ft, 101 to 200 ft, 201 to 300 ft and 301 to 400 ft) since these were rough estimates of the moving sprayer's mean distance during any one minute (Table 4).

Hypotheses Tests
We performed a 75th quantile regression to describe the PMC "peaks" associated with each sprayer. Quantile regression models have several important advantages over linear regression (Koenker & Hallock, 2000). First, they are less influenced by extreme values and outliers so that they can better estimate distributional deviations from the median. Second, there are no distribution assumptions and so data does not have to be log-transformed. Finally, since we expected drift to fluctuate, 75th quantiles would better capture PMC peaks when compared to means. The default Barrodale and Roberts algorithm for datasets up to several thousands of observations was used.

We performed an analysis looking at the effect of sprayer type and sampler height on PMC while controlling for wind speed (Equation 2). For our Aim 1, our null hypothesis was that after adjusting for wind speed and sampler height, the MFT would produce the same amount of PMC as the AFA. Our alternative hypothesis was that the MFT would produce less PMC than the AFA. For our sub-aim 1a, our null hypothesis was that after adjusting for sprayer type and wind speed, the same amount of PMC would be produced above and below the canopy. Our alternative hypothesis was that more PMC would be detected above the canopy than below the canopy.

For our Sub-Aim 1b, we then performed a restricted analysis only looking at spray periods to control for distance on PMC while controlling for sprayer type, wind speed and sampler height (Equation 3). Control (non-spray) periods were automatically dropped from this analysis because they did not have distance values associated with them. Our null hypothesis was that distance from the sprayer would not be associated with PMC after adjusting for sampler type, wind speed and sampler height. Our alternative hypothesis was increased distances would be associated with reduced PMC.

In both analyses, to determine whether there was a difference between any two covariates, we compared their 95% confidence intervals. If confidence interval did not overlap, we concluded that the two covariates were significantly different.

Methods Tables

Table 1. Sprayer Details

Factor	AFA	MFT
Nozzles/side	5	18
Pressure (PSI)	205	Auto-Adjusted
Fan size (in)	28	20
Air Velocity (CFM)	20,000 – 30,000	20,000 – 30,000
Droplet Size	Fine	Very Fine
Droplet Diameter (µm)	110-125	61-105

Table 2. Daily Spray Order

Spray Order	Date	Quadrant Sprayed	Duration (min)	Sprayer
1	6/10/16	3	7	MFT
2	6/10/16	3	5	AFA
3	6/10/16	4	7	MFT
4	6/10/16	4	7	AFA
5	6/10/16	2	7	MFT
6	6/10/16	2	6	AFA
7	6/10/16	1	8	MFT
8	6/10/16	1	6	AFA
9	9/28/16	2	7	AFA
10	9/28/16	2	6	MFT
11	9/28/16	1	7	AFA
12	9/28/16	1	7	MFT
13	9/28/16	3	7	AFA
14	9/28/16	3	7	MFT
15	9/28/16	4	6	AFA
16	9/28/16	4	7	MFT
17	9/29/16	1	7	MFT
18	9/29/16	1	6	AFA
19	9/29/16	3	6	MFT
20	9/29/16	3	7	AFA
21	9/29/16	4	8	MFT
22	9/29/16	4	7	AFA
23	9/29/16	2	8	MFT
24	9/29/16	2	6	AFA
25	9/30/16	1	7	MFT
26	9/30/16	1	6	AFA
27	9/30/16	3	6	MFT
28	9/30/16	3	6	AFA
29	9/30/16	4	7	MFT
30	9/30/16	4	7	AFA
31	9/30/16	2	7	MFT
32	9/30/16	2	8	AFA

Table 3. Unit Conversions for PMC Calculation

Parameter	Starting Units	Conversion Factors	Ending Units
PNC	$\frac{count}{0.01\ ft^3}$	$\frac{100}{100}\ x\ \frac{35.3147\ ft^3}{m^3}$	$\frac{count}{m^3}$
Diameter	$\frac{\mu m}{count}$	$\frac{m}{10^6\ \mu m}$	$\frac{m}{count}$
Assumed Density	$\frac{g}{cm^3}$	$\frac{10^6\ \mu g}{g}\ x\ \frac{10^6\ cm^3}{m^3}$	$\frac{\mu g}{m^3}$
PNC to PMC	$PNC\left(\frac{count}{m^3}\right)$	$\left(\frac{m}{count}\right)^3\ x\ \frac{\mu g}{m^3}$	$PMC\left(\frac{\mu g}{m^3}\right)$

Each bin's PNC values were converted from counts per hundredth of a cubic foot to counts per cubic meters. The geometric mean diameter of each bin was converted from micrometers per count to meters per count. Aerosol density was converted from grams per cubic centimeter to micrograms per cubic meters.

Equation 1. PMC Calculation from PNC

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

For each sample, each bin's PNC was converted to PMC by multiplying that bin's PNC by: π/6, that bin's geometric mean diameter except for the largest bin where the lowest size cut was used (d_1 = 0.71e-6 m, d_2 = 1.58e-6 m, d_3 = 5.00e-6 µm or d_4 = 10.00e-6 m), and an assumed aerosol density of 1 µg/m^3. All bin PMCs were added to estimate total PMC.

Table 4. Distance Zone Ranges

Distance Zone	Sprayer Distance (ft)
Control	-
100	0-100
200	101-200
300	201-300
400	301-400

Equation 2. 75th Quantile Regression

$$Q_{\mathrm{Y|X}}(\tau = 0.75) = \beta_0 + \mathrm{X}_{AFA}\beta_{\tau_{AFA}} + \mathrm{X}_{MFT}\beta_{\tau_{MFT}} + \mathrm{X}_{wind\ speed}\beta_{\tau_{wind\ speed}} + \mathrm{X}_{height}\beta_{\tau_{height}}$$

Quantile regression predicting the 75th quantile for PMC when controlling for sprayer type, wind speed and sampler height.

Equation 3. Restricted Analysis

$$Q_{\mathrm{Y|X}}(\tau = 0.75) = \beta_0 + \mathrm{X}_{MFT}\beta_{\tau_{MFT}} + \mathrm{X}_{wind\ speed}\beta_{\tau_{wind\ speed}} + \mathrm{X}_{height}\beta_{\tau_{height}} + \mathrm{X}_{distance}\beta_{\tau_{distance}}$$

Quantile regression predicting the 75th quantile for PMC when controlling for sprayer type, wind speed, sampler height and sprayer distance from sampling location. Note that since this analysis is restricted to the spray periods, there are no control periods.

Methods Figures

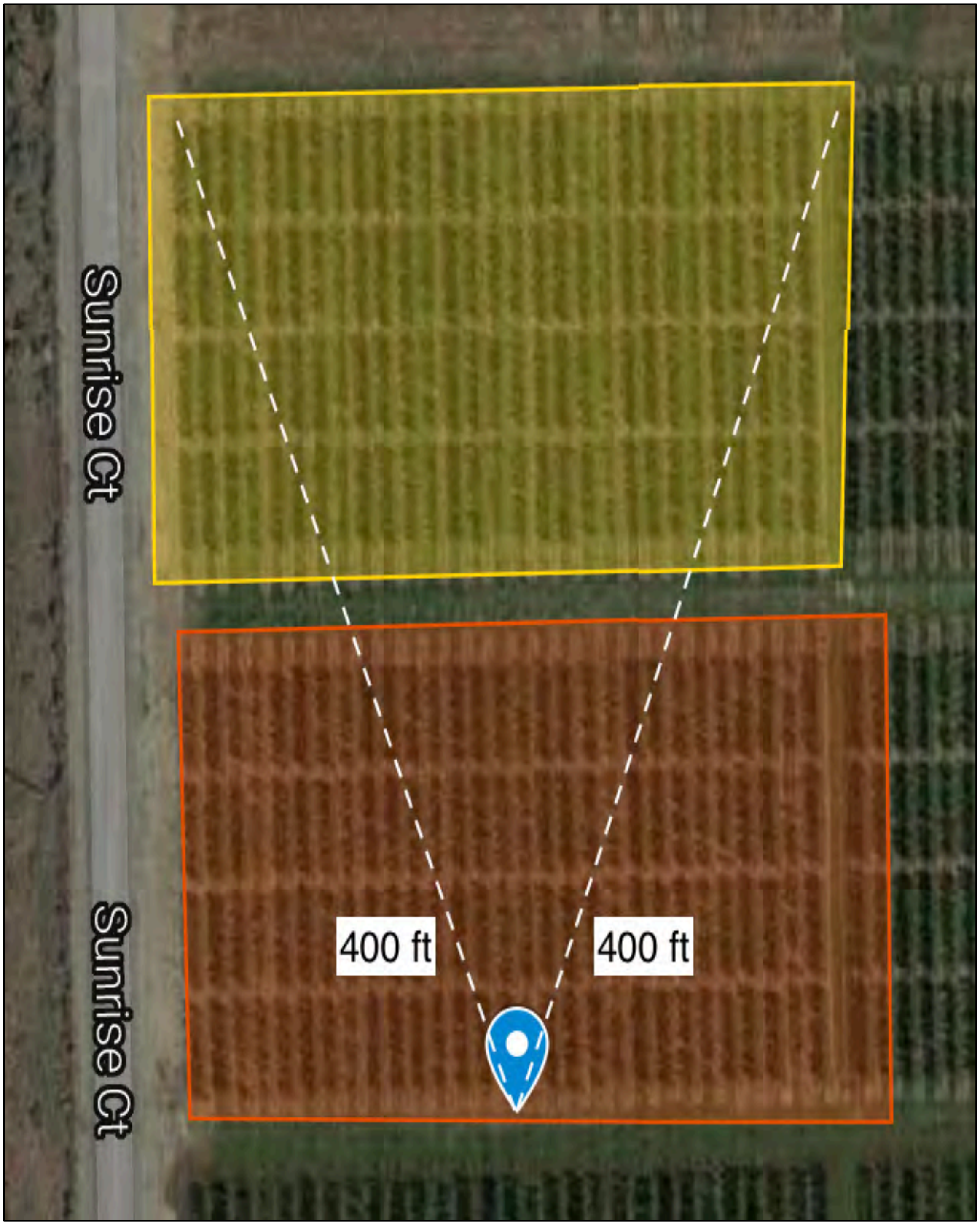


Figure 1. Inclusion Criteria for Sprayer Distance

When measuring the distance from a moving sprayer to a sampler, only sprayer distances below 400 feet were included. This was the furthest possible distance between an active sprayer and our samplers. Larger values were assumed to be a GPS error.

Figure 2. Practice Run with Dylos Particle Samplers at Two and Six Meters

Figure 3. WSU Sunrise Research Orchard in Central Washington

Figure 4. Orchard with a Full Canopy in June 2016 (top) and September 2016 (bottom)

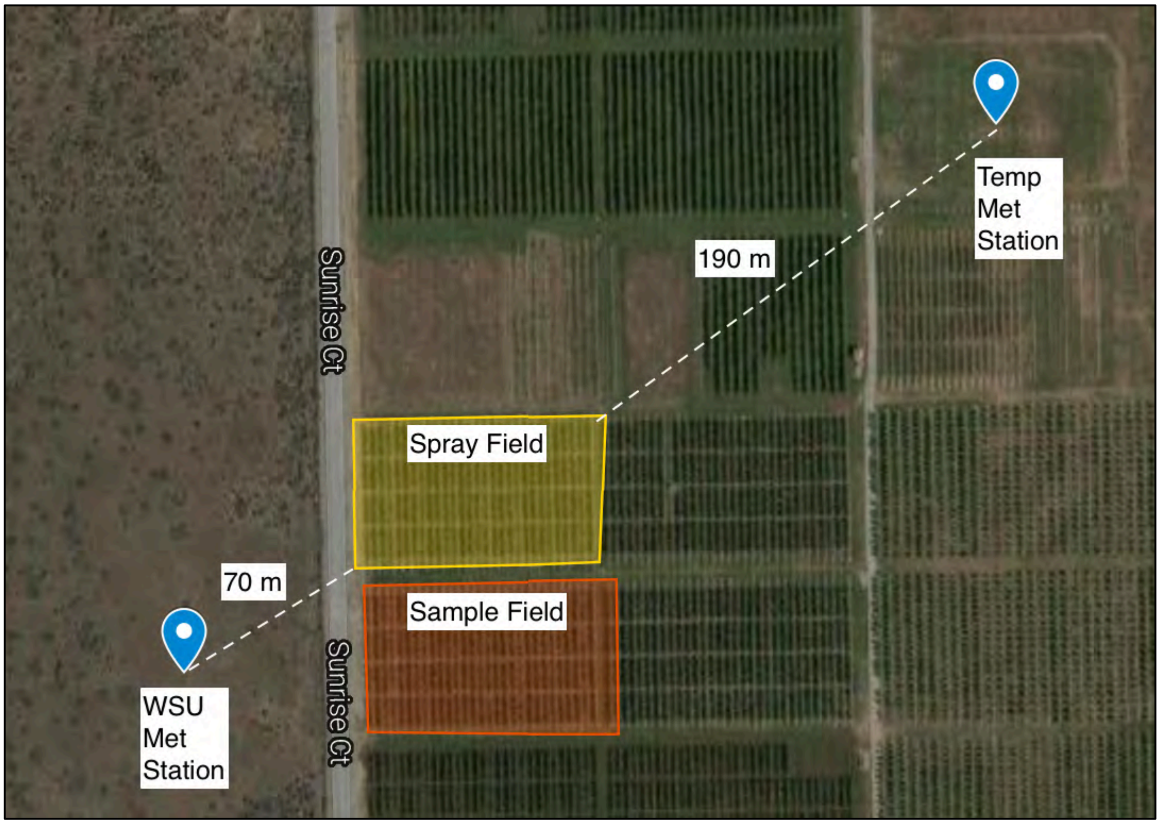


Figure 5. Map of Meteorological Stations and Study Fields

Figure 6. Temporary Meteorological Station Setup

Figure 7. WSU Sunrise Meteorological Station

Figure 8. Dylos DC1100 Optical Real-Time Particle Monitor

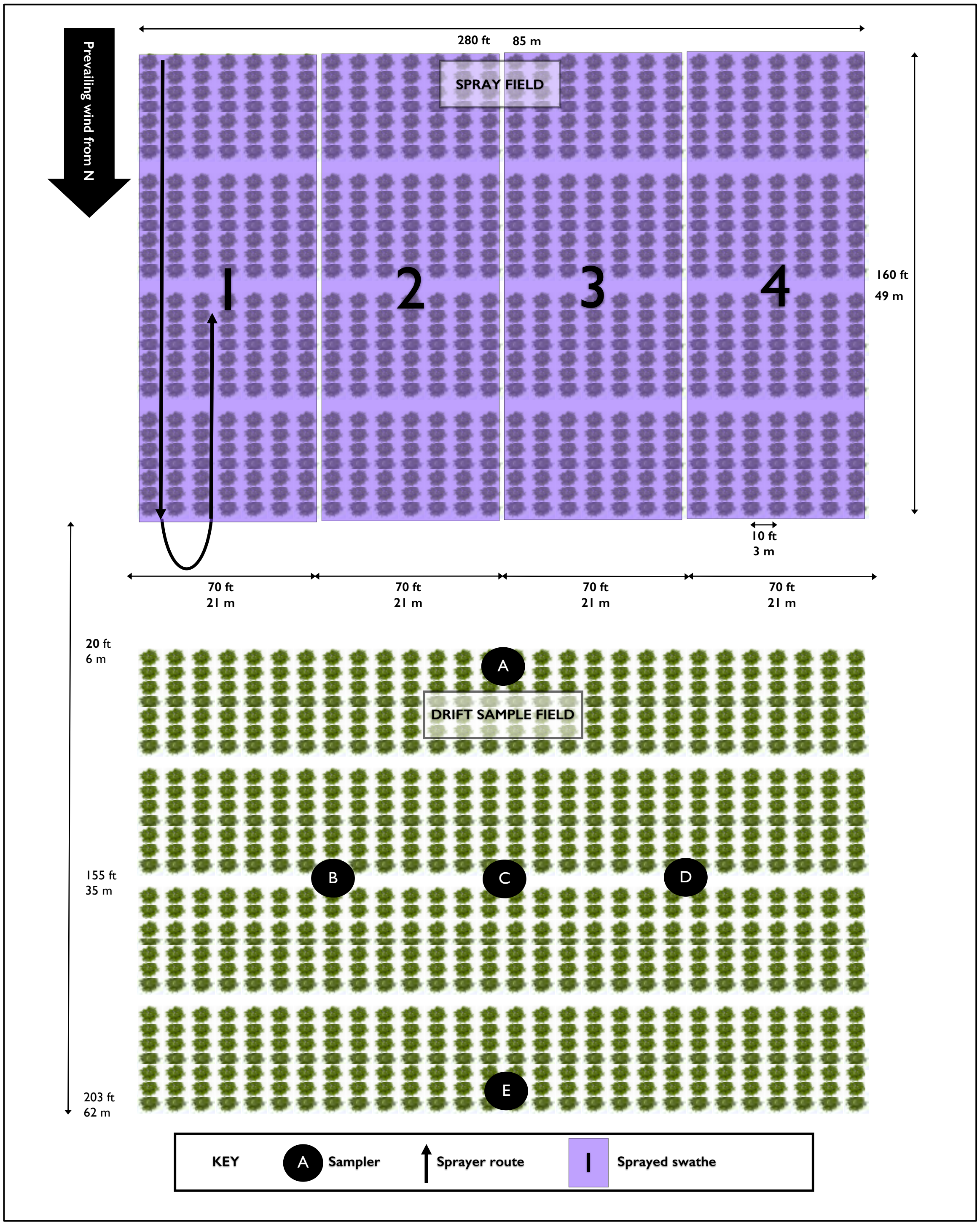


Figure 9. Field Setup for Spraying and Sampling

Figure 10. Dylos Particle Sampler at 2 Meters

Image shows a Dylos monitor set up at 2 meters with a cascasde impactor below that was used in the parent study. A second Dylos at 6 meters is not depicted.

Figure 11. Traditional Axial Fan Airblast (AFA) Sprayer

Figure 12. Multi-Headed Fan Tower (MFT) Sprayer

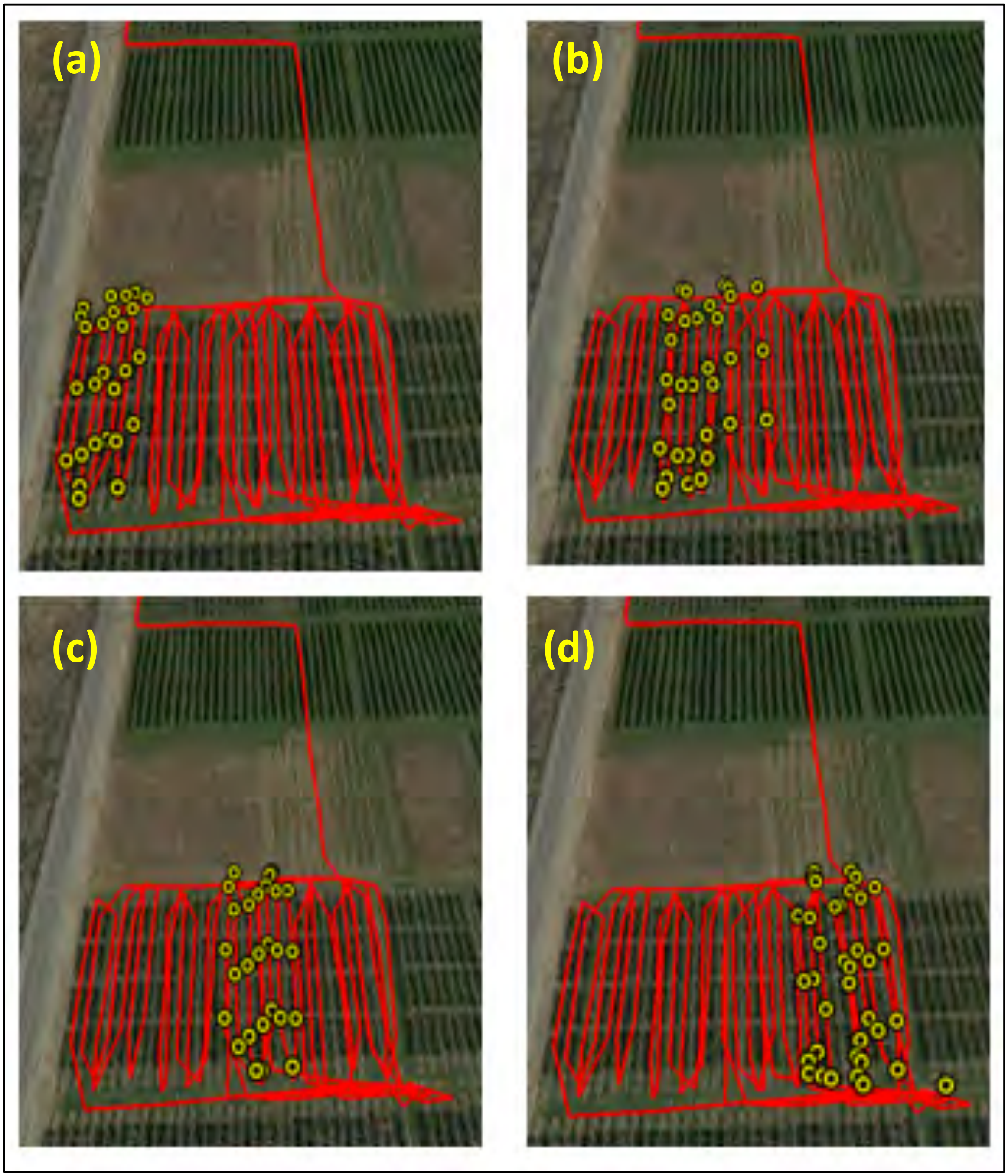


Figure 13. GPS Data for Spray Quadrants 1-4

Red lines indicate a sprayer’s movement throughout a spray day. Yellow circles indicate active spraying of a quadrant: (a) Quadrant 1, (b) Quadrant 2, (c) Quadrant 3 and (d) Quadrant 4.

Figure 14. Aerial View of the Spray and Neighboring Field

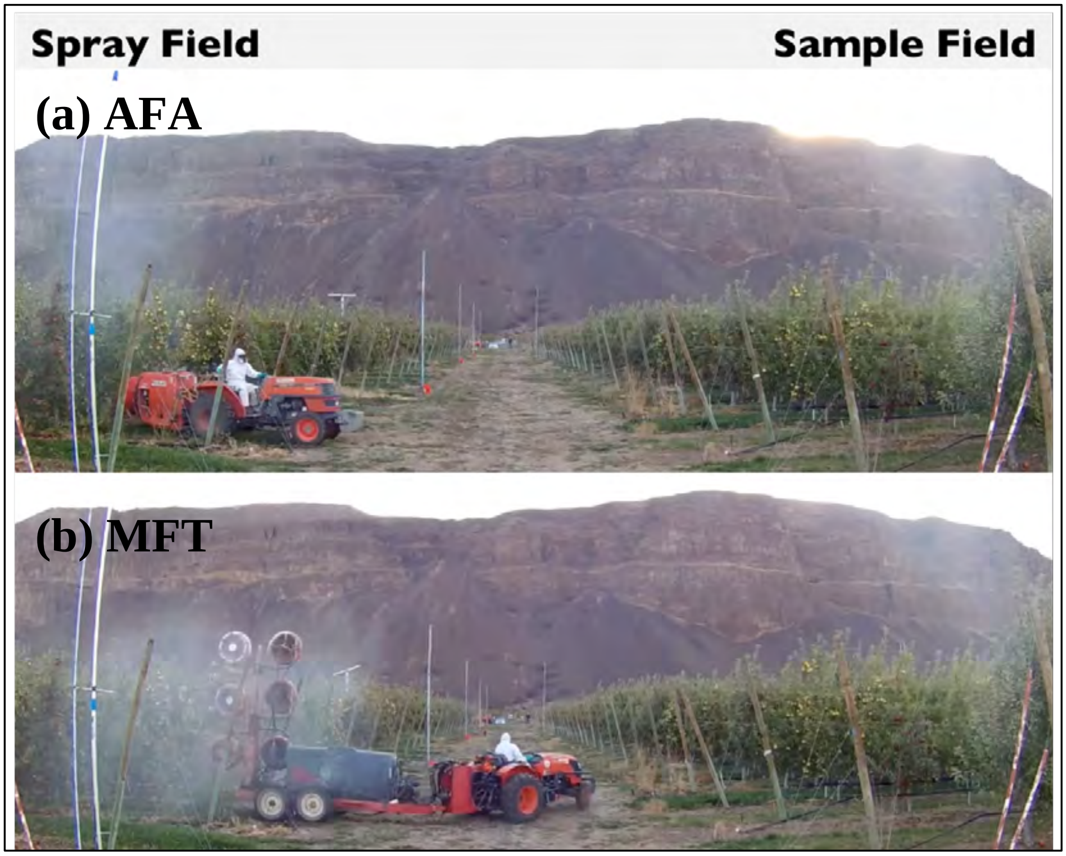


Figure 15. Drift Plumes During Spray Periods

Video:
https://drive.google.com/file/d/0B36r8A7o4CYpa0tjTWZWemhJZjA/view

Figure 16. Back of AFA (Top) and MFT (Bottom) Sprayers

Results

Sample Size

We had sixteen spray events per spray technology, each lasting a mean (SD) of 7.0 (0.6) minutes. Since we were one sampler short during our first spray day, nine samplers collected data during one quarter of the spray events and ten samplers collected data during three quarters of the spray events. We thus initially had around 1092 minute samples per technology (16 sprays/tech*7 min/spray *9.75 samplers), and around 1170 minute samples for the control periods (15 min/period * 2 periods/day * 4 days). Data that did not meet our inclusion criteria, as described earlier in our methods, were not included in our analyses, thus resulting in a total of 2,948 minute-long PMC samples (N_{AFA} = 1,028, N_{MHT} = 1,071, $N_{Control}$ = 849) (Table 5).

Meteorological conditions

During our study periods, WSU's permanent weather station had consistently higher temperature readings, lower relative humidity readings, comparable wind speed readings and narrower wind direction readings when compared to our temporary weather station (Figure 17 - Figure 20). Comparing the permanent and temporary weather stations, their median (interquartile range, IQR) temperature was 66.6 (5.0) ˚F and 61.9 (5.2) ˚F, relative humidity was 41.3 (7.1) % and 49.0 (9.0) %, wind speed was 7.7 (2.4) MPH and 8.6 (3.1) MPH, and wind direction was north and northwest respectively (Table 6). For better overall comparison, all wind direction data was included (not just "south wind" data used in this study), and the temporary station's degree outputs were converted from sixteen to eight principal points of direction (45˚ instead of 22.5˚ increments) to match the permanent station's output. The rest of this study uses our temporary weather station's wind speed and wind direction readings which were comparable to the permanent station's readings and had higher time resolutions.

Meteorological conditions, including temperature, wind speed, wind direction and percent relative humidity during our study were similar to Rock Island, WA's historical conditions for June and September (Table 7) (MyForecast, 2016). Our mean temperature, wind speed and wind direction were all within normal climate ranges, though our percent relative humidity measure was slightly lower than is typical for that time of year. Meteorological conditions were also similar for both sprayers and the control period. Importantly, wind speed and direction was similar across both spray periods and the control (Figure 21).

Background

Ambient PM generally decreased as each morning went on, and was associated with decreasing relative humidity such that periods at the beginning of a spray day were typically associated with greater PM compared to periods at the end that spray day (Figure 22). Over the day, temperatures increased and the boundary layer height increased, causing relative humidity to decrease and thus leading to lower PNC (Gallagher, McKendry, Macdonald, & Leaitch, 2011). In order to make all of our spray events comparable, we subtracted estimated "changing baseline" values from all of our data. Figure 23 shows an example of raw data from September 29th, 2016 of PNC over time for all four bin sizes with calculated 5th percentile, 8-minute rolling average baselines. Figure 24 shows an example of the final data that were used for our analyses after PNCs for each bin were converted to PMCs and all bin masses were added. All of our results are thus adjusted for background PM, converted from PNC to PMC and represent one-minute readings.

Aim 1: Drift Over Space

Descriptive Statistics

Overall, the control period was associated with the lowest PMCs, followed by the MFT sprayer and finally the AFA sprayer (Figure 25, Table 8). The 75th percentiles (IQR) for PMCs were 11.2 (8.1), 38.6 (34.5) and 117.0 (112.8) $\mu g/m^3$ for the control, MFT and AFA sprayer respectively.

Greater PMCs were detected below the canopy (2 meters) than above the canopy (6 meters) (Figure 26, Table 9). The 75th percentiles (IQR) for PMCs above the canopy were 9.6 (6.9), 27.9 (24.5) and 86.3 (80.3) $\mu g/m^3$ for the control period, MFT and AFA sprayer respectively. The 75th percentiles for PMCs below the canopy were 13.1 (9.4), 49.5 (44.2) and 188.0 (178.3) $\mu g/m^3$ for the control period, MFT and AFA sprayer respectively. To determine whether there was a predictable linear relationship between PMCs above and below the canopy, we regressed and fit a linear model on these values, grouping them by date and time (Figure 27). Loess lines were also included to determine whether a linear model was appropriate. During AFA sprayer applications, the PMC below the canopy increased by an average of 1.5 ug/m3 for every additional 1 $\mu g/m^3$ of PMC above the canopy ($R^2 = 0.20$). During MFT sprayer applications, the PMC below the canopy increased by an average of 1.8 $\mu g/m^3$ for every additional 1 $\mu g/m^3$ of PMC above the canopy ($R^2 = 0.12$). During the control period, the PMC below the canopy increased by an average of 0.9 $\mu g/m^3$ for every additional 1 $\mu g/m^3$ of PMC above the canopy ($R^2 = 0.20$). The loess lines and linear models for all three correlations closely matched.

We observed an exponential decay of PMCs at greater distances from a source sprayer, with PMCs below the canopy showing the most decay. This relationship was clear for the AFA sprayer both above and below the canopy, and for the MFT sprayer below the canopy (Figure 28 - Figure 30). Looking at all PMCs by distance zone, the AFA sprayer had the greatest PMCs in the 0 to 100-foot zone (AFA: 223.4 $\mu g/m^3$) while the MFT had the greatest PMCs in the 101 to 200-foot zone (66.2 $\mu g/m^3$) (Figure 31, Table 10 - Table 11). Both sprayers had the lowest PMCs at the 301 to 400-foot distance zone (MFT: 31.3 $\mu g/m^3$; AFA: 112.1 $\mu g/m^3$). The control period was associated with lower PMCs than either of the sprayers at all distance zones (11.2 [8.1] $\mu g/m^3$). PMCs were greater at all distance zones for the AFA sprayer (112.1 – 223.4 $\mu g/m^3$) than the MFT sprayer (31.3-66.2 $\mu g/m^3$). Separating out distance zone PMCs by height showed clearer exponential decay trends, particularly for PMCs below the canopy (Figure 32 - Figure 33, Table 12 - Table 13).

Inferential Statistics

Table 14 lists the results from our 75th quantile regression for PMC. Adjusting for wind speed and sampler height, the 75th percentile for PMC was 105.8 $\mu g/m^3$ greater for the AFA sprayer than the control period. Adjusting for wind speed and sampler height, the 75th percentile for PMC was 25.6 $\mu g/m^3$ greater for the MFT than the control period. Adjusting for sprayer type and sampler height, the 75th percentile for PMC decreased by 1.2 $\mu g/m^3$ whenever wind speeds increased by 1 PMH. Adjusting for wind speed and sprayer type, the 75th percentile for PMC was 11.6 $\mu g/m^3$ greater below the canopy than above the canopy. Thus, we reject the null hypothesis that there is no difference between the PMCs associated with each sprayer, and conclude that the MFT sprayer was associated with significantly less PMCs than the AFA sprayer (MFT 95% CI: 21.0, 30.2 $\mu g/m^3$; AFA 95% CI: 84.1,127.5 $\mu g/m^3$). Furthermore, we reject the null hypothesis that there is no difference in the PMCs below and above the canopy, and conclude that PMCs were significantly higher below the canopy (95% CI: 6.8, 16.5 $\mu g/m^3$).

Table 15 lists the results from our 75th quantile, restricted analysis on spray periods. Adjusting for wind speed, sampler height and sprayer type, the 75th percentile for PMC decreased by 0.1 $\mu g/m^3$ for every additional foot our samplers were from the moving sprayer. Adjusting for wind speed, sampler height and distance, the 75th percentile for PMC was 77.4 $\mu g/m^3$ lower for the MFT than the AFA sprayer. Adjusting for sprayer type, sampler height and distance from the sprayer, the 75th percentile for PMC decreased by

4.3 μg/m^3 whenever wind speeds increased by 1 MPH. Adjusting for sprayer type, wind speed and distance, the 75th percentile for PMC was 33.3 μg/m^3 higher below the canopy than above the canopy. Thus, we reject the null hypothesis and conclude that the 75th quantile for PMC was significantly lower at greater distances (95% CI: -0.2, -0.1 μg/m^3).

Aim 2: Drift Over Time

Descriptive Statistics

We used the data from the Dylos sampler in the middle of the field above the canopy (Sampler C in Figure 9) to plot spray events of PMC over time with distance zone and wind speed labels (Figure 34, Appendix II). In general, we saw higher PMCs when either technology was spraying when compared to the control period. Control periods often had lower PMC values and patterns were flatter than spray periods. While we did not have enough time resolution to determine whether the PMC patterns over time differed for the two sprayers, the AFA was typically associated with higher and sharper peaks than the MFT sprayer, while the MFT sprayer more closely resembled control period's flat PMC pattern over time. Often, PMCs increased after the first minute. Figure 31 illustrates these findings.

Shorter distances were sometimes associated with greater PMCs, but not always. Similarly, greater wind speeds were only sometimes associated with greater PMCs. Peaks seemed to be slightly more influenced by wind speed than tractor distance, which is also supported by our 75th quantile regression coefficient estimates.

Results Tables

Table 5. Sample Sizes

Samples	Size
Spray Events per Technology	16
Spray Event Duration, mean (SD)	7 min (0.6)
One-Minute Control Samples	849
One-Minute MFT Samples	1071
One-Minute AFA Samples	1028
Total One-Minute Samples	**2948**

Since we were one sampler short during our first spray day, nine samplers collected data during one quarter of the spray events and ten samplers collected data during three quarters of the spray events. We thus initially had around 1092 minute samples per technology (16 sprays/tech*7 min/spray *9.75 samplers), and around 1170 minute samples for the control periods (15 min/period * 2 periods/day * 4 days). Data that did not meet our inclusion criteria, as described earlier in our methods, were not included in our analyses, thus resulting in our final values. In general, both sprayers had the same number of spray events, each with similar time durations. We had a similar number of one-minute samples for the control period and both sprayers.

Table 6. Weather Station Comparison

Meteorology	Median	IQR
Temperature (˚F)		
Permanent	66.6	5.0
Temporary	61.9	5.2
RH %		
Permanent	41.3	7.1
Temporary	49.0	9.0
Wind Speed (MPH)		
Permanent	7.7	2.4
Temporary	8.6	3.1
Wind Direction		
Permanent	N	N, N
Temporary	NW	NW, N

Our temporary weather station had lower temperature readings and higher relative humidity readings than WSU’s permanent weather station. Wind speeds and wind directions were similar between both sprayers though our temporary station had greater variability.

Table 7. Average Historical and Study Meteorological Conditions for Rock Island, WA

Meteorology	Historical		Study			
	June	September	Overall	MFT	AFA	Control
Mean Temperature (˚F)	65	61	62	62	62	62
Wind Speed (MPH)	10	8	8.6	8.8	8.7	7.8
Wind Direction	NW	W	NW	NW	NNW	NW
Relative Humidity (%)	54	71	50	49	50	50

The average overall meteorological conditions during our study were within the normal range for Rock Island, WA during June and September (MyForecast, 2016). Meteorological conditions were similar for both sprayers and the control period.

Table 8. Overall PMC (µg/m^3)

Sprayer	75th	IQR
Control	11.2	8.1
MFT	38.6	34.5
AFA	117.0	112.8

The AFA sprayer was associated with the greatest amount of PMC, followed by the MFT sprayer and the control period.

Table 9. PMC (µg/m^3) Above and Below the Canopy

Height	Sprayer	75th	IQR
Above	Control	9.6	6.9
Above	MFT	27.9	24.5
Above	AFA	86.3	80.3
Below	Control	13.1	9.4
Below	MFT	49.5	44.2
Below	AFA	188.0	178.3

Greater PMC was seen below the canopy than above the canopy for both sprayers and the control period.

Table 10. PMC Over Distance Zones (μg/m^3) – Above and Below the Canopy

Sprayer	Control	100 ft	200 ft	300 ft	400 ft
Control	11.2 (8.1)	-	-	-	-
MFT	-	55.9 (46.1)	66.2 (60.7)	36.0 (31.8)	31.3 (27.9)
AFA	-	223.4 (207.6)	118.0 (110.0)	114.8 (106.0)	112.1 (104.4)

PMC estimates represent the 75th percentile for PMCs (IQR) at each distance zone. The control period was associated with lower PMCs than either sprayers at any distance zone. The AFA sprayer was associated with the greatest PMCs at the 100-foot distance zone, while the MFT sprayer was associated with the greatest PMCs at the 200-foot distance zone. The lowest PMCs for both sprayers were seen at the 400-foot zone.

Table 11. Sample Size per Distance Zone – Above and Below the Canopy

Sprayer	Control	100 ft	200 ft	300 ft	400 ft	**Total**
Control	1181	-	-	-	-	
MFT	-	48	191	349	301	**889**
AFA	-	38	174	353	313	**878**
Total	**1181**	**86**	**365**	**702**	**614**	**2948**

Most samples were taken in the 300-foot zone, followed by the 400, 200 and 100-foot zone.

Table 12. PMC Over Distance Zones (μg/m^3) – Above the Canopy

Sprayer	Control	100 ft	200 ft	300 ft	400 ft
Control	9.6 (8.5)	-	-	-	-
MFT	-	35.5 (31.5)	40.3 (35.8)	29.2 (25.9)	26.0 (22.9)
AFA	-	223.4 (143.1)	118.0 (100.0)	86.3 (78.7)	84.7 (79.0)

The 75th percentile PMC (IQR) for samplers above the canopy at each distance zone. The AFA sprayer was associated with the greatest PMCs at the 100-foot distance zone, while the MFT sprayer was associated with the greatest PMCs at the 200-foot distance zone. The lowest PMCs for both sprayers were seen at the 400-foot zone.

Table 13. PMC Over Distance Zones (μg/m^3) – Below the Canopy

Sprayer	Control	100 ft	200 ft	300 ft	400 ft
Control	13.1 (7.5)	-	-	-	-
MFT	-	167.5 (151.9)	83.1 (75.5)	42.4 (37.1)	39.1 (35.4)
AFA	-	866.3 (841.7)	246.0 (233.0)	190.3 (179.4)	150.3 (141.3)

The 75th percentile PMC (IQR) for samplers below the canopy at each distance zone. Both sprayers were associated with the greatest PMCs at the 100-foot distance zone and lowest PMCs at the 400-foot zone.

Table 14: 75th Quantile Regression

$$Q_{Y|X}(\tau = 0.75) = 17.7 + 105.8\beta_{\tau_{AFA}} + 25.6\beta_{\tau_{MFT}} - 1.2\beta_{\tau_{wind\ speed}} + 11.6\beta_{\tau_{below\ canopy}}$$

Covariates	Coefficients	95% Confidence Interval
(intercept)	17.7*	12.3 – 23.2
AFA	105.8*	84.1 – 127.5
MFT	25.6*	21.0 – 30.2
Wind Speed (MPH)	-1.2*	-1.7 – -0.7
Height (Below)	11.6*	6.8 – 16.5

Values are in µg/m^3. All Coefficients were significant contributors to the model (*).

Table 15: Restricted Analysis of Spray Periods

$$Q_{Y|X}(\tau = 0.75) = 190.1 - 75.5\beta_{\tau_{MFT}} - 4.6\beta_{\tau_{wind\ speed}} + 31.5\beta_{\tau_{below\ canopy}} - 0.1\beta_{\tau_{distance}}$$

Covariates	Coefficients	95% Confidence Interval
(intercept)	188.1*	154.8 – 221.5
MFT	-77.4*	-100.1 – -54.6
Wind Speed (MPH)	-4.3*	-5.5 – -3.1
Height (below)	33.3*	18.5 – 48.1
Distance (ft)	-0.2*	-0.2 – -0.1

Values are in µg/m^3. All Coefficients were significant contributors to the model (*).
Note: this restricted analysis of the spray periods drops the control periods.

Results Figures

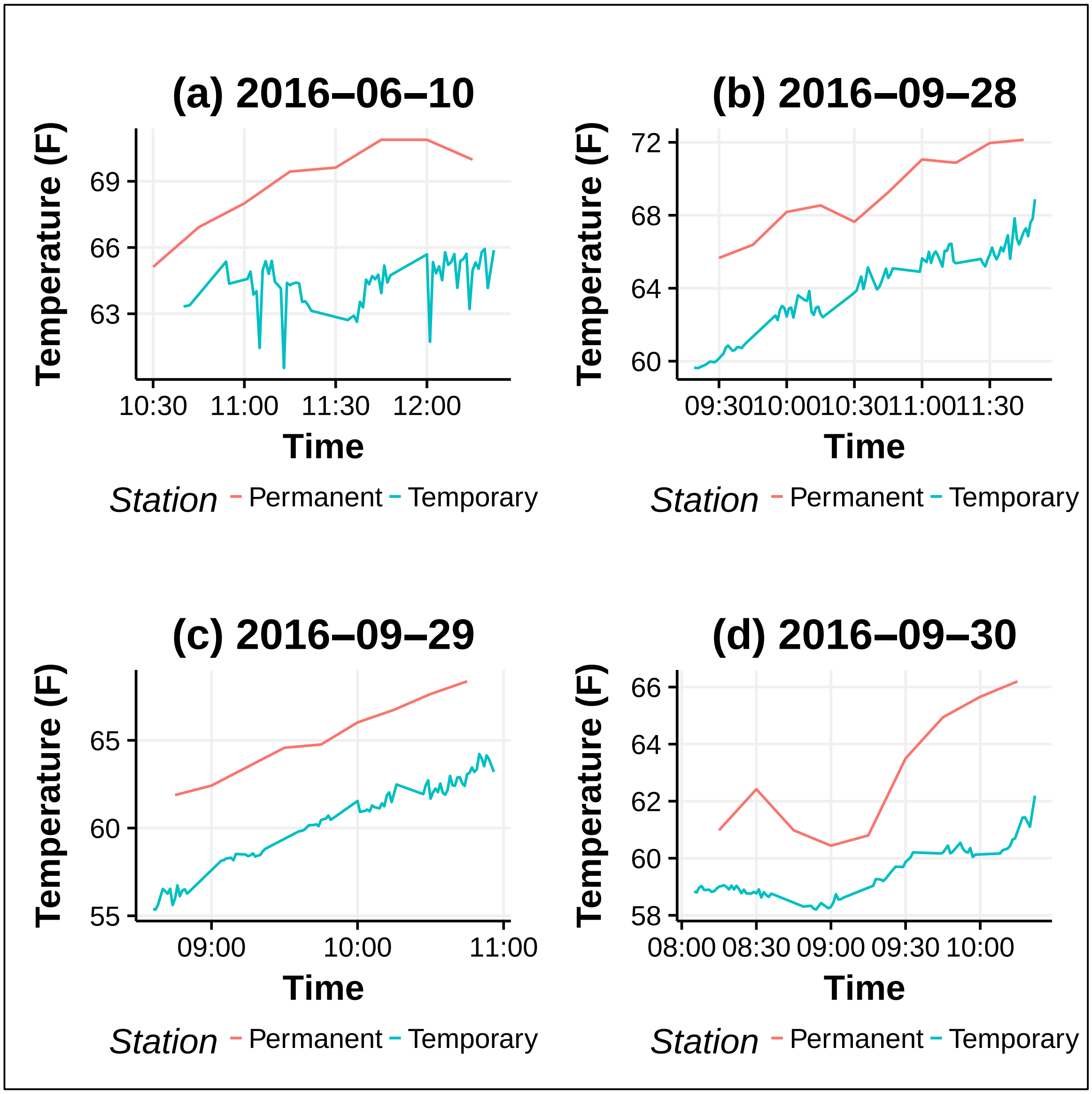


Figure 17. Weather Station Comparison - Temperature Over Time

Our temporary weather station had consistently lower temperature readings than WSU’s permanent weather station.

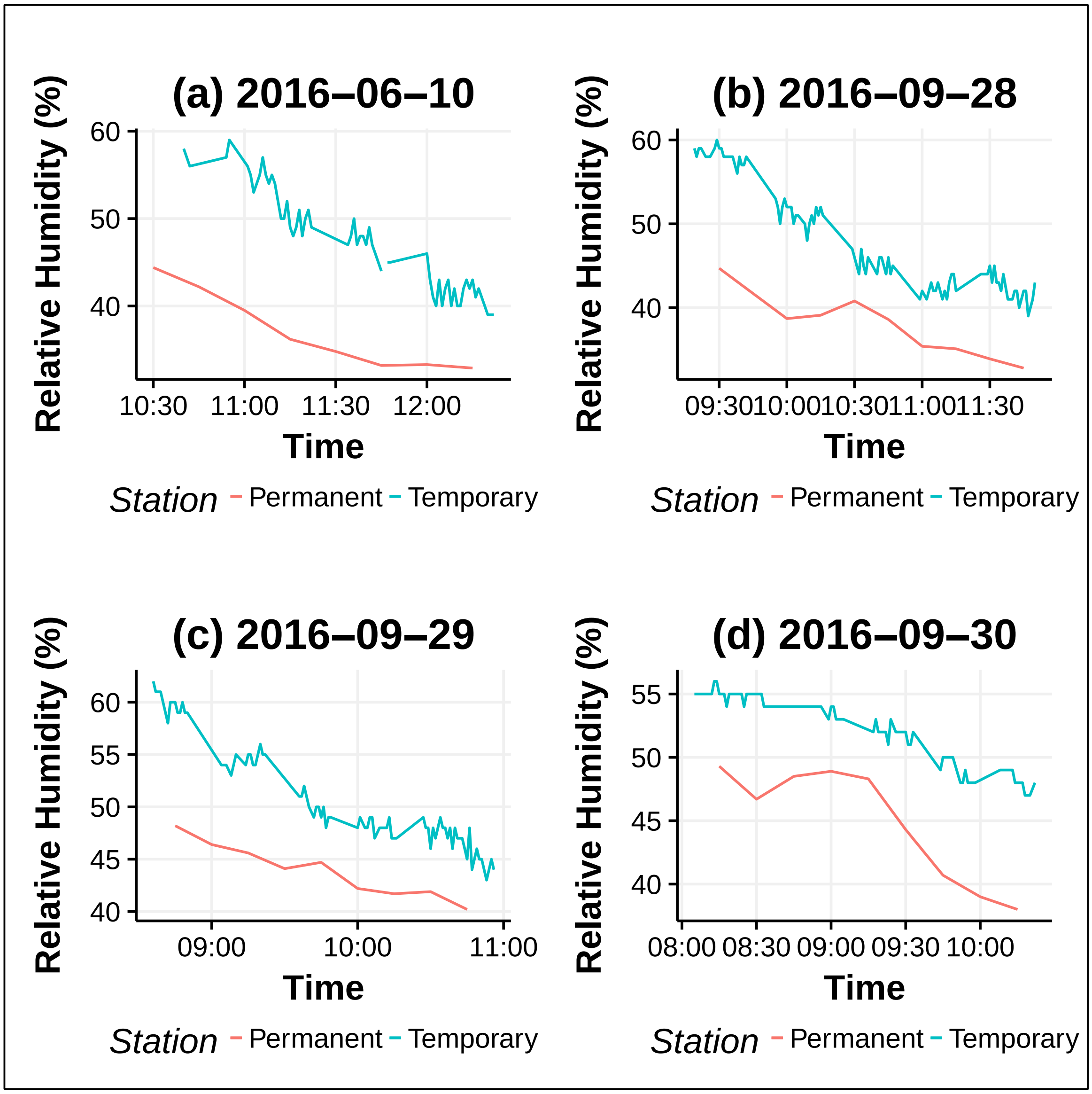


Figure 18. Weather Station Comparison - Relative Humidity Over Time

Our temporary weather station had consistently higher relative humidity readings than WSU's permanent weather station.

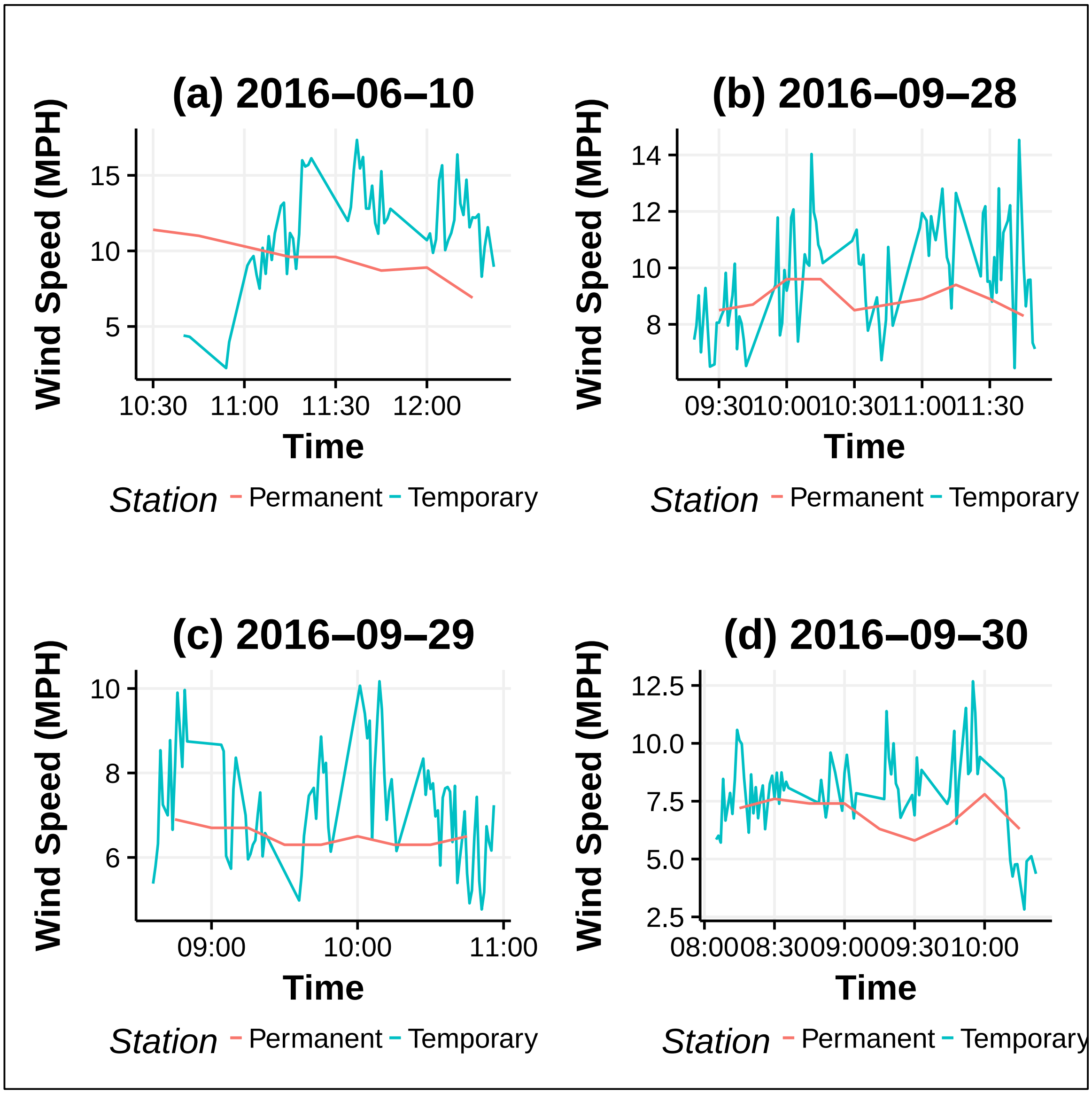
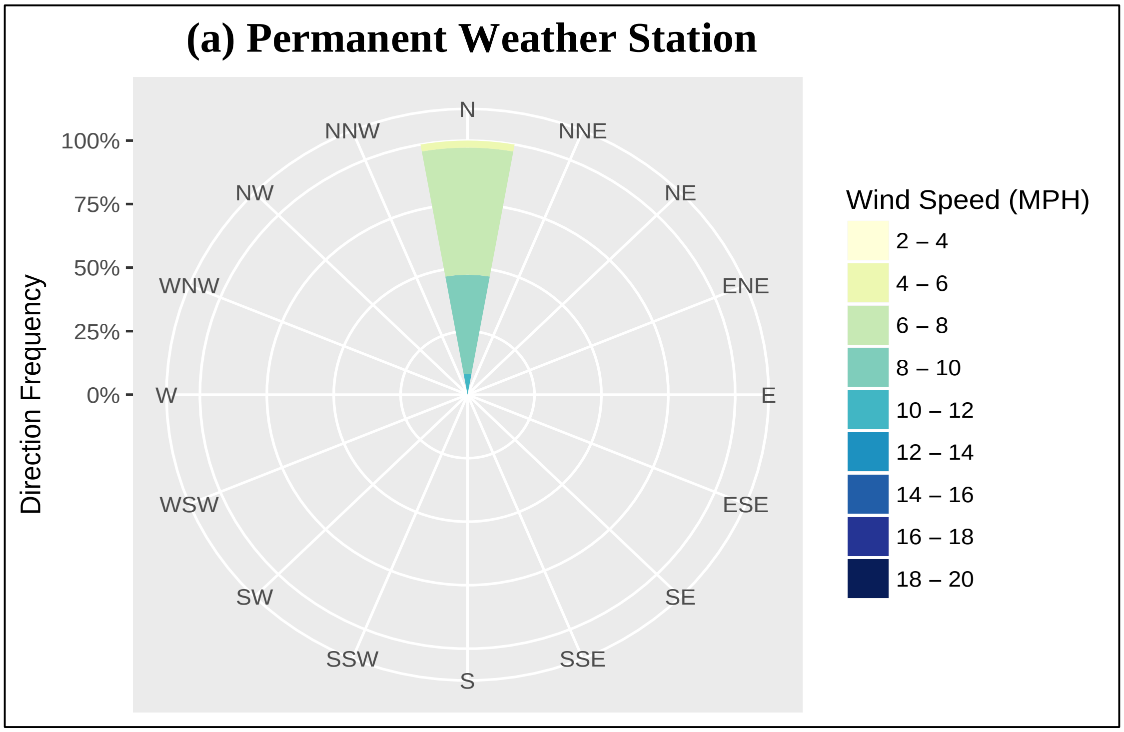


Figure 19. Weather Station Comparison - Wind Speed Over Time

Our temporary weather station had on average similar wind speed readings than WSU's permanent weather station.



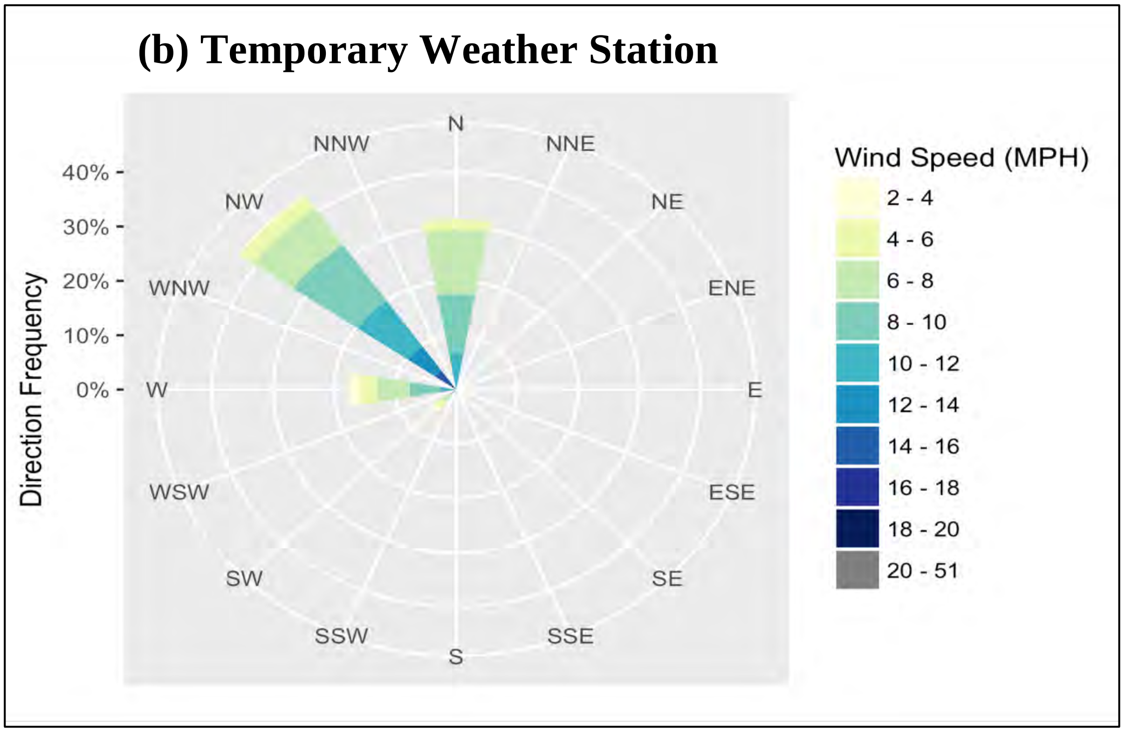
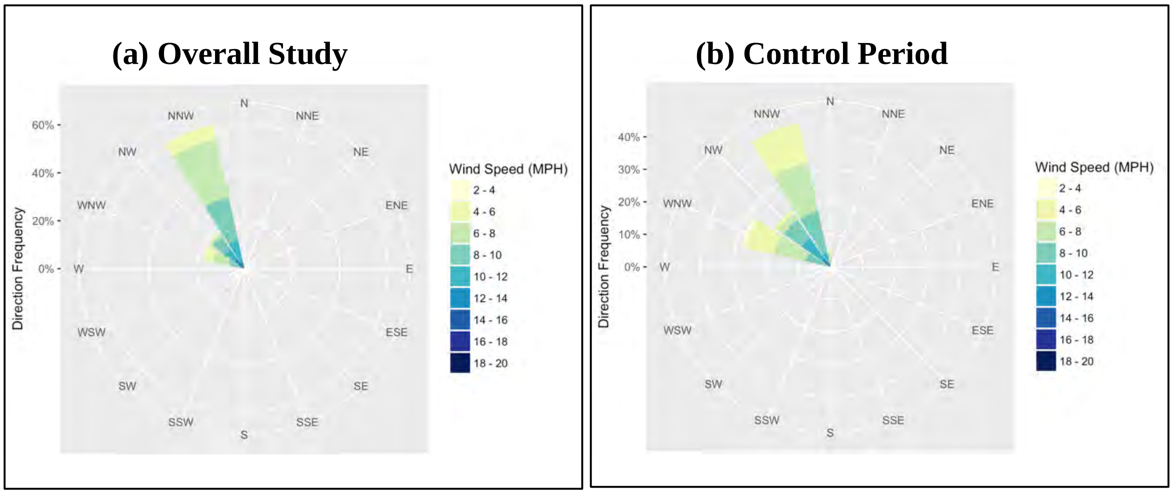
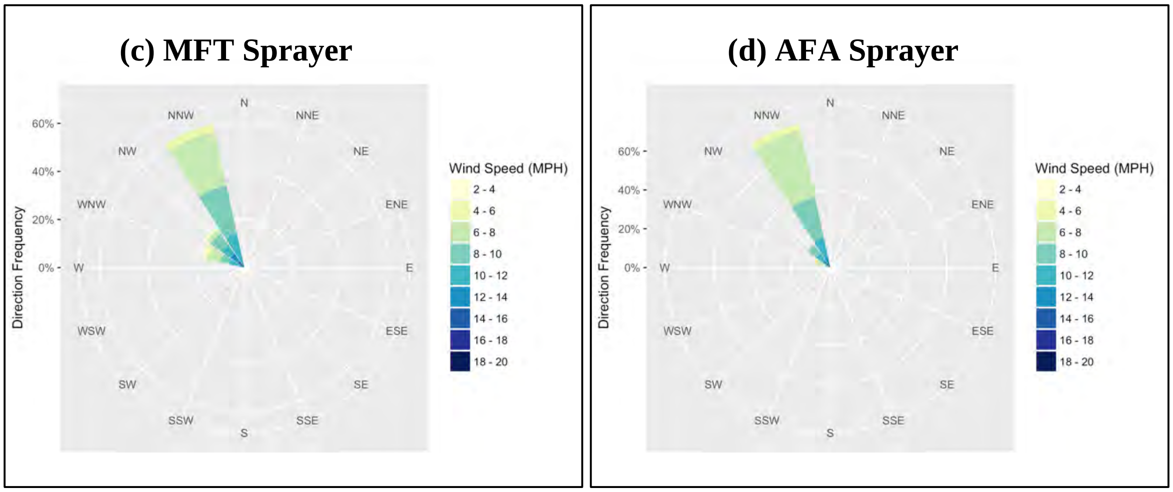


Figure 20. Weather Station Comparison - Wind Speed and Direction

Our temporary weather station had more wind speed and wind direction variability than WSU's permanent weather station. For better comparison to the permanent station's wind data resolution, all wind data within a spray day was included in this plot and degrees were converted to eight principal points of direction instead of sixteen (45˚ vs 22.5˚ increments). Figure 21a, on the other hand, reflects only the wind conditions of the final data that was used and expresses wind in sixteen principal points of direction.


(a) Overall Study

(b) Control Period


(c) MFT Sprayer

(d) AFA Sprayer

Figure 21. Wind Roses for the Study Period

Wind mostly blew from the NNW at 6-10 MPH for the (a) overall study, (b) control period, (c) MFT sprayer and (d) AFA sprayer.

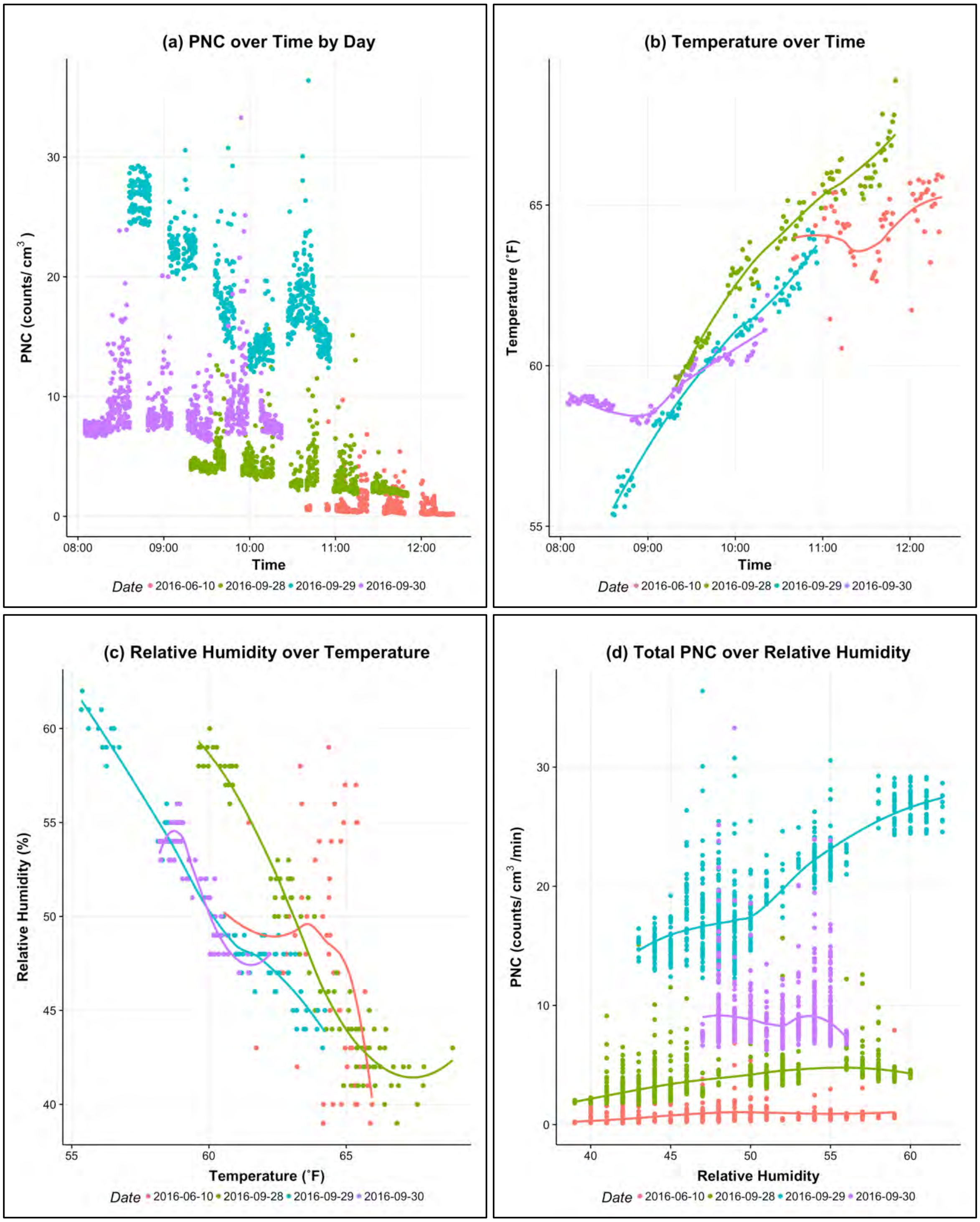


Figure 22. Justification for PNC Adjustments

(a) There were greater PNCs at beginning of every spray day than at the end of every spray day during the control periods, making it necessary to adjust and level off the baselines of every spray day before comparing the PMCs associated with each sprayer. "Baselines", or ambient PM, during each sample day can be estimated by tracing the lower values of every minute. (b) Temperatures generally increase with time. (c) Relative humidity generally decreases as temperature increases. (d) Higher relative humidity is generally associated with greater PNCs, though this relationship varies by day.

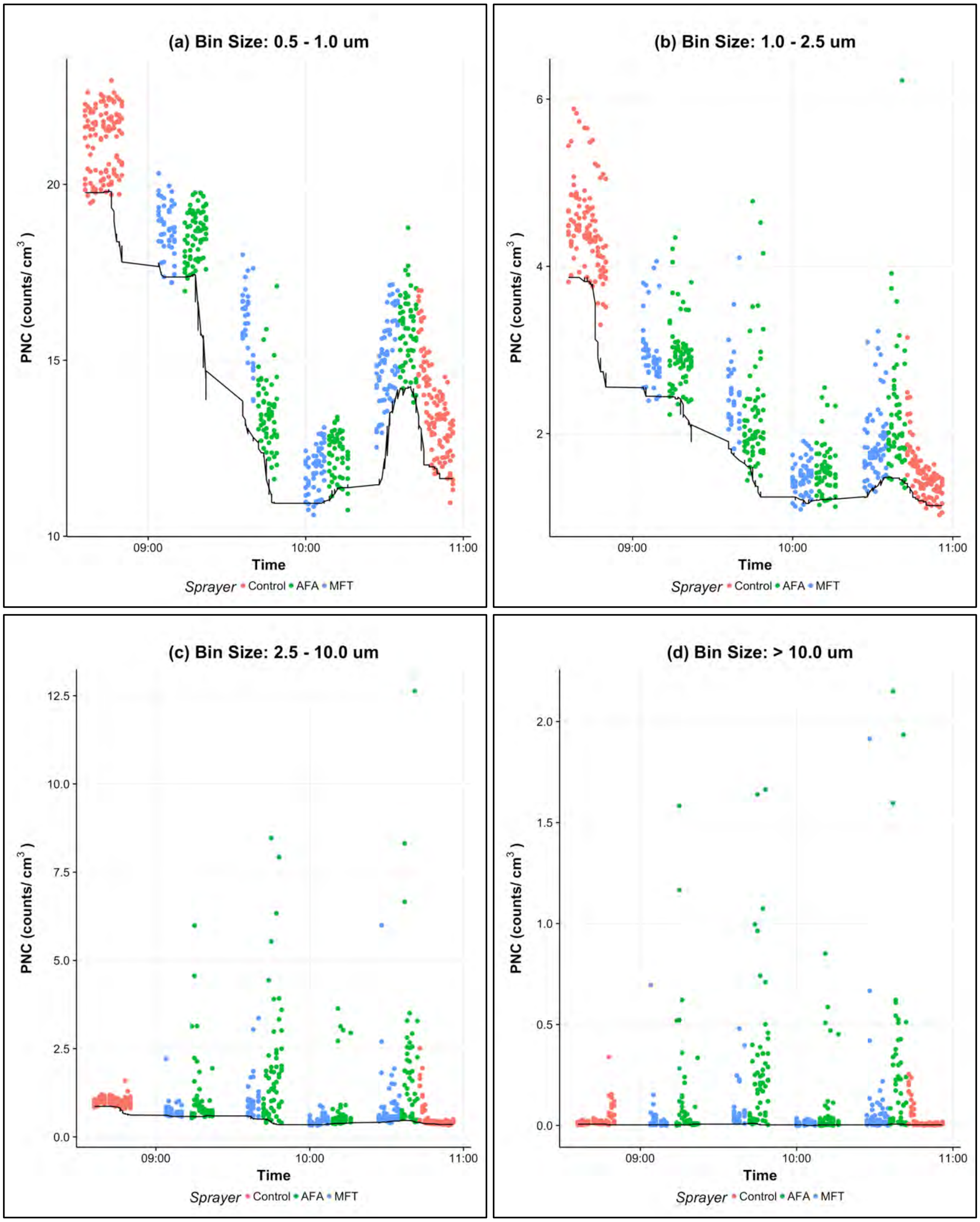


Figure 23. Raw PNC over Time with Calculated Baselines (9/28/16 Example)

To adjust for changing ambient PM levels, we estimated baselines for each day and particle bin size using 8-minute rolling 5th percentile averages.

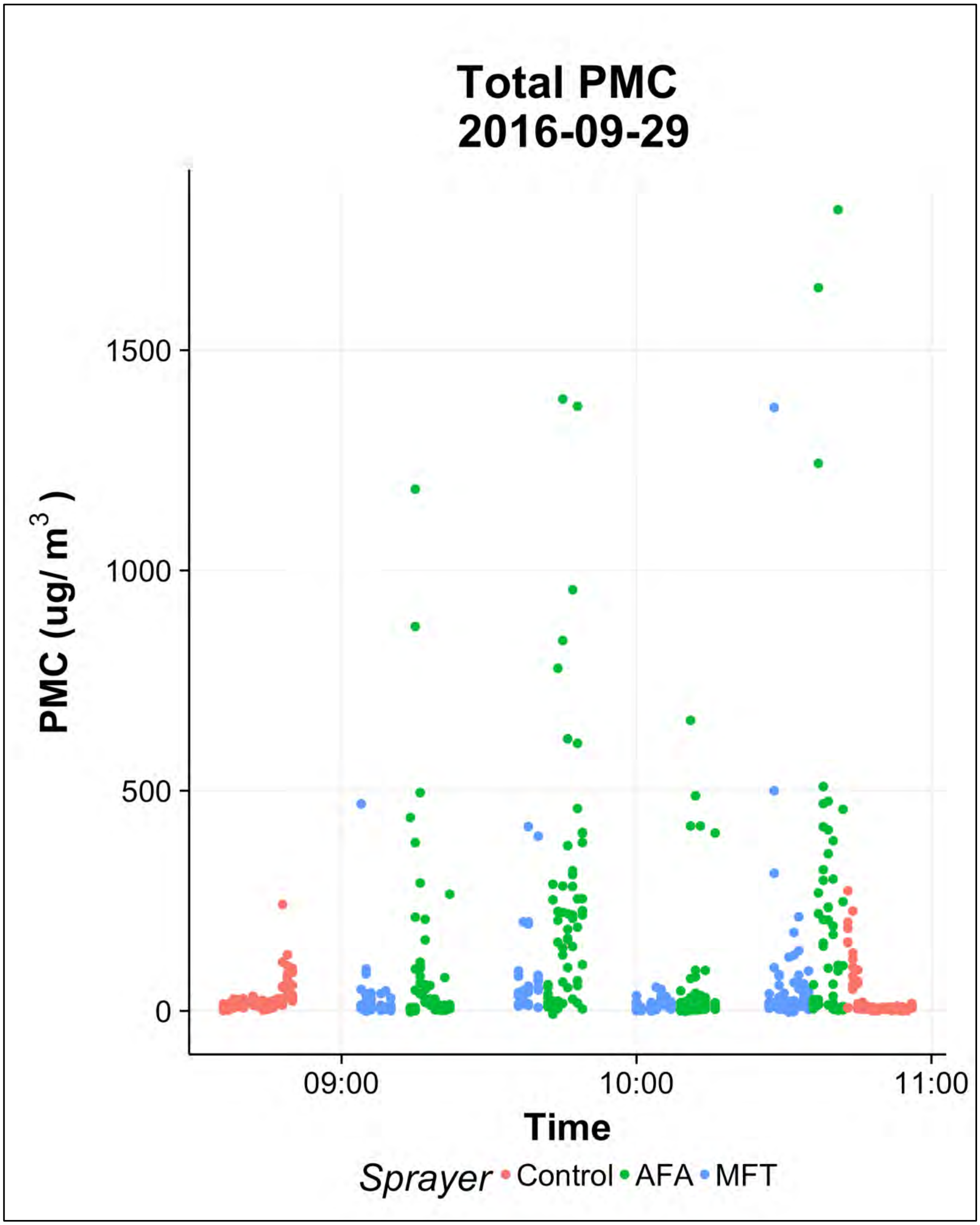


Figure 24. Total PMC Over Time (9/28/16 Example)

Baselines were subtracted from raw PNC values and adjusted PNCs were converted to PMCs for each bin size. All bins were added to calculate total baseline-adjusted PMCs over time for each day (Equation 1).

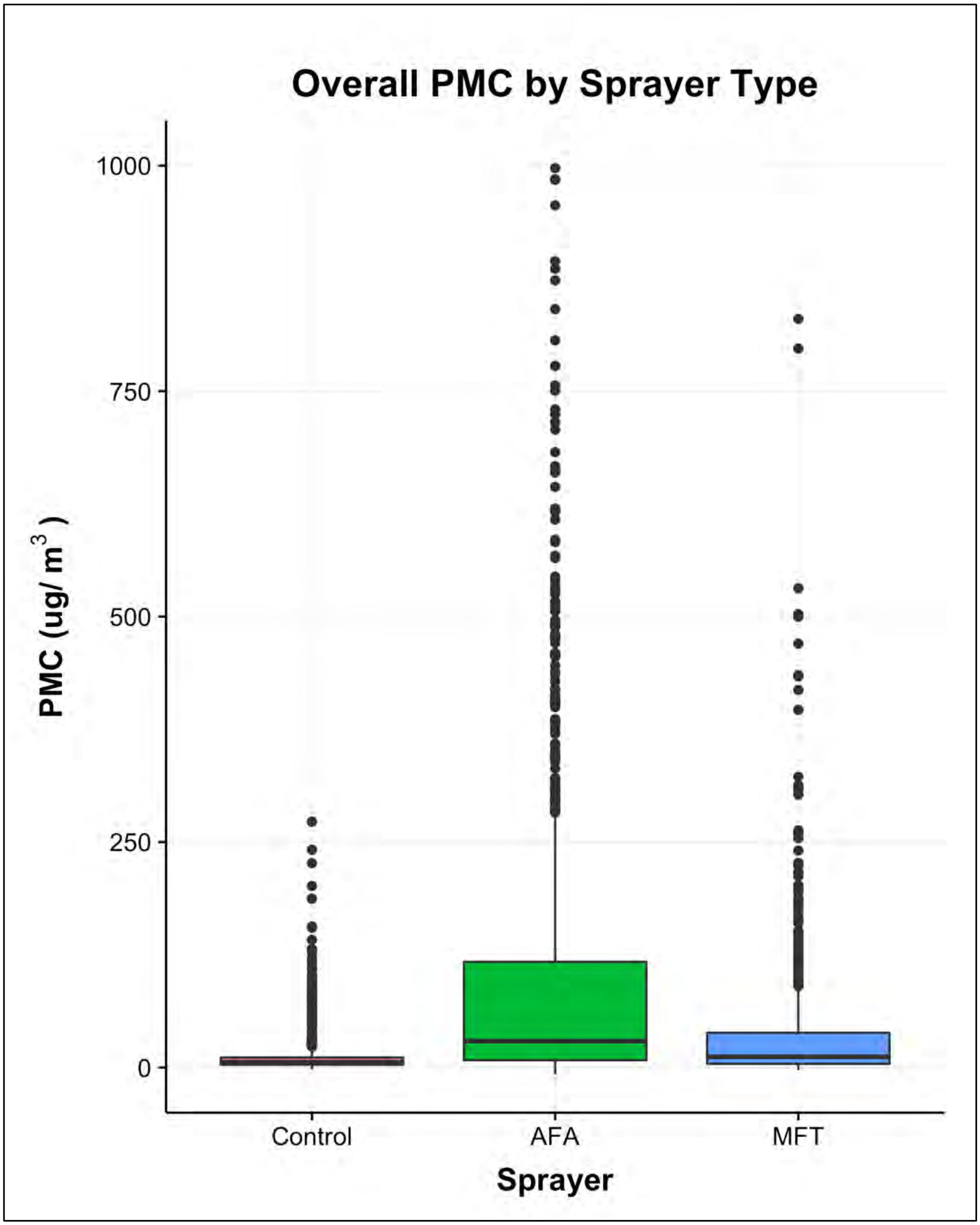


Figure 25. Overall PMC by Sprayer Type

The AFA sprayer was associated with the highest PMCs, followed by the MFT sprayer and the Control period. PMCs greater than 1000 were excluded from this plot (AFA: 1116, 1185, 1243, 1253, 1373, 1389, 1528, 1549, 1642, 1655, 1809, 1819 and 2658 µg/m^3; MFT: 1370 µg/m^3).

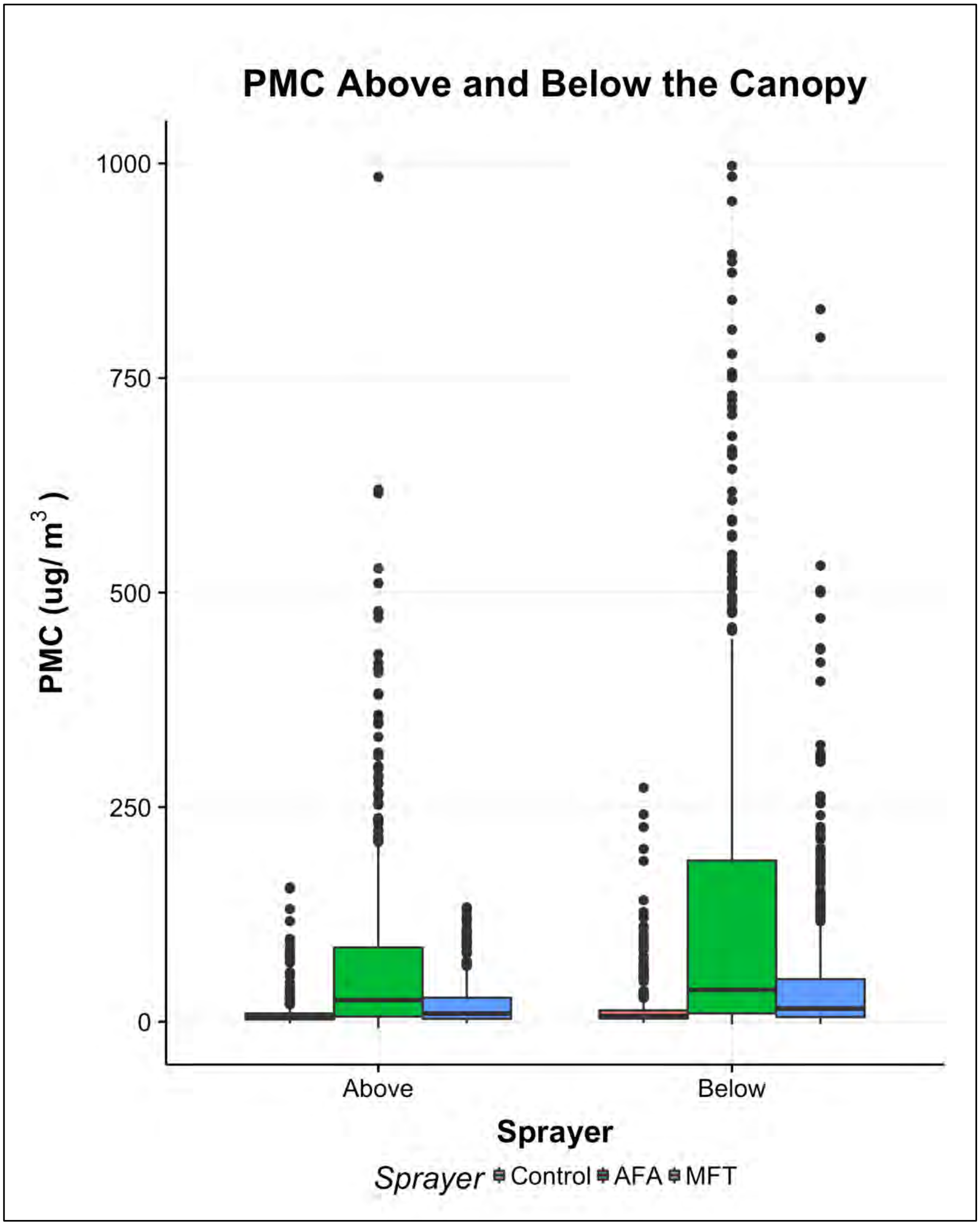


Figure 26. PMC Above and Below the Canopy

Greater PMCs were seen below the canopy than above the canopy for both sprayers and the control period. PMCs greater than 1000 were excluded from this plot (AFA: 1116, 1185, 1243, 1253, 1373, 1389, 1528, 1549, 1642, 1655, 1809, 1819 and 2658 µg/m^3; MFT: 1370 µg/m^3).

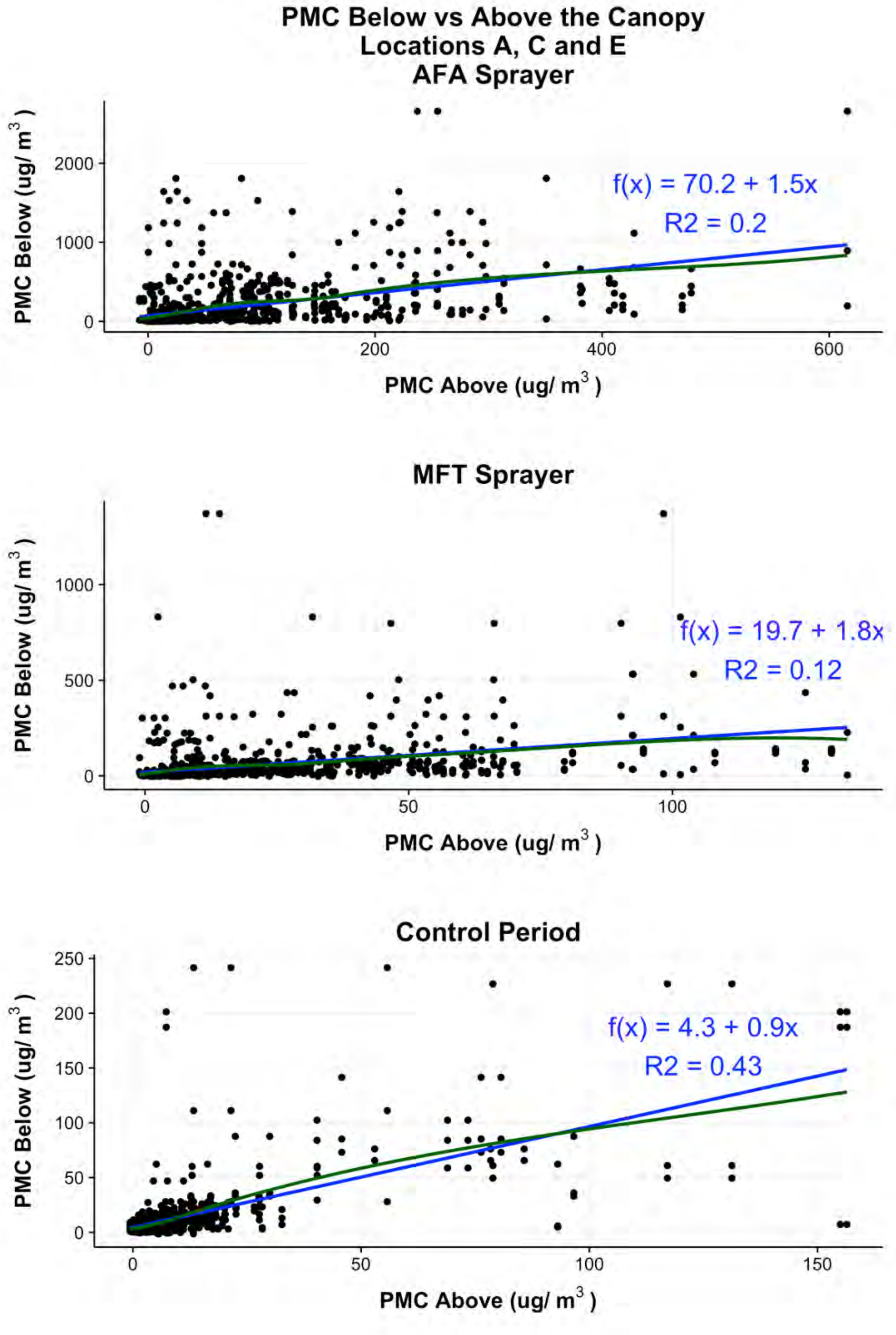


Figure 27. PMC Below vs Above the Canopy

PMCs below and above the canopy at any one time. Only data from samplers A, C and E was used. Both sprayers and the control period had positive relationships between PMCs above and below the canopy. Both sprayers and the control had low coefficient of determination values
(R^2: 0.12 – 0.43).

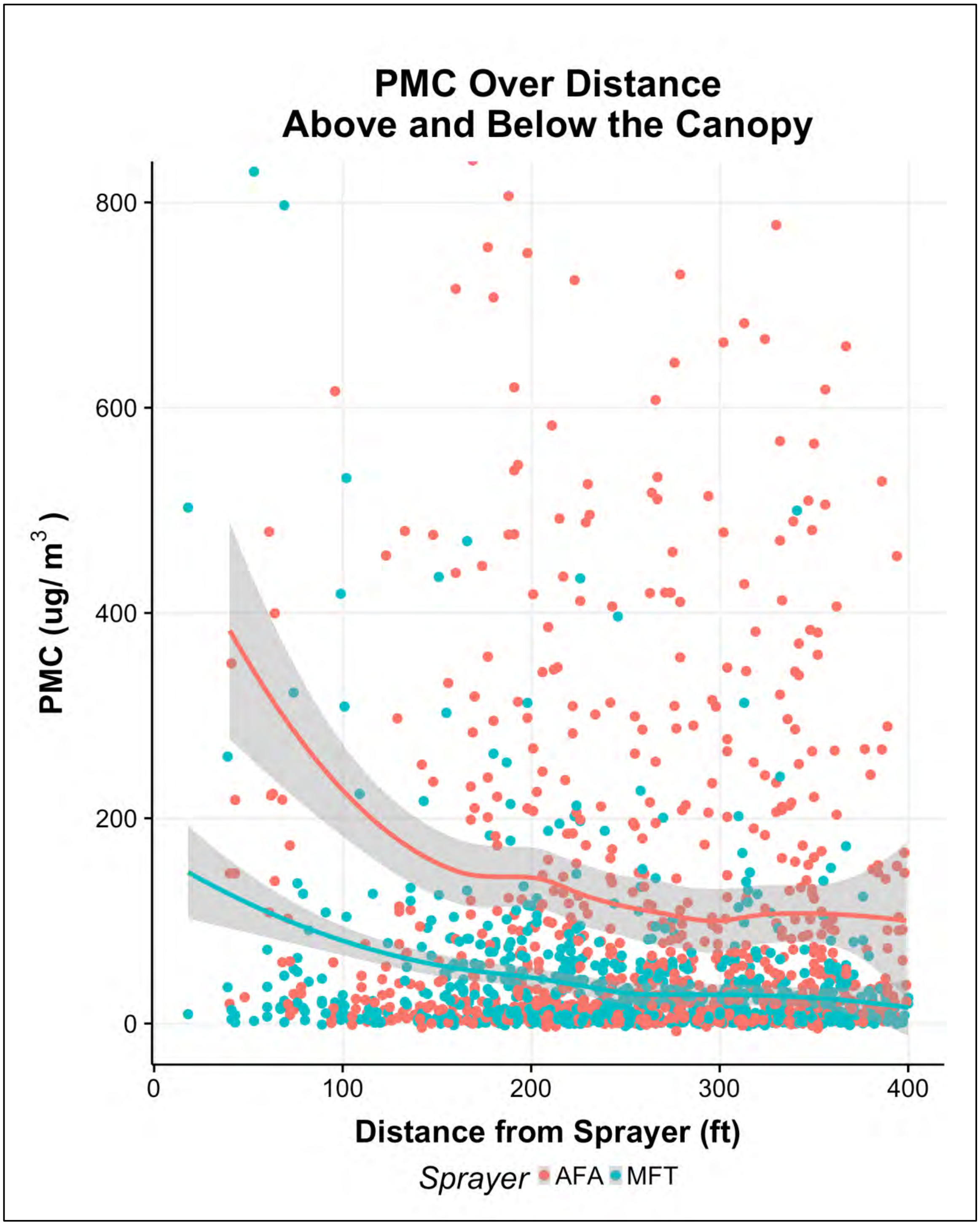


Figure 28. PMC over Distance – Above and Below the Canopy

Scatterplot of decreasing PMCs with increasing distance from a moving sprayer. Loess lines with 95% confidence intervals were added. Distance is defined as the measured value from a moving sprayer source to a stationary sampler. Data from samplers below and above the canopy (2 and 6 m) were used. Some values were excluded from in this plot (AFA: 22 values ranging from 841 – 2658 $\mu g/m^3$; MFT: 8310 and 1370 $\mu g/m^3$).

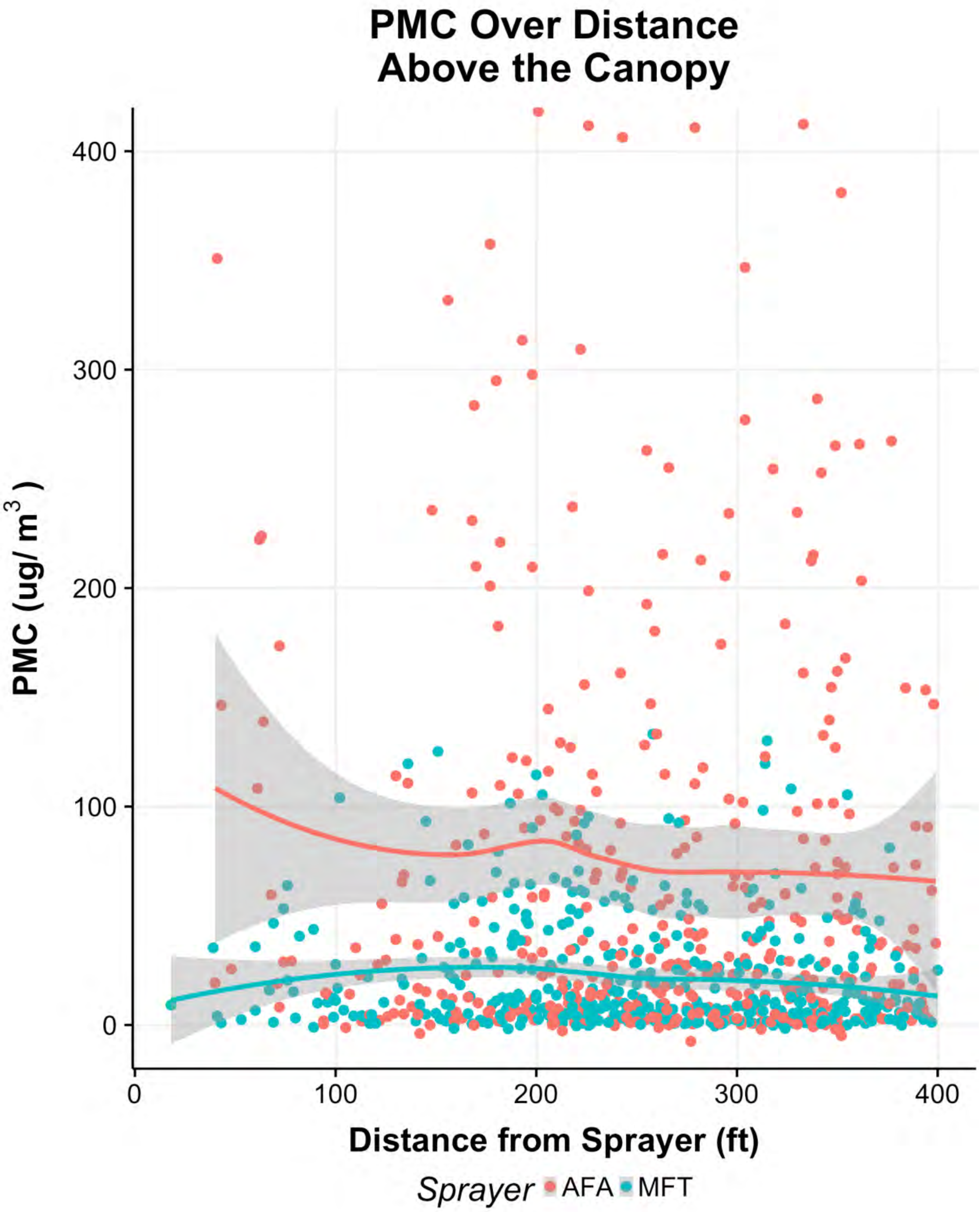


Figure 29. PMC over Distance Above the Canopy

Scatterplot of PMCs over distance from a moving sprayer. Values were measured from samplers above the canopy (6 m). Loess lines with 95% confidence intervals were added. Some values were excluded from in this plot (AFA: 81 values ranging from 411 – 2658 µg/m^3; 10 values ranging from 419-1370 µg/m^3).

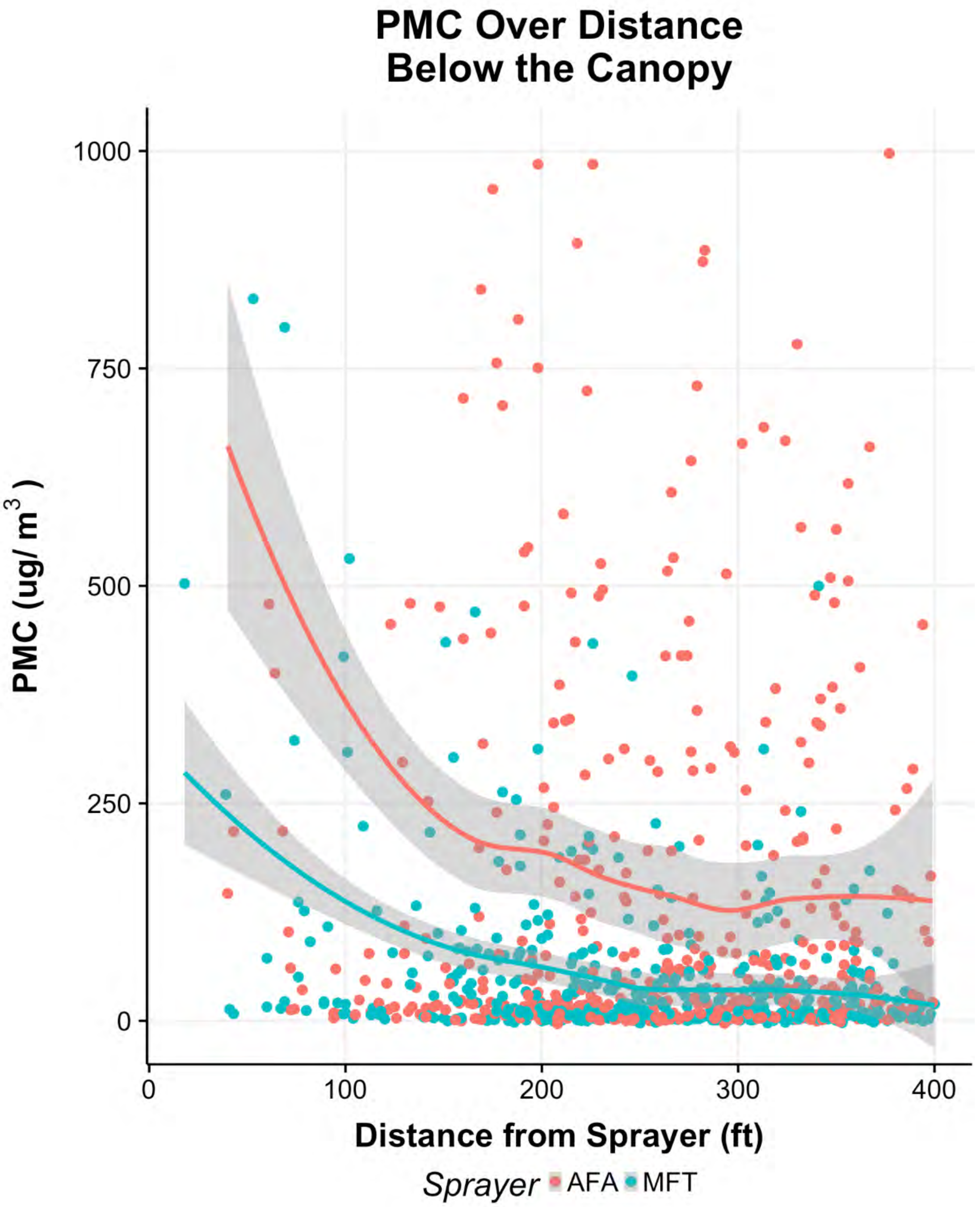


Figure 30. PMC over Distance Below the Canopy

Scatterplot of PMCs over distance from a moving sprayer. Values were measured from samplers below the canopy (2 m). Loess lines with 95% confidence intervals were added. Some values were excluded from in this plot (AFA: 13 values ranging from 1116 - 2658 µg/m^3; MFT: 1370 µg/m^3).

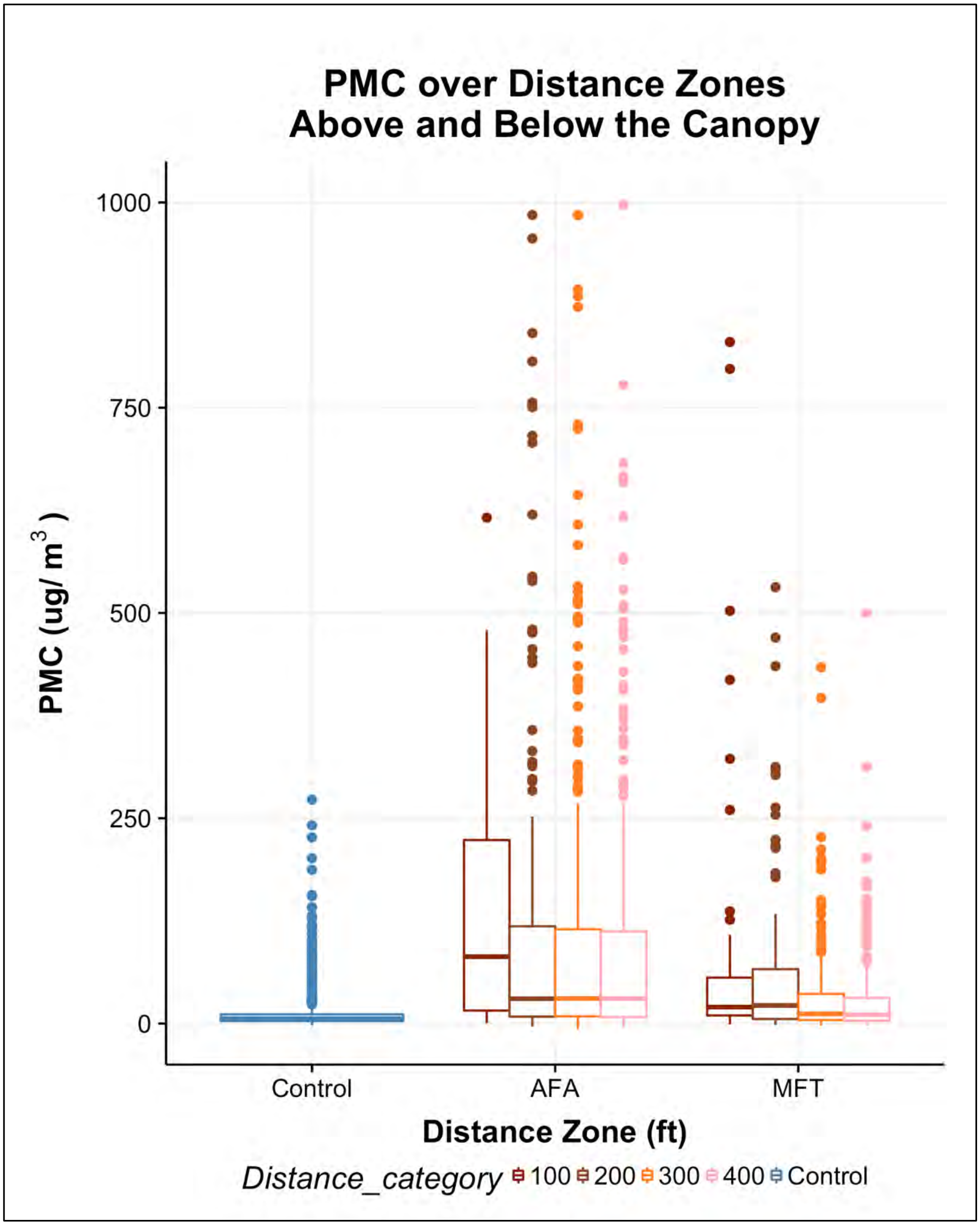


Figure 31. PMC per Sprayer at Various Distance Zones

Distance categories represent 100-foot distance zones. PMCs were greater at all distance zones for both sprayers when compared to the control periods. PMCs generally decreased with increasing distance zones. PMCs greater than 1000 µg/m^3 were excluded from this plot (AFA: 1116, 1185, 1243, 1253, 1373, 1389, 1528, 1549, 1642, 1655, 1809, 1819 and 2658 µg/m^3; MFT: 1370 µg/m^3).

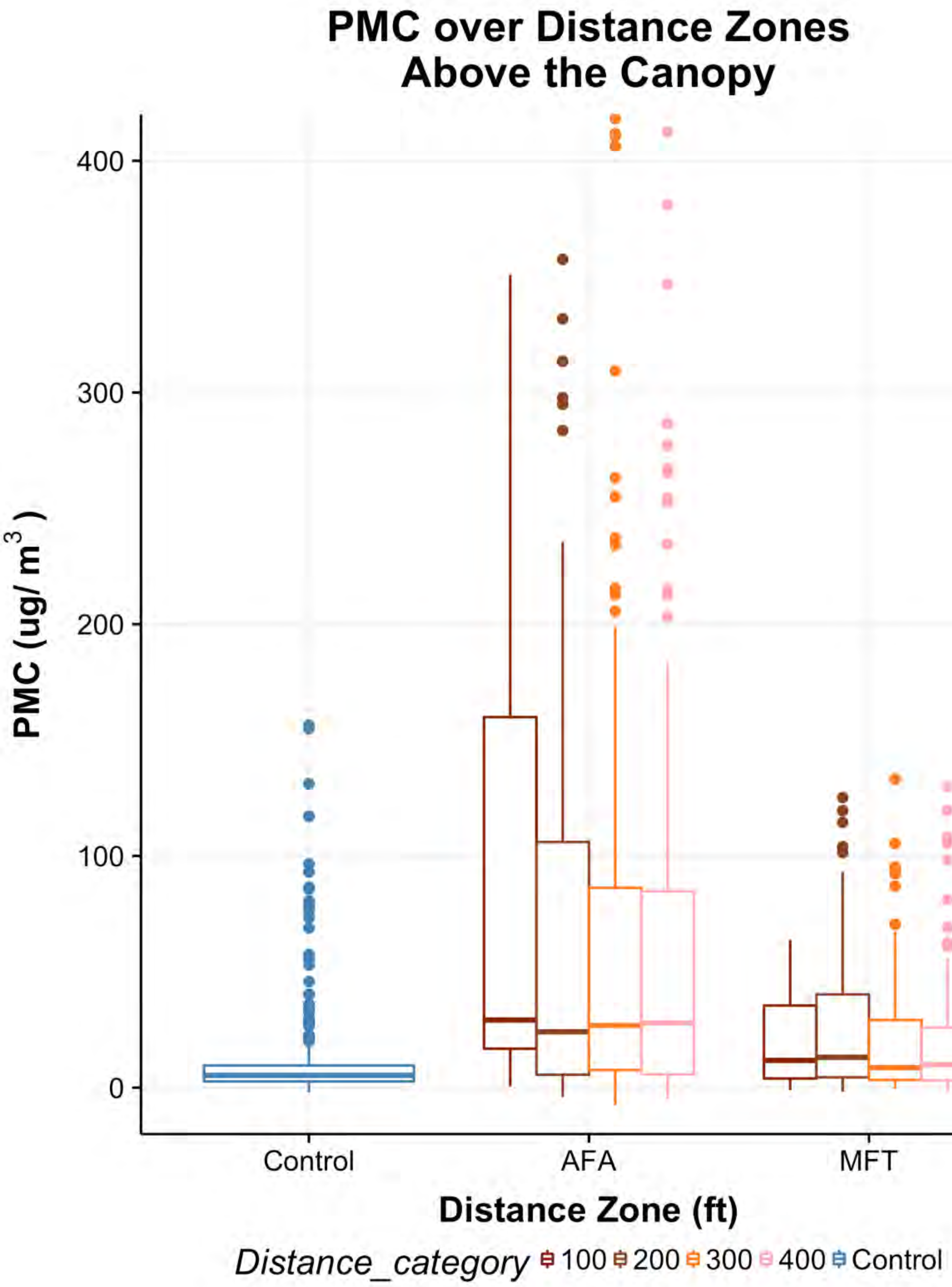


Figure 32. PMC over Distance Zone - Above the Canopy

Distance categories represent 100-foot distance zones. The following PMCs above the canopy for the AFA sprayer were excluded from this plot: 406, 411, 412, 412, 418, 428, 471, 476, 479, 511, 528, 616, 620, and 984 µg/m^3.

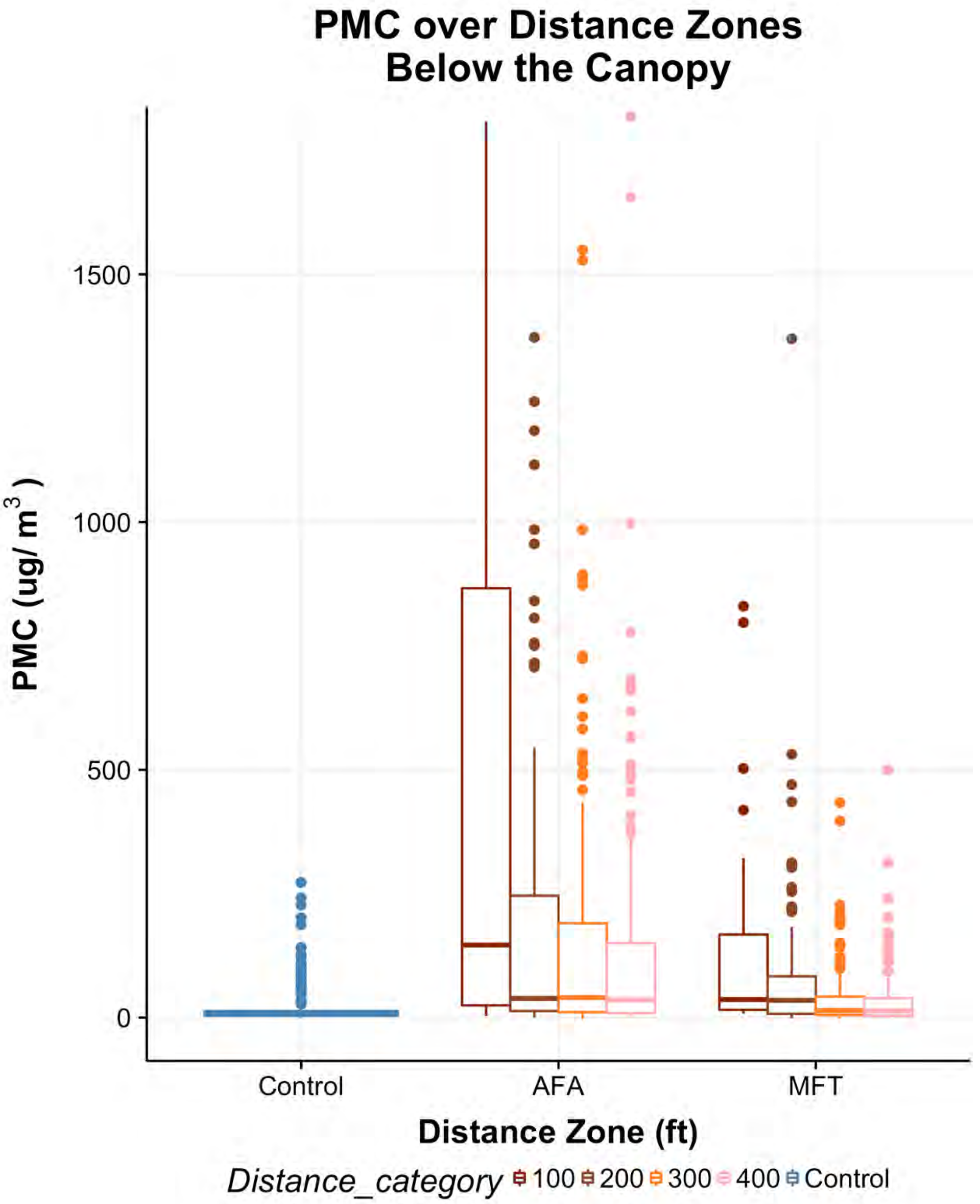
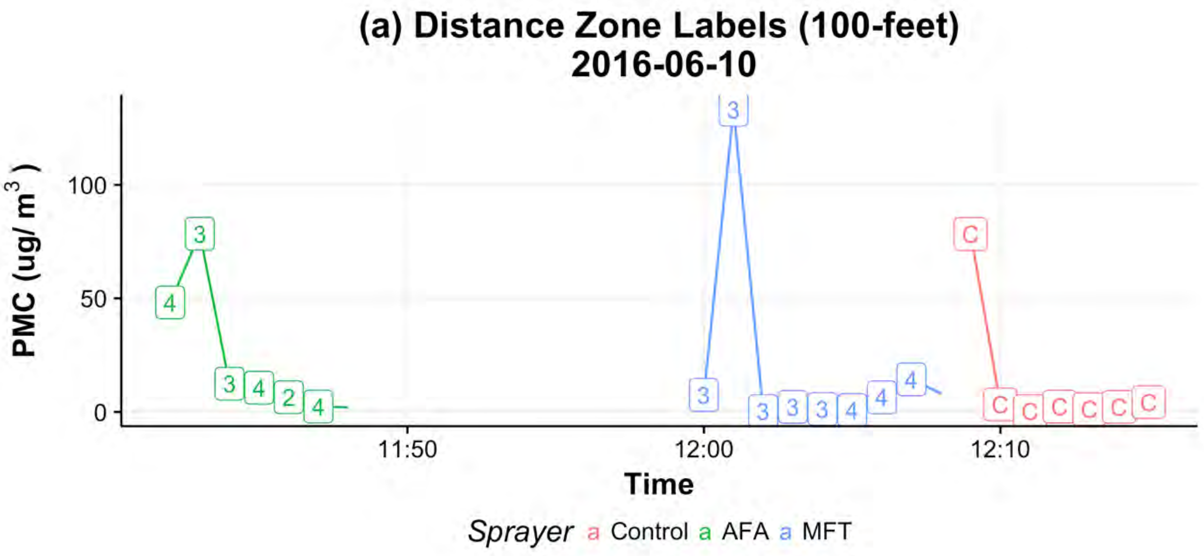


Figure 33. PMC over Distance Zone - Below the Canopy

Distance categories represent 100-foot distance zones. The following PMCs below the canopy for the AFA sprayer were excluded from this plot: 1809, 1819 and 2658 μg/m^3.



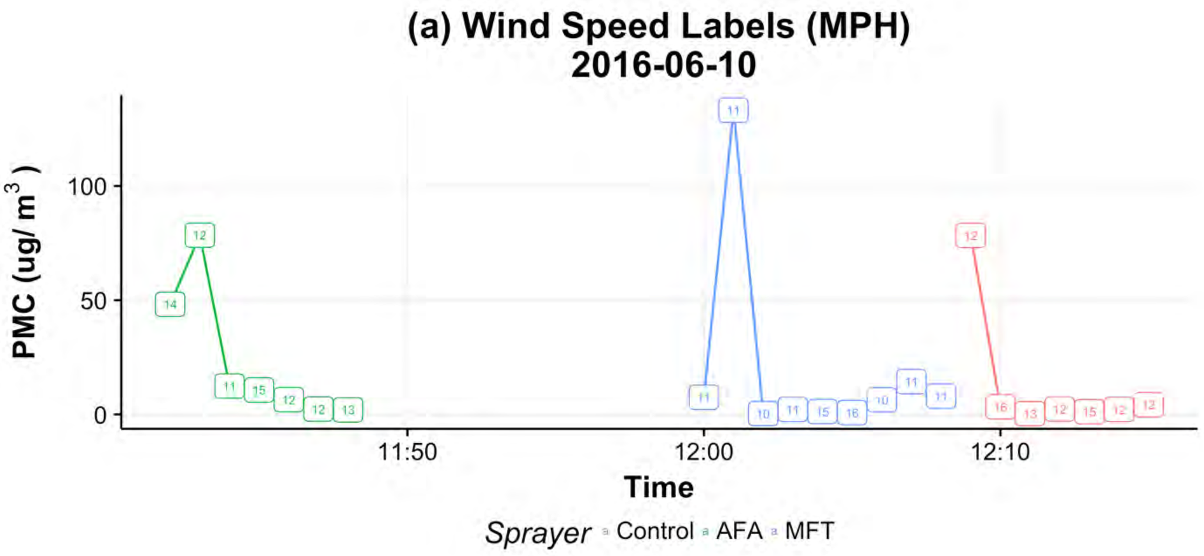
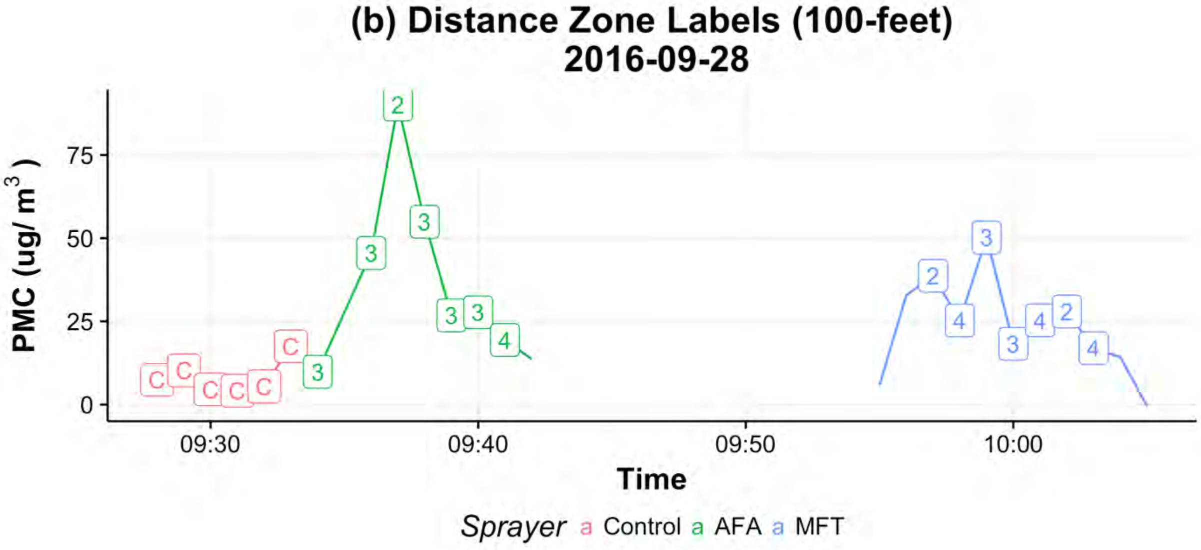


Figure 34. PMC over Time - Distance Zone and Wind Speed Labels

Sample spray events over time with distance zone (100-feet) and wind speed labels (MPH). Distance zones are in 100-foot increments so that labels 1, 2, 3 and 4 represent the 100, 200, 300 and 400-foot distance zone respectively. For more plots see Appendix II: PMC over Time with Distance Zone and Wind Speed Labels.



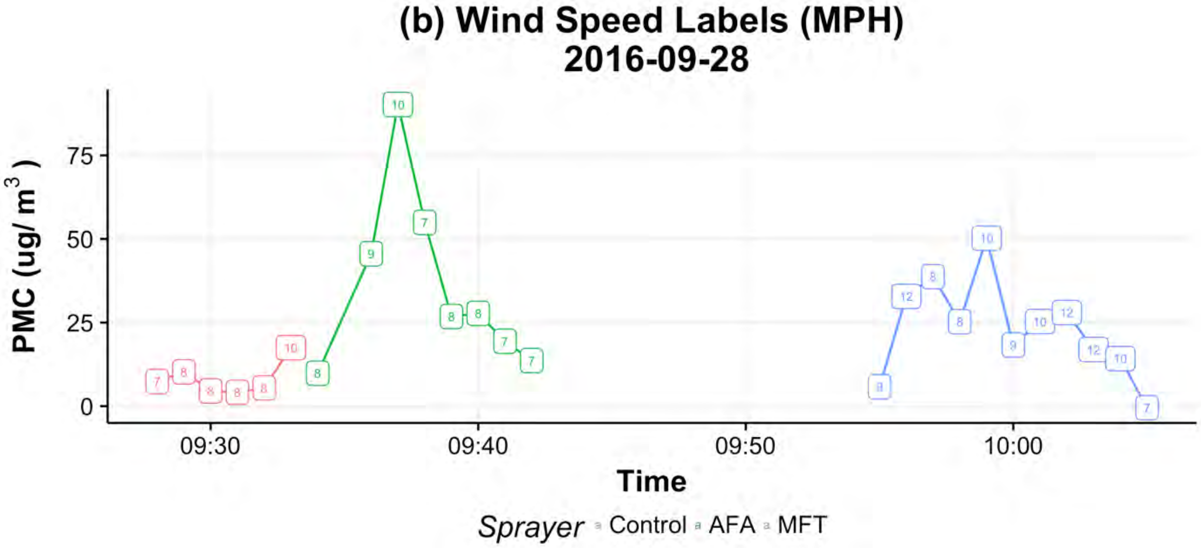


Figure 34. PMC over Time - Distance Zone and Wind Speed Labels (Continued)

Discussion

Sample Size

Both sprayers took very similar amounts of time to spray all quadrants, suggesting that their results count-wise are comparable. This also means that the MFT was not more “efficient” or faster as an applicator than the AFA, at least in our study where both were calibrated equally.

Met conditions

WSU’s permanent weather station had consistently higher temperature and lower relative humidity readings. These differences might have been due to the stations’ different geographical locations. Our temporary station’s proximity to the gorge wall’s morning shadow and the permanent weather station’s location in an open field likely contributed to slightly cooler temperatures and higher humidity values at our temporary station. Moreover, height differences between the permanent and temporary station’s instruments could have contributed to this difference. The temporary station had its temperature probe at a greater height (10 m) than the temporary station (2 m), and recorded cooler temperature readings. Importantly, both stations had positive curves with similar slopes of temperature over time and negative curves with similar slopes of relative humidity over time. Still, wind speed and wind direction compatibility between stations were the most important in this study since they were directly used to analyze our data. The temporary weather station’s wind speeds and wind direction had more variability than the permanent station, as you would expect with higher time resolutions, though the permanent station’s crude data seemed to be within the range of our temporary station’s data. Moreover, our weather station’s ultrasonic anemometer might have not been pointing true north, which might explain why most winds were read as blowing from the northwest whereas the permanent station read north. Because we included winds blowing from WNW- ENE, however, this discrepancy would not have affected our results.

Since meteorological conditions were similar for both sprayers, the control periods and typical weather conditions for the Wenatchee, WA region, all of our spray events should have been representative of typical pesticide application environments in the area (MyForecast, 2016). Additionally, wind speeds were within the EPA’s drift-reducing wind recommendations of 3-10 MPH for spray applications (US EPA, 2016e).

Aim 1: Drift Over Space

Drift Overall

The MFT sprayer was associated with significantly lower PMCs than the AFA sprayer but significantly more PMCs than the control period. In our quantile regression, controlling for sprayer type, wind speed and sampler height, sprayer type was by far the most important predictor of PMC. This study thus supports the MFT sprayer’s drift-reducing claims, at least when compared to the AFA sprayer and when spraying apple orchards. Interestingly, the MFT sprayer was associated with lower PMCs despite naturally producing a finer mist than the AFA (Table 1). Since finer droplets are more prone to drift, the MFT’s canopy-adjusted fans were likely responsible for the drift reduction we observed. Other factors could have also contributed to our findings. For example, the AFA fan had a larger diameter than each of the six MFT fans (71 in vs 50 in), and produced a larger volume output using greater fan speed and system pressure than each individual MFT fan. These factors would make the AFA sprayer more likely to produce drift. These results are thus promising for pesticide applicators who prefer finer mists in order to achieve better foliar coverage.

These results have important implications for drift reduction. First, they suggest that more modern, non-AFA spray technologies that are already out in the market may be effective tools for significantly reducing drift. The EPA’s voluntary Drift Reduction Technology Program is thus promising, as it could introduce sprayers that are more effective yet. Second, this suggests that the EPA's updated WPS requiring a 100-foot AEZ from any active sprayer might benefit from being further refined to differentiate by sprayer-type.

We saw that the control periods had a range of PMCs which included some outliers. These values represent both naturally changing ambient PM (e.g. dust, relative humidity) as well as traces of primary drift from spray events close in time. Earlier we described how start and stop times for spray events were rounded to the nearest minute and one additional minute was added to the end of a spray event. Control outliers could thus represent initial drift from the beginning of a spray event.

While higher wind speeds are a contributing factor for drift, our results showed the opposite. This could have resulted from the fact that the Dylos had a low flow rate which would have limited their ability to capture brief spikes in PMCs at higher wind speeds. While higher wind speeds could have led to increased PMCs, higher winds would have also cleared these PMCs quicker.

Drift Over Height

Samplers below the canopy were associated with significantly greater PMCs than samplers above the canopy. Our quantile regression showed that adjusting for sprayer type and wind speed, sampler height was the second most important predictor of PMC, after sprayer type. Our linear regressions of PMCs above and below the canopy showed similar slopes for both sprayer types and a slightly lower slope for the control period. This shows how the differences in PMCs above and below the canopy increased during spray periods as PMCs below the canopy rose more dramatically than PMCs above the canopy. The low coefficient of determination (R^2) values suggest that these models explained very little of the variation, despite the fact that loess lines closely matched linear models. We had many outliers and influential points in our data that likely affected the fit of this model. One possible explanation could be that heavy dust particles up could have been kicked up below the canopy by the sprayer tractor. These particles might have been too heavy to rise above the canopy, thus creating larger than usual discrepancies between samplers above and below the canopy.

Our results are in line with other studies that have found that orchard structures can greatly affect drift (Endalew et al., 2006). There are several possible explanations for our specific observations. The first may relate to what is commonly known as "urban street canyon effects" which describes how structures (in our case tree rows) may act as air funnels, capturing pollutants already below the canopy and directing them downwind (Kuo, Tzeng, Ho, & Lai, 2015). If we think of an angled wind vector, the horizontal (west-east) aspect of the vector would have been blocked by the trees in our study orchard whereas the perpendicular (north-south) aspect of the vector would have continued flowing downward. In our study, particles would have thus been directed to our samplers. This would include both the spray aerosols as well as the suspended dust particles produced by each sprayer as it moved through the field (Figure 15). Excess dust may still be considered drift since it is intrinsic to sprayer application. Moreover, since dust can be larger and heavier, this would have significantly contributed to PMCs. On the other hand, particles above the canopy are better able to disperse, essentially "diluting" the PMCs that reached our stationary samplers. Finally, the tree canopy likely did not filter out falling particles from the lower samplers like we had previously hypothesized. We believe this was primarily because the particle source was at ground level.

These results are particularly concerning for workers in neighboring fields who often work below the canopy. Since greater PMC was seen at all times, including the control periods, future studies should further investigate how orchard architecture may be modified to minimize drift. Additionally, these findings highlight the importance of more accurate sprayers since much of the drift produced by these technologies may end up traveling to areas below the canopy where workers and non-target crops might be found. Finally, the EPA's WPS in the future could benefit from an architectural or height adjustment when setting an AEZ.

Drift Over Distance

PMCs decreased with increased distances from the sprayer. Our restricted analysis looking at our spray periods showed that after adjusting for sprayer type, wind speed and height, sprayer distance was by far the least influential covariate and was much smaller in magnitude than the other covariates, though it was still significant. This was likely due to the fact that while wind speed and direction along with orchard architecture are known to affect the path that a particle travels, we only controlled for wind speed and direction (Endalew et al., 2006). Thus, the "direct" distances we measured from a moving sprayer to a sampler (e.g. through tree rows) don't necessarily describe particle transportation paths. Still, our measurement methodology in line with regulations such as the WPS that are framed around direct distances. In addition, while each sprayer was able to cover the 160-foot long spray field within one minute, only the sprayer's location at the half minute was used in our calculations. Finally, while we tested a simplified linear model looking the main effect of distance, distance may actually depend on sampling height in relation to the canopy (above versus below) and sprayer. This may explain why we observed stronger exponential decay trends below the canopy (Figure 31,Table 10). Moreover, since the MFT sprayer produced finer droplets, these droplets could have traveled further before depositing.

We saw greater PMCs at all of our spray period distance zones than the control period. These distances far exceed the EPA's new WPS AEZ of 100 feet for airblast sprayers during an application event even within the EPA's recommended 3 -10 MPH wind speeds (US EPA, 2016e). Further research should investigate drift at further locations until values are similar to ambient PM levels, and AEZs should be developed to reflect these findings.

Aim 2: Drift Over Time

One of our strongest findings relating to PMCs over time might be that the Dylos were largely able to distinguish between the control and spray periods on a minute-by-minute basis. The Dylos instruments could thus be useful drift exposure assessment tools for entire agricultural communities including worksites, schools and homes. Other fields of research interested in aerosols and other PM may also find these instruments useful.

The elevated drift concentrations we observed during the post spray minute might be indicative of lagging drift. Earlier in our methods we calculated that at wind speeds of six MPH a particle would travel from the northern edge of our spray field to the southern edge of our sample field in under one minute. Since our median wind speed was 8.7 MPH for the AFA sprayer and 8.8 MPH for the MFT sprayer, drift produced should have largely had enough time to clear the field in under one minute. Nonetheless, these wind speeds measurements were taken in an open field outside of the orchard. We would expect that the true wind speeds closer to the ground and within the orchard would experience friction and thus be much lower. If so, this may explain why we saw elevated PMCs during the control period. In addition, some of these elevated "control" values may have captured some of the PMCs from the beginning of a spray period. Similarly, the low the PMCs we tended to observe during the first minute of a spray event might have resulted from our samplers capturing the end of a non-spray period and the beginning of a spray period.

Distance and wind speed could not independently or jointly explain changing PMCs over time. PMCs are complicated and dependent on other factors such as exact wind direction, canopy structure and aerosol size. Moreover, rapidly changing meteorological conditions make pesticide drift exposures hard to predict. The WPS AEZ, however, only applies to exact application times (US EPA, 2016f). Future WPS modifications should increase AEZ duration to account for this.

Validation

This study was nested in a larger study in which micronutrient drift was measured using accepted methods of passive and active sampling for drift characterization (Kasner, 2017). While this study used inductively coupled plasma mass spectrometry (ICP-MS) to analyze metal tracers, our direct reading particle monitors measured aerosols, a novel and not-yet-validated approach. Nonetheless, since the results of both studies were consistent for drift overall, over height and over distance, this supports the validation of the Dylos monitors for drift characterization (Kasner, 2017).

Limitations

Our choice of sampling instrumentation had some limitations. For one, we did not calibrate the Dylos since they were pre-calibrated by the manufacturer, and the manual did not have calibration procedures. We also performed area sampling using stationary samplers at two and six meters to represent potential worker exposures. These may not best represent the breathing zones of moving workers throughout a workday. In addition, we only considered there to be drift if it was measured by one of our ten samplers. For example, if sprayers produced drift at much higher heights, it was unaccounted for. Our samplers also had low pump flow rates (0.06 ft^3/min, 1699 cm^3/min) and provided us with one-minute summaries. This reduced the probability of capturing quickly moving drift plumes and their concentration variations. Still, real-time particle monitors are a highly efficient and affordable sampling technique when compared to traditional methods of air sampling involving media. If we could replicate this study, we would attach a microcontroller with an SD card shield to each Dylos to extract ten-second data and better capture quickly moving drift plumes. These instruments also measured overall particles, not specific chemicals. We are uncertain of what fraction of our PMCs were strictly pesticide drift, and not other PM. Still our control periods show low ambient PM levels, suggesting that most of our PMCs were due to drift. We also converted Dylos PNC values to PMC, which required us to make several assumptions about aerosols, including their density and diameter. Since our metal micronutrient sprays were largely water, we assumed they had a density of 1.0 g/cm^3, which slightly underestimates their mass. It's also unclear how accurate the Dylos bin size cuts were. Since we used the average diameter of every bin size and cubed this value in our PNC to PMC calculation, our estimated masses could have been significantly affected. Still, there are clear differences between our control and spray periods, with control periods having very low PMCs, which reassures us that our calculations did not have excess error. Finally, slight timing inaccuracies between our ten Dylos samplers, the sprayer's GPS and our meteorological station could have contributed error to our results, which would have been most visible at the beginning and end of any spray event.

Autocorrelation could have affected our comparisons over time since we would expect that spray events near one another would be more similar than spray events at the beginning and end of a spray day. We hope to have minimized this by spraying the same quadrant with alternating sprayers. The reasoning for sampling on two consecutive days as opposed to distributing sample periods was to ensure similar full canopy conditions which allowed for cross-sample comparisons. Our results may thus be more representative of late spring and early fall conditions. In addition, autocorrelation should have been diminished since we allocated more than enough time between trials to for winds to clear all residual drift.

We can only make conclusion for fields with similar tree row architecture as those of apple trees from early summer to early fall because we did not design this study to adjust for the effects of canopy differences on drift. Crop height, shape, spacing and growth stage, however, will impact how drift is transported from one orchard area to the next. Earlier in this discussion, for example, we mentioned how we believed the street canyon effect was responsible for differences in PMCs at different heights.

Moreover, our spraying may not have been representative of common field application behavior.

We would have liked to have collected data on real spray events being conducted by various pesticide applicators around Washington State, but this was not possible in this study. Not only is pesticide drift a controversial topic that is denied by many in the agricultural industry, but drift events can be difficult to predict. Our spray events were thus planned and conducted in a research orchard. An applicator followed all standard spraying operations. Pesticide applicators, however, may choose to save time with different spray techniques or by not pre-calibrating their equipment. Given that spray equipment calibration involves the shutting off of valves, our results may be underestimates of true drift exposures. In addition, we did not spray pesticide, but a safer micronutrient alternative. Though chemical differences may have slightly affected drift, these differences would have been minor since micronutrient and pesticide solutions are mostly water with small traces of metals or active ingredients. Moreover, droplet size and meteorological conditions are known to be the largest predictors of drift (Klein, Schulze and Ogg, 2008). While initial droplet size is inherent to the sprayer, meteorological conditions were similar for both sprayers and thus our results should accurately characterize pesticide drift.

Future Research

Future research should aim to replicate and improve on our study. For one, sampling real spray events would strengthen future studies, though environmental conditions may be difficult to control. Orchard structure such as canopy shape and fullness, for example, should also be taken into account since these are known to affect drift (Endalew et al., 2006). Second, using more sophisticated particle monitors, such as the BAM by Met One Instruments, Inc., an EPA Class III Federal Equivalency Method (EQPM-1013-209), would help strengthen future studies, particularly if more were used at further locations from a spray field (Met One Instruments, Inc., 2016). Since the BAM is more expensive and only provides one-minute resolutions, however, other instruments should be used if studies wanted to better characterize quickly moving drift plumes. Future studies should also further investigate the effects of particle size on drift characterization over time. Finally, future studies should sample a wider array of days and times that represent agricultural spraying times to address potential autocorrelation.

Conclusion

In Washington State, most pesticide-related illness cases between 2010 and 2011 involved orchard airblast applications and drift (WADOH, 2013). In this study, we examined whether a modern MFT sprayer would produce less drift than a traditional AFA sprayer in a neighboring orchard by measuring the PMCs associated with each sprayer. Our results showed that significantly lower PMCs were associated with the MFT than the AFA sprayer, and that PMCs were significantly higher below the canopy. Our restricted analysis of spray periods showed that PMCs decreased over distance, though it was a minor contributor to the model. This is likely due to the fact that we did not adjust for differences in orchard architecture, which is known to affect drift (Endalew et al., 2006; Kuo et al., 2015). The Dylos detected elevated PMCs during all spray periods when compared to the control periods. Sprayer distance and wind speed were not directly responsible for PMC fluctuations, suggesting this relationship is complicated and at least partially dependent on other uncontrolled factors (Endalew et al., 2006). Still, our results are promising as they show that the Dylos may be effectively used to help detect PM fluctuations in the field.

These results highlight the importance of the EPA's voluntary Drift Reduction Technology Program and WPS. Our study showed that MFT sprayers, an emerging technology, may significantly reduce pesticide drift, though they do not eliminate it. Further improvements in sprayer accuracy and drift control can continue to reduce non-target drift. Moreover, though the WPS' 100-foot AEZ is a step in the right direction, it could be strengthened. The AEZ could be increased, adjusted to account for important drift contributing factors including canopy structure.

There are many other important implications of drift that should be considered, though they are beyond the scope of this paper. They include environmental contamination of air, water and soil, all of which can affect the animals and crops that reside in these areas. While our study shed some light on the effect of emerging spray technologies on agricultural drift, drift is a significant public health concern in other areas, and it should be further addressed through research and policy.

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Appendices

Appendix I: Dylos Air Sampling Protocol

Purpose

This procedure describes how to prepare, set up and take down Dylos air sampling stations in order to compare the drift produced by two spray technologies: a traditional axial fan airblast (AFA) sprayer and a modern multi-headed fan tower (MFT) sprayer. Instructions on how to download Dylos data are also included.

Location

- One orchard block (one acre) at Sunrise Research Orchard (south of Rock Island, WA) https://goo.gl/maps/Oh5cb

Sampling Dates

- June 8-10, 2016
- August 26 – 30, 2016

Timeline

- Day 1 (at UW)
    - Pack all necessary materials
    - Charge Dylos
- Day 2 (research orchard)
    - Compete the "Preparation Before Field Work Sampling" procedures
- Day 3 (research orchard)
    - Sampling day 1
- Day 4 (research orchard)
    - Sampling day 2
    - Clean up and pack all materials

Roles and Responsibilities

- Principal Investigator: Richard Fenske
- Field Leader: Eddie Kasner
- Field team: Magali Blanco, Maria Tchong-French, Pablo Palmández, Jose Carmona, Kit Galvin, Jane Gurnick Pouzou, Christine Perez Delgado
- Sprayers: contracted with WSU-Sunrise
    - Pak-Blast traditional AFA sprayer
    - Quantum Mist MFT sprayer

Tracers

- Micronutrient tracers will be Zn (2 treatments – 1 per sprayer) and Mo (2 treatments)

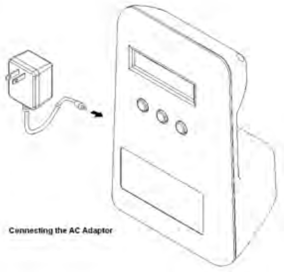
Materials

- Ten Dylos Air Quality Monitors DC1100, with chargers (Magali will take)
- power strip, enough to charge 20 devices (dylos chargers take up space) (Magali)
- two assembled cascade impactors
- met station
- GPS unit
- 5 sampling poles

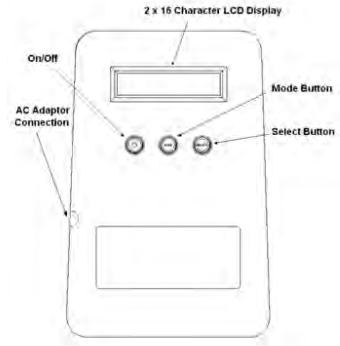
- duct tape (Magali)
- scissors (Magali)
- wire pliers (Magali)
- 15 six-meter-long guy wire (3 per pole) (Magali)
- 5 garden stakes (tall, green)
- hammer
- 15 tent stakes (short, silver) (3 per pole) (Magali)
- zip ties (Magali)
- 10 1-gallon zip lock bags (Magali)
- stickies, labels (Magali)
- notebook, pen (Magali)
- back up materials: guy wire, garden stakes, tent stakes, zip lock bags

Procedures

Preparation before Field Work Sampling – Day 1 & 2



- clear the Dylos sampling history
    - with the “battery/charge” button flipped up, press the on/off button
    - press the “mode” button until the “clear history?” comes up
    - press “select” to clear history
- synchronize time on Dylos with computer (central time is 7 hours ahead)
- fully charge all the Dylos (switch up)
    - connect the Dylos to the AC Adapter, connect the AC adaptor to a wall outlet
    - flip the side switch up towards the “battery/charge” label
    - make sure the Dylos are off by pressing the on/off button
    - when the Dylos are fully charged, disconnect them from the AC adaptor and flip the side switch down “battery/charge”to ensure the sampler is fully off



- turn the Dylos off and flip the side switch **down**
- cut necessary 6 meter guy wire (Day 1 only)
- prepare dylos-zip lock bag setup (Day 1 only)
    - use one strip of tape to tape (from above) a red cap over the three Dylos functional buttons (this will prevent the sampling pole from interfering with the sampling)
    - place Dylos in a zip lock bag (keep it open)
    - wrap duct tape around the center of the Dylos (just below the cap protecting the buttons if possible)
    - cut slits in the zip lock over the Dylos inlet and outlets. Stretch the openings so they expose the inlets and outlets completely

Preparation before Field Work Sampling – Day 2

Set-up for Field Sampling

For each of the five sampling locations…

- Have two people work together to set-up the sampling poles
- Hammer in one garden stake (tall, green)

- Inserts three tent stakes about 5 meters away from the garden stake and 120˚ from each other so that they are evenly distributed around the pole (if there is a trellis nearby, it may be possible to use that in place of a stake)
- Extend the sampling pole by twisting the blue handles and locking in place at the "2m" and "6m" marks; duct tape above the twist handle to keep the pole in place
- Zip tie the bottom of the pole to the garden stake to keep the pole in place; lay pole on the ground
- Tie 3 guy wires to the pole at the 4 m mark

- While in the bags, turn the Dylos on by flipping the "battery/charge" side switch up; ensure the LCD display is on; take note of the start time
- Face the back of the Dylos (where the inlet and outlets are found) towards the spray field (~north) and tape one dylos to the pole at 2m and another at 6m by taping around the middle of the Dylos
- Ensure the inlets and outlets are not obstructed by the plastic bag
- Have two people carefully prop up the pole adjacent to the garden stake and ensure the Dylos inlets are facing the spray field
- While one person holds the pole in place, have a second person zip tie about 3 zip ties around the garden stake and sampling pole (distribute the zip ties throughout the garden stake)
- Have one person hold the pole stable while a second person ties the three guy wires to the tent stakes/trellis
- Ensure the sampling poles look stable

Take-down after Field Sampling

- Have one person hold each pole until its safely on the ground
- Have a second person take off the guy wires and tent stakes
- Use wire pliers to clip the upper zip ties, leaving the bottom zip tie
- Carefully place the sampling pole on the ground
- Check that each Dylos is still running; record the time
- Take off the Dylos by cutting the tape around them with scissors
- Place each Dylos on a protective layer (e.g. towel) to protect them from dirt
- If sampling the next day, the garden stake and pole with guy wires may be left out in the field as long as it is not a tripping hazard and is away from any vehicle roadways; otherwise untie the guy wires, wrap them up and compress the sampling pole

Downloading Data

Open Eddie's PC (ps: 9110)

Connect the Dylos to the PC using the USB-to-serial cord

- Check that it installs drivers (this should happen automatically)

Find the COM port and record it

- Open Device Manager on PC / Select Ports (COM & LPT) / "Prolific USB-to-serial Port (COM____)"

Use PuTTY to download all data [see Dylos manual or Graeme Carvlin for further assistance]

- Download PuTTY software (Putty.exe) online onto a PC computer
- Plug in the Dylos and turn it on

- Open and run PuTTY
- On the left hand side on the Configuration screen select “Serial” and set the parameters: 9600 baud, 8 bits, no parity, 1 stop bit, no flow control). Note what selected COM Port you are using (you will use the same throughout)
- Select “Session” on the left hand of the screen and then select “Serial” radio button (the correct COM Port and baud rate should appear)
- Select the “Logging” category on the left hand side, select “All session output” and “Always append to the end of it” buttons.
- Click “Browse” button, name your file and select its desired saved location
- To save these setup settings, select the “Session” category and enter the name of the session, e.g. “Dylos DS1700” and click “Save”. You can now recall this output in future sessions.
- Click “Open” and the PuTTY terminal will open
- In the PuTTY terminal, enter a capital “D” followed by “Enter” to download the internal memory (note you will not see the “D” appear on the screen)
- The data should output with the oldest samples shown first and newest last. Output is in #/0.01ft^3.
    - The serial output format is: small counts, comma, large counts, carriage return, line feed, e.g.: 675, 19<CR><LF>. Data is outputted every minute. Counts represent counts/0.01 foot cubed (multiply by 100 to get cubic foot)
- Save as .csv or .txt
- Ensure the data is all saved
- Clear the history on the Dylos

Notes:

- On Dylos could increase “baud” rate for faster download (but switch back to original afterwards)
- Can switch Dylos, use from San Isydro if need others (put back in same box)

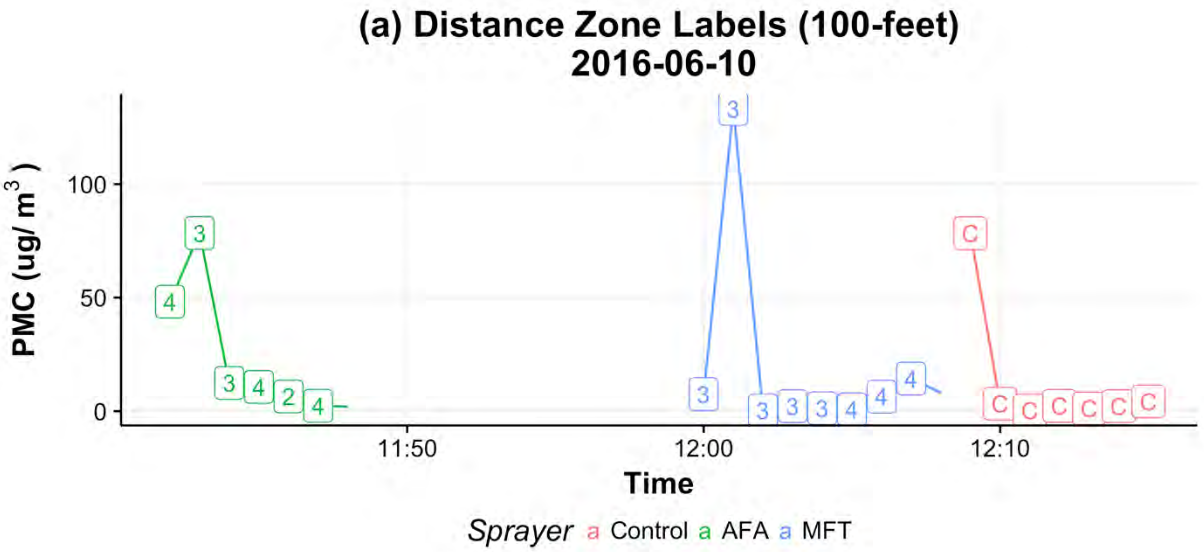
References

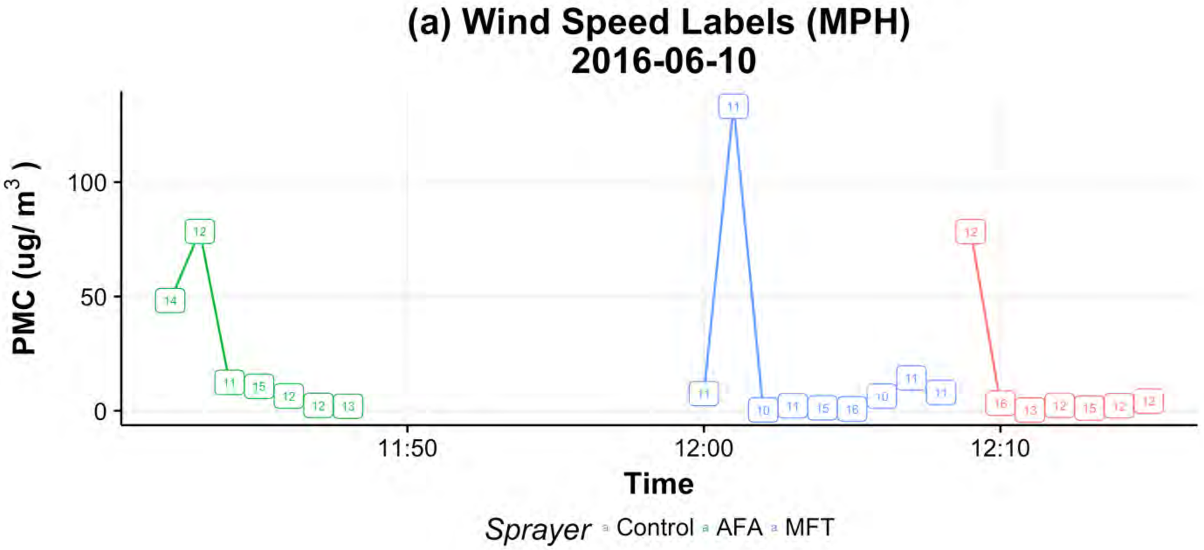
User Manual: DC1100 Air Quality Monitor. Dylos Corporation. 2008.

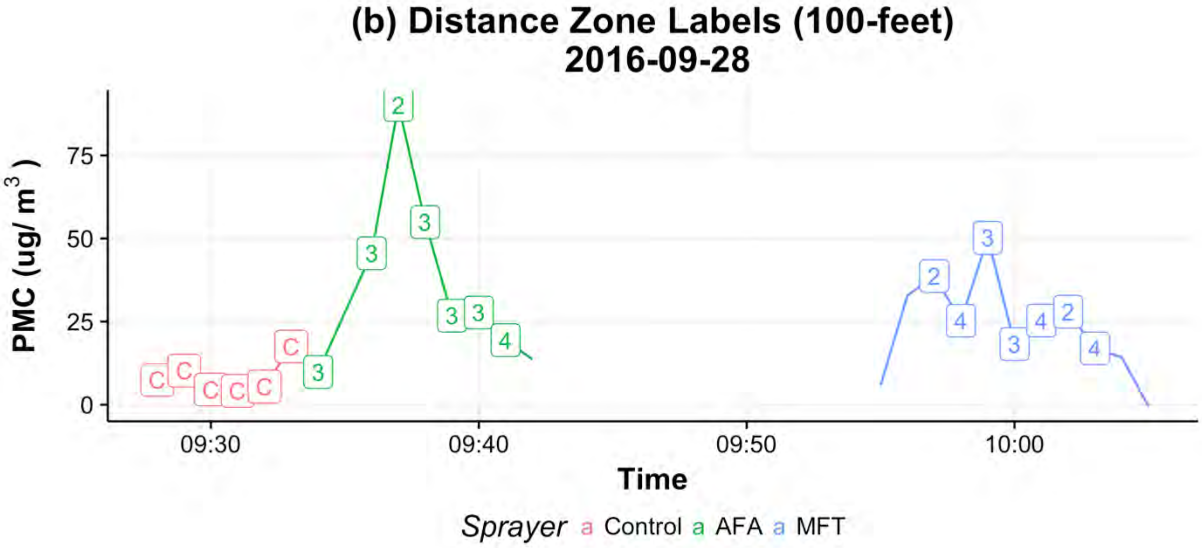
Last Updated: 09/14/2016

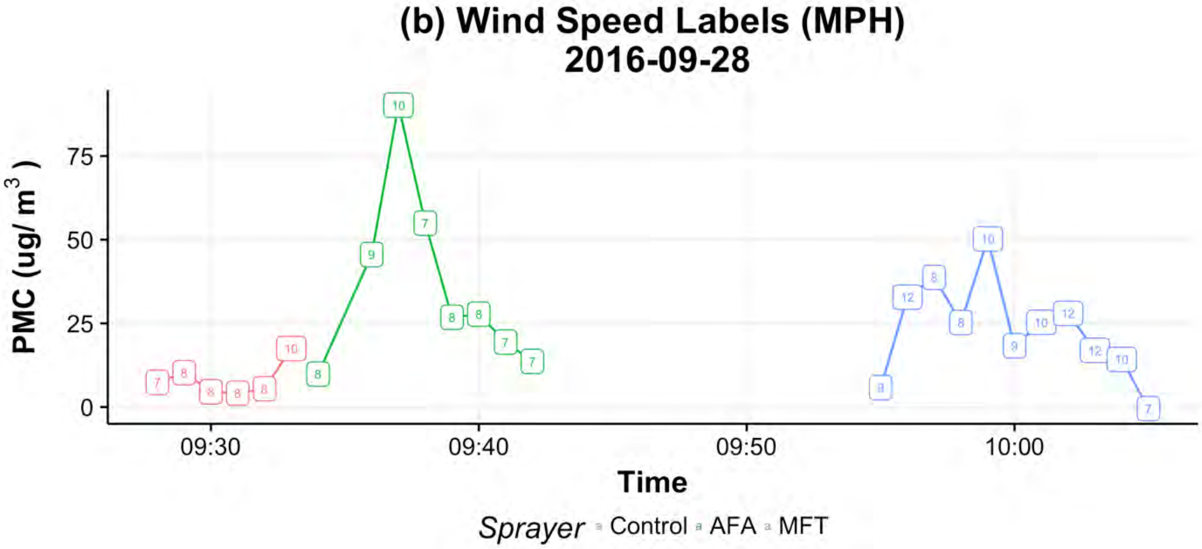
Appendix II: PMC over Time with Distance Zone and Wind Speed Labels

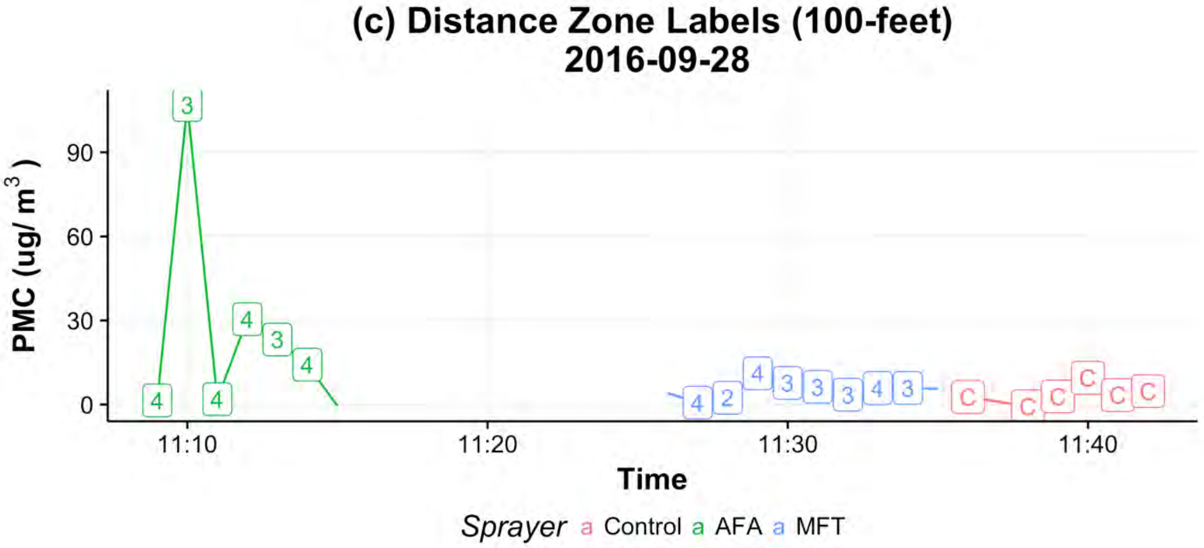
Sample of spray events over time with distance zone (100-feet) and wind speed labels (MPH). Distance zones are in 100-foot increments so that labels 1, 2, 3 and 4 represent the 100, 200, 300 and 400-foot distance zone respectively.



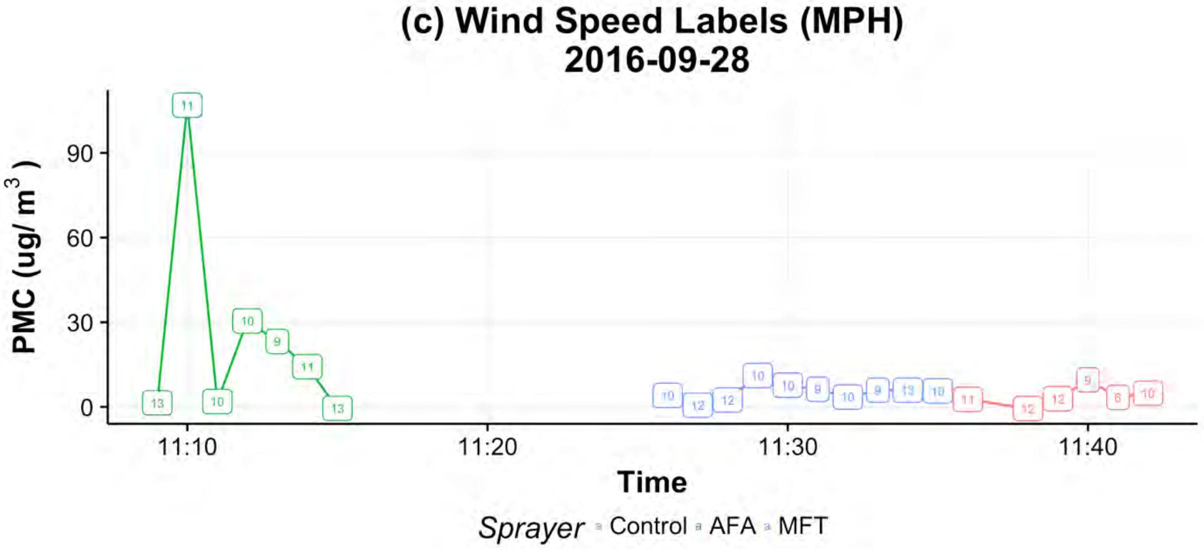



(b) Distance Zone Labels (100-feet)
2016-09-28
PMC (ug/ m^3)
0
25
50
75
Time
09:30
09:40
09:50
10:00
C
C
C
C
C
C
3
3
2
3
3
3
4
2
4
3
3
4
2
4
Sprayer
a Control
a AFA
a MFT

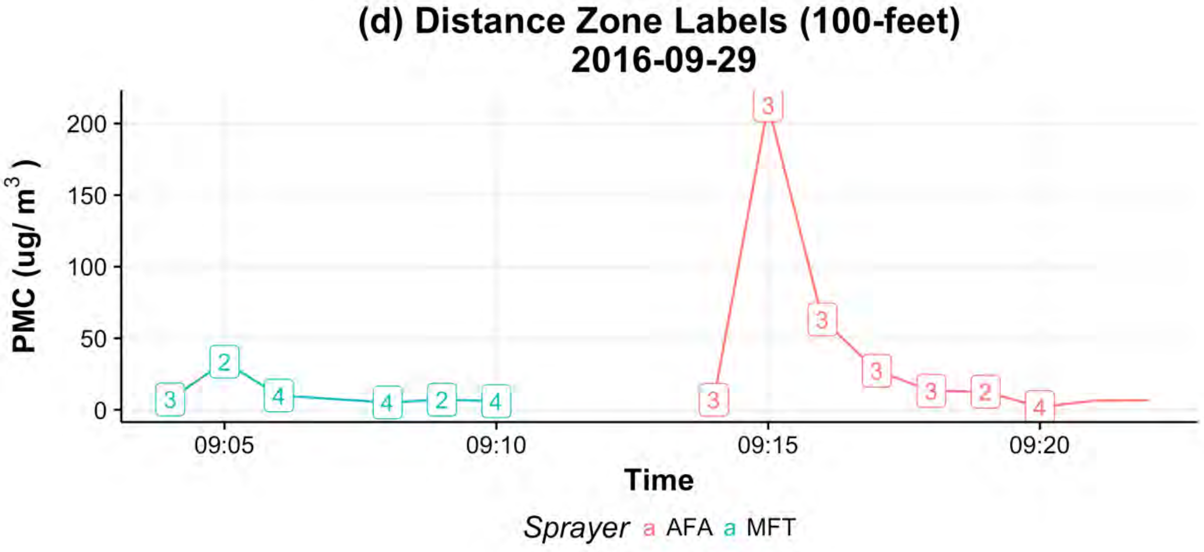

(b) Wind Speed Labels (MPH)
2016-09-28
PMC (ug/ m^3)
0
25
50
75
Time
09:30
09:40
09:50
10:00
7
8
8
8
8
10
8
9
10
7
8
8
7
7
8
12
8
8
10
9
10
12
12
10
7
Sprayer
Control
AFA
MFT



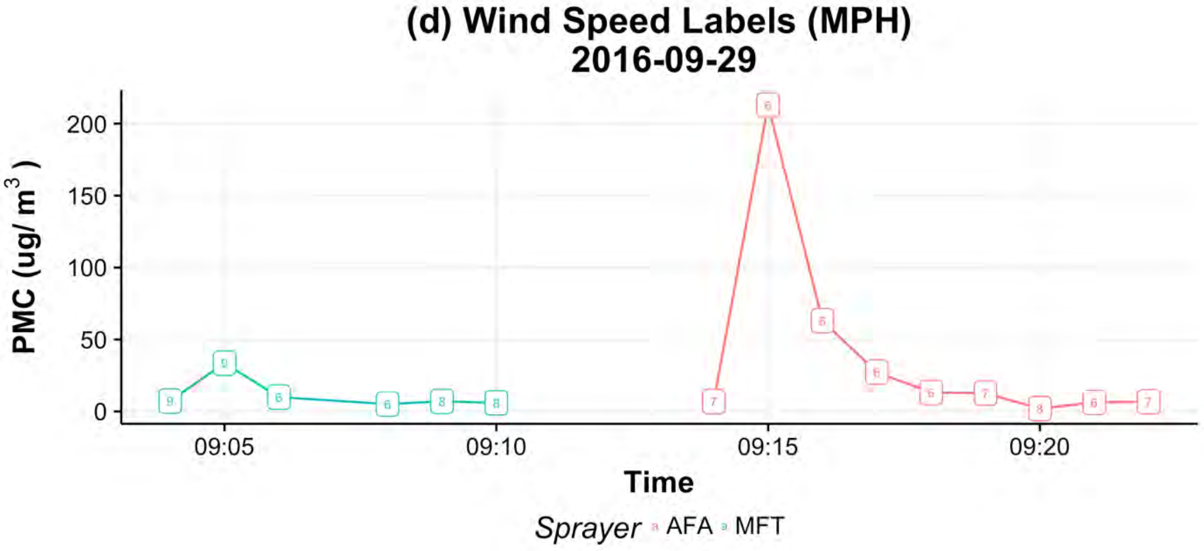
(c) Distance Zone Labels (100-feet)
2016-09-28



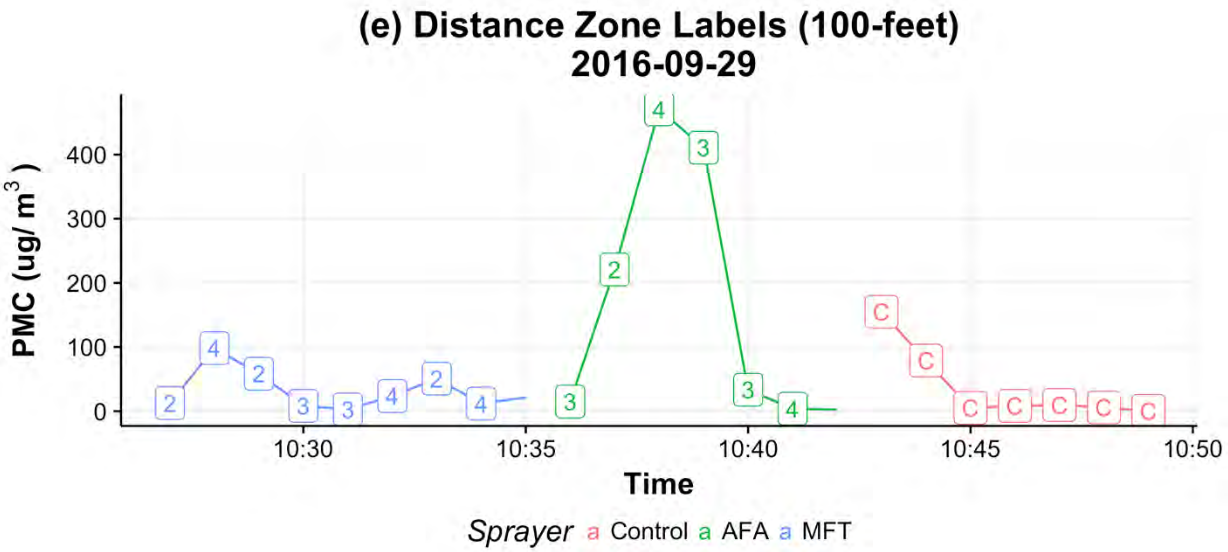
(c) Wind Speed Labels (MPH)
2016-09-28

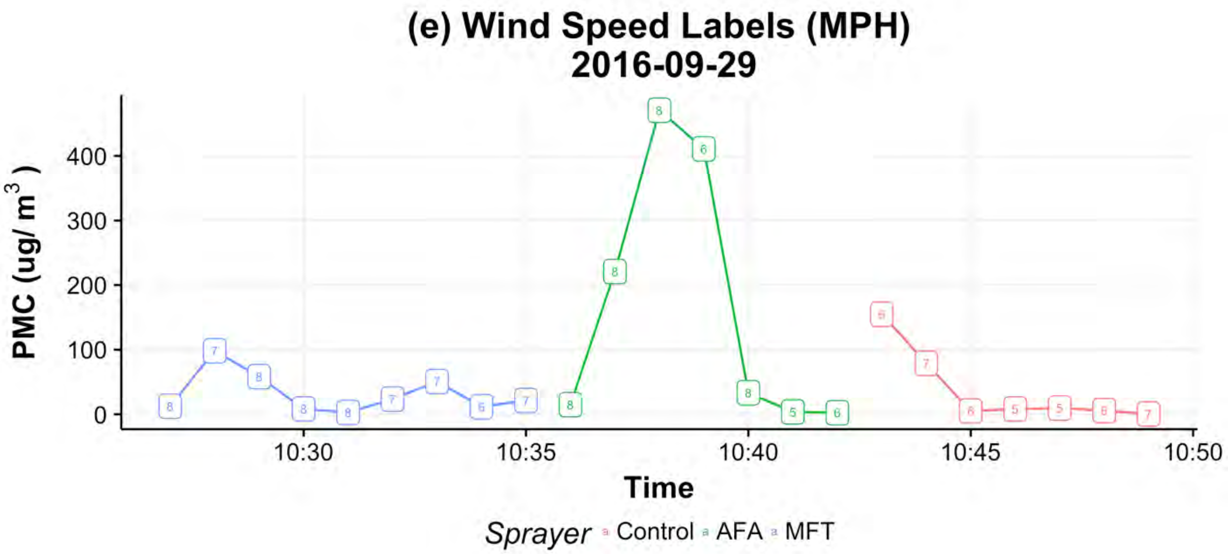


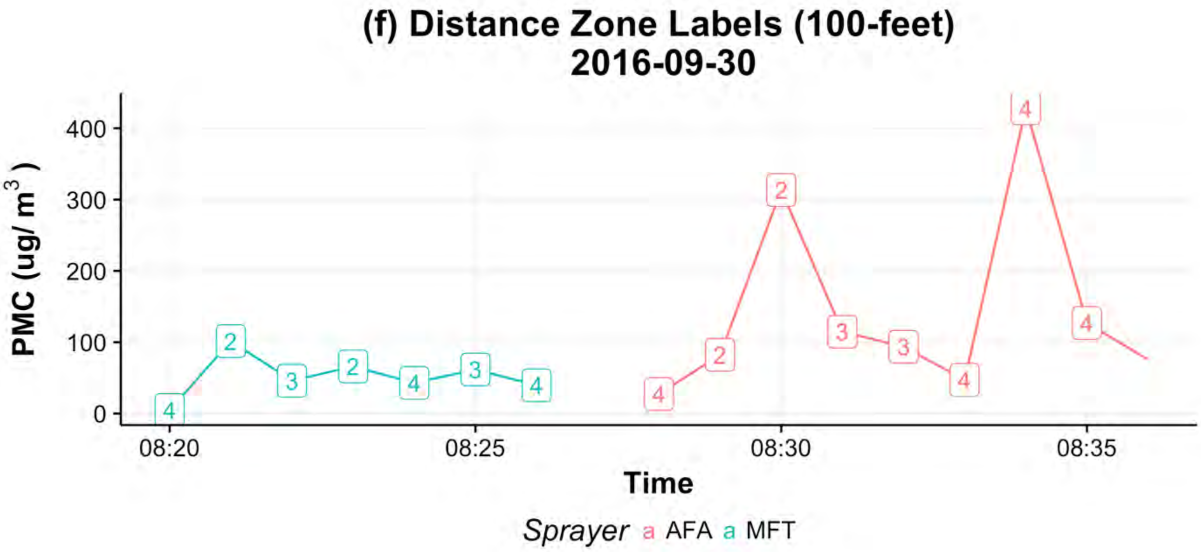
(d) Distance Zone Labels (100-feet)
2016-09-29

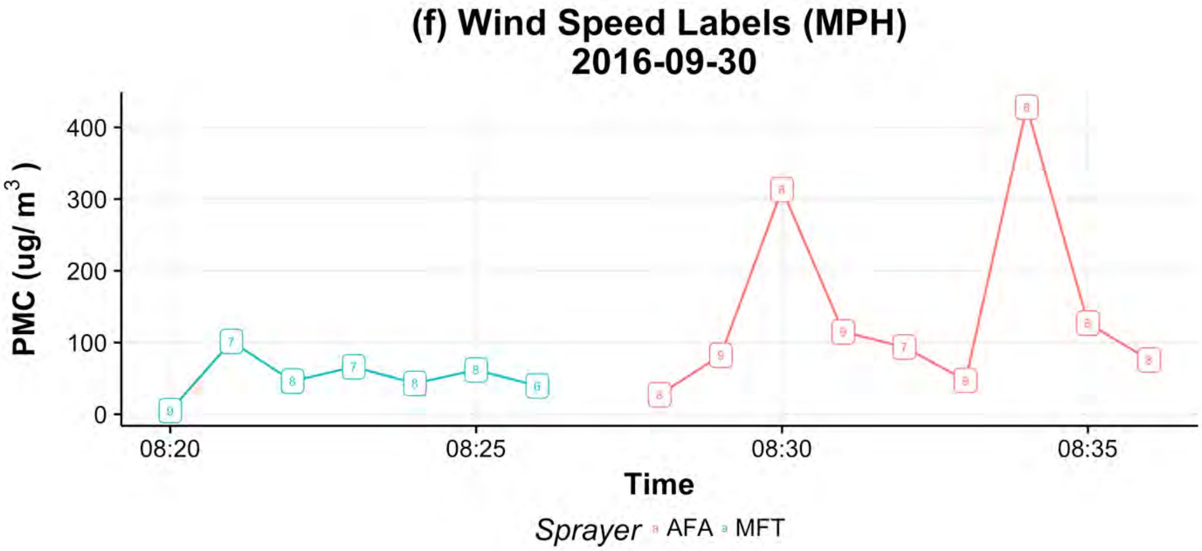


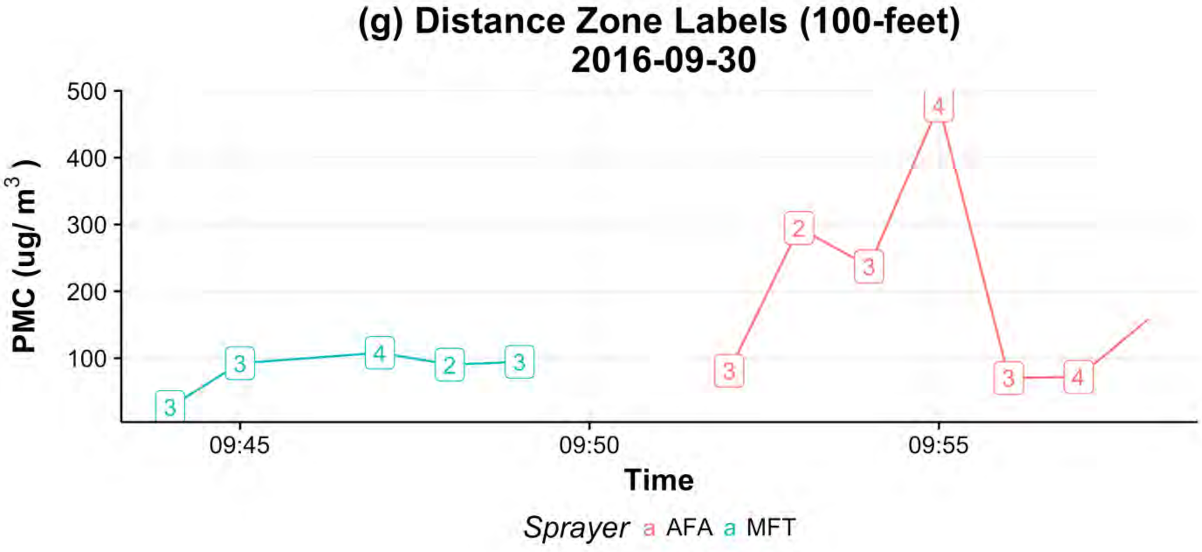
(d) Wind Speed Labels (MPH)
2016-09-29

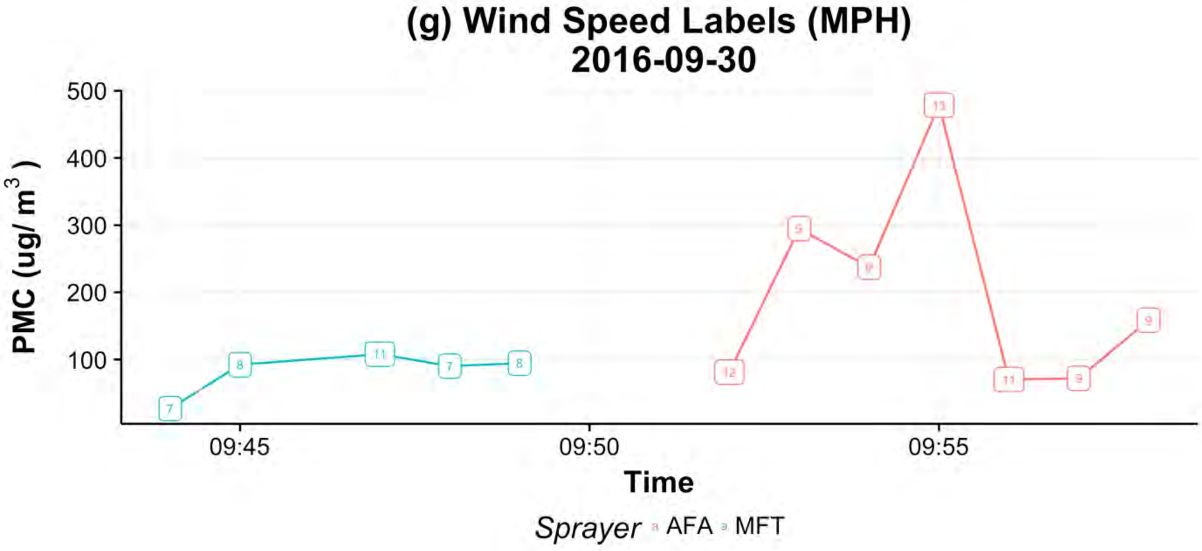

(e) Distance Zone Labels (100-feet)
2016-09-29
PMC (ug/ m^3)
400
300
200
100
0
2
4
2
3
3
4
2
4
3
2
4
3
3
4
C
C
C
C
C
C
C
10:30
10:35
10:40
10:45
10:50
Time
Sprayer
a Control
a AFA
a MFT


(e) Wind Speed Labels (MPH)
2016-09-29
PMC (ug/ m^3)
400
300
200
100
0
8
7
8
8
8
7
7
6
7
8
8
8
6
8
5
6
6
7
6
5
5
6
7
10:30
10:35
10:40
10:45
10:50
Time
Sprayer
a Control
a AFA
a MFT


(f) Distance Zone Labels (100-feet)
2016-09-30
PMC (ug/ m^3)
400
300
200
100
0
08:20
08:25
08:30
08:35
Time
4
2
3
2
4
3
4
4
2
2
3
3
4
4
4
Sprayer
a AFA
a MFT


(f) Wind Speed Labels (MPH)
2016-09-30
PMC (ug/ m^3)
400
300
200
100
0
08:20
08:25
08:30
08:35
Time
9
7
8
7
8
8
6
8
9
8
9
7
9
8
8
8
Sprayer
a AFA
a MFT


(g) Distance Zone Labels (100-feet)
2016-09-30


(g) Wind Speed Labels (MPH)
2016-09-30