On Preventing Farmworker Exposure to Pesticide Drift in Washington Orchards

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Abstract

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Pesticide drift, or the off-target movement of pesticides, represents a key cause of not only crop damage and economic loss but also occupational and bystander illness. Nationally, drift has been shown to account for 37-68% of pesticide-related illnesses among United States agricultural workers (1, 2). It remains a public health concern in the Pacific Northwest, especially among tree fruit workers. Unfavorable wind conditions and a lack of worker notification have been identified as leading contributing factors for acute illnesses resulting from occupational drift exposure (3, 4). No study has systematically examined historical weather data as exposure determinants of drift events with occupationally-related pesticide illnesses (5–7). Our first aim seeks to understand the role of wind in pesticide drift events reported to the Washington State Department of Health and prevent such exposures in the future.

A majority of drift events reported in Washington over the last two decades resulted from orchard airblast applications. The airblast sprayer has been a standard tool for tree fruit pesticide application technology since its rapid and wide-scale adoption in the 1950s (8). Over the last 65 years, a desire for more fruit-bearing trees has changed orchard canopies by reducing tree height and canopy volume. As a result, traditional airblast sprayer output no longer matches modern trees and thereby increases drift potential. New engineering controls such as tower sprayers have been promoted as methods to reduce drift, but few studies have examined how much these new technologies reduce worker exposure. While previous field studies have examined the use of metal cation tracers in spray deposition (9–14), our second aim evaluates new engineering controls by measuring potential worker exposure to orchard spray drift using novel micronutrient tracer methods.

A high priority issue for drift exposure prevention in Washington has been improved communication between farms, handlers, and crew members (15). Currently, there is no system in place to notify workers or employers of applications that will be taking place on adjacent property. To investigate worker notification as a means to prevent exposure to drift, our third aim reviews existing agricultural notification systems and assesses the feasibility of a farm-to-farm notification system in Washington using interviews with tree fruit industry personnel.

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1 Introduction

1.1 Epidemiological surveillance and documented drift events

1.1.1 History of pesticide drift in Washington

Compared to ancient crop protection methods that developed alongside domesticated plants thousands of years ago, modern crop protection has increased physical and chemical inputs over the last century (17, 18). Advances in aerial and ground application technology, combined with the availability of synthetic chemicals, facilitated greater rates of pesticide use beginning in the 1940s (19, 20). By the 1950s, "drift spraying for vegetation baiting" was described as a method to control locust infestations through the intentional release of insecticides into the air at heights adequate for deposition specific distances downwind (21). The first studies of downwind spray deposits started during the same decade (22). Since then, the release of airborne agrochemicals—mainly pesticides, insecticides, herbicides, and fungicides—has been investigated from the research perspectives of entomology, agricultural engineering, horticulture, ecology, and human health.

Pesticide drift has been a long-standing issue in the State of Washington. The most common application method used in Washington orchards is airblast spraying, which has been a standard tool since its rapid and wide-scale adoption in the 1950s (8). Over the last 65 years, the desire for more fruit-bearing trees has changed orchard canopy architecture. Such modern orchard management practices include reducing tree height and canopy volume by pruning and training to a trellis. These changes have resulted in smaller trees, yet standard axial fan sprayers still disperse aerosols to traditional tree height and volume (23, 24). As a result, traditional airblast sprayer output no longer matches modern canopies and thereby increases drift potential. Some estimates indicate that only 55% of airblast spraying hits the intended target, whereas the remaining 45% either becomes airborne as spray drift or deposits on the ground (25–27). Drift can also occur as a result of row crop applications. The United States Environmental Protection Agency (US EPA) estimates that 1-10% of all pesticide application methods is comprised of spray drift and that this portion can be reduced (28).

The off-target movement of pesticides from orchard airblast applications is a continuing health concern for agricultural workers and residents alike (29, 30). According to a recent annual report about agricultural pesticide drift events, the Washington State Department of Health (WA DOH) found that 64% ($\frac{43}{67}$) of affected individuals were workers on nearby farms (31). A majority of drift exposure cases in Washington result from orchard airblast applications while the balance occurs via aerial or other application methods.

1.1.2 Pesticide Illness Surveillance and Prevention

WA DOH is mandated by state law to coordinate an epidemiological surveillance program that documents pesticide-related illness, a reportable condition in the State of Washington (32, 33). The state program gathers a suite of information that is coded according to a standardized case definition created by the National Institute for Occupational Safety and Health (NIOSH) (34). The national program, known as the Sentinel Event Notification System for Occupational Risks (SENSOR)-Pesticides program, is comprised of 12 member states that compile reports of pesticide illnesses in a national aggregated dataset (34). In addition to detailed health information, each report contains characteristics about the application (e.g. location, timing, application method, crop type, active ingredient, formulation) and factors contributing to the exposure (e.g. notification lacking, application equipment failure, excessive application) (34). The WA DOH, Washington State Department of Agriculture (WSDA), and Washington State Department of Labor & Industries (L&I) collaborate to investigate pesticide exposure incidents. A drift case meets the shared WA DOH and NIOSH case definition (35, 36). Briefly, a case is an individual with a documented drift exposure. For this project, the term "drift" will be used as shorthand for primary spray drift, which is discussed in detail below. A "drift event" is defined as an "incident where one or more drift cases experienced drift exposure from a particular source" (3).

In 2011, a NIOSH study about drift-related illnesses that included WA DOH data from 2001 through 2006 highlighted unfavorable weather conditions and a lack of communication between farms as leading contributing factors for drift exposure (3). In May 2014, WA DOH announced that about 60 workers became ill in 15 drift events over a 2 month period, which is as many cases as the agency's epidemiological surveillance program has averaged each year (37). The events occurred in the dense orchard regions of central and eastern Washington and largely involved airblast sprayers.

1.1.3 Meteorological conditions and the science of drift

A comprehensive assessment and mitigation of agrochemical spray drift describes several important factors: method of application, sprayer release height, droplet size, adjuvants, wind speed, wind direction, air stability, relative humidity, and temperature (38).

Meteorology plays a key role in the fate and transport of spray droplets (3, 39, 40). Computer modeling has shown that meteorological variables are least controllable by applicators and vary constantly over time and space (41). Wind speed and direction are the primary meteorological drift determinants. Droplet size and release height modify the effects of meteorology on spray droplet movement. Fluctuation in wind direction indicates the amount of atmospheric turbulence, which contributes to dilution and dispersion of small droplets. Smaller droplets increase crop coverage, but they also promote drift in the presence of smaller gravitational forces and larger wind speed and direction changes (23, 41). Wind speed, wind direction, relative humidity, and temperature are frequently recorded in pesticide drift sampling studies. Wind influences the movement of spray droplets in the atmosphere, which reinforces the need for pesticide handlers to adhere to weather-related requirements during applications (3, 39).

One of the May 2014 drift events consisted of 20 cherry orchard workers who were drifted upon by a neighboring pear orchard application of an insecticide and fungicide mixture (4). Applicator and meteorological records showed that wind speeds were low (0-4 miles per hour, mph) and blowing away from the workers early in the day; at the time of the event, however, wind speeds were as high as 18 mph (4). While WA DOH gathers a suite of information about illnesses resulting from drift events, it does not systematically gather exposure determinants related to weather.

1.1.4 Pesticide application labels and records

Certified applicators in the State of Washington are required to fulfill basic recordkeeping requirements for pesticide applications to more than one acre of agricultural land in a calendar year. Records must be completed the same day as the application, kept for a period of seven years, and made readily available to WSDA or other agencies. Basic application records include applicator contact information; location, crop, and area of the treatment site; start and end time on the application date; wind direction and speed; and the name, amount, rate, and concentration of the pesticide product applied (42).

Pesticide product labels are legal documents promulgated by the US EPA that provide directions to applicators about the handling, mixing, applying, storing, and disposal of pesticides. Many states, including Washington, have explicit policies that prohibit drift. Wording such as “Do not allow drift” and “A person may not apply a pesticide when wind speed exceeds 10 miles per hour” appears on some product labels and in state laws (43). In 2009, the US EPA provided guidance for adding more detailed drift control statements to pesticide product labels. The purpose was to provide improved and consistent label statements about controlling drift. An example of a new statement reads: “For orchard/vineyard airblast applications, do not direct spray above trees/vines and turn off outward pointing nozzles at row ends and outer rows. Apply only when wind speed is 3-10 mph at the application site as measured by an anemometer outside of the orchard/vineyard on the upwind side" (44). The US EPA also examines pesticide incident history and exposure risks to determine the need for additional mitigation measures such as limiting application height, identifying spray droplet size, using no-spray buffer zones, and prohibiting a particular application method (44, 45).

1.2 Engineering controls and spray drift field studies

1.2.1 Defining the drift exposure pathway

Experts in the fields of entomology, agricultural engineering, horticulture, ecology, and human health occasionally describe the airborne movement of agrochemicals differently with respect to time and space. According to the exposure pathway paradigm, sprayers are sources from which airborne pesticides travel to unintended receptors such as nearby orchard workers or sensitive crops. The airborne movement of agrochemicals has been described in various ways. Himel defines "exo-drift" as the spray lost from a target area by wind on droplets and "endo-drift" as spray lost to the soil instead of plant or insect targets (46). More recently, use of the term "exo-drift" has been replaced by "spray drift." Several sources describe spray drift as the "part of a pesticide application that is deflected away from the target area by action of the wind" (20, 23).

Regulatory agencies tend to differentiate between "primary spray drift," which occurs during application or soon thereafter, and "secondary off-target movement," such as volatilization after application or movement on windborne dust particles. This differentiation is made because only primary drift is enforceable. Spray drift has been further categorized as "sedimenting drift," larger droplets that fall out of a spray cloud as deposits on horizontal surfaces, and "airborne drift," smaller droplets that are carried large distances by the wind (23). In addition to droplet size, aerosols generated by agricultural sprays are influenced by several physical and chemical parameters such as spray-mix additives, formulation types, and atomization through different hydraulic nozzle types (47). The US EPA continues to seek a consistent framework for both spray drift and volatilization in its pesticide risk assessment policies (48, 49). For this dissertation, the terms "drift" and "off-target movement of pesticides" are used interchangeably.

1.2.2 Exposure science and precision agriculture technology

The most common pesticide application method for applying pesticides to tree fruit is with an airblast sprayer, which is a basic orchard sprayer with an axial fan. The traditional design consists of an airstream generated by a fan that is deflected through a 90 degree turn and up to approximately 10 or more hydraulic nozzles at the outlet (23). As modifiable features of these sprayers, nozzles are an important determinant of droplet size. The need for coarse spraying, which reduces drift by generating larger droplets, competes with the need for fine spraying, which increases crop coverage through atomizing smaller droplets. Fine spraying also reduces the volume of liquid released. Thus, nozzle selection requires an understanding of an agricultural engineering concept known as volume median diameter (VMD), which is a way to classify the range of possible droplet sizes. As with the field of industrial hygiene, VMD is a typical value (e.g. mean or median) used to describe a particle size distribution; it specifically expresses the value where 50% of the total volume of liquid sprayed consists of droplets with diameters larger than the median value and 50% with smaller diameters (20, 23, 50). The American Society of Agricultural and Biological Engineers (ASABE) provides VMD size classifications based on a standard testing method (51, 52).

Principles of aerosol science are employed in the fields of exposure science and precision agriculture, an industry concept that optimizes field management, including application technology. To limit "drift potential" both fields rely on engineering controls to improve sprayer efficacy, manage chemical inputs, and reduce off-target exposure. New orchard sprayer technologies such as towers and multi-headed fans are being marketed as low drift alternatives to traditional airblast sprayers. Sprayer efficacy can also be improved with technology such as air-induction nozzles that increase droplet size, canopy density sensors that adjust spray rate, and solid set canopy delivery systems that altogether eliminate sprayers pulled by tractors (23, 53, 54). Precision agriculture and exposure science continue to incorporate new technology such as unmanned aerial vehicles (55–57). However, cost and reliability can be substantial barriers to the adoption of new technologies by Washington State orchard growers (58).

The US EPA recently launched a voluntary Drift Reduction Technology (DRT) Program that utilizes a four-star rating system to rank the ability of application technologies such as nozzles, spray shields, and chemical additives to reduce spray drift potential (28, 59, 60). The primary purpose of the program is to encourage "manufacture, marketing, and use of spray technologies scientifically verified to significantly reduce pesticide drift" (59). Manufacturers are asked to use standardized wind tunnel and field methods to measure the drift reduction potential of different spray technologies. The ranking system is organized by the following criteria:

- One star: 25-49% reduction
- Two stars: 50-74% reduction
- Three stars: 75-89% reduction
- Four stars: 90+ % reduction

Once the ratings are complete and added to an online database, manufacturers can use DRT star ratings in product labeling and literature. Likewise, pesticide applicators can search the database for DRT-rated technology by manufacturer and system pressure. US EPA hopes that successful implementation of the program will promote wider use of low-drift technology in the agricultural industry. The program is presently being rolled out for row and field crop spraying and will be expanded to orchards and vineyards. Washington State has the opportunity to be an early adopter for this voluntary program (59, 60).

1.2.3 Components of orchard spray drift field studies

Methods for the field-based measurement of pesticide drift are quite variable. Basic study components typically include selection of a field site, spraying equipment, pesticide or tracer of interest (stability, level of detection), collector (representativeness, size, collection efficiency), collector location, maximum sampling distance, number of swaths applied and swath length, meteorological data, laboratory analysis, labeling and storage scheme, replication, and data management systems (61).

Over the last 60 years, spray drift studies have used both passive and active sampling of pesticide ingredients (62–66), colorimetric dye tracers (67–70), and metal nutrient tracers (9, 13, 71, 72) to measure deposition without visualizing the distribution of spray deposits (73). Other studies have used fluorescent pigments to visualize the distribution of spray deposits without measuring deposition (74, 75). Radioactive isotopes have also been used as highly sensitive tracers, but safety and cost have largely limited such efforts (76, 77).

Passive collection surface options used in spray drift studies have included pans of water, sheets (glass plates, silica gel plates, aluminum sheets, Mylar), line collectors (cylindrical 2.0 mm polyethylene, PTFE, cotton, or woolen lines), coated slides or films, glossy or sensitive papers, cotton piping, pipe cleaners, scouring pads, cotton clothing on bystanders, filter paper, petri dishes, hair curlers, leaf surfaces, and fibrous media (20, 23, 38, 78). Special consideration must be given to the experimental design of passive collection techniques used for comparative spray drift measurements, as discussed by Matthews, Bateman, Miller, May, and Clifford (23, 79, 80):

> "it may not be important to define the detailed collection characteristics (sampling volume/cross-sectional area and collector efficiencies) of the sampling system used provided that these are the same for different systems being evaluated. Miller (1993) indicates that this may be difficult to achieve since many passive sampling collectors for airborne spray have a sampling volume and collection efficiency that are a function of both droplet size and wind speed conditions at the collector (May and Clifford 1967)." –*Pesticide Application Methods: Spray Drift (Chapter 12) p. 342* (23)

The next section outlines nationally and internationally accepted standards for conducting pesticide drift studies and the sections that follow describe key sampling methodology studies related to foliar airblast applications of micronutrients in apple orchards.

1.2.4 Standard protocols for drift sampling in the field

At least two technical standards exist for the measurement of spray drift of airblast sprayers: American Society of Agricultural and Biological Engineers (ASABE) S561.1 APR2004 and International Standards Organization (ISO) 22866:2005(E) (78, 81).

The purpose and scope of ASABE S561.1 outlines a "test procedure for use in measuring and reporting in-swath and out-of-swath ground deposits from sprayers" and a record of all deposit, operational, equipment, and weather data (81). Basic study design recommendations include: one or more passes of a sprayer over a predetermined land area, 25 or more tests on the same site for a robust drift modeling dataset, and a spray line (center line along which sprayer is operated) perpendicular to a sample line (line along which spray deposit targets are placed) (81). Additionally, the ASABE guidelines (81) call for a detailed sketch of the test site along with the following information:

- Natural barriers
- Crop type and height
- Crop row orientation
- Approximate degree of land slope both parallel and perpendicular to sample line
- Size and location of wind obstructions 0.4 km upwind of test area
- Spray line should be at least 1.2 times as long as sample line
- Presence and location of weather station relative to spray and sample lines with the following:
  - Dry bulb air temperature at 1.8 m elevation
  - Percent relative humidity at 1.8 m elevation
  - Horizontal wind speeds at 10 m elevation (and also 1 m above tree canopy inside orchard)
  - Horizontal wind direction at 10 m elevation
  - Atmospheric stability should be recorded by noting percent cloud cover and qualitative assessment of solar radiation
- Meteorological station located at least 20 tree heights outside of the orchard
- Nominal tree height, spacing, and width
- Visual assessment of canopy density, leaf development and percent porosity

Other guidelines state that spray material deposits should be collected on targets that are made of the same shape and material, and spaced equally along the horizontal sample line at the same elevation relative to the canopy. Only the area between the last two rows on the downwind side of the orchard should be sprayed, with the location of the first sampling target spaced 3 m from the downwind edge of the spray swath and the last target spaced at least 100 m from the swath. Thus, the minimum recommended spray area dimensions should be one row in width by 120 m in length (81).

The purpose and scope of ISO 22866:2005(E) outlines largely similar recommendations for orchard airblast sampling (78). There are, however, some notable differences: 1) spray area dimensions should be at least 20 m in width by 50 m in length, with the spray line twice as long as the sample line, 2) measurements should be made no less than 10 m downwind from the edge of the sprayed trees, 3) the height of sampling targets should be at least 6 m for tree orchards, 4) sampling targets may consist of a 2.0 mm diameter line or material that can be related to this reference value, 5) a point measurement should be made at a height close the center of the spray plume, and 6) recorded temperature difference between two heights (78).

1.2.5 Previous drift field studies

As a reflection of the worldwide agricultural commodity markets, most pesticide drift research has involved row crop applications. Fewer studies have focused on tree fruit, specifically apples, the largest crop in the State of Washington. The US EPA organized the Spray Drift Task Force (SDTF), which was a consortium of pesticide registrants that created a generic database of aerial, airblast, and boom spray applications to examine the influence of several factors on primary spray drift deposition profiles (23, 82–84). Notably, the consortium determined that spray drift was the movement of droplets and not specific to pesticide active ingredient. Field drift testing results were combined with evaporation and atomization data to quantify the relationship between application conditions and the magnitude of off-target movement (23, 82–84). The SDTF found that important factors contributing to drift generally involved environmental and meteorological conditions, spray technique, and crop (47). More specifically, these included wind speed and direction, temperature, relative humidity, application site, application height, sprayer driving speed, applicator behavior, atmospheric turbulence, application equipment, spray formulation and velocity, fall speed of droplets, droplet evaporation, and localized movement related to the operation of the application vehicle (23, 82–84).

The Pacific Northwest Agricultural Safety and Health (PNASH) Center has a rich history of conducting studies about the residential pesticide drift exposure pathway in Washington State, especially for organophosphorus (OP) compounds. PNASH studies have modeled spray drift dispersion and deposition to characterize children's exposures resulting from aerial application to potato fields (5, 85). Notably, an Orchard Spray Drift Model (OSDM) was validated in a study of airblast application (86). More recently, active and passive sampling techniques were used to understand residential exposures to spray drift and volatilization among households in a rural Washington community (87, 88). These studies have focused largely on the Yakima Valley and North Central Washington.

1.2.6 Foliar application of micronutrients as metal tracers

Foliar application of essential nutrients (i.e. "micronutrients") such as iron, zinc, copper, boron, manganese, and magnesium has long been recognized as a means for crop nutrition (89–91). Unlike many other agrochemicals, micronutrients are not regulated as pesticides by US EPA. A key difference between macronutrients (e.g. protein, carbohydrates, and fats) and micronutrients (e.g. vitamins and minerals) is the amount needed for good plant health, much like vitamins in the human diet. Micronutrients have proven to be excellent tracers in pesticide drift studies since at least 1978, when methods for sampling and assessing deposits of insecticide metal tracers near forests were used (9, 14). In another study, experimental treatments with four metal tracers (manganese, cobalt, copper, and zinc) were used to study the distribution of spray deposits, spray drift, and losses to the ground (11). Most recently, multiple metal salt solutions have been applied to a field target and later recovered in a single inductively coupled plasma mass spectrometry (ICP-MS) procedure (13, 14). Fall was an ideal time for testing these methods in Washington State because the Crop Recommendation Guide suggests the use of several metals in postharvest applications, tree fruit would have been harvested so there weren't any detrimental effects on the crop, and the trees were still in full canopy. It should be noted, however, that some drift events occurred in early spring when trees did not have canopies and there was little risk of damaging the finish on fruit surfaces.

1.3 Farm-to-farm notification

1.3.1 A call for improved communication

A survey of growers in Ohio revealed the use of multiple strategies to reduce drift, concern about impacts of drift reduction on farm profitability, more could be done to identify sensitive areas potentially impacted by drift, and little incentive to communicate with neighbors (92). In response to the spike in work-related drift exposure incidents, WA DOH renewed its call for improved communication between farms, handlers, and crew members as a high priority issue for prevention (15). Currently, there is no system in place to notify workers or employers of applications that will be taking place on adjacent property.

1.3.2 Worker notification

Worker notification can be broadly defined as risk communication in an occupational setting. Traditionally, worker notification occurs after an event of interest, comes in the form of spoken or written word, and is directed at individuals or a group. In 1991, a group of leaders from academia, industry, labor, and government gathered for a workshop to discuss the methodology of worker notification. The proceedings were published in an entire issue of the *American Journal of Industrial Medicine*, where worker notification was defined as the "communication of job-related health risks to workers: whether to do it, when, how, and, to what end" (93). One article from the workshop described the developing concept of worker notification:

> "Over the past two decades, worker notification has gained increasing acceptance both as a worthwhile public health measure and as an ethical imperative linked to the right to know. In some cases, informing occupationally exposed individuals about their long-term health risks can save lives and promote health through early disease detection. It can also stir deep fears, produce unintended social consequences, and expose with painful clarity some of the nation's unresolved political tensions" (Needleman 1993). –*Worker Notification: Lessons from the Past p.11* (94)

Other articles discussed whether it was necessary to return results of worker health studies to the workers themselves. Discussion was limited to notification of health risks after the time of exposure. Our study, on the other hand, aims to explore the utility of risk communication before exposure occurs.

1.3.3 Federal rules for worker notification of pesticide applications

1.3.3.1 Worker Protection Standard

The federal Worker Protection Standard (WPS) for Agricultural Pesticides was established by the US EPA to reduce the risk of pesticide-related illness and injury among agricultural workers and handlers—those workers who mix, load, or apply pesticides (95, 96). The WPS has requirements for agricultural employers about central posting and notification of workers. Central posting rules require employers to display three basic items: pesticide-specific information, emergency information, and a pesticide safety poster (96). Central posting must be in a location easily seen by all on-site agricultural workers, occur before the application, and continue for 30 days after the application or REI expiration. Notification rules require employers to share two basic items: location of the treated area and timing of application and re-entry interval (REI) (96). Workers must be notified either orally or by posted warning signs, though some pesticide labels require both types of notification (i.e. "double notification"). Oral warnings must be delivered to workers in an understandable manner before the application (or re-entry) and must contain specific instructions not to enter the treated area until the REI has expired. Posted warning signs must be in place before application and during any REIs, visible and legible from all worker entry points, and removed within 3 days after REI expiration. Oral and posted warnings are not needed for agricultural employees who stay at least a quarter mile from the treated area (96, 97).

US EPA finalized extensive revisions to existing WPS requirements in November 2015, including some pertaining to notification and central posting that agricultural employers and handler employees were required to comply with beginning in 2017. Changes to notification requirements called for more robust posting of treated areas (any products with an REI greater than 48 hours) and re-entry workers to receive information in advance about pesticides to be used, area to be worked, tasks to be performed, required personal protective equipment (PPE) to be worn, and a maximum amount of time to be spent in the treated area (98). Changes to central posting requires employers to post pesticide application information and safety data sheets (SDS) for all pesticides used on the farm at a central location (i.e. "central display"). Agricultural employers are now required to maintain—and make available upon request to workers, handlers, designated representatives, and treating medical professionals—records of all central display information used on the agricultural establishment for two years (98). This change reflects US EPA efforts to make WPS consistent with the Occupational Safety and Health Administration (OSHA) Hazard Communication Standard (HCS), which is rooted in the "Right-To-Know" legal principle and was recently updated to align with the Globally Harmonized System of Classification and Labeling of Chemicals (97–99).

1.3.3.2 Application exclusion zones (AEZ)

In an attempt to minimize drift exposures, revisions include "application exclusion zones" (AEZ) around active application equipment and strengthened requirements for handlers during applications (i.e. "suspending application" if an unequipped person enters a restricted area) (100). The AEZ refers to the "area surrounding pesticide application equipment that must be free of all persons other than appropriately trained and equipped handlers during pesticide applications" (100). Essentially, the AEZ is a buffer that moves with application equipment as it travels through an area while spraying. The size of an AEZ depends on the application equipment method and the droplet sizes (VMD) that it produces. An AEZ of 100 feet is required for aerial, airblast, fumigant, smoke, mist, and fog applications and also for any applications that produce droplets with VMDs of 294 microns or smaller. An AEZ of 25 feet is required for applications that produce droplets larger than 294 microns and at a distance of more than 12 inches from a target surface. All other applications that do not fit into these categories do not require an AEZ (100).

1.3.3.3 Between-farm communication

Farm-to-farm communication to prevent neighboring workers from drift exposure is not addressed by the current or revised WPS. Although proposed WPS revisions state that communication barriers can increase the risk of pesticide exposure due to tasks performed by agricultural workers, between-farm communication is not listed as a possible solution. The most closely related requirements pertain to the exchange of pesticide-specific information for handlers and agricultural employers on the same farm. In an effort to minimize drift exposures, the revisions include buffer zones around treated areas and strengthened requirements for handlers during applications (i.e. "ceasing application" if someone other than a properly trained and equipped handler enters a restricted area). Such measures do not ensure drift protection from neighboring workers, as they are likely to be excluded from within-farm exchanges of information while working outside buffer areas.

1.3.4 Washington State rules for notification of pesticide applications

Pesticide applications for agricultural purposes in Washington are subject to WPS requirements, including central posting and notification (96, 101, 102). Additionally, the Washington State Legislature passed a law that allows pesticide-sensitive individuals to register with the state and be contacted by certified applicators in writing, in person, or by telephone when making landscape or right-of-way applications near their homes (103). The same law also requires posting and notification of nearby public schools, daycares, and nursing homes when pesticides are used (104). These codes set a precedent for notification by applicators, but do not extend protection to those exposed in occupational settings.

1.3.5 Use of notification technology in prevention

Recent advances in mobile and web-based technologies have increased capacity for rapid, one-way public notification systems that businesses, government agencies, educational institutions, and many private groups are utilizing to enhance their emergency preparedness by communicating actionable risk (105, 106).

Examples of this are messages receivable after voluntary self-subscription to a notification system that sends automated email or Short Message Service (SMS) messages. Such notifications are not only crucial for life safety during events such as severe weather, chemical spills, flooding, fires, or evacuation notices, but also have utility as workplace alerts.

1.3.6 Framework for a modern occupationally-based notification system

Although there is no system in place to notify workers or employers about pesticide applications taking place on adjacent property, the framework for an agriculturally-based electronic notification system already exists to some degree. Short Message Service (SMS) and email notification systems have been proposed and used by organizations in New Zealand, the United Kingdom, China, Canada, and the United States. None of these programs have the stated goal of preventing occupational exposure to pesticide drift on adjacent land, but many possess the potential to be modified in such a way.

1.3.7 Spray notification methods and models

A 2006 United Kingdom (UK) study categorized public spray notification methods in two ways: property-based direct notification and field-based remote notification (107). Property-based direct notification describes applicators who notify residents of each individual adjacent property via direct contact, typically in writing such as a leaflet, a telephone call, or even an in-person visit. Field-based remote notification involves an applicator who creates a notification for a field and does not have direct contact with residents. Residents of any adjacent properties are either notified automatically or seek the information themselves, typically via the internet, automated telephone messaging, or public rights of way (PROW) notice boards posted in visible locations around sprayed fields. According to the 2006 study, direct notification tended to be more popular with residents but farmers preferred remote notification. The study also made a clear distinction between notification and disclosure. Notification was defined as supplying information before spraying about the proposed field location, pesticide product, and date. Disclosure was defined as fulfilling requests from the public after spraying about the same parameters plus application rate and weather conditions (107).

1.4 Study aims

This study seeks to identify risk factors for documented occupational pesticide drift events, evaluate new engineering controls to reduce worker exposure due to pesticide drift, and prevent worker exposure to drift by assessing the feasibility of farm-to-farm spray notification. The dissertation is organized according to the following specific aims:

- **Chapter 2: Identify risk factors for documented occupational pesticide drift events involving workers in Washington State, 2000-2015**
  - Establish spatio-temporal extent of occupationally-related drift events and weather data
  - Compare applicator self-reported weather conditions to historical weather conditions
  - Estimate risk of occupationally-related drift events due to wind speed and direction changes
- **Chapter 3: Evaluate new engineering controls to reduce worker exposure to pesticide drift during pest control applications in tree fruit orchards**
  - Measure potential inhalation and dermal exposure to pesticide drift for three pesticide spray technologies using a micronutrient tracer method
  - Develop relative ranking of tree spray technologies for reducing farmworker exposures
- **Chapter 4: Assess the feasibility of farm-to-farm spray notification to prevent farmworker exposure to drift in Washington**
  - Examine existing pesticide spray notification systems to determine their strengths and limitations, as well as their relevance to the Washington tree fruit industry
  - Interview tree fruit industry personnel responsible for pesticide applications regarding the desirability of a notification system and barriers to the implementation of such a system
- **Chapter 5: Summary of findings and final conclusions**

2 Wind Conditions and the Risk of Pesticide Drift Exposure Among Washington Agricultural Workers

2.1 Abstract

Pesticide drift, or the off-target movement of pesticides, represents a key cause of not only crop damage and economic loss but also occupational and bystander illness. Nationally, drift has been shown to account for 37-68% of pesticide-related illnesses among United States agricultural workers (1, 2). Compared to residential exposure to pesticide drift, illness from occupational exposure tends to be reported with similar frequency but higher severity (3). It remains a significant public health concern in the Pacific Northwest, especially among tree fruit workers (4). New approaches are needed to understand the mechanisms of pesticide drift exposure. To our knowledge, no study has systematically linked historical weather data to a large body of documented pesticide drift illness reports (5–7). For this study, we linked data from the Washington State Department of Health (WA DOH) with data from the Washington State University (WSU) AgWeatherNet (AWN) system to characterize drift-related weather conditions for 252 reported drift events involving 738 individuals between 2000 and 2015. We then determined the risk of exposure due to wind speed and direction changes. To match conventional agricultural use, units in this chapter are expressed in US customary units and converted to SI units when necessary.

This chapter addresses the following sub-aims:

- Establish spatio-temporal extent of occupationally-related drift events and weather data
- Compare applicator self-reported weather conditions to historical weather conditions
- Estimate risk of occupationally-related drift events due to wind speed and direction changes

2.2 Introduction

Growers in Washington utilize fertile soil, diverse growing conditions, and extensive irrigation networks to produce over 300 crops each year on 36,000 farms that cover nearly 15 million acres (108, 109). Washington leads the nation in production of apples, hops, sweet cherries, pears, and blueberries; it also ranks highly for potatoes, grapes, onions, raspberries, and asparagus (108, 109). Large-scale food production in the United States (US) involves the use of conventional pesticides, which includes herbicides, insecticides, fungicides, and fumigants. According to the most recent estimates from 2012, the agricultural sector accounted for 899 million pounds or 89 of conventional pesticide use in the US (110). During the 2012 growing season in Washington, conventional pesticides designed to control weeds, crop diseases, insects, and plant growth were applied to 4.5, 1.6, 1.3, and 0.4 million acres, respectively (111).

Pesticides play an important role in protecting the food supply by controlling agricultural pests and plant diseases and protecting public health by controlling vectors of human and animal diseases (112, 113). By their nature, pesticides can be toxic to unintended target organisms, including humans (114). Agencies therefore track the magnitude and characteristics of pesticide-related illnesses through public health surveillance to ensure that pesticides do not pose unreasonable burdens (115). For example, the Washington Department of Health (WA DOH) is mandated to coordinate a surveillance program that documents pesticide-related illness, a reportable condition in Washington (32, 33). WA DOH gathers a suite of information that is coded according to a standardized case definition that was created by the National Institute for Occupational Safety and Health (NIOSH) Sentinel Event Notification System for Occupational Risks (SENSOR)-Pesticides Program (35, 36). Washington is one of twelve states in the program. Data collected by WA DOH Pesticide Illness Monitoring and Prevention Program investigators are used to identify public health problems and develop strategies to prevent human exposure and illness related to pesticides (31). In 2010, WA DOH, Washington State Department of Agriculture (WSDA), and the Department of Labor and Industries (L&I) renewed a Memorandum of Understanding that "describes the cooperative efforts of the three agencies relative Agricultural Pesticide Worker Protection Standards and their respective roles and responsibilities" (31).

Pesticide drift, or the off-target movement of pesticides, represents a key cause of not only crop damage and economic loss but also occupational and non-occupational illness among bystanders (3). Nationally, drift has been shown to account for 37-68% of pesticide-related illnesses among US agricultural workers (1, 2). Compared to non-occupational pesticide drift exposure, illness from occupational exposure tends to be reported with similar frequency but higher severity in the US (3). It remains a public health concern in the Pacific Northwest. In 2010-2011, WA DOH estimated that 51% ($\frac{67}{131}$) of cases resulting from agricultural applications were drift-related, of which 64% ($\frac{43}{67}$) were workers drifted on by an adjacent farm (31). Between 2010 and 2015, agricultural drift illnesses in Washington ranged from 0.33 to 1.85 cases per 100,000 individuals (116). In May 2014, WA DOH reported that 60 individuals, mostly orchard workers, became ill in 15 drift events over a two-month period, a number normally seen in one year (37, 117). The events occurred in dense orchard regions of Washington and largely involved airblast sprayers, which have been the standard tool for orchard pesticide application since the 1950s. Over time, the desire for more fruit-bearing trees has reduced tree height and canopy volume. As a result, traditional airblast sprayer output no longer matches modern canopies, increasing drift potential (8, 118, 119). In Washington, the majority of drift exposure cases result from orchard airblast applications.

US EPA and state regulatory agencies differentiate primary spray drift, which occurs during an application or soon thereafter, from secondary off-target movement, which occurs well after application. The term "drift" is used as shorthand for primary spray drift in this chapter. A "drift event" is generally defined as an "incident where one or more drift cases experienced drift exposure from a particular source" (3) (Figure 2.1). A "drift case" is an individual with a documented drift exposure. The Spray Drift Task Force (SDTF), formed by pesticide registrants in collaboration with EPA, determined that spray drift was the movement of droplets irrespective of pesticide active ingredient, and that contributing factors included environmental and meteorological conditions, spray technique, and crop type (82, 83).

Meteorology plays a key role in the fate and transport of spray droplets (3, 39, 40). Computer modeling has shown that meteorological variables are least controllable by applicators and vary constantly over time and space (41). Wind speed and direction are the primary meteorological drift determinants. Droplet size and release height modify the effects of meteorology on spray droplet movement. Fluctuation in wind direction indicates the amount of atmospheric turbulence and dilution of small droplets. Smaller droplets increase crop coverage, but they also promote drift in the presence of smaller gravitational forces and larger wind speed and direction changes (23, 41). Unfavorable wind conditions have been identified as leading contributing factors for acute illnesses resulting from drift (3, 4). In one of the May 2014 drift events, applicator and meteorological records showed that wind speeds were low (0-4 miles per hour, mph) and blowing away from the workers early in the day; at the time of the event, however, wind speeds were as high as 18 mph (4). The public health sector could better exploit meteorological data to understand the influence of weather on health, using that information to forecast—and thereby reduce exposure to—health risks.

New approaches are needed to understand the mechanisms of pesticide drift exposure, particularly in orchard regions. To our knowledge, no study has systematically linked historical weather data to a large body of documented pesticide drift illness reports (5–7). We linked data from WA DOH with data from the Washington State University (WSU) AgWeatherNet (AWN) system to characterize drift-related weather conditions for reported drift events involving individuals between 2000 and 2015. The network is intended to assist growers with "advisories, customized weather alerts and decision support systems…[to] help improve production and product quality, optimize resource use, and reduce environmental impact" (120). AWN provides remote, real-time weather monitoring on its website using continuous updates via cellular telemetry networks and the internet (120, 121). We intended to enhance surveillance of occupational illness by looking back in time at those locations for specific weather conditions or patterns that could indicate different pesticide application timing. This study explores the use of meteorological data in the context of pesticide illness surveillance and epidemiological investigation in Washington.

We hypothesized that: 1) applicator-reported wind conditions would not significantly differ from nearby weather stations and 2) spray periods with drift events would have greater wind speeds and larger, more frequent wind direction changes than spray periods without drift events. We expected that the risk of exposure would increase with more dramatic shifts in wind speed and direction.

2.3 Methods

2.3.1 Establish spatio-temporal extent of drift events and weather stations

We developed a geographic information system (GIS) that linked geocoded and time-specific drift event data from WA DOH to two geospatial layers: weather and cropland. To generate best estimates of wind speed and wind direction for the time and location of each drift event, we drew on historical data from AWN by using a nearest neighbor approach. WSU's AWN system makes historical meteorological data available for more than 170 stations across the state (120). Features of interest were 15-min average wind speed (miles per hour, mph) and direction (22.5° increments). Crop-mapping specialists at WSDA have developed an agricultural land use geodatabase that contains annual estimates of crop area and type in a regularized grid of one square mile sections (109). A geodatabase stores and organizes GIS data in one large folder as point, polygon, or polyline layers. In addition to our best estimates of wind speed and wind direction at the time of exposure, we characterized regions susceptible to drift events by computing descriptive statistics for such variables as method of application, target crop, work activity of individuals at the time of exposure, and number of individuals who reported a drift-related illness for each event. We stratified by crop type because application methods vary greatly among orchard, row, and field crops.

2.3.1.1 Washington Department of Health data

Pesticide exposure and illness database

We collaborated with the WA DOH Pesticide Illness Monitoring and Prevention Program to geocode time-specific data for agricultural drift events between the years 2000 and 2015. The Washington State Institutional Review Board determined that the project was research not involving human subjects. The analysis included the following pesticide exposure variables: date and time of event, zip code and county of event, event location, equipment used for application, target crop being sprayed, activity of the exposed individual at the time of exposure, work-relatedness of the exposure, and illness severity category. The dataset was limited to pesticide applications in agricultural settings and exposures that resulted from drift, defined by NIOSH as individuals who were "exposed via the movement of pesticides away from the treatment site. The pesticide spray, mist, fumes, or odor are carried from the target site by air" (122).

Drift events were restricted to those involving at least one confirmed case. Each year, WA DOH personnel investigate hundreds of potential pesticide exposure cases to determine whether there is a causal relationship between reported symptoms and pesticide exposure (31). Investigators conduct interviews; take field visits; and review pesticide application records, medical records, and reports from other state agencies (31). The NIOSH Case Classification System is used to categorize illnesses as 'Definite', 'Probable', 'Possible', 'Suspicious', 'Unlikely', 'Insufficient information', 'Asymptomatic', or 'Unrelated' (123) (Appendix A). In this study, we restricted the analysis to 'Definite', 'Probable', and 'Possible' (DPP) cases and refer to them collectively as 'Confirmed' cases based on a preponderance of evidence. Confirmed cases had documentation of pesticide exposure, adverse health effect, and evidence supporting a causal relationship between pesticide exposure and toxicological effects (31). Like other states in the SENSOR-Pesticides program, WA DOH identifies confirmed cases based on documentation of the pesticide exposure pathway, adverse health effects (symptoms or signs of illness), and toxicological evidence of a causal relationship between the observed exposure and health effects in a likely time frame. Any other individuals associated with drift events were classified as 'Unconfirmed' cases. 'Event size' was computed by counting the number of confirmed cases associated with each event.

Although we included all agricultural drift events for the study period, our focus for the analysis was on those involving tree fruit.

Review of application and exposure records

WA DOH data from the study period were reviewed to extract spatio-temporal features, applicator-reported weather conditions, and intended target crops for each event with at least one confirmed case. Pesticide application and exposure information was then organized for subsequent spatial analysis in a way that would safeguard the identity of individuals (124).

Pesticide application information involved a detailed review of spray records for:

- Date and time of application
- Reported wind speed, wind direction, and temperature (minimum, average, maximum)
- Target crop and acreage
- Geodata: lat/long, township/range/section codes, address, intersection, city, zip code, county

Exposure information involved a detailed review of WA DOH and WSDA investigation reports for:

- Date and time of exposure
- Reported distance of exposed individual from spray source
- Drift basis: interview; sampling result; corroboration by manager, spray record, or map
- Geodata: lat/long, township/range/section codes, address, intersection, city, zip code, county

2.3.1.2 AgWeatherNet data

We extracted geolocation (latitude and longitude, lat/long), 15-min average wind speed (miles per hour, mph), and 15-min average wind direction (degrees) from AWN meteorological stations throughout the state between the years 2000 and 2015 (120, 121). Meteorological variables are recorded every 5 s and summarized every 15 min by battery-powered data loggers that are recharged through a solar panel. Standard sensors are installed on each AWN station to record air temperature and relative humidity, soil temperature and moisture, wind speed and direction, leaf wetness, rainfall, solar radiation, and air pressure (125). Data were provided courtesy of Washington State University AgWeatherNet and are copyright of Washington State University (120).

2.3.1.3 Washington State Department of Agriculture land use data

Crop-mapping specialists at WSDA have developed an agricultural land use geodatabase that contains annual estimates of crop area and type in a regularized grid of one square mile (640 acre, 259 hectare) sections (126, 127). These one square mile sections match the naming structure of the Township/Range/Section feature class originally developed by the Public Land Survey System (PLSS) (126–128). The PLSS divides land into 6-mile square townships (Figure 2.3), which are subdivided into 36 one-mile square sections (Figure 2.4). Each section is identified by a unique township (north-south) and range (east-west) designation (128). We added the land use layer to our GIS to confirm the DOH target crop coding and to restrict the analysis to tree fruit only. Orchard regions tended to have a higher density of weather stations because they generate inputs for insect pest life cycle models. This suggested that historical weather data were available in locations reasonably close to drift event sites involving orchards (Figure 2.5).

2.3.1.4 Geocoding process

Geocoding is the process of converting locations, addresses, or other geographic information into geographic coordinates, which can then be positioned on a map. All drift event locations were processed according to their estimated lat/long. Locations were available at various levels of precision, depending primarily on event year and depth of investigation. The geocoding process involved the following hierarchical workflow:

1. Global positioning system (GPS) coordinates
2. Township/Range/Section (TRS) centroid
3. Street address
4. City centroid
5. Zip code centroid

The most precise locations were reported as a pair of GPS coordinates (lat/long) and the least precise locations were reported as zip codes only. If an event did not have GPS coordinates, then TRS centroid (geometric center of a feature) was considered the next optimal choice in rural areas, followed by street address, city centroid, and zip code centroid. Zip codes in rural areas usually contained multiple cities. Geocoding was performed by taking the text description of a location and translating it to lat/long so it could be added as a GIS layer. Washington Master Addressing Services (WAMAS), a Microsoft Excel add-in tool available to government agencies, was used to correct addresses to US Postal Service standard format and add lat/long coordinates to addresses for displaying on a map or in a GIS (129–131). Accuracy and source values were also returned. Approximately 10% of randomly selected geocoded locations were checked against land use and satellite data imagery to ensure accuracy. After coordinates were assigned to each drift event, geoprocessing was completed with ArcMap 10.3 (132). Washington Department of Ecology technical standards were followed to create the GIS (133–135):

- North American Datum (NAD) of 1983 and High Accuracy Reference Network (HARN)
- Lambert Conic Conformal projection system
- Washington State Plane Coordinates system (South Zone)

- Lat/long were converted to coordinate units of US Survey Feet with an accuracy standard of ±40 feet or better

The "Generate Near Table" proximity tool in ArcMap 10.3 was used to find the point-to-point Euclidean planar distance between each drift event and the 10 nearest AWN stations (136). In addition to distance between drift event and nearest AWN stations, the tool also provided the angle (0° to the east and 90° to the north) from the drift event point to each of the nearest AWN points on the near feature (136). Due to a two-fold increase in the number of stations between 2007 and 2008 (Figure 2.11), we expected that mean distance to the nearest station would be significantly greater for the first half of the study period.

Data were managed and analyzed with R version 3.4.0 (2017-04-21) using the following packages: beeswarm, bookdown, ggplot2, ggthemes, gridExtra, knitr, lattice, lubridate, pander, reshape, and survival (16, 137–146). We produced descriptive statistics tables; scatter, bar, and time series plots; and chorpleth maps.

2.3.2 Compare applicator-reported and historical weather conditions during time of spray

Certified pesticide applicators in the State of Washington are required to record the start and stop time, wind speed, and wind direction for applications to more than one acre of agricultural land in a calendar year (42) (Figure 2.2). For all drift events involving tree fruit with complete records (n=47), we computed the difference between applicator self-reported average wind speed at the start of application and the 15-min averaged historical wind speed for the same time period. Under the assumption that the differences followed an approximately normal distribution, we used a two-sided paired t-test to evaluate the null hypothesis that the true mean difference between applicator-recorded and historical wind speeds was zero at the α = 0.05 level. We reported point estimates, 95% confidence intervals, and p-values. For a sample size of 30 drift events, we expected to be able to detect a difference of 5 miles per hour 97% of the time when the standard deviation (SD) of the differences was 5. Finally, we evaluated the proportion of paired wind direction records that differed from each other by more than 45°, proportion of wind speed records that differed by more than 25%, and the impact of weather station proximity on these differences. These values were based on our *a priori* definition of wind speed ramping and direction change events (see next section).

2.3.3 Estimate risk of drift events due to wind changes during time of exposure

We employed a case-crossover study design to investigate the impact of wind speed and direction changes during drift events (n=252) by comparing determinants of exposure on drift event days with non-drift days (i.e. referent days). Instead of comparing cases to noncases like a case-control study, the case-crossover study uses subjects as their own control to minimize confounding (147). The design uses separate time windows to define periods of momentarily elevated risks (i.e. "cases") and periods with baseline levels (i.e. "controls"). It compares exposure (i.e. wind conditions) at an index time close to the event with exposure at other referent times. The case-crossover design is computationally equivalent to a matched case-control study apart from the fact that controls are the same person before the event occurs. Cases in our study were drift-prone locations instead of humans.

To avoid overlap bias from event-based referent selection centered on the event itself (e.g. symmetric bidirectional sampling) (148, 149), we selected referents *a priori* based on time-stratified spray periods that are typical of the Washington State growing season (Mar-Oct). We divided the growing season into 14-day referent windows to have referent days with comparable pesticide applications hypothetically occurring without drift events (Figure 2.7). For example, a drift event day occurring anywhere in referent window 1 was on a "blue" day or a "green" day in (Figure 2.7). The drift event day was then compared to all other days in the referent window that were the same color (i.e. referent days). Each referent window color was a set of 7 days that represented all days of the week (i.e. 7 days in the two-week period). Based on previous field experience, we expected the likelihood of spraying to be no different on weekdays compared to weekends.

For each drift event day, wind speed and direction data were restricted to 2-hr exposure windows with 15-min resolution (i.e. 8 data points per window). We defined an exposure window as the 2-hr period immediately preceding the last reported time of exposure. Referent windows included the same 2-hr period (e.g. 6-8 AM) as the index exposure window of a drift event day. Any referent window falling on another WA DOH-recorded drift event day or in a window with measurable rainfall was excluded from analysis.

Exposure windows were compared with referent windows in terms of: 1) magnitude of wind speed changes as measured by the coefficient of variation (CV), which is the ratio of the arithmetic standard deviation (SD) to the arithmetic mean, and 2) magnitude of wind direction changes as measured by arithmetic standard deviation (SD). We explored the change of wind speed over time using a novel metric known as "wind ramping," which is being developed for wind power forecasting and can be described as large shifts in wind speed at a given location over a short period of time (150–155). Since there is no standard, we defined a wind speed ramping event as a 25% or greater change in wind speed during each 2-hr exposure window. Similarly, we defined a wind direction change event as a 12.5% (45° azimuth wind angle) or greater change in wind direction during each 2-hr exposure window (Figure 2.6).

We used conditional logistic regression to model the probability of a drift event occurring as a function of wind speed change and wind direction change in a generalized linear model with Bernoulli response and a log-odds link function (Equation (1)).

$$\text{logit}(Event) = \beta_0 + \beta_1 Wind\ Speed\ CV + \beta_2 Wind\ Direction\ SD + \beta_3 Speed\ CV \times Direction\ SD + \epsilon \quad (1)$$

Wind covariates were handled continuously according to significant wind changes during the exposure window, including an interaction term for wind speed and direction. Model results provided point estimates and confidence intervals for the probability of tree fruit drift events (i.e. odds ratio produced by the clogit function from the "survival" package in R). Our secondary model had the same terms but was expanded to include all crop drift events.

We also conducted a sensitivity analysis that included wind speed, temperature, relative humidity, and humidex as categorical predictors in the primary model. For wind speed, 25th, 50th, and 75th percentiles of wind speed measurements from two hour exposure windows (n=9 data points) of tree fruit events were each divided into tertile-based categories (low, medium, and high). For temperature, relative humidity, and humidex, 50th percentiles of tree fruit events were divided into tertile categories.

2.4 Results

Between the years 2000 and 2015, we identified 252 drift events involving 738 individuals, 690 of whom were confirmed cases. In tree fruit only, there were 151 drift events involving 320 confirmed cases. Weather data were available for 78% ($\frac{197}{252}$) of all crop drift events and 81% ($\frac{122}{151}$) of tree fruit events.

2.4.1 Descriptive statistics

2.4.1.1 Drift events

The mean number of events occurring annually in all crops was 15.8, ranging from 9 (4%) in 2010 to 25 (10%) in 2002 (Table 2.1). The confirmed cases to event ratio was 2.7 ($\frac{690}{252}$) for the entire study period, with the highest years being 2008 (6.4) and 2014 (5.9). About 64% of events involved 1 confirmed case and 8% involved 5 or more confirmed cases (Table 2.2). Tree fruit was the most common application target among all events (60%) and confirmed cases (46%) (Table 2.3). About 68% of all agricultural drift events involved a ground sprayer, 23% involved aerial application, and all other methods were used fewer than 4% of the time (Table 2.4). When restricted to events occurring in tree fruit only, the proportion involving ground sprayers—also known as orchard airblast sprayers—was 89%.

2.4.1.2 Drift cases

Among 690 confirmed drift cases involving all target crops, 69% were work-related (Table 2.5). A similar distribution was observed for tree fruit drift cases (n=320). At the time of reported exposure, 68% of confirmed cases were engaged in work activities not involving application to all target crops and the remaining 1% were handling pesticides or application equipment (Table 2.6). Approximately 19% of cases involving all target crops and 23% of cases involving tree fruit were engaged in routine outdoor living activities. Low severity illneses, which typically resolved without medical treatment, were by far the most common at 91% and 89% of cases drifted on from all target crops and tree fruit, respectively (Table 2.7). Low severity illnesses typically included skin, eye or upper respiratory irritation and fever, headache, fatigue, or dizziness.

2.4.2 Spatio-temporal extent of tree fruit drift events and weather data

2.4.2.1 Temporal extent

The AWN was comprised of 47 stations in 2000, grew to 171 by 2015, and now has 177 as of 2017 (Figure 2.11). Notably, the number of stations nearly doubled from 76 to 131 between 2007 and 2008.

The mean number of all crop events occurring annually was 15.8, ranging from 9 (3.6%) in 2010 to 25 (9.9%) in 2002 (Table 2.1). Restricting to tree fruit events only, the number of events per year remained relatively constant throughout the study period, but the number of confirmed cases per year was higher in more recent years. For example, there were 52 and 53 confirmed cases in 2013 and 2014, which was nearly twice the magnitude of cases (n=27) in 2002, which was the next highest observed year (Figure 2.12).

Approximately 78% ($\frac{26+37+22+33}{151}$) of all tree fruit events occurred in March, April, May, or June, with

25% ($\frac{37}{151}$) occurring in April (Figure 2.13). Confirmed cases in tree fruit showed a similar trend with 28% ($\frac{88}{320}$) occurring in April. Tree fruit events were distributed equally across all days of the week, with the exception of Sunday (Figure 2.14). The largest proportion of events ($\frac{30}{151} = 20\%$) and cases ($\frac{86}{320} = 27\%$) occurred on Thursday. Tree fruit events were distributed somewhat normally across hour of day, with 21% ($\frac{28}{133}$) of events and 16% ($\frac{43}{264}$) of cases occurring between the hours of 10:00 AM and 11:00 AM (Figure 2.15). Very few cases reported a time of exposure before 5:00 AM or after 4:00 PM (16:00). About 12% ($\frac{18}{151}$) of tree fruit events did not have exposure time of day data available.

Two additional figures provide evidence for the seasonality of drift events on day of year and calendar date time scales. Figure 2.16 indicates that no tree fruit drift events occurred before the 60th day of the year (March 1 in non-leap years) or after the 290th day (October 17 in non-leap years). Aside from the relatively short periods of about 115 days or less in 2001, 2002, 2005, and 2012, there does not appear to be clear trends in terms of the start, frequency, and length of the "drift season" across study years. The large drift events in 2011, 2013, and 2014 are also notable as larger vertical stacks of red marks. Figure 2.17 plots each event as a purple mark on the day of occurrence, with deeper purple marks indicating drift events with more cases involved. This figure illustrates that the first week of June is a particularly common time for drift events to occur. It also highlights the possible trend of events with 5 or more cases occurring earlier each year, on average.

2.4.2.2 Spatial extent of tree fruit drift events

Listed in terms of decreasing accuracy for rural areas, events were geocoded according to lat/long GPS coordinates (6.0%), TRS centroid (21.8%), street address (56.7%), city centroid, (7.9%), and zip code centroid (1.6%) (Table 2.9). About 6% of all crop events and 8% of tree fruit events did not have location of exposure data available and therefore could not be geocoded. Geometric mean (GM) distances from the nearest AWN station to all crop events and tree fruit events were 4.0 miles (6.4 km) and 3.8 miles (6.1 km), respectively (Table 2.10 and Figure 2.18). Before the substantial increase of AWN stations in 2008 (Figure 2.11), GM distance was 4.2 miles (6.8 km) among tree fruit events. In 2008 and after, GM distance was 3.5 miles (5.6 km) (Table 2.10).

Confirmed cases who were exposed in all crop events reported a range of distances between 291 and 439 ft (88.7-133.8 m), on average, from the source of the spray (Table 2.11). When restricted to tree fruit only, the range of distances from the spray source were 197 and 224 ft (60.0-68.3 m), on average.

Approximately 80% of all drift events occurred in a ZIP code with at least one weather station. We estimated that 70% of all crop drift events occurred in Grant, Yakima, and Douglas counties. Combined, these three counties had about 44 weather stations in 2015. Many tree fruit growing regions of Washington have a high density of AWN stations, as shown in the the Yakima Valley (Figure 2.5). Choropleth maps of all crop drift events (n=252) and confirmed cases (n=690) by county, zip code, and zip code and year indicate good AWN station coverage (green) for grower decision-making needs (Figures 2.8, 2.9, and 2.10).

2.4.3 Applicator-reported vs. historical wind conditions at application start

Spray records were available for 36% ($\frac{90}{252}$) of drift events. Among those, 47 events in tree fruit had enough information about spray start time, location to be linked based on wind speed and 39 had enough information to be linked based on wind direction. Approximately 85% ($\frac{40}{47}$) of paired wind speed records differed from each other by more than 25% and 59% ($\frac{23}{39}$) of paired wind direction records differed from each other by more than 45°.

Applicator-reported wind speed was not associated with 15-min AWN wind speed ($R^2 = 0.05$) (Figure 2.19). AWN average wind speeds represented the 15-min interval containing the applicator spray start minute, which was reported as time of day (hh:mm). The line of unity represents perfect agreement between the two values. AWN 15-min average wind speed at the nearest AWN station was higher than 83% (n=39) of the average wind speeds reported by applicators at the spray start time.

Greater differences between applicator-reported wind speed and AWN wind speed were strongly associated with increasing AWN speed ($R^2 = 0.68$) (Figure 2.20). Data points for 8 wind speed difference measurements were on the line of unity, indicating instances where the applicator-reported zero wind speed during non-zero AWN wind speed. Conversely, 8 wind speed difference measurements were negative, indicating instances where the applicator-reported a wind speed that was higher than AWN speed. The x-intercept indicates that, on average, AWN speeds were higher than applicator-reported speeds when AWN speeds were above 2.3 mph. The slope indicates that, on average, there was an 0.86 mph increase in mean difference for each 1.0 mph increase in AWN speed.

Weather station proximity did not impact the observed differences between paired wind speed and direction records. The difference between applicator-reported wind speed and AWN wind speed was not associated with distance to the nearest AWN station ($R^2 = 0.01$) (Figure 2.21). Similarly, the difference between applicator-reported wind direction and AWN wind was not associated with distance to the nearest

AWN station ($R^2 = 0.03$) (Figure 2.22).

Two-sided paired t-test results suggest that the true mean difference between applicator-reported wind speed and AWN wind speed was non-zero (Table 2.8). On average, the highest applicator-reported speeds were 1.8 mph lower than 15-min average AWN speeds (95% CI: -2.97, -0.70; $p = 0.0021$). Average applicator-reported speeds were 2.8 lower than 15-min average AWN speeds (95% CI: -3.76, -1.79; $p < 0.001$). The lowest applicator-reported speeds were 3.7 mph lower than 15-min average AWN speeds (95% CI: -4.64, -2.78, $p < 0.001$).

2.4.4 Risk of drift events due to wind changes before time of exposure

A total of 15,252 wind speed measurements were available for 2-hr exposure windows containing 9 data points each from 120 tree fruit events. There were 1,082 measurements from drift days and 14,170 from control days (Table 2.14). Median wind speeds for drift days and control days were 4.0 and 3.9 mph, respectively; maximum wind speeds were 21.4 and 26.3 mph. There were no profound interquartile range (IQR) differences between drift days and control days for each 15-min measurement interval preceding the reported time of drift exposure (Figure 2.23). Between 0 and 105 minutes preceding the reported time, median wind speeds on drift days were equal to or greater than control days. Between 0 and 180 minutes preceding, 75th percentile wind speeds were always greater on control days. There was no appreciable difference between median temperature, relative humidity, or humidity index (humidex) on drift days versus control days (Table 2.14). Median temperature was 60-61°F, relative humidity was 48-50%, and humidex was 58-59°F.

Empirical cumulative distribution function (ECDF) plots for 15-min average wind speed, wind speed coefficient of variation (CV), and wind direction standard deviation (SD) for 2-hr exposure windows indicate that differences between drift days and control days were small, if not absent (Figure 2.24). The top panel shows that approximately 90% of the wind speeds on drift days and control days were below 10 mph in all crops and tree fruit only. Median wind speed was 3.71 mph (1.66 m/s) in all crops and 3.81 mph (1.70 m/s) in tree fruit. Maximum drift day wind speed was 21.41 mph (9.57 m/s) in all crops and tree fruit. The middle panel shows slightly higher drift day wind speed CV compared to control days between the 60th and 95th percentiles in all crops. However, the same trend in wind speed CV is not observable in tree fruit. The bottom panel indicates slightly higher drift day wind direction SD compared to control days between the 30th and 80th percentiles. Again, the same trend in wind direction SD is not seen in tree fruit.

Results from the primary model provided an odds ratio (OR) of 1.007 (95% CI: 0.990, 1.025, p = 0.43) for wind speed CV in tree fruit only (Table 2.12). Similarly, ORs for wind direction SD and the interaction of wind speed CV and wind direction SD were not significantly different than the null hypothesis at the $\alpha = 0.05$ level. In other words, our model did not demonstrate that changes in wind speed and wind direction would increase the probability of a drift event in tree fruit.

Results from the secondary model provided an OR of 1.011 (95% CI: 1.001, 1.020, $p < 0.05$) for wind speed CV in all crops (Table 2.13). Thus, the odds of a drift event happening in all crops increased by 1.1% for each 1 unit increase in wind speed CV. However, ORs for wind direction SD and the interaction of wind speed CV and wind direction SD were still not significantly different than the null hypothesis at the $\alpha =$ 0.05 level.

Table 2.15 provides a summary of sensitivity analysis results, which are reported as odds ratios (OR) and 95% confidence intervals (CI) for tree fruit drift event probabilities. As shown in Models 1-3, effect estimates generally increased with 25th, 50th, and 75th wind speed percentile covariates, but there was no observable exposure-response relationship within wind speed percentiles categorized by tertiles. In Model 4, the relationship between wind speed and drift event probability was attenuated by adjusting for temperature and relative humidity categorically. Similarly, Model 5 showed that adjusting for humidex attenuated the relationship between wind speed and drift events. It should be noted that humidex had the strongest effect estimates and exposure-response trends.

2.5 Discussion

Washington agriculture is diverse, productive, and a large component of the State's economic engine (108, 109). The use of pesticides has an important role in protecting the food supply; with it comes the responsibility of safe use. Sixteen years of human incident data indicate pesticide drift is a recurring issue and that illness severity is often low. Understanding the mechanisms behind pesticide drift can help minimize exposures not only to humans but also to sensitive crops. Meteorology is a known contributing factor for pesticide drift (3, 4, 39, 40). Not well understood, however, is the effect of wind speed and direction on human exposure incidents. Each drift event could be considered an individual case study unto itself, with an array of factors such as environmental conditions, geography, orchard architecture, sprayer settings, and human behavior impacting the final outcome. These challenges notwithstanding, our study tried to shed light on this complex issue by utilizing the known spatio-temporal aspects of drift events and historical weather data. Sixteen years of detailed data from WSU AWN and WA DOH provided us with a unique opportunity to conduct a retrospective exposure assessment to determine the risk of changing wind on the probability of drift events. Our findings did not fully support our hypotheses, but the effort yielded several novel findings and directions for future research.

We attempted to link data from 171 weather stations to 252 drift events in all crops and 151 events in tree fruit between the years 2000 and 2015. On average, there were 15.8 drift events in all crops per year, with 78% of tree fruit events occurring in March-June, the bulk of which occurred between the hours of 6:00 and 10:00 AM. Weather data were available for about 80% of the events at a median distance of 3.8 miles (6.1 km) away from the site of exposure. Although we used geocoordinates to determine distances, there was some imprecision with this approach due to using centroids of larger administrative areas such as cities, zip codes, and TRS codes. Even when spray records were available, we occasionally had to rely on the "Address of Person for Whom Pesticide was Applied" field, which could have been the location of a separate administrative building away from the application site (Figure 2.2). Confirmed cases reported a distance of 197-224 ft (60-68 m), on average, between themselves and the spray source in tree fruit. The range of reported distances was due to discrepancies between reports (e.g. applicators vs. exposed individuals) or multiple individuals whose distances varied from one drift event source. Distance information was usually gathered from the narratives in the DOH and WSDA reports. Sometimes, distance was reported as the number of tree rows between the applicator and exposed individuals; we used a standard row width of 8 feet. While crude, the confirmed case distance estimate provides important evidence for the US EPA's Application Exclusion Zone (AEZ), which states that orchard airblast sprayers must be free of all untrained persons within a 100 ft (30 m) radius during pesticide applications (100).

On average, applicator-reported speeds were 2.77 mph (1.24 m/s) less than 15-min AWN speeds (95% CI: -3.76, -1.79; $p < 0.001$, n=47) (Table 2.8). AWN speeds were higher than 83% of applicator-reported speeds. These findings have important implications for the accuracy of our study and the applicator's anemometer reading methods. For example, a mean distance of 3.8 miles may not be sufficient for capturing the microclimates and wind variability experienced in orchard settings. Alternatively, it is possible that applicators were not using a standardized approach for measuring and reporting wind conditions. In one study about human exposure to pesticide drift, applicator and meteorological records showed that wind speeds were low (0-4 mph, 0-1.8 m/s) early on a spray day, but wind speeds increased to 18 mph (8.0 m/s) during the time of exposure later in the day (4). This finding is consistent with the highest AWN wind speed readings during tree fruit drift days: 21.4 mph (9.6 m/s).

For each drift event, we restricted 15-min average wind data to the 2-hr period immediately preceding the reported time of exposure and analyzed for shifts in wind speed or direction. No signal was present in our primary case-crossover model results. The secondary model, which included drift events in all crops, showed a small association between wind speed CV and the probability of a drift event occurring. As highlighted by the ECDF curves, wind conditions did not differ greatly between spray days and control days (Figure 2.24). There are a number of considerations as to why this could be the case. First, there might not have been a true difference between spray days and control days in terms of wind conditions. Second, 15-min average wind readings in the absence of wind gust data might have "muted" the effect of strong wind pulses, also known as wind ramping events, on drift days. Third, other factors could have a larger impact on the probability of drift event occurrence. Distance or elevation could have been included in the model, as well as other meteorological variables such as humidity, temperature, and presence or absence of inversion conditions. Although we did not see evidence of a relationship between wind speed accuracy and distance from the nearest meteorological station, having a weather station that is representative of the event conditions at the time of exposure, especially in microclimate terms. Our study likely faced the same challenge of detecting a small signal that other air pollution studies encounter. Most of these issues related to our construction of controls and the lack of granularity in the data. Finding ideal controls for each drift event scenario was challenging in the absence of spray records or pesticide use data for applications that avoided drift (i.e. data for sprays that successfully reached the application target only). The presence of nearby workers during control sprays is a crucial element that could not be recreated for this study. Instead, we could only match within a two-week window based on time of day.

Some practical solutions can be gleaned from this work. Installation of wind meters in orchards with digital readouts on a tractor pulling a sprayer would assist applicators with recording accurate weather conditions not only at the spray start time but also throughout the spray period. If our model is improved upon, an alert system would be possible. Both Washington State and US EPA would like to provide farm managers and workers better guidance in the area of pesticide drift (44, 45). This study aimed to provide a better understanding of how meteorological factors contribute to drift events and could lead to new training materials to improve the practice of pesticide application and better documentation of spray drift events. The linkage of occupational health drift event data with historical weather data over multiple years is a new approach to the study of pesticide drift. Despite its null findings, our use of a time-stratified sampling frame in a case-crossover study of drift events represented a state-of-the art approach.

There are several avenues to explore for future research. Our study used a "nearest neighbor" geoprocessing approach to estimate wind conditions for each drift event (156, 157), but a more elegant approach would be to use data from several nearby station instead of one. Despite the challenges of spatializing meteorological data in heterogeneous landscapes, Venäläinen (2002) and Luo et al. (2008) have described successful kriging methods for using a network of weather stations to interpolate measured weather data onto a grid (158, 159). Gridded data can then be used to run agricultural models such as crop yield or pest life cycles (158). Future studies could use cokriging (wind speed) and anisotropic kriging (wind direction) to generate estimates across a grid appropriate for AgWeatherNet wind data (159). We explored the change of wind speed over time using a novel metric known as "wind ramping," which is being developed for wind power forecasting and can be described as large shifts in wind speed at a given location over a short period of time (150–155). Wind ramping is a promising development in the wind energy industry and could have utility for predicting future drift events. To our knowledge, the concept has not been used in agricultural or air pollution settings. Our study has demonstrated that wind speed CV and wind direction SD are possible metrics by which to define wind ramping for drift events.

2.6 Tables

Table 2.1: Year of drift event by case status, all crops, 2000-2015.

Year	Events n(%)	Confirmed cases n(%)	Unconfirmed cases n(%)	Confirmed cases to event ratio
2000	19 (7.5)	59 (8.6)	1 (2.1)	3.1
2001	12 (4.8)	24 (3.5)	-	2.0
2002	25 (9.9)	45 (6.5)	2 (4.2)	1.8
2003	13 (5.2)	22 (3.2)	-	1.7
2004	13 (5.2)	17 (2.5)	-	1.3
2005	13 (5.2)	30 (4.3)	-	2.3
2006	12 (4.8)	16 (2.3)	-	1.3
2007	12 (4.8)	20 (2.9)	-	1.7
2008	13 (5.2)	83 (12.0)	-	6.4
2009	16 (6.3)	27 (3.9)	-	1.7
2010	9 (3.6)	22 (3.2)	-	2.4
2011	16 (6.3)	49 (7.1)	14 (29.2)	3.1
2012	15 (6.0)	43 (6.2)	2 (4.2)	2.9
2013	18 (7.1)	60 (8.7)	9 (18.8)	3.3
2014	22 (8.7)	129 (18.7)	6 (12.5)	5.9
2015	24 (9.5)	44 (6.4)	14 (29.2)	1.8
Total	252 (100)	690 (100)	48 (100)	2.7
Mean	15.8	43.1	3	
Median	14.0	36.5	0	

Table 2.2: Drift event size by case status, all crops, 2000-2015. Drift event size reflects the number of cases involved in a drift event.

Event size	Events n(%)	Confirmed cases n(%)	Unconfirmed cases n(%)
1	162 (64.3)	162 (23.5)	9 (18.8)
2	39 (15.5)	78 (11.3)	3 (6.3)
3	16 (6.3)	48 (7.0)	4 (8.3)
4	12 (4.8)	48 (7.0)	-
5	3 (1.2)	15 (2.2)	7 (14.6)
6+	20 (7.9)	339 (49.1)	25 (52.1)
Total	252 (100)	690 (100)	48 (100)

Table 2.3: Intended application target in drift events by case status, all crops, 2000-2015.

Application target	Events n(%)	Confirmed cases n(%)	Unconfirmed cases n(%)
Tree fruit	151 (59.9)	320 (46.4)	30 (62.5)
Undesired plant	23 (9.1)	41 (5.9)	-
Vegetable	21 (8.3)	124 (18.0)	8 (3.2)
Soil	12 (4.8)	66 (9.6)	-
Cereal	12 (4.8)	30 (4.3)	-
Small fruit	8 (3.2)	12 (1.7)	-
Other grain/fiber	6 (2.4)	22 (3.2)	3 (6.3)
Grass	3 (1.2)	49 (7.1)	-
Beverage crop	3 (1.2)	7 (1.0)	7 (14.6)
Landscape/ornamental	3 (1.2)	6 (0.9)	-
Oil crop	3 (1.2)	5 (0.7)	-
Flavoring/spice	3 (1.2)	4 (0.6)	-
Forest	2 (0.8)	2 (0.3)	-
Building surface	1 (0.4)	1 (0.1)	-
Other fruit	1 (0.4)	1 (0.1)	-
Total	252 (100)	690 (100)	48 (100)

Table 2.4: Spray equipment used in drift events, all crops and tree fruit only, 2000-2015.

Equipment	All crops n(%)	Tree fruit n(%)
Ground sprayer	170 (67.5)	134 (88.7)
Aerial	58 (23.0)	13 (8.6)
Chemigation	9 (3.6)	-
Soil injector	4 (1.6)	-
Backpack sprayer	3 (1.2)	-
Fumigator	1 (0.4)	-
Dip tank or tray	1 (0.4)	1 (0.7)
Unknown	6 (2.4)	3 (2.0)
Total	252 (100)	151 (100)

Table 2.5: Work-relatedness for confirmed cases, all crops and tree fruit only, 2000-2015.

Work-related	All crops n(%)	Tree fruit n(%)
Yes	476 (69.0)	216 (67.5)
No	214 (31.0)	104 (32.5)
Total	690 (100)	320 (100)

Table 2.6: Activity at time of exposure for confirmed cases, all crops and tree fruit only, 2000-2015. (*) Includes exposure to field residue. (**) Includes applying, mixing, or loading pesticides or repair and maintenance of application equipment.

Activity at time of exposure	All crops n(%)	Tree fruit n(%)
Work activity not involving application*	467 (67.7)	210 (65.6)
Outdoor living activity not involving application	129 (18.7)	75 (23.4)
Indoor living activity not involving application	83 (12.0)	27 (8.4)
Handling pesticides or application equipment**	8 (1.2)	5 (1.6)
Unknown activity	3 (0.4)	3 (0.9)
Total	690 (100)	320 (100)

Table 2.7: Severity of illness for confirmed cases, all crops and tree fruit only, 2000-2015. Illness severity was categorized into low, moderate, and high using criteria developed by the SENSOR-Pesticides program. (*) High was life threatening and could have resulted in permanent disability. (**) Moderate involved systemic manifestations and required treatment. (***) Low typically resolved without treatment and included skin, eye or upper respiratory irritation and fever, headache, fatigue, or dizziness.

Severity of illness or injury	All crops n(%)	Tree fruit n(%)
High*	2 (0.3)	1 (0.3)
Moderate**	58 (8.4) 3	3 (10.3)
Low***	628 (91.0) 2	84 (88.8)
Unlikely, insufficient, asymptomatic, unrelated	1 (0.1)	1 (0.3)
Unknown	1 (0.1)	1 (0.3)
Total	690 (100) 3	20 (100)

Table 2.8: Two-sided paired t-tests suggest the true mean difference between applicator-reported wind speed and AWN wind speed was non-zero. On average, the highest applicator-reported (* AR-High) speeds were 1.8 mph less than 15-min average AWN speeds at the time of application start (95% CI: -2.97, -0.70; $p = 0.0021$). Applicator-reported average (** AR-Avg) and lowest (*** AR-Low) wind speed comparisons to AWN are also provided.

Speed comparison	Mean of differences (mph)	95% CI	p-value
AWN vs. AR-High*	-1.83	(-2.97, -0.70)	0.0021
AWN vs. AR-Avg**	-2.77	(-3.76, -1.79)	< 0.001
AWN vs. AR-Low***	-3.71	(-4.64, -2.78)	< 0.001

Table 2.9: Final breakdown of geocoding sources by latitude/longitude (Lat/Long), Township/Range/Section (TRS), street address, and centroids (geometric center of a feature).

Final geocoding source	n	(%)
Lat/Long	15	(6.0)
TRS centroid	55	(21.8)
Street address	143	(56.7)
City centroid	20	(7.9)
Zip code centroid	4	(1.6)
None	15	(6.0)
Total	252	(100)

Table 2.10: Distance to nearest station (miles), 2000-2015, by number of events (n), minimum (MIN), median (MED), arithmetic mean (AM), arithmetic standard deviation (ASD), and maximum (MAX).

Category	n	MIN	MED	AM	ASD	MAX
Distance - All crops	197	0.2	3.8	6.4	7.3	34.3
Distance - Tree fruit only	122	0.2	3.8	5.5	5.7	33.6
–2000-2007	48	0.2	4.1	5.6	4.8	26.8
–2008-2015	74	0.3	3.1	5.4	6.3	33.6

Table 2.11: Reported distance between confirmed case location and drift event source (feet), 2000-2015, by number of events (n), minimum (MIN), median (MED), arithmetic mean (AM), arithmetic standard deviation (ASD), and maximum (MAX).

Category	n	MIN	MED	AM	ASD	MAX
Distance - All crops						
–Minimum reported	118	0	78	291	683	5438
–Maximum reported	35	15	200	439	1100	6600
Distance - Tree fruit only						
–Minimum reported	71	0	65	197	659	5438
–Maximum reported	24	15	180	224	202	700

Table 2.12: Case-crossover 2-hr exposure window model summary - tree fruit only

	Pr(Drift Event):
	exp(coeff)
Wind Speed CV	1.007 (0.990, 1.025)
Wind Direction SD	0.878 (0.442, 1.744)
Wind Speed CV x Wind Direction SD	0.997 (0.982, 1.012)
Observations	1,704
R^2	0.001
Max. Possible R^2	0.241
Wald Test	1.080 (df = 3)
LR Test	1.074 (df = 3)
Score (Logrank) Test	1.088 (df = 3)
Note:	*p<0.1; **p<0.05; ***p<0.01

Table 2.13: Case-crossover 2-hr exposure window model summary - all crops

	Pr(Drift Event):
	exp(coeff)
Wind Speed CV	1.011** (1.001, 1.020)
Wind Direction SD	1.076 (0.638, 1.814)
Wind Speed CV x Wind Direction SD	0.997 (0.988, 1.006)
Observations	2,727
R^2	0.002
Max. Possible R^2	0.242
Wald Test	6.550* (df = 3)
LR Test	6.661* (df = 3)
Score (Logrank) Test	7.381* (df = 3)
Note:	*p<0.1; **p<0.05; ***p<0.01

Table 2.14: Descriptive statistics for 2-hr exposure window model covariates for wind speed (WS, mph), temperature (T, °F), relative humidity (RH, %), and humidex (Hx, °F). Listed by minimum (MIN), 25th, 75th, and 90th percentiles, median (MED), and maximum (MAX). CD = control days and DD = drift days. There were 14,170 measurements for control days and 1,082 for drift days.

Variable	n	MIN	25th	MED	75th	90th	MAX
WS-CD	14,170	0.0	2.4	3.9	6.2	9.4	26.3
WS-DD	1,082	0.0	2.5	4.0	6.1	9.4	21.4
T-CD	14,170	21.2	52.4	59.8	69.5	78.0	102.2
T-DD	1,082	32.1	51.2	61.2	71.5	79.7	92.6
RH-CD	14,170	10.4	37.0	49.6	63.7	77.1	100.0
RH-DD	1,082	12.2	36.3	48.1	59.3	71.7	99.4
Hx-CD	14,170	21.0	50.0	58.0	68.0	77.0	138.0
Hx-DD	1,082	32.0	49.0	59.0	71.0	79.0	93.0

Table 2.15: Sensitivity analysis of model results for probability of tree fruit drift events (n=121) associated with categorical wind speeds (WS, mph), adjusted for temperature (T, °F), relative humidity (RH, %), and humidex (Hx, °F) for 2-hr exposure windows. Low (L), Medium (M), and High (H) categories for 25th, 50th, or 75th percentiles. There were n=121 events in each model.

Variable	Model 1 OR (95% CI)	Model 2 OR (95% CI)	Model 3 OR (95% CI)	Model 4 OR (95% CI)	Model 5 OR (95% CI)
WS25L	Ref				
WS25M	0.92 (0.52,1.60)				
WS25H	0.87 (0.49,1.57)				
WS50L		Ref		Ref	Ref
WS50M		1.11 (0.63,1.95)		1.01 (0.57,1.81)	1.06 (0.60,1.88)
WS50H		0.99 (0.55,1.78)		0.91 (0.49,1.67)	0.98 (0.55,1.76)
WS75L			Ref		
WS75M			1.16 (0.67,2.01)		
WS75H			1.02 (0.57,1.83)		
T50L				Ref	
T50M				1.02 (0.55,1.89)	
T50H				1.61 (0.71,3.63)	
RH50L				Ref	
RH50M				0.90 (0.52,1.56)	
RH50H				0.69 (0.32,1.48)	
Hx50L					Ref
Hx50M					1.18 (0.64,2.19)
Hx50H					2.14 (0.96,4.73)

2.7 Figures

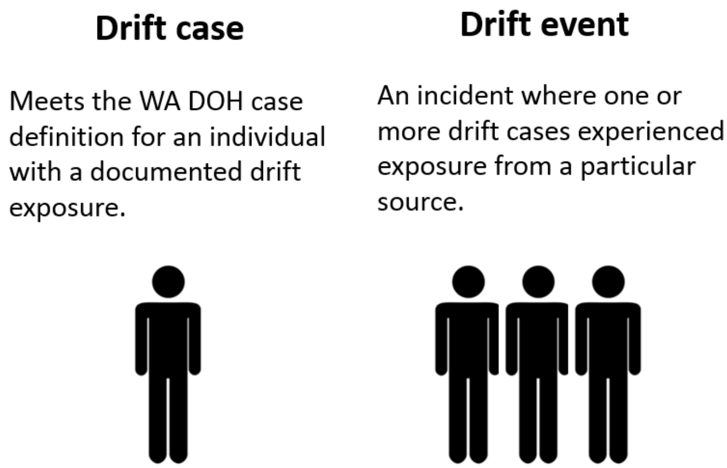
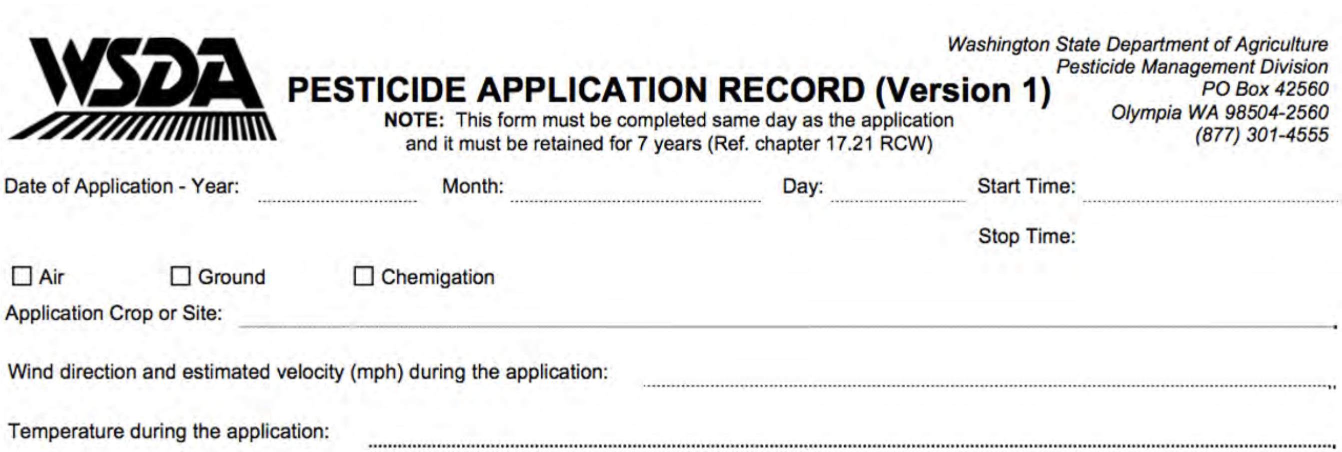


Figure 2.1: Definition of a drift case and drift event.



WSDA

PESTICIDE APPLICATION RECORD (Version 1)

NOTE: This form must be completed same day as the application and it must be retained for 7 years (Ref. chapter 17.21 RCW)

Washington State Department of Agriculture
Pesticide Management Division
PO Box 42560
Olympia WA 98504-2560
(877) 301-4555

Date of Application - Year: .... Month: .... Day: .... Start Time: ....

Stop Time:

☐ Air ☐ Ground ☐ Chemigation

Application Crop or Site: ....

Wind direction and estimated velocity (mph) during the application: ....

Temperature during the application: ....

Figure 2.2: Excerpt from application record. Note: fields have been condensed to fit on page.

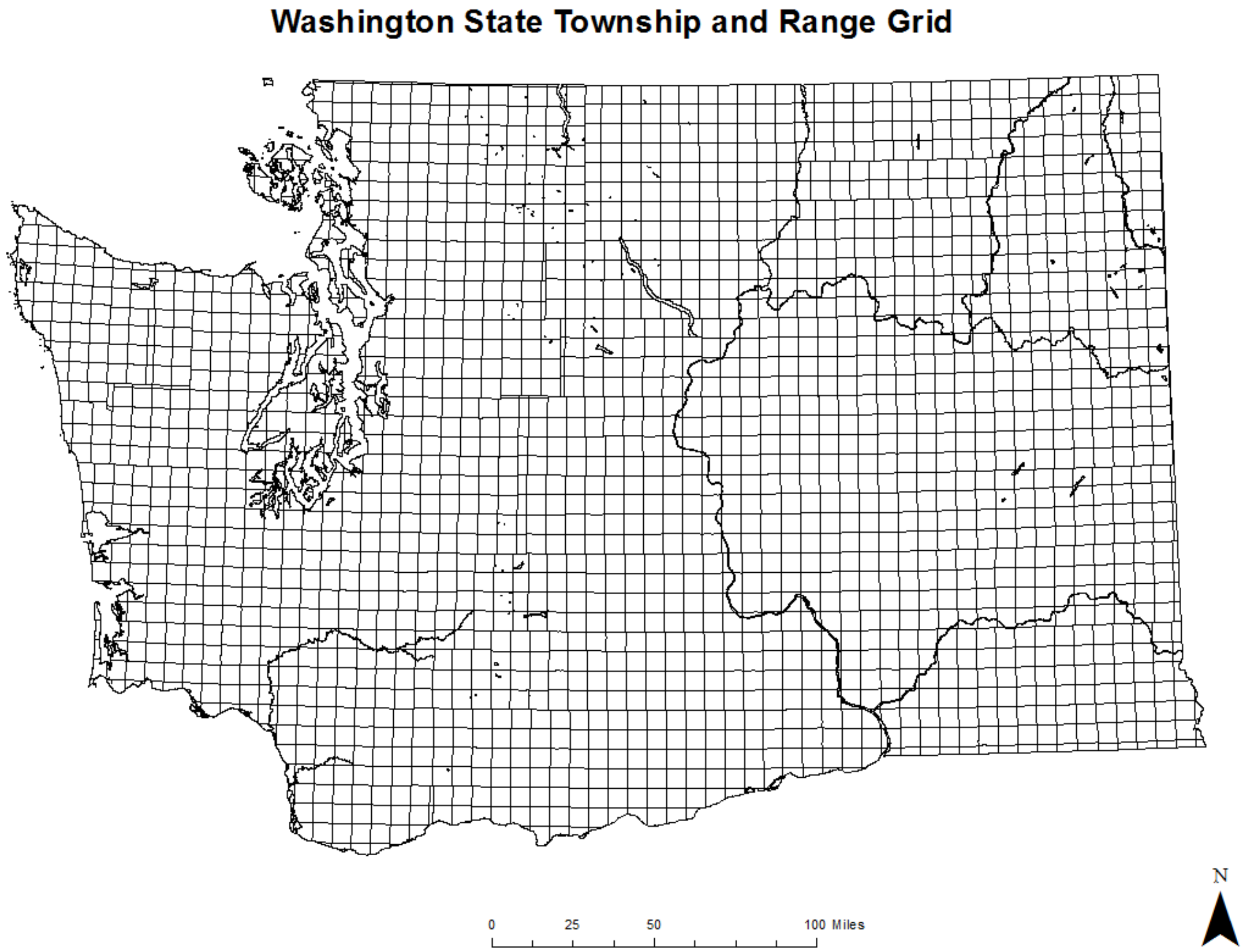


Figure 2.3: This image shows an example of the 6 $\times$ 6 mile Township and Range (TR) grid in Washington. The Public Land Survey System divides Washington into a gridded coordinate system defined horizontally as Township and vertically as Range.

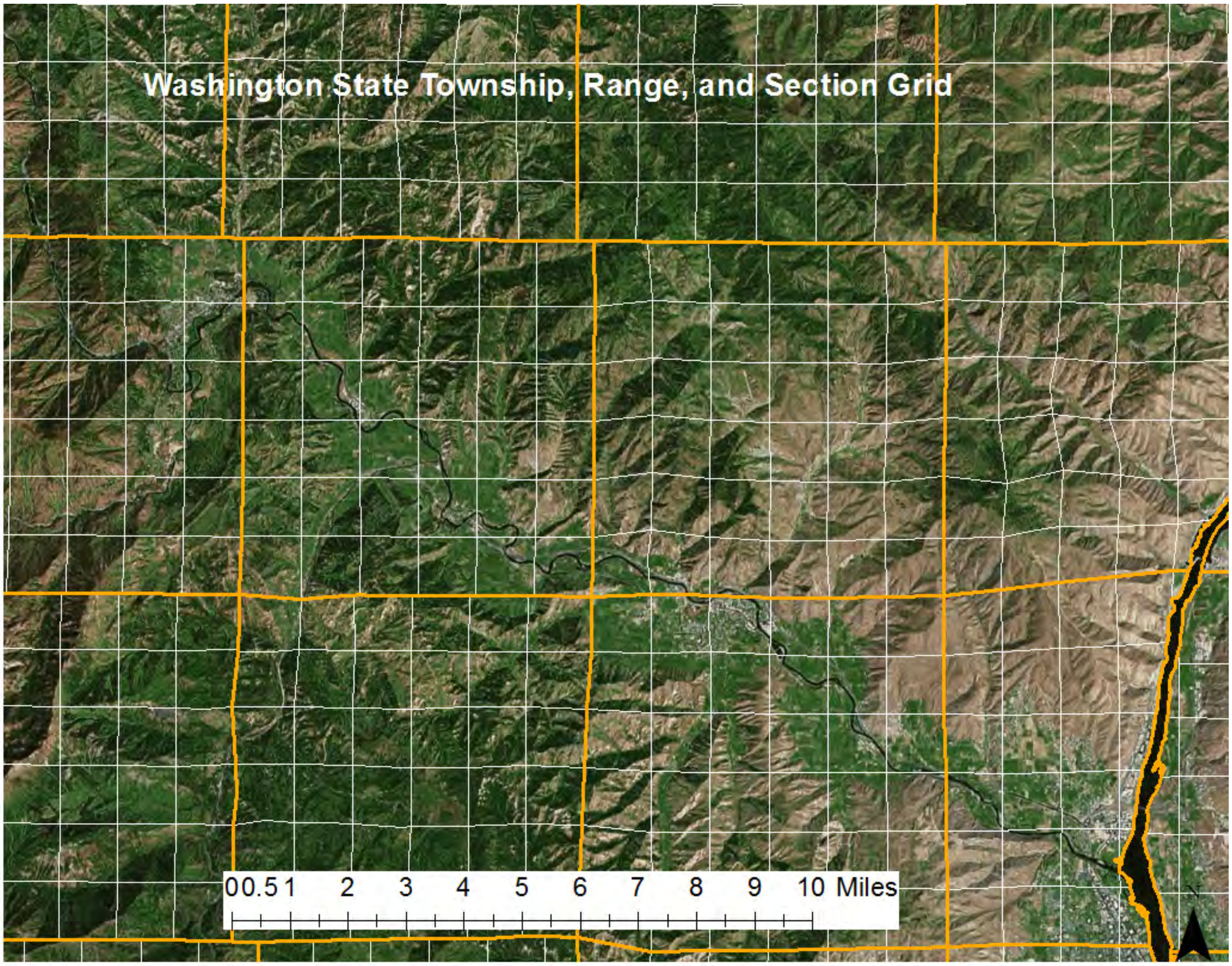


Figure 2.4: This image shows an example of the more detailed Township, Range, and Section (TRS) grid in Washington. Orange lines represent 6 × 6 mile Township and Range pairings and white lines represent 1 × 1 mile Sections. Inside each Township and Range pairing, there are 36 Sections of one square mile each. For events with a TRS code, lat/long centroids were used.

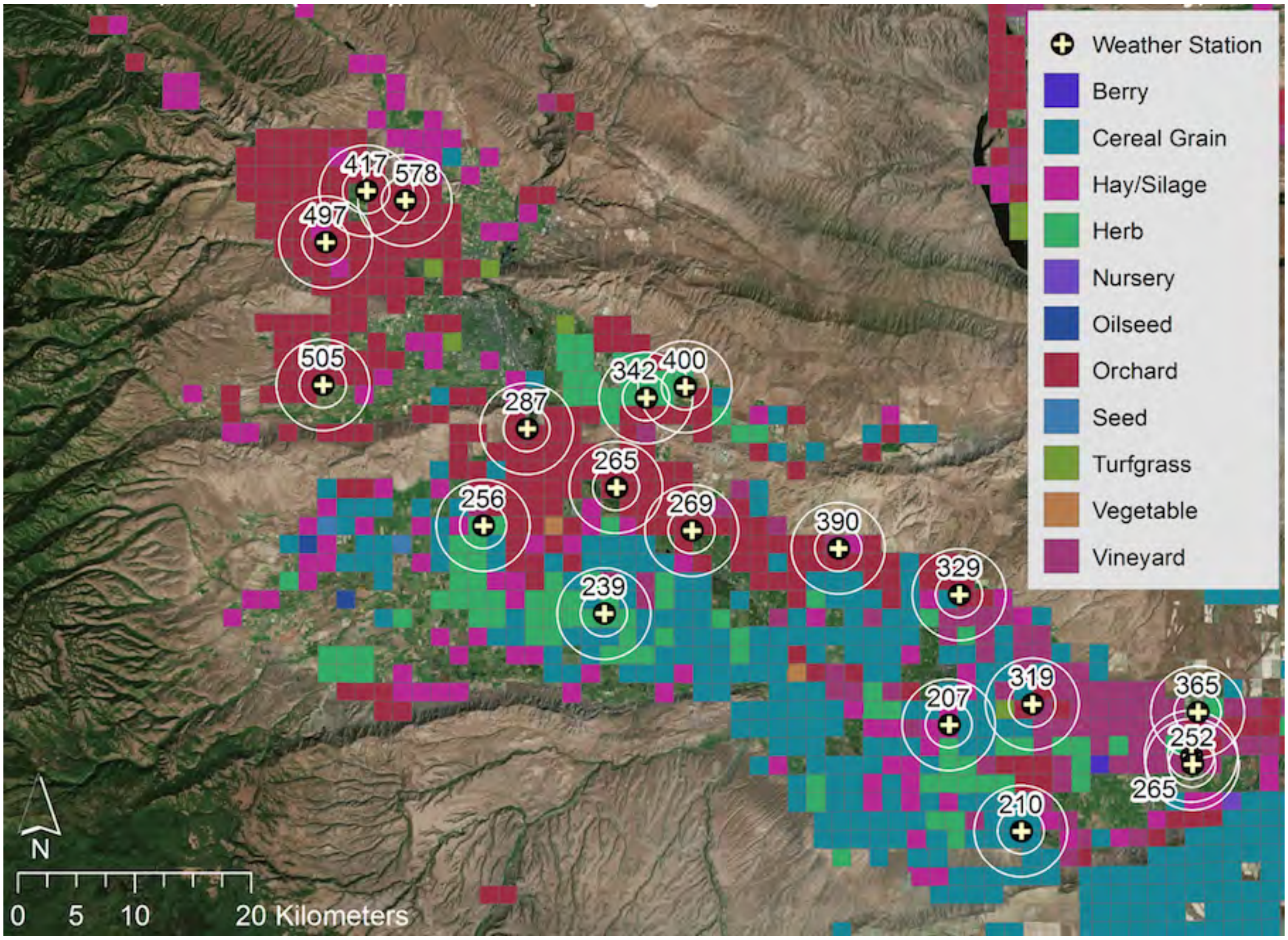


Figure 2.5: Elevation (m), buffer (2,4 km), and crops near AWN stations in the Yakima Valley, 2014.

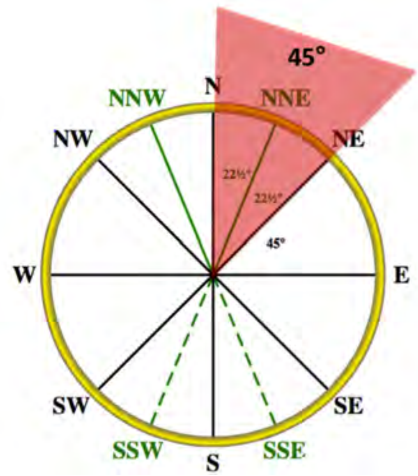


Figure 2.6: Example of a wind rose. A wind direction change event was defined as a 45° or more change in 15-min wind direction readings.

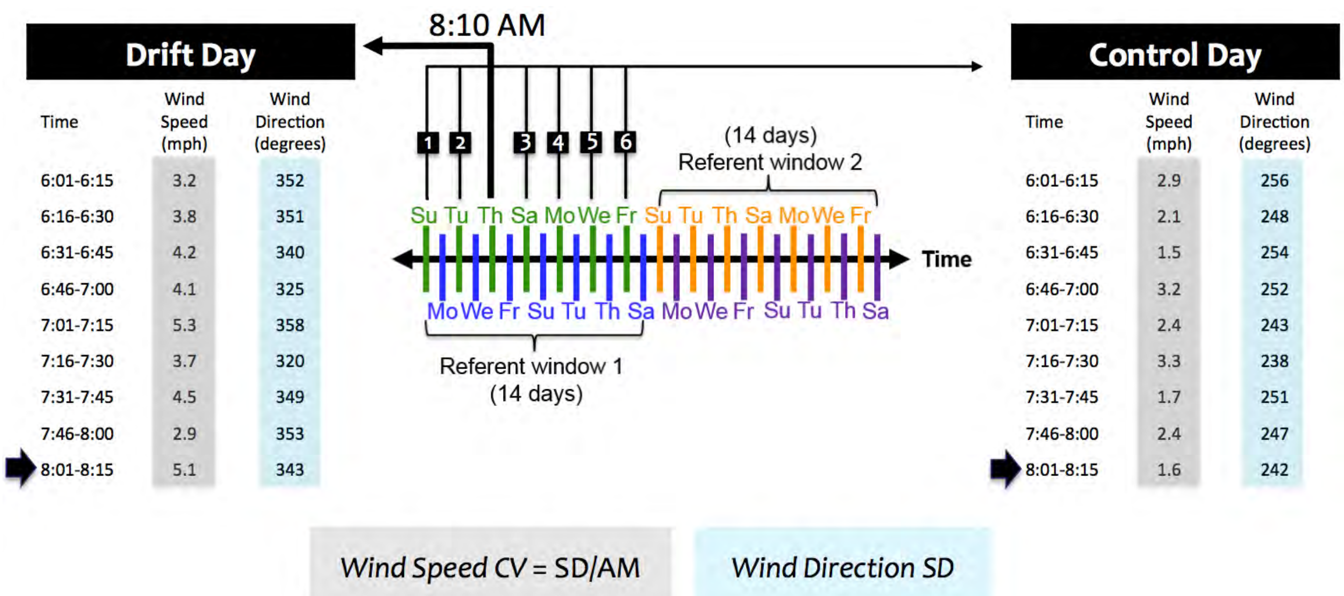


Figure 2.7: Construction of *a priori* referent windows for case-crossover analysis. The growing season was divided into 14-day referent windows to have referent days with comparable pesticide applications hypothetically occurring without drift events. Each referent window was a set of 7 days that contained all days of the week. For example, a drift event occurring on a green day at 8:10 am would be compared to the six other green days (i.e. control days) in the referent window without drift events or measurable rain. The 2-hr exposure window for this example would be 6:10-8:10, which is included in the 15-min measurement interval range shown in the figure.

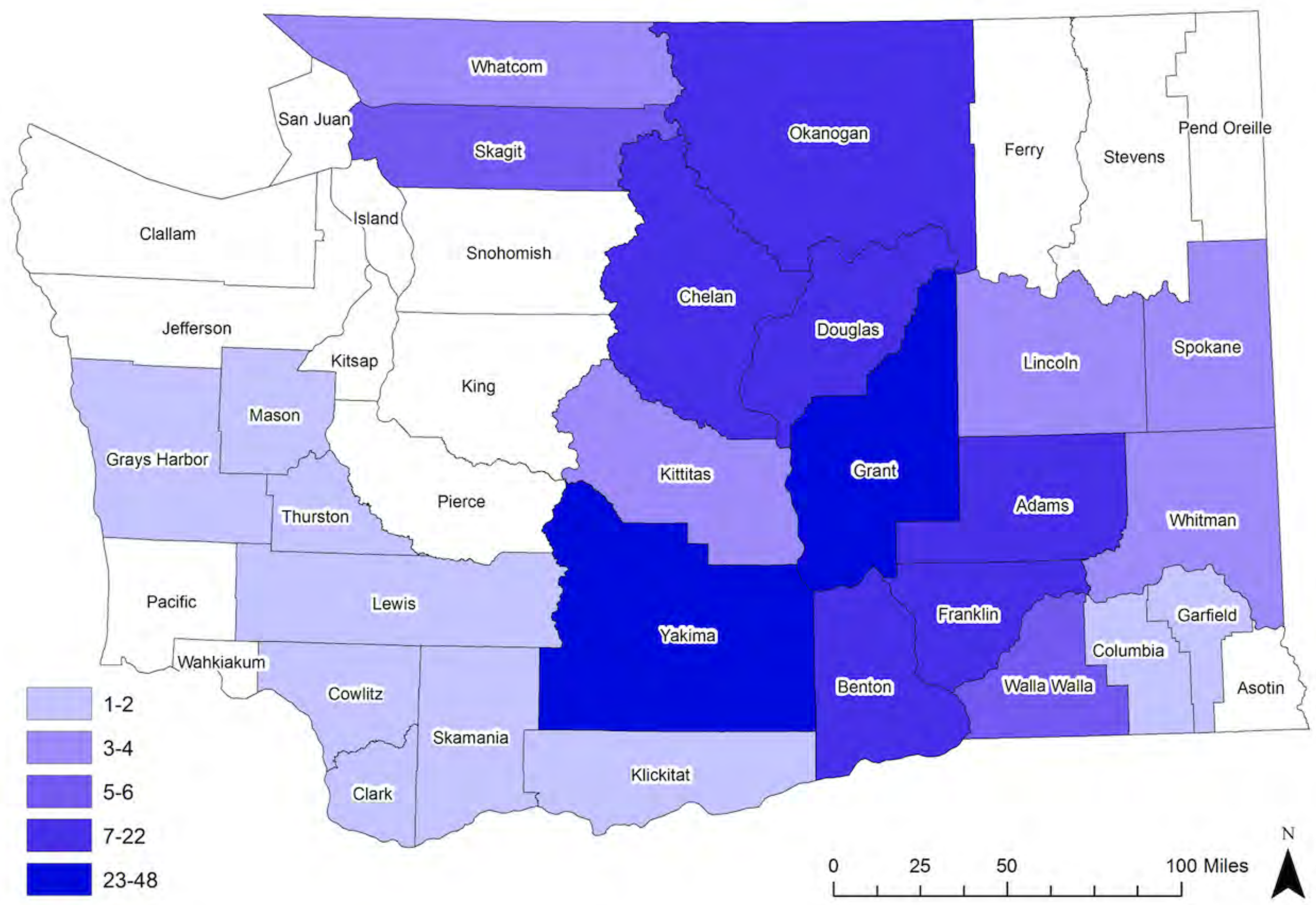


Figure 2.8: Number of events with confirmed cases by county, all crops, 2000-2015.

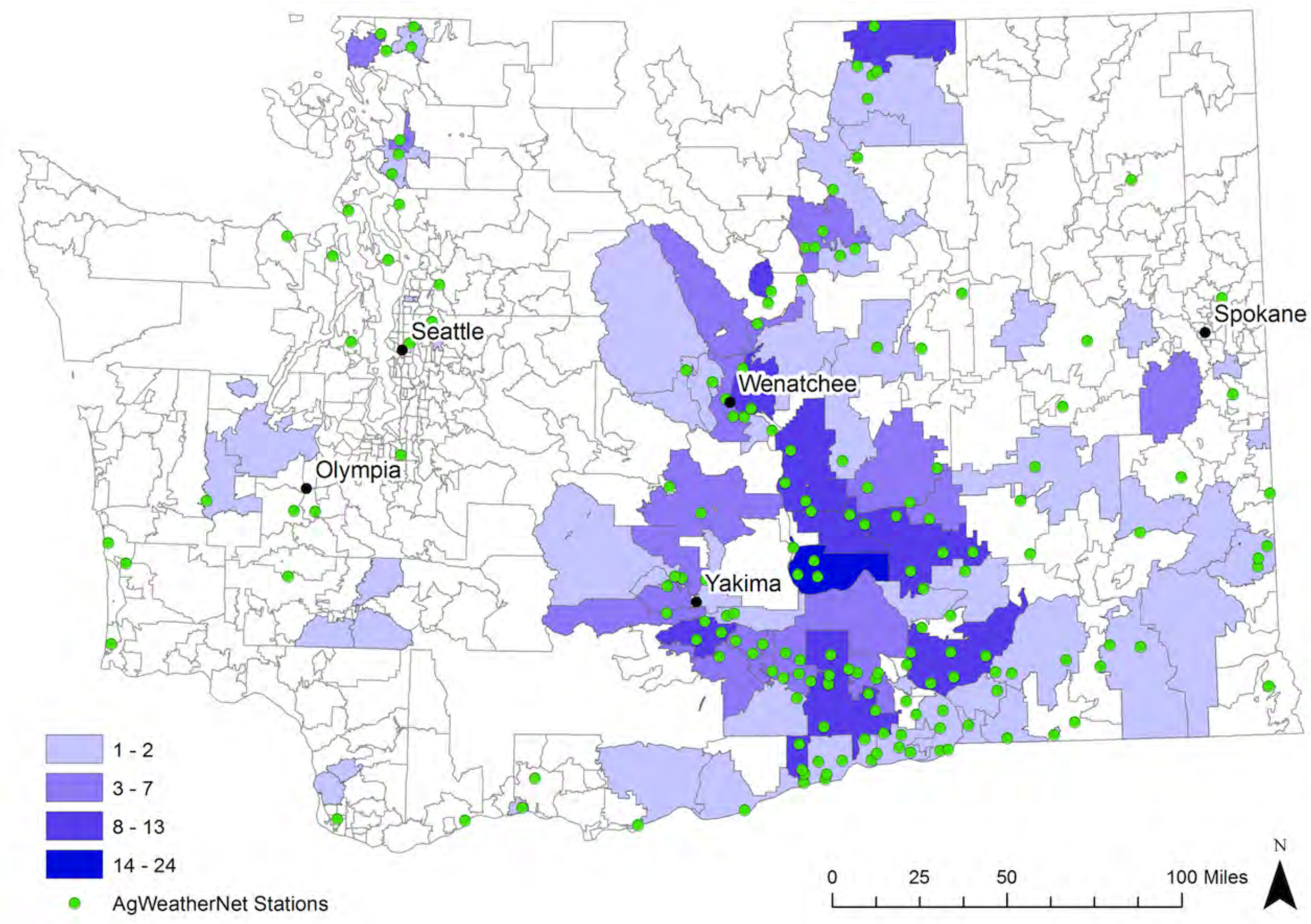


Figure 2.9: Number of events by zip code, all crops, 2000-2015.

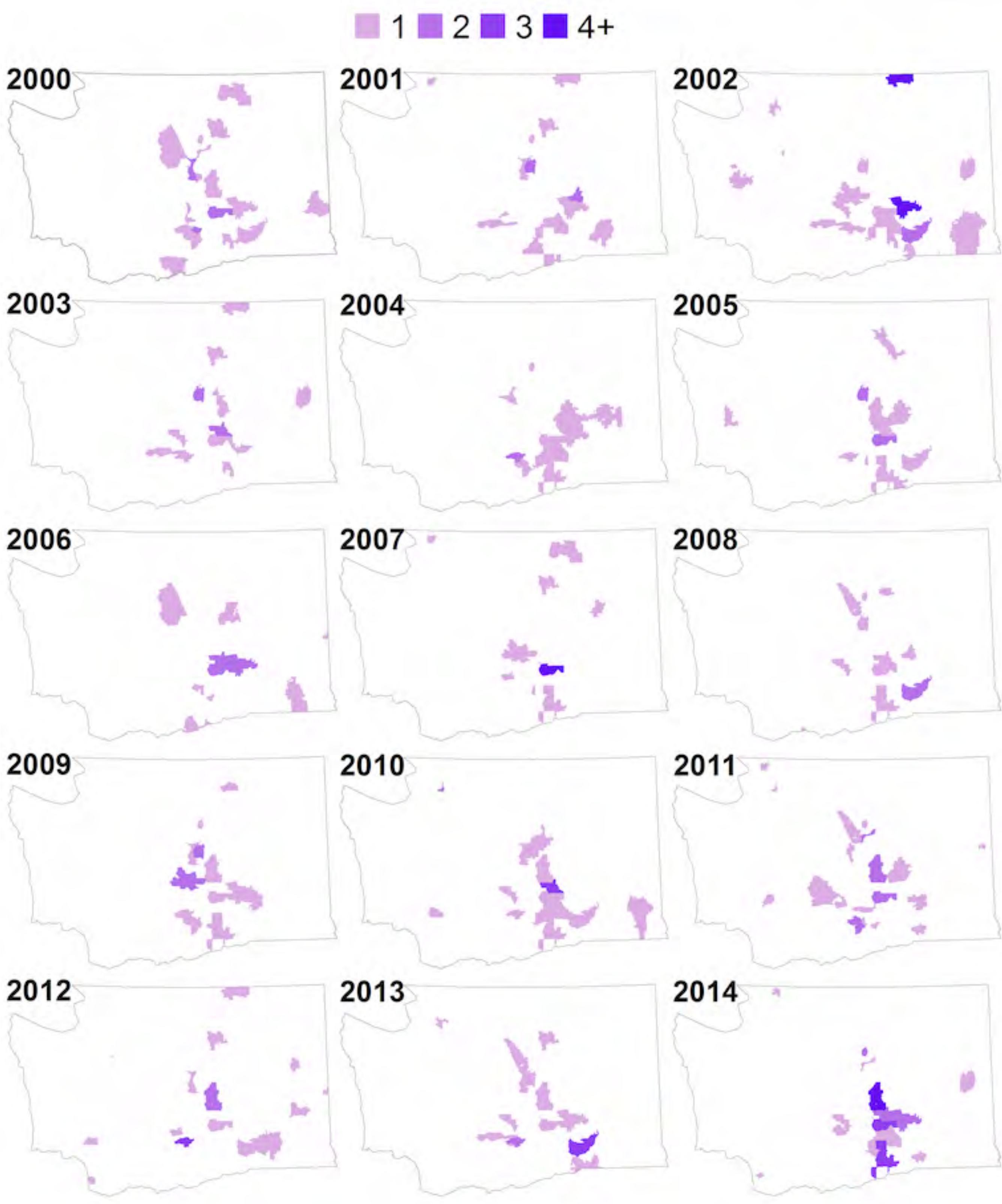


Figure 2.10: Number of events by zip code and year, all crops, 2000-2014.

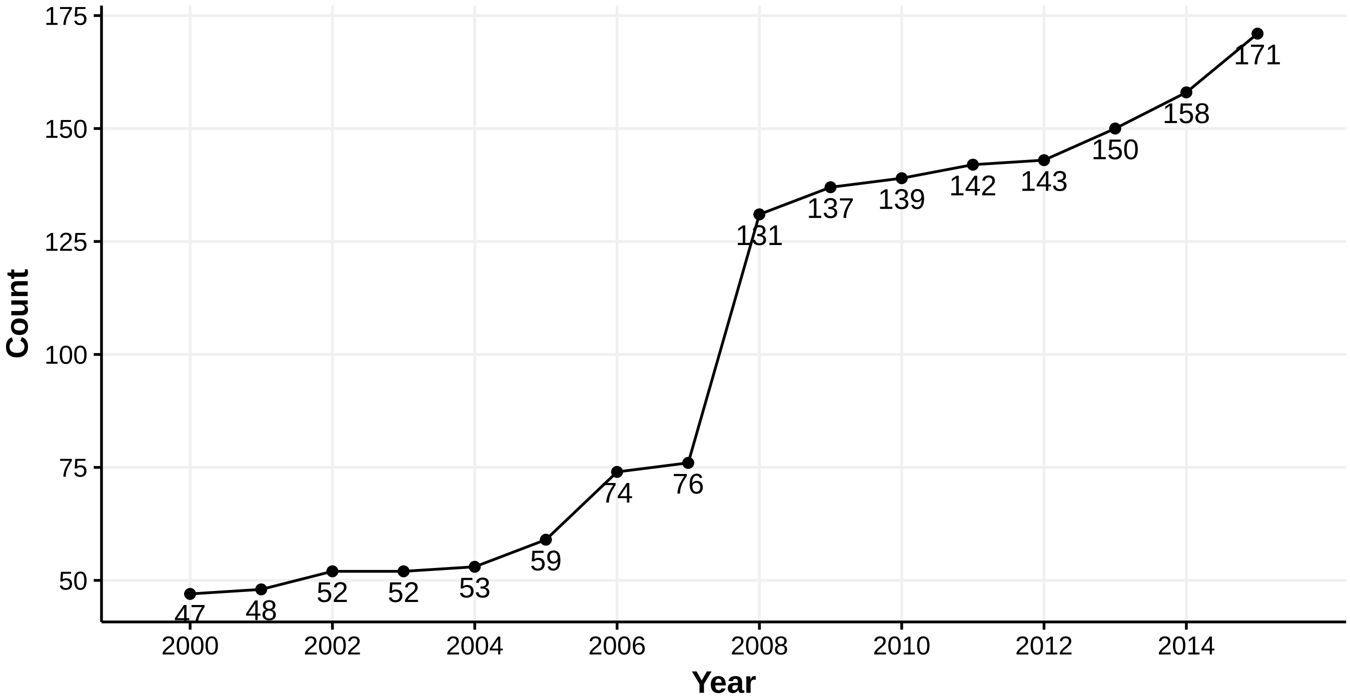


Figure 2.11: Number of AWN stations available by year, 2000-2015.

Figure 2.12: Number of drift events and confirmed cases, tree fruit only, 2000-2015. The number of events per year remained relatively constant throughout the study period, but the number of confirmed cases per year increased in recent years. For example, there were 52 and 53 confirmed cases in 2013 and 2014, which was nearly twice the magnitude of cases (n=27) in 2002, the next highest observed year. This suggested a recent uptick in the case to event ratio for tree fruit. The largest proportion of events (16/151 = 11%) and cases (53/320 = 17%) occurred in 2014.

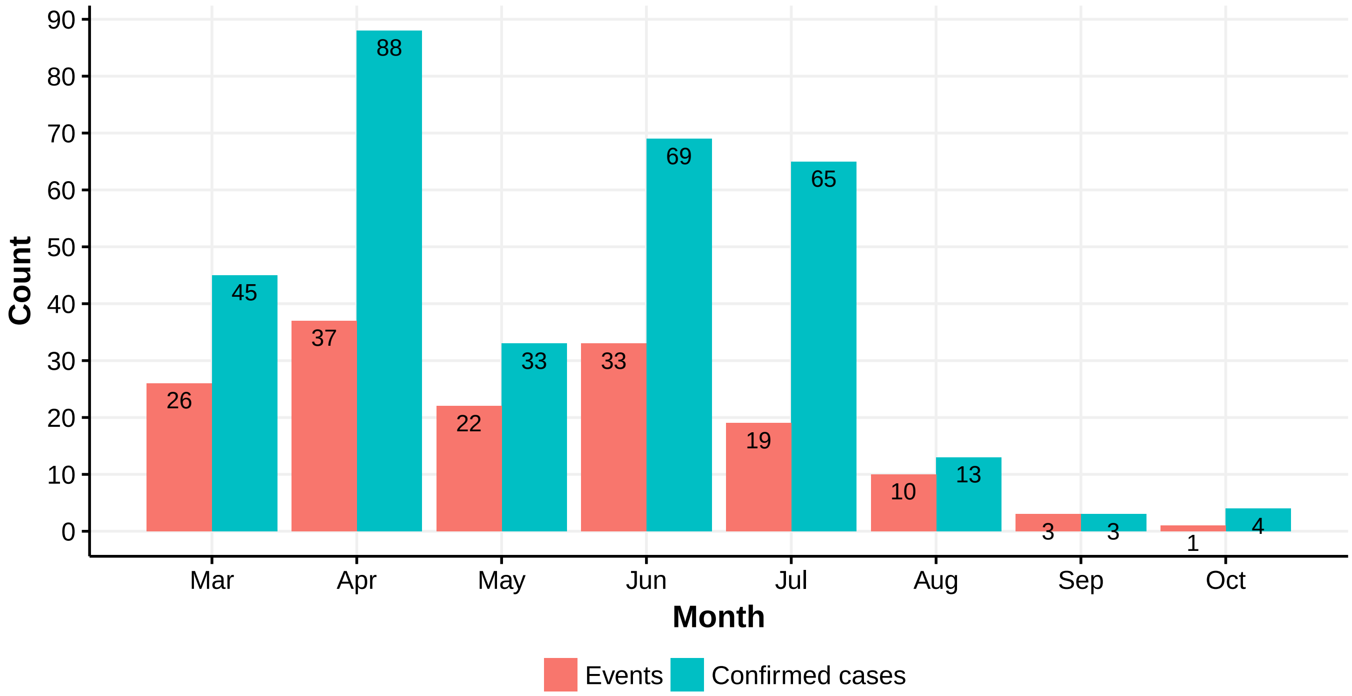


Figure 2.13: Drift events and confirmed cases by month, tree fruit only, 2000-2015. Approximately 78% [(26+37+22+33)/151] of all tree fruit events occurred in March, April, May, or June, with 25% (37/151) occurring in April. Confirmed cases in tree fruit showed a similar trend with 28% (88/320) occurring in April.

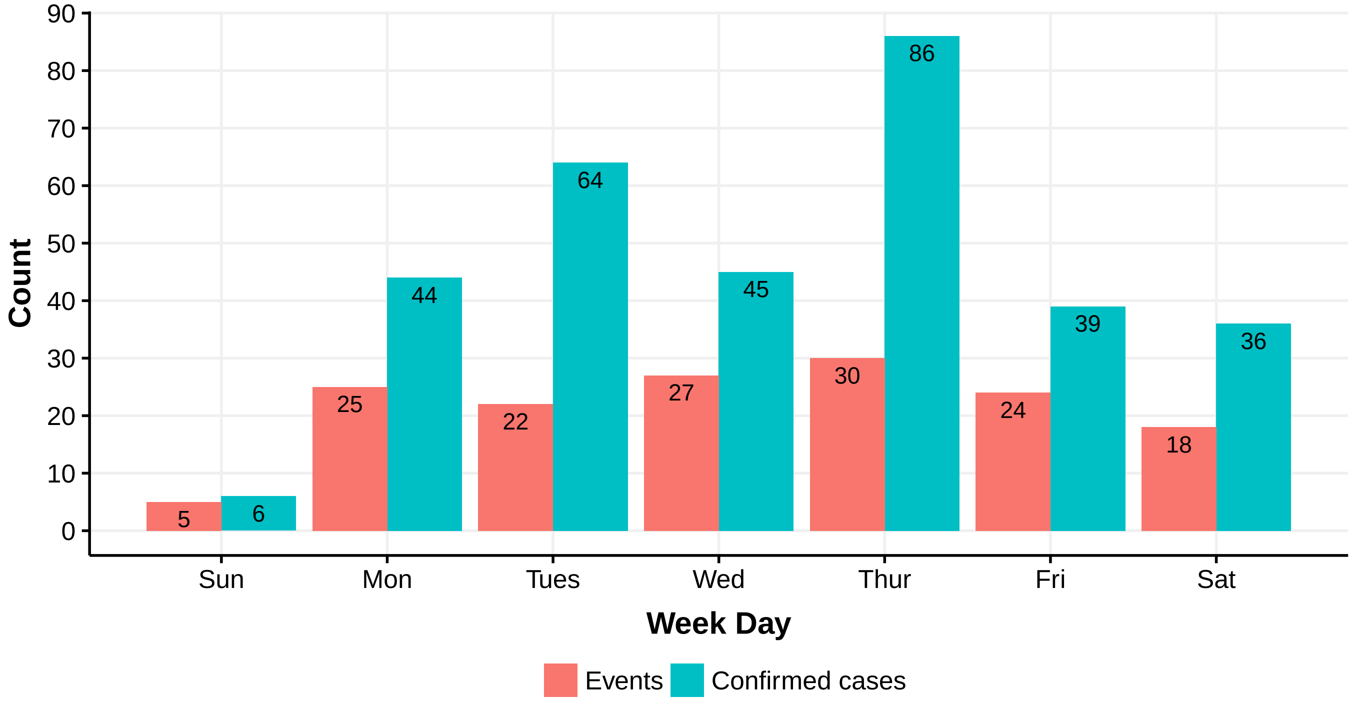


Figure 2.14: Drift events and confirmed cases by week day, tree fruit only, 2000-2015. Events were distributed equally across all days of the week, with the exception of Sunday. The largest number of events (30/151 = 20%) and cases (86/320 = 27%) occurred on Thursday.

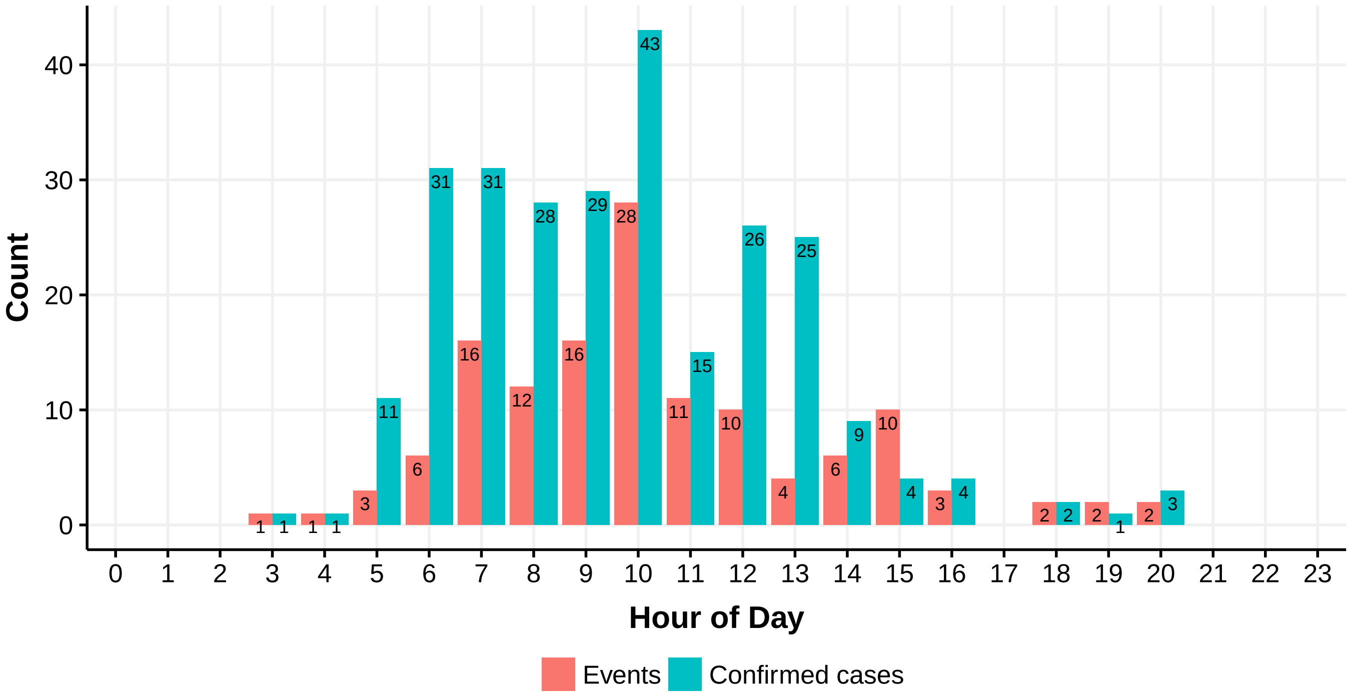


Figure 2.15: Drift events and confirmed cases by hour of the day, tree fruit only, 2000-2015. Tree fruit events were distributed somewhat normally across hour of day, with 21% (28/133) of events and 16% of cases (43/264) occurring between the hours of 10:00 AM and 11:00 AM. Very few cases reported a time of exposure before 5:00 AM or after 4:00 PM (16:00). Approximately 12% (18/151) of tree fruit events did not have adequate time of exposure data available.

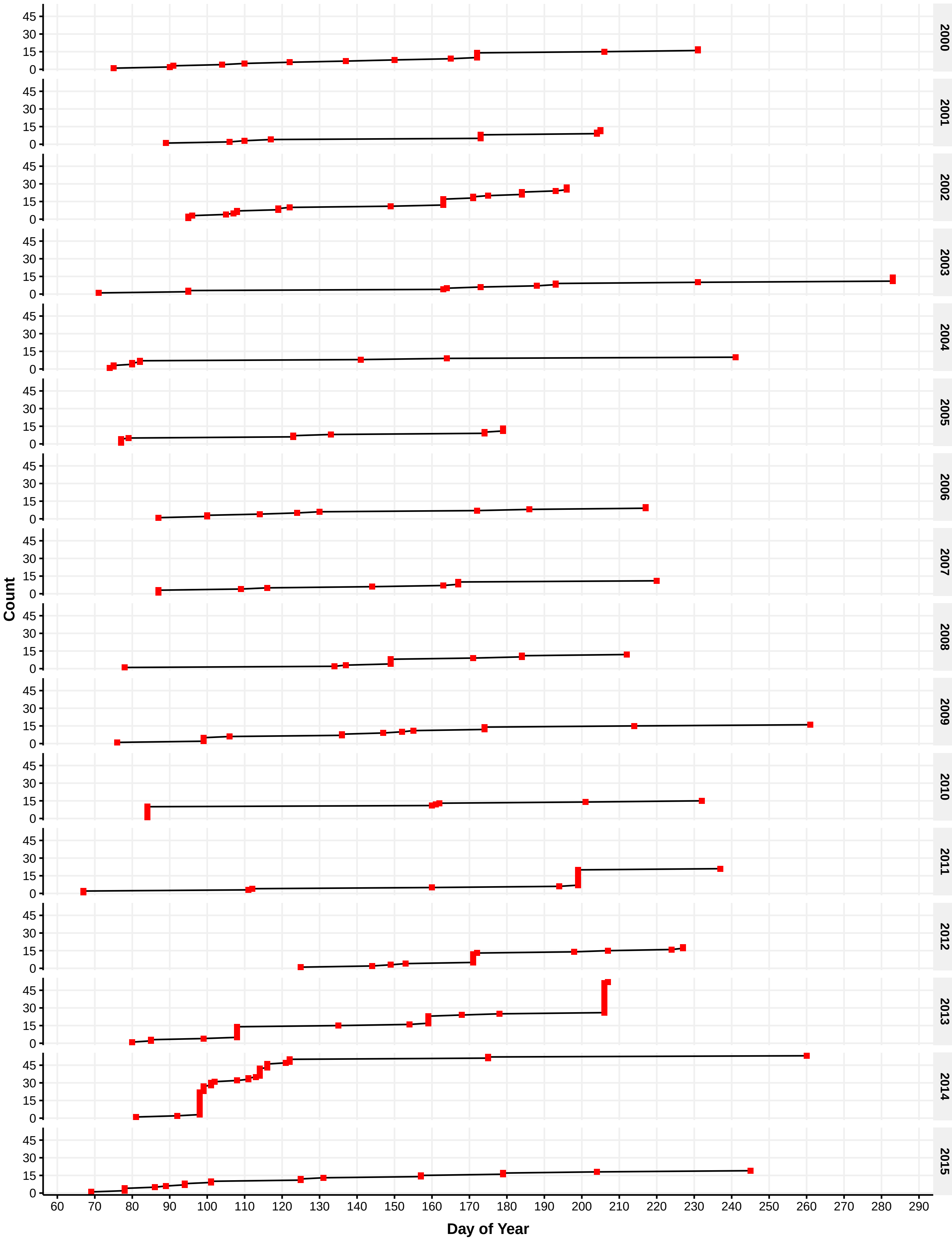


Figure 2.16: Drift cases (n=320) by day of the year, tree fruit only, 2000-2015. Each confirmed drift case is plotted as a red mark on the day of occurrence in an annual cumulative total.

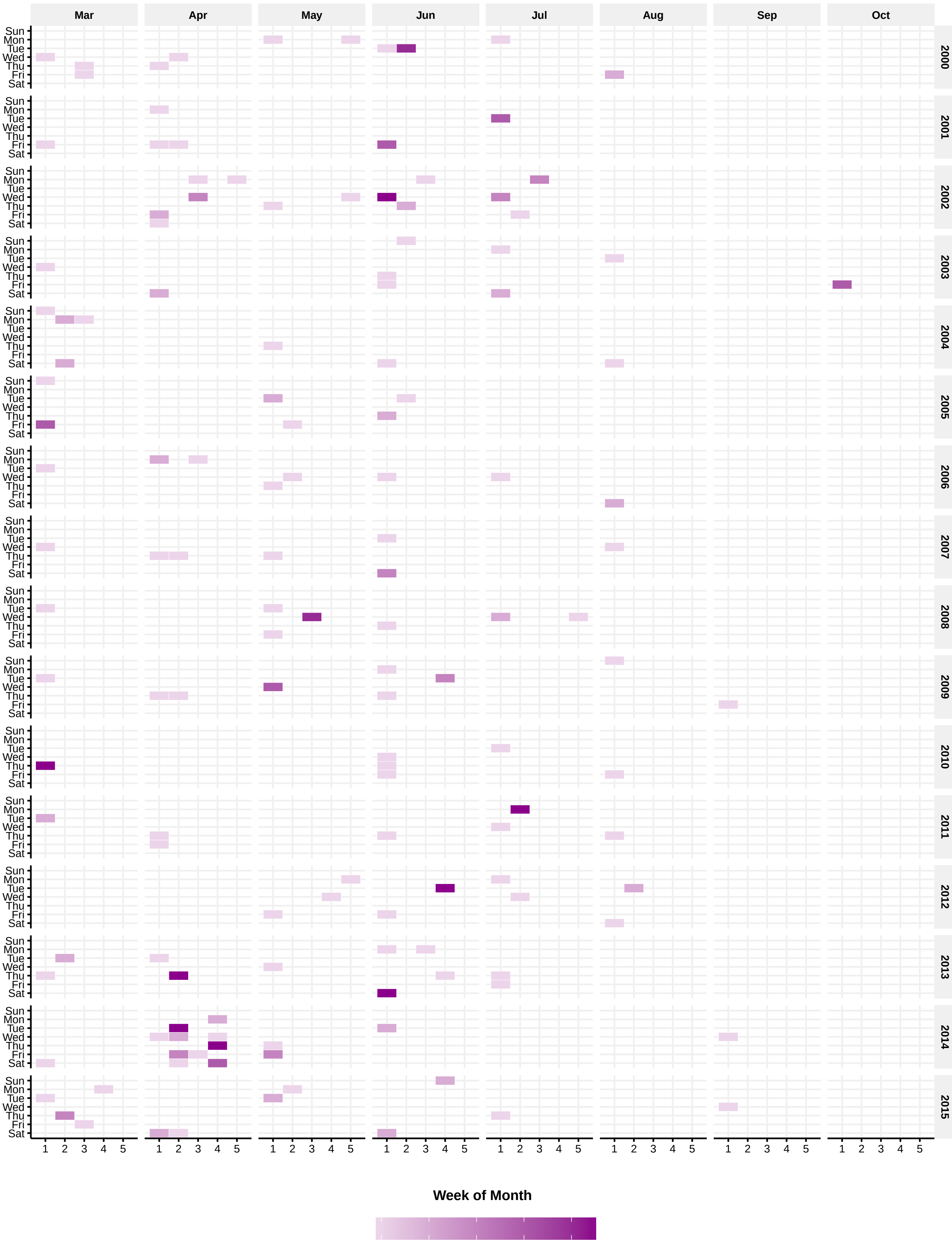


Figure 2.17: Drift events (n=151) by calendar day, tree fruit only, 2000-2015. Color indicates number of cases per event. Events with 5+ cases are deepest purple.

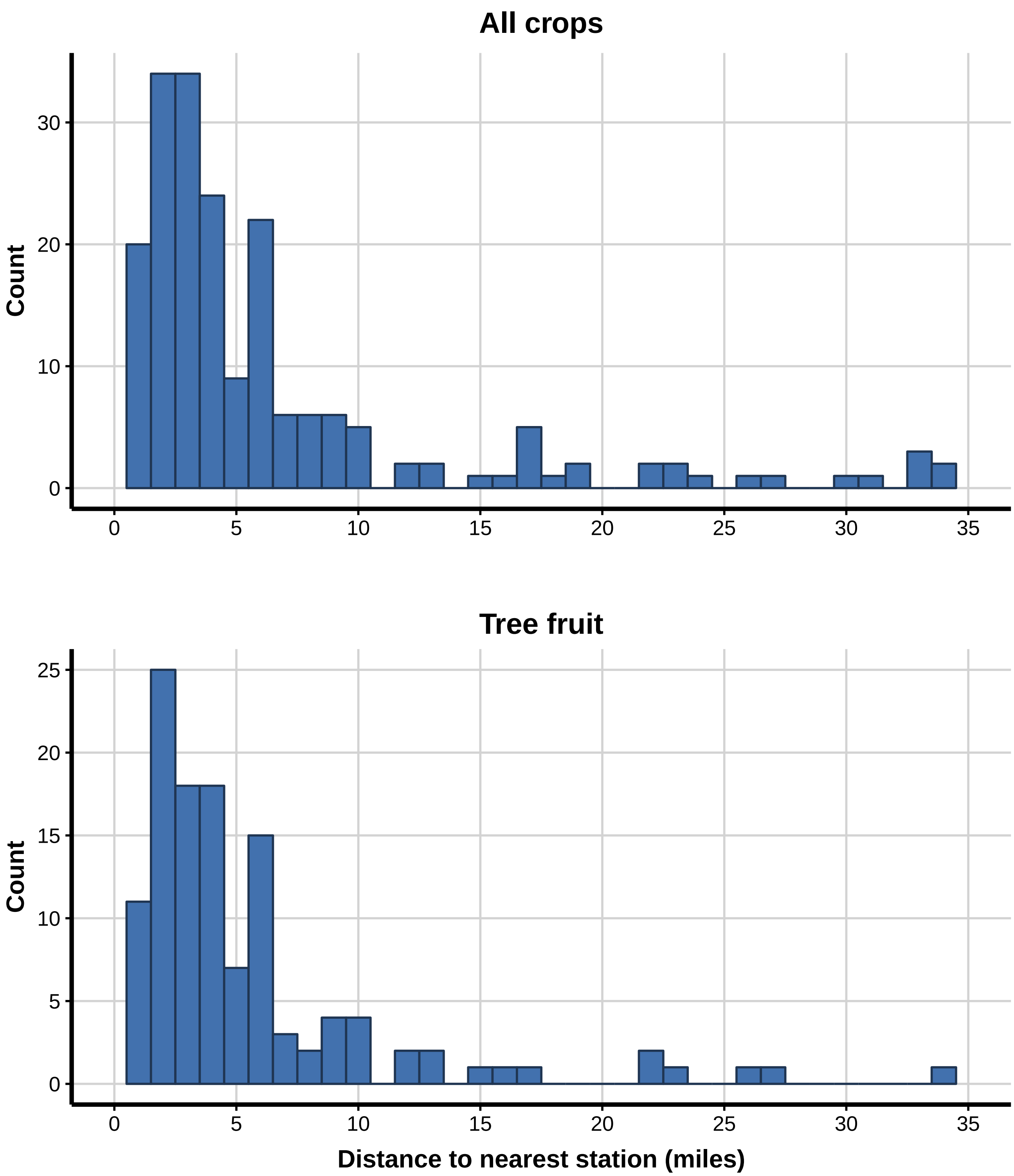


Figure 2.18: Distance to nearest AWN station, all crops and tree fruit only, 2000-2015.

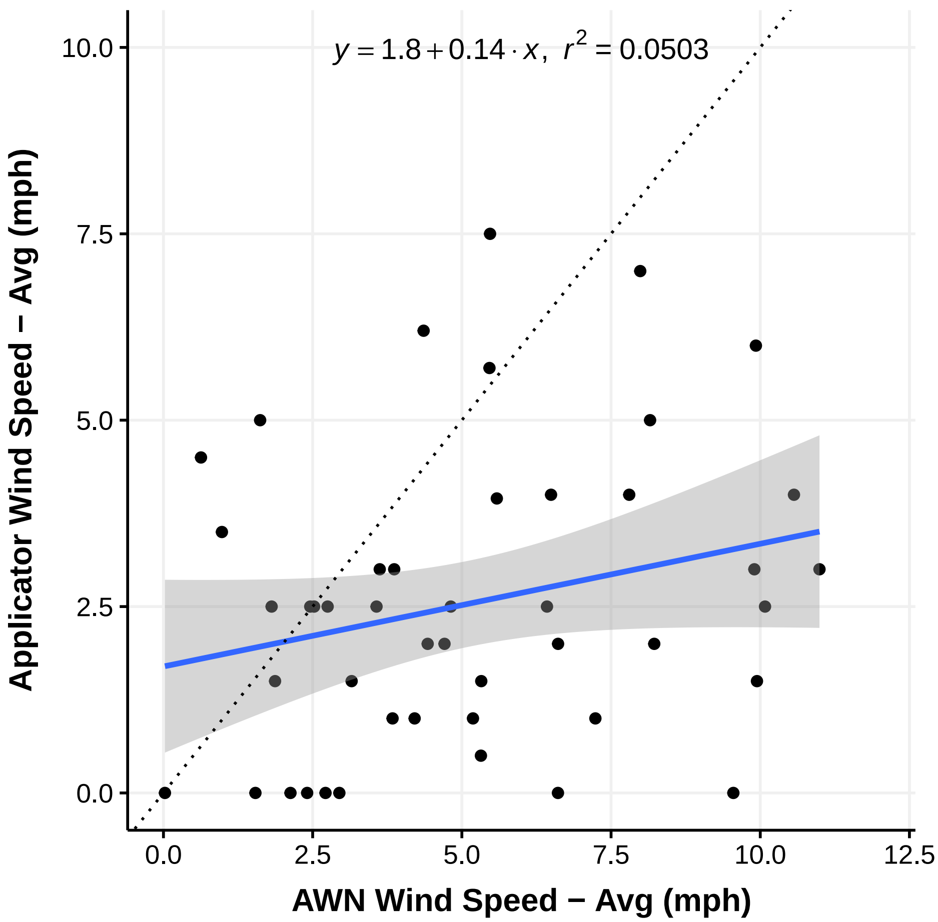


Figure 2.19: Among 47 tree fruit events with complete application records, 15-min average wind speed at the nearest AWN station was higher for 83.0% (n=39) of the average wind speeds reported by applicators. AWN average wind speed is the 15-min interval containing applicator spray start time (hh:mm). The line of unity represents perfect agreement between the two values.

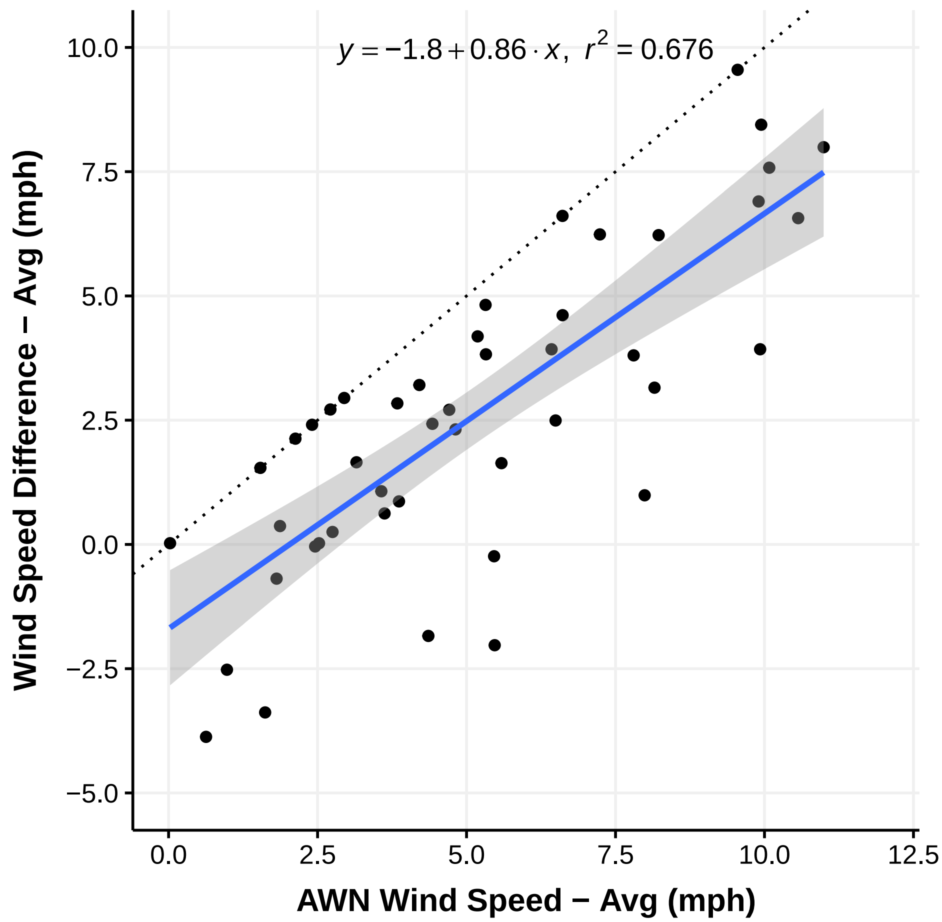


Figure 2.20: Among 47 tree fruit events with complete application records, 15-min average wind speed at the nearest AWN station had a moderate-to-strong association with the difference between AWN station and applicator self-reported wind speed. AWN average wind speed is the 15-min interval containing applicator spray start time (hh:mm).

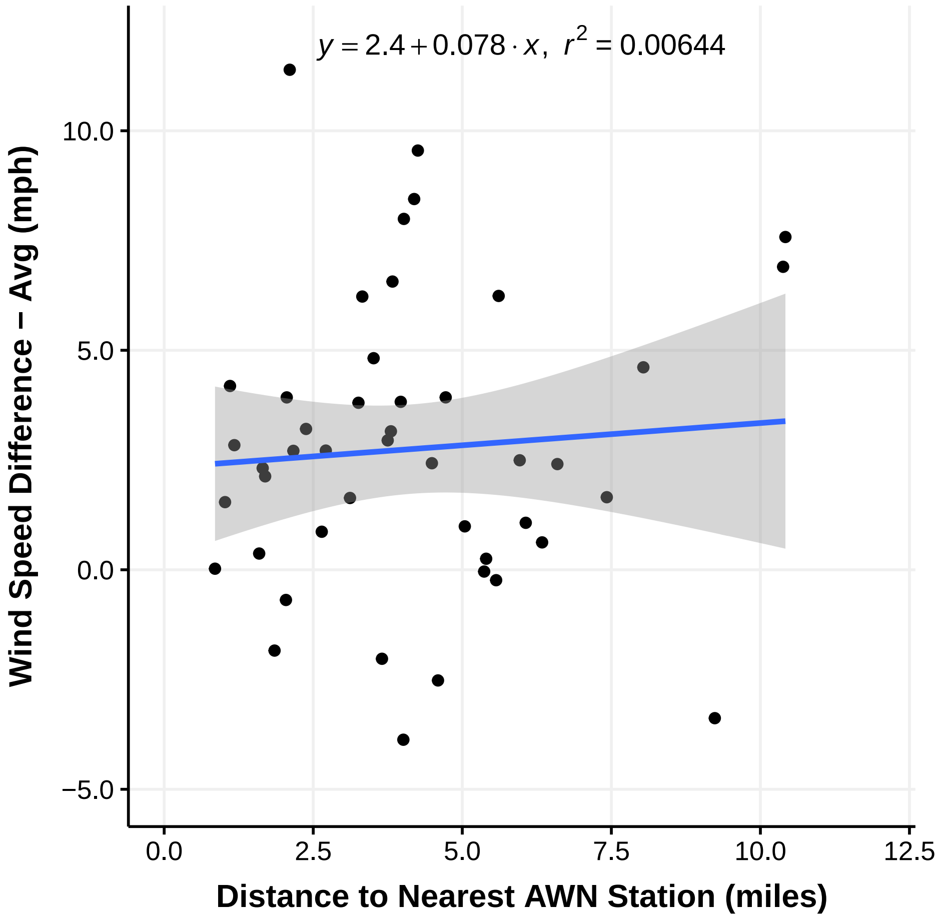


Figure 2.21: Among 47 tree fruit events with complete application records, distance to nearest AWN station had no association with the difference between AWN station and applicator self-reported wind speed.

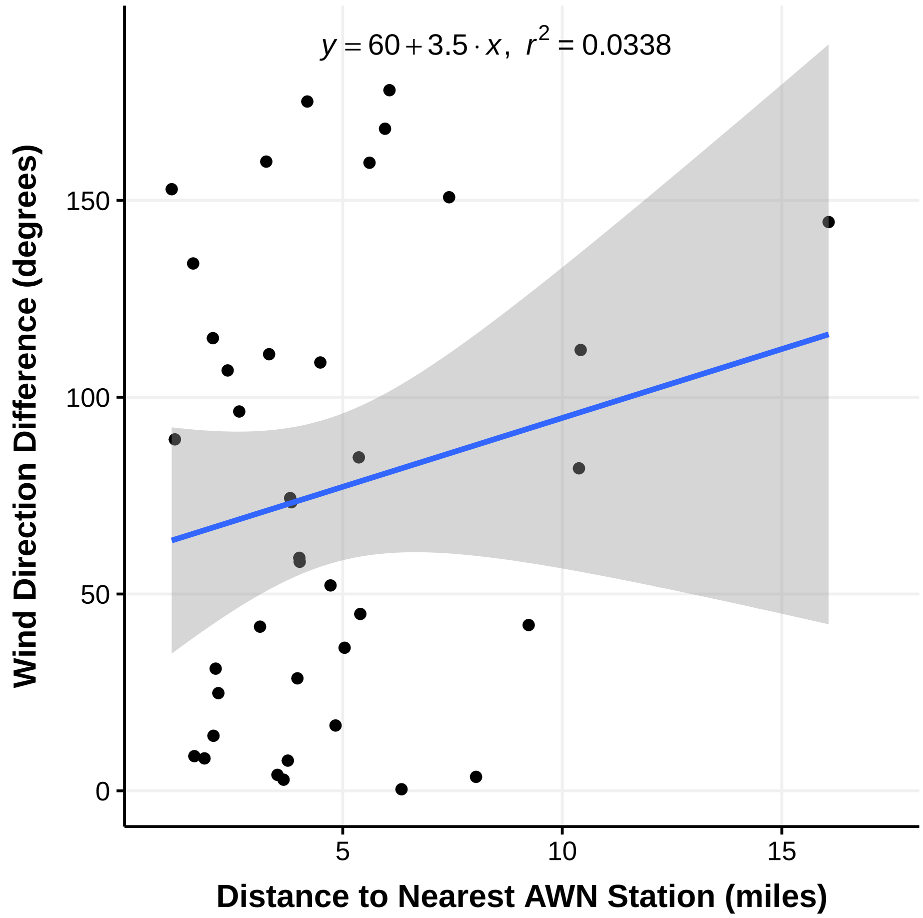


Figure 2.22: Among 39 tree fruit events with complete application records, distance to nearest AWN station had no association with the difference between AWN station and applicator self-reported wind direction.

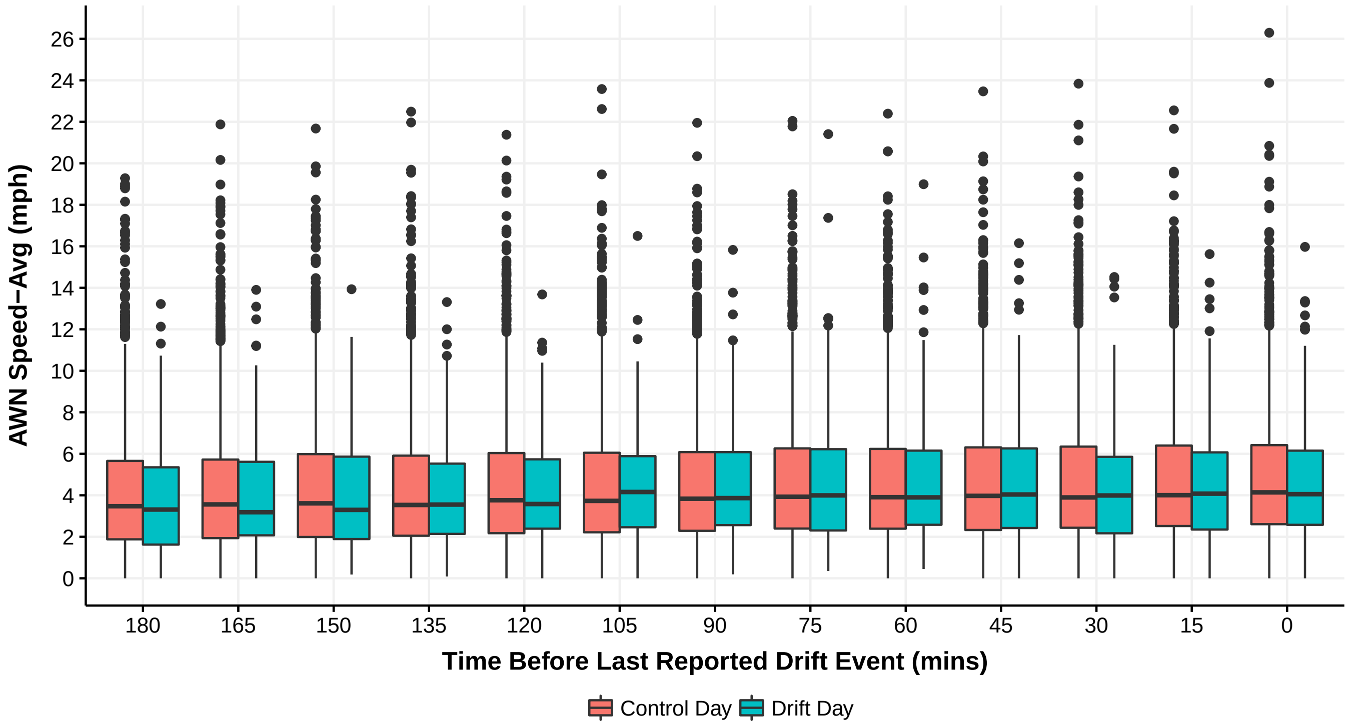


Figure 2.23: Wind speed comparisons between drift days and control days at each 15-min measurement interval preceding the last reported tree fruit drift event (time=0). The 2-hr exposure window used in the case-crossover model includes all 15-min wind speed measurements between 0 and 120 min.

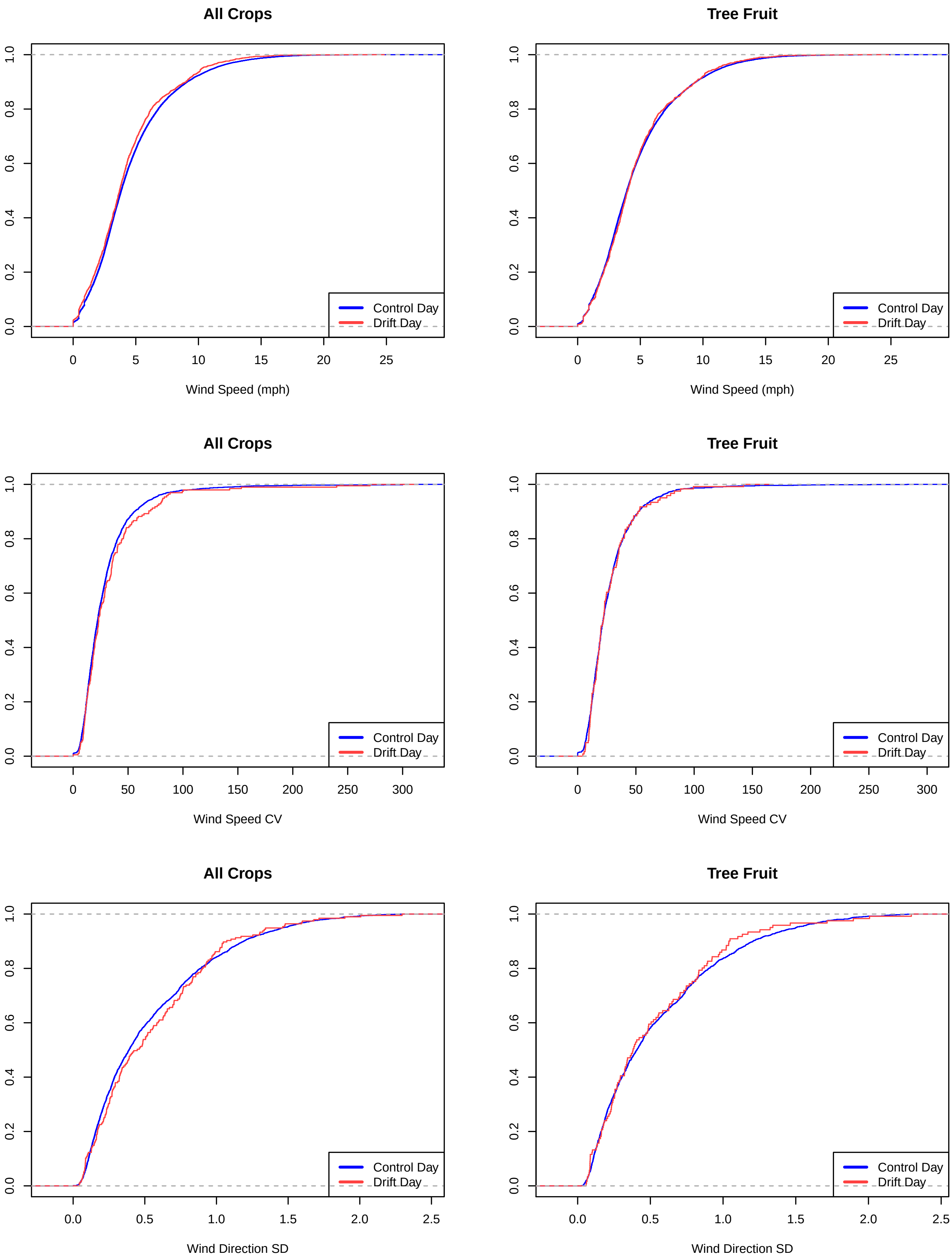


Figure 2.24: Empirical Cumulative Distribution Function plots for 15-min average wind speed, wind speed coefficient of variation (CV), and wind direction standard deviation (SD) for 2-hr exposure windows.

2.8 Appendices

2.8.1 Appendix A: NIOSH SENSOR-Pesticides case definition and classification matrix

Details for the SENSOR-Pesticides case definition and classification matrix are available on the program website. WA DOH identifies confirmed cases based on documentation of the pesticide exposure pathway, adverse health effects, and toxicological evidence of a causal relationship between the observed exposure and health effects. Evidence for each category is scored on a 1-4 scale, with 1 being the highest and 4 being the lowest in terms of robust evidence. Confirmed cases have exposure and health effect scores of 1 or 2 and a casual relationship score of 1. This matrix ensures that a preponderance of evidence exists before a report can be classified as a confirmed case. The SENSOR-Pesticides case classification matrix, included below, indicates that "Definite", "Probable", and "Possible" (DPP) cases are commonly used for analysis because there is documentation of "new adverse health effects that are temporally-related to documented exposure and consistent evidence of a causal relationship between the pesticide and the health effects based on the known toxicology of the pesticide" (123).

CLASSIFICATION CATEGORIES [1]											
CLASSIFICATION CRITERIA	Definite Case	Probable Case		Possible Case	Suspicious Case	Unlikely Case	Insufficient Information		Not a Case		
									Asymptomatic[2]	Unrelated[3]	
A. Exposure	1	1	2	2	1 or 2	1 or 2	4	-	-	3	
B. Health Effects	1	2	1	2	1 or 2	1 or 2	-	4	3	-	
C. Causal Relationship	1	1	1	1	4	2	-	-	-	-	3

[1] Only reports meeting case classifications of Definite, Probable, Possible and Suspicious are reportable to the National Public Health Surveillance system. Additional classification categories are provided for states that choose to track the reports that do not fit the national reporting criteria.
[2] The matrix does not indicate whether asymptomatic individuals were exposed to pesticides although some states may choose to track the level of evidence of exposure for asymptomatic individuals.
[3] Unrelated = Illness determined to be caused by a condition other than pesticide exposure, as indicated by a >3' in the evidence of >Exposure= or >Causal Relationship= classification criteria.

In addition to WA DOH, 11 other state programs provide scores based on three criteria (35, 36, 123). WA DOH—like other SENSOR-Pesticides program states—recognizes all DPP cases as meeting the required level of evidence to establish the existence of:

1. A reasonable exposure pathway
2. Human health symptoms or signs of illness, and
3. A pesticide active ingredient that can produce symptoms observed in a likely timeframe.

3 Comparative Evaluation of Orchard Sprayer Technology Based on Potential Worker Exposure to Pesticide Drift

3.1 Abstract

The airblast sprayer has been a standard tool for tree fruit pesticide application technology since its rapid and wide-scale adoption in the 1950s. Present-day orchard management practices have greatly altered tree architecture. As a result, traditional airblast sprayer output no longer matches modern canopies without sprayer modification and thereby increases the potential for drift and human exposure. To strike a balance between improving spray coverage and reducing drift, output from new sprayer technologies is being matched to modern canopies. A series of trials was designed to compare the ability of different spray technologies to minimize potential worker exposure to pesticide drift. Spray trials involved the collection of active and passive air samples downwind of foliar applications of micronutrient tracers zinc (Zn), molybdenum (Mo), and copper (Cu) that were later analyzed in a sensitive mass spectrometry procedure.

This chapter addresses the following sub-aims:

- Measure potential inhalation and dermal exposure to pesticide drift for three pesticide spray technologies using a micronutrient tracer method
- Develop relative ranking of tree spray technologies for reducing farmworker exposures

3.2 Introduction

The airblast sprayer has been a standard tool for tree fruit pesticide application technology since its rapid and wide-scale adoption in the 1950s (8). Present day high-density orchard management practices have greatly altered tree architecture. As a result, traditional airblast sprayer output no longer matches modern canopies and thereby increases the potential for drift and human exposure (8, 118, 119). The need for coarse spraying, which reduces drift by generating larger droplets, competes with the need for fine spraying, which increases crop coverage through atomizing smaller droplets. To strike a balance between improving spray coverage and reducing drift, output from new sprayer technologies is being matched to modern canopies without sprayer modification (58, 160). We designed a series of trials to compare the ability of different spray technologies to minimize potential worker exposure to pesticide drift. Pesticide drift can be influenced by factors associated with sprayer technology, meteorological conditions, drift collectors, spray liquid and aerosol properties, or operator skill (47, 161). In this study, we aimed to isolate drift potential differences due to sprayer technology by controlling for other factors.

The movement of pesticides through air has been described in various ways. Himel defines exo-drift as the spray lost from a target area by wind on droplets and endo-drift as spray lost to the soil instead of plant or insect targets (46). More recently, use of the term exo-drift has been replaced by spray drift. Some sources describe spray drift as the “part of a pesticide application that is deflected away from the target area by action of the wind” (20, 23, 162). Regulatory agencies tend to differentiate between primary spray drift, which occurs during application or soon thereafter, and secondary off-target movement, such as volatilization after application or movement on wind-borne particles, because only the former is enforceable (163–165). Spray drift has been further categorized as deposition drift, larger droplets that fall out of a spray cloud as deposits on horizontal surfaces, and airborne drift, smaller droplets that can be carried greater distances by the wind (23, 162). Larger aerosols settle out quickly through gravitational force and impaction processes, while smaller particles are influenced by Brownian diffusion. Particles of intermediate size (approximately 0.3 µm) tend to settle out more slowly because neither force acts strongly on them.

Foliar application of elements such as iron (Fe), zinc (Zn), copper (Cu), boron (B), manganese (Mn), magnesium (Mg), and molybdenum (Mo) has long been recognized as a means for crop nutrition (i.e. micronutrients). Conveniently, multiple metal salt solutions can be applied to a single field target, recovered through acid extraction, and then analyzed in a sensitive inductively coupled plasma mass spectrometry (ICP-MS) procedure (9–14). Our drift field spray trials took advantage of this efficiency. In a pilot study, we developed field sampling methods and tested whether foliar applications of Zn, Mo, and Cu could be collected on downwind field targets and then recovered in the laboratory. In our full-scale spray trials, passive target matrices were placed at regular intervals in horizontal (deposition drift) and vertical (airborne drift) planes downwind of an orchard block that was sprayed with label-recommended concentrations of micronutrients. We also collected active air samples on each tractor and at two downwind locations.

Several matrix options for passively sampling drift have been investigated by agricultural engineers and health scientists (88, 162). Filter paper has been used to measure deposition drift through horizontal sampling, but it has a low collection efficiency for vertical sampling of airborne drift (166–170). Better collection efficiency for airborne drift has been demonstrated with cotton line, wool line, polyethylene line, pipe cleaners, filter cloth, scouring pads, metal cylinders, and hair curlers (161, 162). Line collectors are useful for airborne drift because they can be used for continuous sampling and then sectioned to obtain vertical profiles. Polyethylene line has a defined collection surface area and good recovery, but poorer collection efficiency than other options (171–175). Wool line and pipe cleaners have better collection efficiency and will not easily saturate, but have more variable collection surface areas (80, 162, 174, 178–181). To capture the best characteristics for airborne passive sampling, we deployed two types of vertical sampling matrices: low-density polyethylene (LDPE) line and polyester (PE) line (i.e. continuous pipe cleaners).

Miller (162) notes that when the same passive matrices are used across comparative spray drift measurements, it may not be necessary to precisely define sampling volume, cross-sectional area, and collector efficiency. However, he adds that sampling volume and collection efficiency are a function of both droplet size and wind speed conditions and should not mask the relative drift magnitudes (79, 80).

Orchard sprayers share many basic modifiable design characteristics. They typically consist of a several hundred gallon tank that is towed behind an orchard tractor, which has a wheelbase narrow enough to fit between tree rows and the horsepower necessary to pull a full tank. Using the tractor's battery and power take off (PTO), a driver can operate a tank's chemical mixing agitator, system pressure valve, spray nozzles, and an axial fan 'air-assist'. These sprayers are often classified as broadcast 'air-assisted' sprayers to distinguish them from other, usually larger, boom sprayers used in field crops. When a conventional orchard sprayer is near tree rows being treated, a curved deflector directs airflow laterally to the spray nozzles. Axial fans, which move large volumes of air at low pressure, typically act as impellers directing airflow into a fan and out through the nozzle area (23, 182). Sprayer nozzles come in a wide variety of sizes and spray pattern shapes (23, 51, 182). The sprayer nozzles in our study created a hollow-cone spray, which is common in Washington orchards.

We collected comparable exposure measurements for three orchard application technologies (Figure 3.1 and Table 3.1):

- Axial Fan Airblast (AFA)
- Directed Air Tower (DAT)
- Multi-headed Fan Tower (MFT)

Our central hypothesis was that the three sprayers would generate different drift plumes and therefore create different exposures for downwind orchard workers. We hypothesized that the newer 'low-drift' sprayers–DAT and MFT–would have lower drift measurements (by volume) due to: 1) shorter nozzle-to-tree canopy travel distances for DAT and MFT aerosols and 2) a higher likelihood of more vertically-directed AFA aerosols escaping above the tree canopy (Figure 3.2).

3.3 Methods

3.3.1 Measure drift potential of three spray technologies

3.3.1.1 Field study site

All field studies took place at Washington State University's (WSU) Sunrise Research Orchard near Rock Island, Washington. The orchard proved to be ideal for the trials because it is situated in a river valley approximately 300 m west of a 270 m rock face that orients the wind prevailingly from the north. Figure 3.3 provides a map of the field study site, approximate acreage by block, and apple varieties. The orchard consisted of individual trees with columnar shaped canopies. Trees were trellised, approximately 3.5-4 m (11.5-13 ft) tall, and spaced 0.9 m (3 ft) within rows and 3 m (10 ft) between rows. The tree rows were oriented on a north-south axis. The spray site was bordered by other orchard blocks on its south and east sides, by open flat land on its north side, and by a small private service road with no traffic on its west side.

3.3.1.2 Study design

Pilot

Our October 8, 2014 pilot study demonstrated that we could successfully collect samples of potential worker exposure to drift during airblast applications in a research orchard. Equivalent sprays of Zn, Mo, and Cu were applied to a one-quarter acre block of apple trees in serpentine fashion with the AFA sprayer, as shown by its GPS-tracked movement throughout the spray period (11 am - 2 pm). Between micronutrient sprays, the tank was washed with an all-purpose cleaner and then triple-rinsed. To account for changes in wind direction during the spray trials, samples were collected at 5 fixed locations on a 120° arc downwind (Appendix A). In addition to the 5 fixed arc locations, there were 3 reference locations (200 m upwind, center of the sprayed area, and inside arc on the edge of the sprayed area). Each location had a 6 m telescoping pole with 11 passive airborne sampling matrices (4 filter paper, 4 polyester line, and 3 polyethylene plastic line sections) in a vertical plane and 3 passive deposition sampling matrices (1 filter paper, 1 polyester line, and 1 polyethylene plastic tape) in a horizontal plane.

Key findings from the pilot study demonstrated proof of concept for sampling design and standard operating procedures: Zn and Mo were effective for all sample matrices, pipe cleaner samplers needed to be free of Cu and other metals, wind conditions were favorable for drift studies that compare different sprayer technologies, and inductively coupled plasma mass spectrometry (ICP-MS) was validated as an appropriate analytical method for micronutrient tracers. To simulate potential orchard worker activities (e.g. pruning and thinning) and exposures at greater distances, we changed the sampling arc into a gridded system that followed the layout of downwind orchard rows. Regarding pesticide type, we concur with the Spray Drift Task Force (SDTF) and US Environmental Protection Agency (US EPA) view that spray drift is the result of movement of droplets irrespective of the pesticide active ingredient (23, 82, 83).

Full-scale trials

Three micronutrient tracers (Zn, Mo, and Cu) were applied separately with AFA, DAT, and MFT sprayers to the same one-acre orchard block over a series of seven days (Figure 3.7). Full-scale trials were conducted during three sampling periods: July 1-2, 2015; June 9-10, 2016; and September 28-30, 2016. On all of these dates the trees were at full canopy. A *spray day* was defined as a day in which the orchard block was sprayed with micronutrients in the presence of our field sampling equipment. A spray day consisted of 2-3 *spray trials*, each of which involved one application technology spraying a single micronutrient to the entire one-acre orchard area. Downwind, we set up a series of field targets as surrogates for worker location during a *drift event*, which is defined by the Washington Department of Health (WA DOH) as an incident when one or more human illness cases were exposed to a pesticide that drifted away from the application target (31, 116).

We used a randomized block design to mitigate the effect of changing environmental conditions throughout the study period. The one-acre block (28 tree rows) was divided into four quadrants, or approximately 7 rows (Figure 3.6), and every row in each quadrant was sprayed in serpentine fashion along the orchard's north-south axis. The applicator turned both sides of the sprayer on as it traveled through the rows, and off during turns. Nozzles on both sides of the sprayer were on as the tractor traveled between tree rows. The outer half of exterior rows was not sprayed to ensure interior and exterior quadrants were treated equally. Quadrant spray order was randomized on each spray day over short time intervals. To ensure similar environmental conditions during each spray, each quadrant was sprayed in succession with the AFA, DAT, and MFT before moving to the next quadrant. For example, Quadrant 3 was sprayed with AFA, DAT, and MFT before Quadrant 2 was sprayed with the same sprayers. The order of succession was also randomized (Appendix B).

Each sprayer was outfitted with a global positioning system (GPS) unit to verify the sprayer route and obtain time-location data (See SOP 6 in Appendix C). Time-location data were used to confirm that appropriate rows were sprayed and determine spray start and stop times. Sprayer GPS data were downloaded as KML files and Google Earth (v 7.1) was used to determine timing to the nearest minute for each quadrant. One minute was added to the end of each spray event to capture any residual spray. Two team members had 98% concordance when following these methods independently and full concordance was reached after discrepancies were discussed.

We also used three cameras to record the spray trials. Camera #1 was located on the southern edge of the sampling area with an aerial view of the sprayed area from approximately 35 m downwind and 6 m above the ground (Figures 3.4), near Target I (Figure 3.6). Camera #2 was positioned on the sprayer's tractor facing backwards during the spray trial (Figure 3.5). Camera #3 was located approximately 10 m from the western edge between the sprayed and sampling fields (Figures 3.6), with a side view of the sprayers (Figure 3.7).

3.3.1.3 Sprayer features and calibration

We used three orchard airblast sprayers in our full-scale trials (Figure 3.1): Axial Fan Airblast (AFA), Directed Air Tower (DAT), and Multi-headed Fan Tower (MFT). These sprayers differed in terms of engineering design—a feature we aimed to test—but their fundamental components were similar and typical of orchard airblast sprayers. Each was powered by an orchard tractor with a PTO running the agitator in the tank and the hydraulic pressure of the spray system. Each sprayer took advantage of axial fan design to move large volumes of air to assist spray nozzles that created a hollow-cone shaped droplet pattern. We were able compare their drift potential by isolating their respective engineering controls (e.g. tower or multi-headed fan) through calibration of the spray volume delivered to the canopy.

To facilitate the fairest comparison, each sprayer's output was matched to the orchard canopy and calibrated to apply a fixed volume per area of 100 gal/acre (379 L/hectare). Proper calibration in a particular orchard block involves checking tractor speed, adjusting the sprayer's airflow direction, matching the air volume and speed to the canopy, calculating expected nozzle output, and measuring observed nozzle output (183). Before field calibration, we calculated expected nozzle output, or volumetric flow rate in gal/min, by using parameters for the orchard (row width, tree spacing), tractors (speed), and sprayers (boom type; operating pressure; nozzle number, size, and arrangement). Several tools are available for performing such calculations (184, 185). During field calibration, we checked tractor speed, adjusted sprayer airflow direction into the column-shaped tree canopy, inserted new nozzles, and measured nozzle output to compare against our earlier calculations (Appendix D). Finally, we estimated theoretical droplet sizes based on the parameters of our spray trials (Table 3.2). Below, we discuss key features of the sprayers used in this study.

Sprayer booms and axial fans

The AFA was a conventional orchard sprayer with a curved boom. The DAT and MFT were newer sprayer technologies with vertical implements (i.e. 'tower' booms), which were designed to move nozzles and air closer to the tree canopy (182). This minimizes the distance that liquid aerosols must travel to reach the target surface. The smaller distance-to-target of tower sprayers is intended to improve spray coverage and reduce drift in modern high-density orchards (182). Tower heights were approximately 2.7 m (108 in) for the DAT and 3.7 m (144 in) for the MFT. The AFA and DAT each had one rear-facing axial fan with diameters of 71 cm (28 in; 8 blades) and 76 cm (30 in; 10 blades), respectively. The MFT had six 50 cm (20 in) fans with five blades mounted on the tower (3 fans per side). Airblast sprayers have been shown to have fan speeds between 1835 and 3700 revolutions per minute (rpm) that produce outlet air velocities between 34 m/s and 73 m/s (76-163 mph) and air flow rates between 3.8 and 25 m^3/s (8,000-53,000 cfm) (186, 187). Settings on the sprayers in our study fell within those ranges. The AFA, DAT, and MFT fans were each estimated to produce approximately 9.4-14 m^3/s (20,000-30,000 cfm), with the AFA and the tower sprayers producing flow rates at the low and high ends of the range, respectively.

Nozzles, operating pressure, speed of travel, and theoretical droplet size

The AFA had 14 nozzles (7 per tree canopy side) and the DAT had 58 nozzles (29 per side). Each of the 6 MFT fan heads had 8 nozzles for a total of 48 nozzles on the sprayer. Several nozzles were closed on each sprayer to match the tree canopy and achieve the desired application volume. For our trials, there were 10 open nozzles on the AFA, 22 on the DAT, and 36 on the MFT. All nozzles produced a hollow-cone spray shape. The MFT used one-piece nozzles and the AFA and DAT used disc-core nozzles. A disc-core nozzle is a replaceable hollow-cone nozzle made of polymer, brass, stainless steel, aluminum, or ceramic (182, 188). As the name implies, a disc-core nozzle is made up of two pieces: a disc and a core. We used stainless steel hollow-cone discs (sizes 3-5) and cores (size 25) on the AFA and DAT. A one-piece nozzle is a replaceable hollow-cone nozzle made of one piece of stainless steel, brass, or ceramic (182, 188). We used ceramic hollow-cones with grey (TXVK08) and green (TXVK04) nozzles on the MFT. To ensure that expected and measured nozzle output matched, new nozzles were installed. Nozzle output was tested with a flow rate meter, which measured in units of gallons per min (gpm).

Table 3.2 shows that we used two D3, one D4, and two D5 nozzles with 25 cores on each side of the AFA; eleven D3 nozzles with 25 cores on each side of the DAT; and twelve VK08 and six VK04 nozzles on each side of the MFT. With 25 cores at 200 pounds per square inch (PSI) on the AFA, expected outputs for D3, D4, and D5 nozzles were 0.40, 0.62, and 0.75 gpm, respectively; we measured means of 0.36, 0.56, and 0.68 gpm. With 25 cores at 100 PSI on the DAT, expected output was 0.29 gpm; we measured a mean of 0.27 gpm. At 100 PSI on the MFT, expected outputs for VK08 and VK04 were 0.207 and 0.101 gpm, respectively; we measured means of 0.190 and 0.096 gpm. With the exception of the AFA, measured outputs for the other sprayer nozzles fell within the acceptable range of ± 0.02 gpm. To compensate for the low measured output of the AFA, which was likely due to the presence of nozzle filters, we increased the operating pressure to 205 PSI (51).

It should be noted that the MFT had an automatic rate controller, which is common on newer spray technologies. Rate controllers are designed to provide consistent application volumes by increasing or decreasing operating pressure based on sprayer speed (182, 189). To reduce variability due to the rate controller in our trials, we set and tested the travel speed for all tractors at 1.3 m/s (3 mph).

Nozzle and pressure settings were used to find the expected VMDs produced by the sprayers in our study. The need for coarse spraying, which reduces drift by generating larger droplets, competes with the need for fine spraying, which increases crop coverage through atomizing smaller droplets. Thus, nozzle selection demands an understanding of volume median diameter (VMD), which classifies the range of possible droplet sizes. VMD expresses the value where 50% of the total volume of liquid sprayed consists of droplets with diameters larger than the median value and 50% with smaller diameters (20, 23, 50). Expected VMDs for the AFA, DAT, and MFT were approximately 110-125 (fine), 125-130 (fine), and 61-105 µm (very fine), respectively (51, 52).

3.3.1.4 Application

Before each spray trial, sprayer tanks were flushed with all-purpose tank cleaner containing sodium tripolyphosphate and sodium carbonate and then triple-rinsed. A certified pesticide applicator then mixed, loaded, and applied label-recommended concentrations for one of three water soluble micronutrient product mixes: *Carbol Zinc* (10% Zn; 2.5 mL/L; 32 oz/100 gal), *Manni-Plex B Moly* (0.5% Mo; 1.25 mL/L; 16 oz/100 gal), and *Biomin Copper* (4% Cu; 2.5 mL/L; 32 oz/100 gal) (Appendix E). These products are not registered or classified as pesticides. Instead, they are used as fertilizers that are absorbed by trees through foliar application, which can improve tree performance and fruit quality by overcoming or preventing mineral deficiencies (190). Sprayer tanks were filled with 379 L (100 gal) of water before the desired amount of one product was added and allowed to mechanically agitate until the solution was thoroughly mixed.

Low-density polyethylene (LDPE) containers with screw caps were then used to collect bulk tank mix samples of approximately 180 mL from each sprayer's tank before spraying began. Each day, a similar 180 mL sample was taken from the water source at the mixing station so micronutrient background levels could be determined.

3.3.1.5 Meteorological measurements

Local meteorological conditions were recorded at two different locations in the orchard. A permanent on-site station (AgWeatherNet WSU-Sunrise) provided access to current and historical wind speed, wind direction, air temperature, and relative humidity. The station was located 70 m west of the nearest corner of the sprayed block and the instruments were approximately 1.8 m (6 ft) above the ground. Meteorological variables were recorded every 5 s and summarized every 15-min by a battery-powered data logger (*Campbell Scientific CR-1000*) that was recharged through a solar panel. Measurements were sent via cellular telephone data telemetry and the internet to WSU, preprocessed, posted on an online portal, and then downloaded. The wind speed sensor (*Model 014A Met One*) was a three-cup anemometer designed for continuous monitoring of speeds from 0 to 45 m/s with an accuracy of 0.11 m/s. The wind direction sensor (*Model 024A Met One*) was a wind vane that measured 0-360° with 5° accuracy, which was reported as one of eight 'principle' wind direction categories [4 cardinal(N-E-S-W) and 4 ordinal (NE-SE-SW-NW)]. The temperature and relative humidity probe (*Rotronic HC2S3*) measured air temperature from -40 to 60°C with a ±0.1°C tolerance and an additional temperature probe (*Model 107*) measured air between 0° and 50°C with a ±0.2°C tolerance (120, 191).

A second, temporary station (UW DEOHS) measured wind speed, wind direction, air temperature, and relative humidity. To be consistent with ASABE standards, the station was located approximately 190 m northeast of the nearest corner of the sprayed block. The second station provided: 1) estimates of atmospheric stability by taking temperature measurements at two sufficiently different heights, 2) measurements taken from the opposite side of the study site, and 3) weather data at a finer time resolution (1-min vs. 15-min). Meteorological variables were summarized every 1-min by a battery-powered data logger (*Campbell Scientific CR-1000*). Data were stored locally and downloaded to a laptop after each spray day. Measurements were taken at two different heights (3 m and 10 m). At 3 m (10 ft), there was a three-cup anemometer with a wind vane [*Met One Model 034B*; 0-75 m/s (±0.1 m/s); 0-360° (±2°)] and temperature probe [*Model 109*; –10 to 70 °C (±0.25 °C)]. At 10 m (33 ft), there was a 3-axis ultrasonic anemometer [*RM Young Model 81000V*; 0-45 m/s (±0.05 m/s); 0-360° (±2°)] and temperature and relative humidity probe

[*HMP45C-L*; -40° to 60 °C (±0.3°C); 0-90% RH (±2%)]. The temporary meteorological station measured wind direction as a continuous variable in degrees, which was converted to one of 16 categorical points of the wind compass [4 cardinal(N-E-S-W), 4 ordinal (NE-SE-SW-NW), and 8 intermediate (e.g. NNE)].

Meteorological measurements followed applicable protocols from the American Society of Agricultural (and Biological) Engineers (ASABE) (81). ASABE guidelines state that meteorological stations should be located at least 20 tree heights (70-80 m) outside the orchard and that measurements should be time-averaged for the duration of each spray pass or for 2 mins, whichever is greater. The same guidelines state that dry bulb air temperature should be measured at 1.8 m (6 ft), relative humidity at 1.8 m (6 ft), horizontal wind speed at 10 m (33 ft) and wind direction at 10 m (33 ft) for orchard tests (81). To ensure that meteorological conditions were measured on opposite sides of the study area, we set up the temporary meteorological station in the nearest eligible area east of the orchard.

Only spray trials that met International Organization for Standardization (ISO) meteorological data quality standards for drift sampling were included. Sample measurements were replicated at least three times in wind conditions that were as similar as practicable, wind speeds were at least 1 m/s, mean wind direction was at 90° ± 30° to the downwind edge of the sprayed area, and temperatures were between 5 °C and 35 °C (78). We excluded data points that did not fit the following criteria: wind direction 0-360°, wind speed 0-25 m/s, temperature 0-50 °C, and relative humidity 0-100%.

3.3.1.6 Sample collection

Aerosol samples were collected in horizontal and vertical planes at 15 fixed downwind grid locations for spray days in July 2015, June 2016, and September 2016. Our SOPs (Appendix C) provided detailed methods for horizontal (deposition) and vertical (airborne) sampling at a single location and a diagram (Figure 3.6) for setting up a grid of such targets near an orchard being sprayed with micronutrients. In accordance with applicable ISO drift sampling guidelines, we used a coordinate reference system with an array of sampling collectors, measured all distances from the downwind edge of the sprayed area (with a minimum at 5 m), and set up collector masts that were at least 6 m tall for air-assisted sprayers operating in tree crops (78). Sample targets were placed in rows that were 5 m (Targets B-F), 26 m (Targets G-K), and 52 m (Targets L-P) downwind of the sprayed area. Reference samples were also collected in the middle of the sprayed block (Target A) and 200 m upwind (Target Q).

Additionally, we collected 15 horizontal (September 29, 2016) and 60 vertical (September 30, 2016) 20

cm^2 water sensitive paper (WSP) card samples (Appendix F) to confirm the presence of liquid aerosols in the sampling grid. WSP samples were analyzed with quantitative image analysis software (Icy) (192) to determine the number and size of droplets collected at different locations and heights. Horizontal WSP samples were placed on the same platforms as the filter paper and vertical WSP samples were suspended from crossbars on the 6 m vertical masts at heights of 0, 2, 4, and 6 m. WSP card samples represented average estimates by day, as they were not changed between sprayers.

Passive sampling measurements

Three matrices were used for passive sampling of deposition and airborne drift: filter paper, low-density polyethylene (LDPE) plastic tubing line, and polyester (PE) line (Figure 3.8). Chromatography filter paper was made with sheets of cellulose that were 0.35 mm thick (*Fisherbrand*; 05-714-4). Plastic tubing was made of LDPE with an outer diameter of 6 mm ($\frac{1}{4}$ in), inner diameter of 4 mm (0.170 in) and 1 mm (0.040 in) wall (*Dynalon*; #1248) (Figure 3.9). The PE line was continuous polyester pile with wireless cotton core (*Hewitt and Booth*; 12 mm diameter) (Figure 3.10). Filter paper was cut into 20 cm by 10 cm rectangles with clean (wiped with 90% isopropanol) ceramic scissors and then placed on horizontal wooden platforms that were approximately 30 cm (12 in) above the ground. Continuous strands of LPDE line and PE line were placed on 6 m vertical masts and, in accordance with ISO guidelines, cut into discrete sections (2 m) with ceramic scissors as they were collected to investigate each sprayer's vertical drift profile (78).

As with most any environmental sampling scenario, our conditions involved turbulent air flow due to wind speed. In addition to wind speed, Stokes number (Stk, the ratio of the stopping distance of a particle to a characteristic dimension of the obstacle) (193) and gravity were the main parameters that influenced collection efficiency in our study.

We defined the sampling collection surface areas as rectangular (Equation (2)) or cylindrical without circular bases (Equations (3) and (4)). Using surface areas, we estimated the sampling efficiency for each collection matrix. Because polyester (PE) lines did not have a purely cylindrical surface, co-located low-density polyethylene (LDPE) line samples were collected at all distances during July 2015 to assist with defining PE line surface area. With a radii of 0.6 cm and 0.3 cm, respectively, the PE line was expected to be at least twice the surface area of the LDPE line (754 cm^2 vs. 377 cm^2):

$$SA_{filter\ paper} = l \times w = 20\ cm \times 10\ cm = 200\ cm^2 \tag{2}$$

$$SA_{LDPE\ line} = 2\pi \times r \times h = 2\pi \times 0.3\ cm \times 200\ cm = 377\ cm^2 \tag{3}$$

$$SA_{PE\ line} = 2\pi \times r \times h = 2\pi \times 0.6\ cm \times 200\ cm = 754\ cm^2 \tag{4}$$

Given its larger projected area and fibrous texture, the actual surface area of the PE line (Figure 3.10) was much greater than twice that of the LDPE line (Figure 3.9).

Aerosol deposition, which can be defined as wet or dry, is the process by which particles collect on solid surfaces (193). The effective rate that particles migrate to a surface, or deposition velocity ($V_{deposition}$), is defined by flux density ($F_{density}$) and undisturbed air concentration (C_{air}) in Equation (5):

$$V_{deposition} = \frac{F_{density}}{C_{air}} = \frac{\frac{number\ deposited}{m^2 \times s}}{\frac{number}{m^3}} = m/s \tag{5}$$

We expected PE lines to have a larger projected area and thicker boundary layer compared to LDPE lines. The fibrous surface on the PE lines would likely trap more stagnant air and each fiber would contribute to an equivalent total surface area. To define the number, mass, or volume deposited, PE line and LDPE line surfaces must be understood in terms of single fiber interception efficiency (E_Σ), as described in Equation (6):

$$E_\Sigma = \frac{number\ collected\ on\ unit\ length}{number\ geometrically\ incident\ on\ unit\ length} \tag{6}$$

Based on the expected particle sizes of our field study, interception efficiency (E_R), impaction efficiency (E_I), and gravitational settling efficiency (E_G) are the three main mechanisms by which the micronutrient tracer aerosol particles were deposited on LDPE lines and PE lines (193). Interception is the process of a particle following a gas streamline that comes within one particle radius of a fiber surface and hits the fiber (193). Inertial impaction occurs when a particle following a gas streamline cannot adjust quickly enough to changing streamlines near the fiber surface and hits the fiber due to inertial force (193). Gravitational settling efficiency is a dimensionless number that describes deposition, which is relatively small compared to the other single-fiber efficiency mechanisms, especially in horizontal flow (193).

Active sampling measurements

We also conducted active sampling to characterize aerosol size distributions and check for potential masking of relative drift magnitudes as measured by passive matrices. We developed consistent procedures using eight air sampling pumps (*SKC Universal Pump Model PCXR8*) that were calibrated to 2.0 L/min using a primary calibration standard (*Bios DryCal Defender*) on the day of use. Tygon tubing connected the pumps to six inhalable dust samplers (*IOM Inhalable Dust Samplers*) and two cascade impactors (*Marple Personal Cascade Impactor, 290 Series*). These instruments are commonly used for personal air monitoring in occupational settings, but are more accurately described as area monitors in this study. Three IOM samplers were mounted on tractors, two were placed 5 m downwind (Mast D @ 2 m and 6 m heights), and one was placed 52 m downwind (Mast N @ 2 m height). One impactor was placed 11 m downwind (@ 2 m height) and the other was placed 39 m downwind (@ 2 m height).

IOM sampler field methods called for the use of 25 mm mixed cellulose ester (MCE) filters in polypropylene cassettes, as detailed in *IOM Inhalable Dust Sampler* instructions and previous validation studies (194, 195). The 50% cut point was 100 µm at a flow rate of 2.0 L/min.

Cascade impactor field methods involved 34 mm radial slotted mylar matrices on eight stages and one polyvinyl chloride (PVC) final filter, as detailed in the *Marple Personal Cascade Impactor* instructions (196). The radial slot design is known for its accuracy, minimal internal losses, and ability to characterize aerosol penetration into the human respiratory tract. At a flow rate of 2.0 L/min, cut points for the stages were 21.3, 14.8, 9.8, 6, 3.5, 1.55, 0.93, and 0.52 µm.

Percent flow difference, total air volume sampled, and mass concentration were calculated for each air filter.

3.3.1.7 Laboratory analysis

Samples were submitted to the DEOHS Environmental Health Laboratory (EHL) Trace Organics Analysis Center (TOAC) in Seattle and analyzed for micronutrient tracer mass (Table 3.3). Aliquots of the sprayer bulk tank and water source samples were prepared using microwave assisted digestion (open vessel, ramp to 90°C in 10 min and hold for 20 min) and then diluted with deionized water to final concentration of 10% HNO3, 6% HCl, and 10 ppb Tb recovery standard. Bulk samples were digested because of precipitation and apparent microbial growth in some sample containers. To all other samples, 10% HNO3 with 10 ppb Tb was added. IOM cassettes were rinsed twice with 2.5 mL 10% HNO3 and the rinses were added to the tube with the filter.

The extraction/digestion solutions were analyzed by Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) using EHL Standard Operating Procedure 07, which is adapted from EPA 6020a Rev.1 2007 (197). The instrument was operated in He-gas mode, which eliminates polyatomic isobaric interferences. ^{55}Mn, ^{63}Cu, and ^{66}Zn were acquired with ^{45}Sc as internal standard. ^{95}Mo and ^{159}Tb were acquired with ^{89}Y as internal standard. Calibrant solutions in the same final acid concentration as samples were prepared from commercial calibrant stocks (*ISO Guide 34 certified, BDH Aristar, VWR*, West Chester PA). Independent check standards were prepared from commercial stocks (*ISO Guide 34 certified, BDH Aristar and Ultra Scientific*, N. Kingstown RI).

Matrix spike recovery determinations were performed when blank media was provided to the lab. A minimum of three matrix blanks were analyzed with each batch of samples to quantify background metal levels. Bulk tank and water samples were corrected for the mean process blank level. Other samples were corrected by the mean matrix blank level.

Samples with resulting negative values were considered to be below the limit of blank (LOB), or the concentration found when replicates of a blank sample containing no analyte are tested (198). The limit of quantitation (LOQ) was determined by multiplying the standard deviation (SD) of the matrix blanks by 3. We explored both substitution (e.g. $\frac{LOQ}{\sqrt{2}}$) and imputation techniques for samples below the LOQ, but any gains made by these methods did not compare to using the log-normally distributed raw lab values themselves. As such, we included sample measurements that were below LOQ but above LOB. Measurements below LOB (n=6) were excluded (199).

3.3.1.8 Sample measurement normalization

To compare across sprayers, we normalized values by dividing the mass per sample (e.g. M_{sample} in µg per 2 m section of PE lines) by the concentration of the tracer in the tank mix (C_{tank} in µg/mL). We did this for all sampling media. This allowed comparison of corresponding normalized values (in mL or µL) for different spray trials in a way that eliminated micronutrient effects, which we define as differences in concentration due to label mixing instructions and variability. Thus, sample results were the mL volume (V_{drift}) of the tank mix (C_{tank}) that was deposited on the target surface. This calculation assumes it was not necessary to adjust for small differences in molecular weight of the metals. This assumption was appropriate because the effect of gravitational settling was small relative to interception and impaction efficiency for vertical sampling media in horizontal flow. This showed the total volume of liquid (V_{drift}) that was deposited on each target by each sprayer, which gave a convenient interpretation shown by the worked example in Equation (7):

$$V_{drift} = \frac{M_{sample}}{C_{tank}} = \frac{0.871\mu g}{11.436\frac{\mu g}{mL}} = 0.076\ mL\ = 76\ \mu L \tag{7}$$

Results from passive sampling were reported in terms of volume tank equivalents (µL) intercepted from drift plumes and active sampling is reported in liquid volume tank equivalents (µL) per unit volume of air (mL^3).

3.3.2 Rank drift potential of three spray technologies

3.3.2.1 Descriptive statistics

Data were managed and analyzed with R version 3.3.3 (2017-03-06) using the following packages: beeswarm, bookdown, ggplot2, ggthemes, gridExtra, knitr, lattice, lme4, lubridate, pander, and reshape (16, 137–145, 200). We produced plots of distributions, arithmetic and geometric means and standard deviations, scatter plots, box plots, and a heat map. To simplify data summaries in tables and figures, we listed results from each 0-2 m section as *2 meters*, each 2-4 m section as *4 meters*, and each 4-6 m section as *6 meters*.

A total of 926 samples from 20 spray trials was collected (Table 3.5), which included bulk tank, filter paper, PE line, LDPE line, mylar, MCE, and PVC samples. Data from October 8, 2014 and June 9, 2016 were excluded; the former was from the pilot study, which had a different sampling layout than the full studies, and the latter was from a day in which the mean wind direction was outside the acceptable range (90° ± 30° to the downwind edge of the sprayed area). After demonstrating that the relative micronutrient mass deposits were similar for co-located samples on July 1, 2015 (Figure 3.15), we did not analyze LDPE lines from July 2, 2015 or June 10, 2016 trials and did not collect LDPE lines from the September 28-30 trials. A total of 357 line samples (306 PE and 51 LDPE) was used for modeling (Table 3.6). Each sample was analyzed for multiple micronutrients, so the final dataset used for the statistical analysis included 675 PE line-based measurements that were not from reference masts (Targets A and Q).

3.3.2.2 Linear mixed model regression

We built a mixed-effects model for airborne drift as measured by PE lines (N=675 (samples), k=3 (sprayer groups), n=225 (samples per sprayer), volume of liquid droplets) (Equation (8)). The model described the relationship between potential worker exposure as an outcome variable (log-µL) and the following covariates:

sprayer type, location, downwind distance, height, and wind speed. Field targets were considered surrogates for worker location during a drift event (e.g. on the ground 26 m from the sprayed block or 52 m away on a ladder), which were derived from WA DOH drift event data scenarios. Sprayer type and location were categorical variables and distance, height, and wind speed were continuous variables. We modeled sprayer, distance, height, and wind speed as fixed effects and location as a random effect. Individual locations were entered as a random effect to adjust for within-location variance.

$$\log(E(Drift)) = \beta_0 + \beta_1 Sprayer + \beta_2 Distance + \beta_3 Height + \beta_4 Wind\ Speed + \beta_5 Location + \epsilon \qquad (8)$$

We used restricted maximum likelihood (REML) estimates to find within- and between- location variance components that would provide further insights about potential worker exposure. In a secondary model, we used the same terms, but with log-transformed distance, height, and wind speed covariates, mainly to aid with interpretation of the log-transformed response variable. The three sprayers were compared by ranking them according to their ability to limit drift to neighboring orchards and potential worker exposure. The following criteria were used:

- Results from our statistical model to show drift differences, if any, across sprayers
- 'Star ratings' approach outlined in EPA's Drift Reduction Technology program (28, 59, 60)
- Evidence of drift outside the 100 ft (30 m) Application Exclusion Zone (AEZ) for orchard sprayers, as described in EPA's Worker Protection Standard (100)

3.4 Results

3.4.1 Meteorological measurements

Table 3.4 provides a summary of meteorology by spray trial. Spraying typically began between 8:00 and 11:00 AM and ended around noon. Duration was longer in September 2016 because 3 sprayers were used each day compared to only 2 in July 2015 and June 2016. Only 15-min data were available from July 1-2, 2015 due to a malfunctioning data logger. Compared to the 2016 trials, July 2015 saw higher mean temperatures (32-33 °C vs. 15-19 °C) and relative humidity (30% vs. 44-52%) and comparable wind speeds (3-5 m/s) and wind directions (generally from north).

Mean air temperature ranged from 15°C in early fall to 30 °C in the peak of summer. Relative humidity ranged from 30% during the summer to 52% during the fall. The 15-min wind speed measurements taken 70 m west of the sprayed block at a height of 2 m ranged from 2.9 to 4.0 m/s; 10 s measurements taken 190 m northeast at a height of 10 m ranged from 3.3 to 4.7 m/s. Wind direction was more variable, but largely from the north as expected. The 2 m station to the west always averaged within 20° of true north. The 10 m station once averaged 48° (northwest) on June 10, 2016, but otherwise no more than approximately 20° from north.

Time series comparisons of meteorological station data

Meteorological data collected 70 m west of the sprayed block at the permanent station were compared with data collected 190 m northeast of the sprayed block at the temporary station.

Temperature measurements from the permanent station (15-min Avg @ 2m) were slightly higher than the temporary station measurements (1-min Avg @ 3m, 1-min Avg @ 10m, 10-sec Avg @ 10m) (Figure 3.11). In June, the temperature was relatively constant over time, whereas temperature generally increased as spraying continued. July 2015 data showed similar trends. Throughout all trials, there was no evidence of inversion conditions because the atmospheric layer was stable had normal temperature decreases with height.

Relative humidity measurements ranged between approximately 40% and 60% for 2016 spray trials. Data recorded by the two relative humidity instruments tracked well, with slightly higher readings from the 1-min instrument than the 15-min instrument. On average, humidity decreased by about 15-20% from the start of spraying until it stopped.

Wind speed measurements from the permanent station (15-min Avg @ 2m, 15-min Gust @ 2m) were consistent with those from the temporary station (1-min Avg @ 3m, 10-sec Avg @ 10m) (Figure 3.13). Wind speed on June 10 was more variable than any other spray day (including July), as gustiness ranged from about 2.5 m/s at 10:45 AM to more than 7.5 m/s at 11:30 AM. On other days, average wind speed ranged from about 2.5 to 5.0 m/s according to the 10-second data and from about 2.5 to 3.5 m/s according to the 1-min and 15-min data.

Wind rose data for 2016 spray trials indicate that the wind was generally from the north at 2-4 m/s, with excursions from the northwest (Figure 3.14). The 15-min wind data collected west of the sprayed block were almost exclusively from the north and the 10 s data collected east of the sprayed block were from north-northwest or northwest. The highest wind speeds were reached when approximately 10% of the 10 s readings on June 10 were at speeds of 6-8 m/s out of the northwest.

3.4.2 Sample collection

A total of 926 samples from 20 spray trials was collected (Table 3.5), as indicated by the number of bulk tank samples per day. There were 20 bulk tank, 110 filter paper, 399 PE line, 231 LDPE line, 112 mylar, 40 MCE, and 14 PVC samples in total. A total of 357 line samples (306 PE and 51 LDPE) was used for modeling (Table 3.6). Each sample was analyzed for multiple micronutrients, so the final dataset used for the statistical analysis included 675 PE line-based measurements that were not from reference masts (Targets A and Q).

3.4.3 Laboratory analysis

Samples were analyzed in three batches to accommodate the different sampling periods in July 2015, June 2016, and September 2016 (Appendix G). The lab corrected bulk tank and water samples for the mean process blank level. Other samples were corrected for mean matrix blank level. Spike recovery efficiency ranges for Zn, Mo, and Cu in bulk tank samples were 97-112%, 98-101%, and 93-108%. Some bulk tank mix samples had floating biofilm precipitates, which dissolved upon digestion with acid. For PE lines, recovery efficiency ranges were 102-115%, 82-101%, and 92-108%. MCE filters were 80-103%, 94-103%, and 99-103% and mylar filters were 96-103%, 94-99%, and 98-99% (Table 3.7). Reporting limits are provided in Table 3.8. In all cases, micronutrient LOB was lower than LOQ. With the exception of 7% of PE line Zn measurements from 52 m downwind, 100% were above LOB and therefore had a value that contributed to the statistical analysis (Table 3.9). With respect to the reference locations (in sprayed block and 200 m upwind), 100% of the former and 83-100% of the latter values were above LOB. No other adjustments wee made to the measurements before statistical analysis.

3.4.4 Statistical analysis

3.4.4.1 Descriptive statistics

Bulk tank mix concentrations and background micronutrient levels

To eliminate micronutrient effects, different tracers were used in each of the sprayers across all spray days (Table 3.5). Regardless of sprayer type, geometric means (GM) and standard deviations (GSD) for Zn, Mo, and Cu tank mix concentrations were 252 (1.3), 8.0 (1.2), and 112 (1.2) µg/mL. Background levels for Zn, Mo, and Cu in the water source were 0.12 (2.0), 0.00083 (1.9), and 0.00087 (1.8) µg/mL, which equates to very low background levels of 0.047%, 0.010%, and 0.00078%, respectively.

Passive sampling

Summary statistics for estimated drift volume (µL) indicated that among 675 micronutrient measurements on PE lines, 669 were above LOB (Table 3.10). The 6 measurements below LOB were all 52 m downwind. As expected, the data were log-normally distributed. For all drift volume data, the GM (GSD) was 58 (3.8) µL. AFA, DAT, and MFT sprayers were 66 (3.6), 60 (3.7), and 45 (4.3) µL, respectively. When restricted to data collected at distances farther than 25 m downwind, the same trend was observed across sprayers. At 26 m, mean drift volumes for AFA, DAT, and MFT were 52 (2.0), 50 (1.8), and 33 (2.3) µL. At 52 m, they were 20 (2.3), 17 (2.5), and 13 (2.8) µL. By this metric, the MFT sprayer had 35-37% (e.g. 1-$\frac{33}{52}$) less drift measured by volume than the AFA sprayer at mid and far field distances. The DAT sprayer had 4-15% less than the AFA at the same distances.

Because drift volume estimates were log-normally distributed and spanned several orders of magnitude, most plots are in units of log-µL. A side-by-side comparison of PE line and LDPE line collection volumes indicated that the pattern of relative values at each mast height were strikingly similar (Figure 3.15). Despite PE lines having larger collection surface areas than LDPE lines, the drift volume 'signal' was quite similar across the two sampling matrices.

The locally weighted scatterplot smoother (LOWESS) curve for all tracer drift volume data by distance and sprayer indicated that the MFT sprayer was less drift prone than the other two sprayers (Figure 3.16). When further stratified by height, the same data showed that tracer drift volume decreased with mast height at near field locations (5 m downwind) but increased with mast height at mid and far field locations (26 and 52 m downwind) (Figures 3.17 and 3.18).

Tracer drift volumes by location and sprayer revealed that the group median of the near-field (5 m) targets (B-F) was greater than the group median of the mid-field (26 m) targets (G-K), which was in turn greater than that of the far-field (52 m) targets (L-P) (Figure 3.19). The AFA sprayer produced the largest median drift volume at 67% ($\frac{10}{15}$) of the locations, followed by the DAT at 20% ($\frac{3}{15}$), and MFT at 13% ($\frac{2}{15}$). At mid and far field distances only, AFA was largest for 80% ($\frac{8}{10}$) and DAT was for 20% ($\frac{2}{10}$) of the locations.

Combined box and swarmplots by sprayer show that median drift volumes intercepted at 26 and 52 m downwind were lowest for the MFT and highest for the AFA sprayer (Figure 3.20). This was true both native and log-transformed scales. As expected, most of the volumes measured at 26 m were higher than those at 52 m. These trends were largely true when stratified by micronutrient tracer (Figure 3.21).

Figure 3.22 indicates mean tracer drift volume (µL) intercepted by PE lines for each sprayer and height across the sampling field. The color ramps from white to red, with red indicating the highest drift volumes. As expected, near field samples (Targets B-F in first row) had the highest volumes at any height, with ranges of 152-486, 87-597, and 74-578 µL for the AFA, DAT, and MFT, respectively. The MFT performed better than the other sprayers at mid field distances, especially at 4 m and 2 m heights.

Active sampling

IOM air samplers and pumps traveling with the sprayers demonstrated that the DAT sprayer had lower drift tracer volumes than those for the AFA and MFT sprayers, which were very similar in terms of distribution (Figure 3.23). All sprayers had larger drift tracer volumes than those measured at the near (5 m downwind @ 2 and 6 m heights on Mast D) and far (52 m downwind @ 2 m height on Mast N) sampling locations.

Cascade impactor data collected 11 m and 39 m downwind showed similar aerosol size distributions at both locations (Figure 3.24). Drift volumes measured at near locations were higher. These data seem to suggest that the most common volume median diameter (VMD) range was 6.0-9.8 µm. It should be noted that these data were above LOB but not LOQ.

3.4.4.2 Model results

Figure 3.25 provides a plot of the model point estimates and 95% confidence intervals for the primary model. The table below it contains point estimates, 95% confidence intervals, and p-values for each of the fixed parts of the model. The random part of the model output was $\sigma^2 = 0.498$, $\tau_{00,location} = 0.128$, $N_{location} = 15$, $ICC_{location} = 0.205$, and $R^2 : \Omega_0^2 = 0.733 : 0.733$. Similarly, the secondary model results are provided in Figure 3.26.

According to both models, MFT sprayer and distance were significantly associated with a decrease in volume and height and wind speed were significantly associated with an increase in drift volume. The DAT sprayer drift volume was not significantly different than the AAS sprayer drift volume. With the exception of distance, the relative impact of using log-transformed covariates did not change in either model. The influence of distance in the latter was much stronger, however. When the other covariates were not included in either model, the MFT sprayer yielded a 35% [95% confidence interval (CI): 22-49%] decrease in drift volume. More of the remaining variance was within-location ($\frac{0.128}{0.128+0.498}$, 80%) than between-location (20%).

3.5 Discussion

We tested the performance of the conventional AFA sprayer against more modern DAT and MFT sprayers based on drift reduction. The field study site proved to be ideal for the trials because it allowed us to isolate and test the factors of interest. The orchard was situated on a flat site that oriented the wind in a relatively predictable direction. Although we would have liked to sample in a private orchard, the research orchard allowed us to carry out the stratified randomized block study design in a way that minimized environmental differences across sprayer type. It also allowed us to create orchard drift scenarios typical of Washington State and capture empirical evidence with sampling matrices and cameras.

Overall weather conditions were relatively similar across spray days, orchard locations, and measurement intervals. There were some notable differences. Temperatures in July 2015 were 10-15 °C higher than other spray days in early summer or fall. During each spray day, temperatures increased by no more than 4 °C. The permanent station tended to have higher temperature and lower relative humidity measurements, due at least in part to the morning shadow cast by the gorge wall. Relative humidity was 40-60% with uniform decreases across trials. Our model did not account for humidity decreases or temperature increases because these changes were consistent and occurred over much larger time scales than wind direction or speed changes, which are important determinants of spray drift. In general, the temporary station's wind speed and direction measurements were more variable than the permanent station, as would be expected with higher time resolution. When averaged to the same time scale, temporary station wind measurements were within the range of the permanent station. Wind speed data included in the model were summarized according to time spent by each sprayer in each orchard block quadrant (plus one minute). Average wind speeds at 2 m were within US EPA's drift-reducing wind recommendations of 3-10 mph (44). We tested the use of 15-min versus 1-min wind speed data in our model and found that it did not impact our overall findings. Our weather station's ultrasonic anemometer might not have been pointing true north, which could explain why average direction measured by that instrument tended to be more westerly. It is also a possible effect of measurement height (10 m vs. 2 m) or proximity to the gorge wall. Because we included winds from WNW-ENE, the ultrasonic readings did not affect our results.

Tank-adjusted tracer drift volumes were collected by passive and active sampling methods. Per drift sampling standards, sampling occurred on the downwind side of the sprayed area at different distances and heights. Row orientation in the sprayed block was parallel to the prevailing wind direction as opposed to perpendicular, the latter of which is required by some standards (78, 81). Our north-south axis layout provided an opportunity to analyze potential "tree canyon" effects in downwind rows by isolating components of wind flow below canopy height, where orchard workers might be located. Below the canopy, the east-west component of the angled wind vector would have continued flowing southward. Drift aerosols would either follow the below-canopy streamline or be filtered by the canopy itself. Above the canopy, drift was better able to disperse in an east-west direction as it would in an open field.

If the sprayers produced drift at heights above 6 m, our sampling field did not capture that part of the plume. Pre-spray sample setup and post-spray sample harvesting involved time and labor intensive tasks while following the standard operating procedures (Appendix C). In the process, some sample surfaces contacted gloved hands, tree leaves, or the ground. In July 2015, some samples contacted the canopy surface or the ground due to sampling masts tipping. In all cases, these "contacts" were noted. Exclusion of these potentially contaminated samples (n=12), which were not statistically different than other repeated measurements at the same location, did not affect our study conclusions.

Both active and passive methods demonstrated drift decay with downfield distance as expected. Our trials found evidence of drift at distances about 1.7 times greater than the 100 ft (30 m) AEZ radius for orchard sprayers defined by the Worker Protection Standard (100). According to this standard, the first two rows of our sampling area should have been free of all persons other than appropriately trained and equipped handlers when the sprayer was at the southern edge of the sprayed block (100). Vertical profiles demonstrated greater deposition at the highest sampling level with increasing distance. For Drift Reduction Technology (DRT) testing and AEZ setting, our study findings highlight the importance of differentiating not only by downwind distance, but also by sprayer type, sampling height, and orchard architecture.

One of our most important findings was that the MFT sprayer produced less measurable drift than the AFA and DAT sprayers. Model results and summary statistics found that the MFT sprayer reduced drift by approximately 35% compared to the AFA sprayer. These MFT drift reduction findings may fit into EPA's DRT one-star category consisting of a 25-50% reduction. It should be noted that the voluntary DRT program is currently limited to protocols that test row and field crop application technologies, but it may expand to orchard crops in the future (28, 59, 60). Although a one-star rating is encouraging, it also suggests that more drift reduction may be possible by continuing to advance application technology relative to conventional orchard airblast spraying (28, 59, 60).

Proper sprayer calibration and maintenance are fundamentally important to drift reduction (160, 182, 183). Although each sprayer's output was matched to the orchard canopy and calibrated to apply the same volume per area with similar droplet sizes and spray shapes, there was still uncertainty in the sprayers due to system pressure, liquid volume output, air-assisted volume and speed, design, tank volume measurements (± 10 gal), tractor used, and general maintenance. Although the AFA air-assisted fan volume was lower than the other sprayers, its operating pressure was at the high end of acceptable calibration setting range. Relative to the other sprayers, higher pressure was needed on the AFA to achieve the same liquid volume output and droplets with similar volume median diameters (VMD). The DAT likely had the highest fan speeds and most concentrated air volume output, which could have increased its drift potential relative to the lower speeds and volume output for each fan of the MFT. The AFA had a 100 gal tank that was built onto the frame of a tractor and the other sprayers had 400 gal tanks that were tow-behind. To avoid complications due to multiple change-outs required during the randomized quadrant spray order, each sprayer was associated with a different orchard tractor.

Our approach compared sprayers through tracer-based volume estimates. This metric was useful because it indicated tank mix equivalents intercepted along a continuous 6 m sampling surface. Future studies are needed to compare sprays with equal concentration of tracers in each tank. We recommend measurement with passively sampled PE lines and comparison to results from actively sampled filters and direct-reading monitors to obtain higher resolution of the drift plume over time. This, in conjunction with PE line surface area comparisons to LDPE line, could help define sampling efficiency of PE lines. Conceivably, a mass per air volume (or mass per surface area) estimate can be derived from these relationships to better relate with potential dermal and inhalation exposures. Our study modeled stationary area sampling for workers who are normally moving. It would be ideal to sample in a private orchard, or better yet, during a real drift event. That would require equipping orchardists and orchard workers with low-cost and easy-to-use tools to identify when drift is occurring.

Tower sprayers appear to be a promising means by which to decrease drift through shorter nozzle-to-tree canopy distances and more horizontally-directed aerosols that do not escape the tree canopy. However, application technology alone cannot reduce drift, as evidenced by our finding that the AFA and DAT drift plumes were not significantly different. Our calibration may not be reflective of common field behavior and the measurements could therefore be underestimates of true drift exposure. Systematic evaluation of orchard sprayers is essential for developing recommendations about pesticide drift reduction.

3.6 Tables

Table 3.1: Description of air-assisted sprayers used in this study.

Spray equipment	Definition
Axial fan airblast (AFA)	Traditional orchard sprayer without vertical implements such as towers or multi-headed fans. Refers to original "Okanagan air blast orchard sprayer" and similar designs that have not changed much since 1950s. The AFA sprayer in this study had one axial fan and 10 open disc-core nozzles (5 nozzles per side).
Directed air tower (DAT)	Similar to an AFA sprayer but with a vertical implement (tower) added to move nozzles closer to the target compared to curved AFA arrangement. The DAT sprayer in this study had one axial fan and 22 open disc-core nozzles on the tower (11 nozzles per side.)
Multi-headed fan tower (MFT)	Tower sprayer with three propeller axial fans per side that assist with blowing aerosols toward a target. The MFT sprayer in this study had six fans and 36 open one-piece nozzles on the tower (3 fans per side; 6 nozzles per fan).

Table 3.2: Comparison of sprayer specifications and settings. More information about nozzle types can be found in a technical catalog. Categories were obtained from the ASABE 572.1 droplet size classification standard (52).

Sprayer factor	Axial Fan Airblast (AFA)	Directed Air Tower (DAT)	Multi-headed Fan Tower (MFT)
Nozzles/side	5	11	18
Nozzle set(n)	D3(2);D5(2);D4(1)	D3(11)	VK-8(12);VK-4(6)
Core size	25	25	NA
Pressure(PSI)	205	100	Auto-adjusted
Fan size(in)	28	30	20
Air vol(cfm)	20,000-30,000	20,000-30,000	20,000-30,000
Droplet size	Fine	Fine	Very fine
Diameter(μm)	110-125	125-130	61-105

Table 3.3: Laboratory extraction methods for each media type.

Sample media	Volume (mL) extractant/digestate	Preparation method
Tank water source; Bulk tank mix	2.5 mL HNO_3, 1.5 mL HCl	Microwave assisted digestion of aliquot (4 mL)
Filter paper	50 mL 10% HNO_3	Rocker table for 10 min in sample container, centrifuged, and supernatant transferred to new tube
PE line	100 mL 10% HNO_3	Rolled for 10 min in sample container
LDPE line	50 mL 10% HNO_3	Rolled for 10 min in sample container
MCE; Mylar; PVC	5 mL 10% HNO_3	Transferred to centrifuge tube, vortexed for 10 min

Table 3.4: Summary of meteorological data collected during trials. Measurements for wind speed and direction are reported from two locations: 15-min averages at 2 m wind cup anemometer and 10 s averages at 10 m ultrasonic anemometer. Wind speed is reported in azimuth degrees, where 0° or 360° represents wind from the North. (*) Duration was longer in September 2016 because 3 sprayers were used each day compared to only 2 in July 2015 and June 2016. Only 15-min data were available for July 1-2, 2015.

Date	Time	Temp (°C)	Wind Speed AM (ASD) (m/s)	Wind Direction AM (ASD) (°)	Duration (min)
01-Jul-15	10:41-12:13	32.4	3.3(0.3); -	360(0); -	92
02-Jul-15	10:15-11:21	31.6	4.0(0.3); -	360(0); -	66
10-Jun-16	10:44-12:08	19.3	3.7(1.5);4.7(2.0)	340(0.6);312(0.5)	84
28-Sep-16*	09:34-11:35	18.9	4.0(0.2);4.4(1.1)	360(0.0);338(0.2)	121
29-Sep-16*	08:50-10:42	16.0	2.9(0.2);3.4(0.9)	12(0.4);343(0.2)	112
30-Sep-16*	08:20-10:07	15.5	3.2(0.2);3.7(1.0)	360(0.0);340(0.2)	107

Table 3.5: Summary of field studies. We collected 926 samples from 20 spray trials, as indicated by the number of bulk tank samples per spray day. There were 10 AFA, 5 DAT, and 5 MFT spray trials. (*) Data from October 8, 2014 and June 9, 2016 were excluded from the analysis; the former was the pilot study, which had a different sampling layout than the full studies, and the latter was a day in which the mean wind direction was outside the acceptable range (90° ± 30° to the downwind edge of the sprayed area). See Table 3.6 for a summary of data used in the statistical models.

Spray day	Study	Bulk tank	Filter paper	PE line	LDPE line	Mylar	MCE	PVC	Total
08-Oct-14*	Pilot	3	42	42	27	0	5	0	119
01-Jul-15	Full	2	17	51	51	16	5	2	144
02-Jul-15	Full	2	17	51	51	16	5	2	144
09-Jun-16*	Full	2	17	51	51	16	5	2	144
10-Jun-16	Full	2	17	51	51	16	5	2	144
28-Sep-16	Full	3	0	51	0	16	5	2	77
29-Sep-16	Full	3	0	51	0	16	5	2	77
30-Sep-16	Full	3	0	51	0	16	5	2	77
Total		20	110	399	231	112	40	14	926

Table 3.6: Summary of data used from 15 spray trials (6 AFA, 5 DAT, and 4 MFT) in the statistical models. We collected 102 line samples (3 PE and 3 LDPE line on 17 masts) during each of the first three spray days. After demonstrating that the relative micronutrient mass deposits were similar for co-located samples on July 1, 2015 (Figure 3.15), we did not analyze LDPE lines from the July 2, 2015 or June 10, 2016 trials and did not collect LDPE lines from the September 28-30 trials.

Spray day	Spray trials (sprayer-micronutrient)	Total collected	PE analyzed	LDPE analyzed
01-Jul-15	AFA-Zn; DAT-Mo	102	51	51
02-Jul-15	AFA-Mo; DAT-Zn	102	51	0
10-Jun-16	AFA-Zn; MFT-Mo	102	51	0
28-Sep-16	AFA-Zn; DAT-Cu; MFT-Mo	51	51	0
29-Sep-16	AFA-Mo; DAT-Zn; MFT-Cu	51	51	0
30-Sep-16	AFA-Cu; DAT-Mo; MFT-Zn	51	51	0
Total	15 trials	459	306	51

Table 3.7: Sample recovery efficiency. Percentages represent the range of recovery efficiency from three sample analysis batches after field collection in July 2015, June 2016, and September 2016.

Sample type	Zn (%)	Mo (%)	Cu (%)
Bulk tank	97-112	98-101	93-108
PE line	102-115	82-101	92-108
MCE filter	80-103	94-103	99-103
Mylar filter	96-103	94-99	98-99

Table 3.8: Limit of blank (LOB) and limit of quantitation (LOQ) in µg for sample analysis.

Sample type	Zn LOB	Zn LOQ	Mo LOB	Mo LOQ	Cu LOB	Cu LOQ
Bulk tank	-	0.014	-	0.0025	-	0.0037
PE line	2.85	8.00	0.029	0.076	0.69	1.67
LDPE line	0.1	0.2	0.001	0.005	0.01	0.04
MCE filter	0.0019	0.0165	0.00005	0.0005	0.0010	0.0028
Mylar filter	0.022	0.068	0.0038	0.0080	0.0022	0.0066

Table 3.9: Percent of PE line samples above limit of blank (LOB) by micronutrient and distance.

Location	Zn (%)	Mo (%)	Cu (%)
Reference - In sprayed block	100	100	100
Downwind 5 m	100	100	100
Downwind 26 m	100	100	100
Downwind 52 m	93	100	100
Reference - 200 m upwind	83	83	100

Table 3.10: Summary statistics for estimated drift volume (µL) collected on PE line sampling matrices. Counts are reflective of each micronutrient tracer analyzed in a single inductively coupled plasma mass spectrometry (ICP-MS) procedure (e.g. one sampling matrix had Zn, Mo, and Cu measurements). The number of measurements for AFA, DAT, and MFT sprayers are different because only two sprayers were used in July 2015 and June 2016 (Table 3.5). Listed by limit of blank (LOB), number of measurements (n), arithmetic mean (AM), arithmetic standard deviation (ASD), geometric mean (GM), and geometric standard deviation (GSD).

Sample	<LOB	n	AM	ASD	GM	GSD
All data	6	669	128	172	58	3.8
-AFA sprayer	4	266	136	179	66	3.6
—Near (5 m)	0	90	310	216	257	1.8
—Mid (26 m)	0	90	66	42	52	2.0
—Far (52 m)	4	86	28	24	20	2.3
-DAT sprayer	2	223	129	169	60	3.7
—Near (5 m)	0	75	300	197	247	1.9
—Mid (26 m)	0	75	59	37	50	1.8
—Far (52 m)	2	73	25	25	17	2.5
-MFT sprayer	0	180	114	166	45	4.3
—Near (5 m)	0	60	276	203	200	2.5
—Mid (26 m)	0	60	44	32	33	2.3
—Far (52 m)	0	60	21	19	13	2.8

3.7 Figures

Figure 3.1: Images of Axial Fan Airblast (AFA), Directed Air Tower (DAT), and Multi-headed Fan Tower (MFT) sprayers (from left to right).

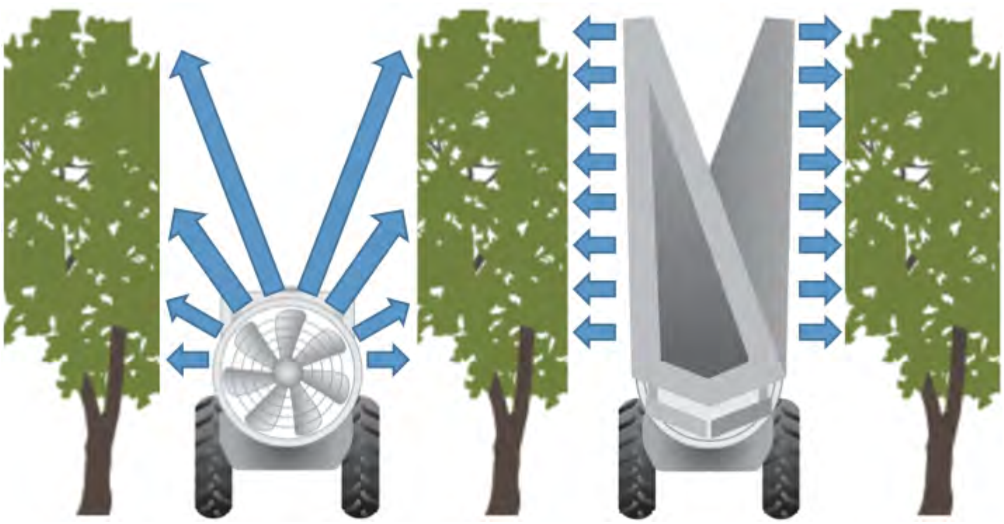


Figure 3.2: Drift potential for traditional (AFA, left) and tower (DAT/MFT, right) airblast sprayers. Images adapted with permission (182).

Figure 3.3: Satellite view of study location, research orchard blocks, and apple varieties.

Figure 3.4: Overhead view of spray trials in research orchard blocks. Camera #1 was positioned on the southern edge of the sampling area with an aerial view of the sprayed area from approximately 35 m downwind and 6 m above the ground, near Target I (Figure 3.6).

Figure 3.5: Tractor view of spray trials in research orchard blocks. Camera #2 was positioned on the seat of the tractor pulling the sprayer, facing backwards during the spray trials. Images are from the AFA, DAT, and MFT sprayers (from left to right).

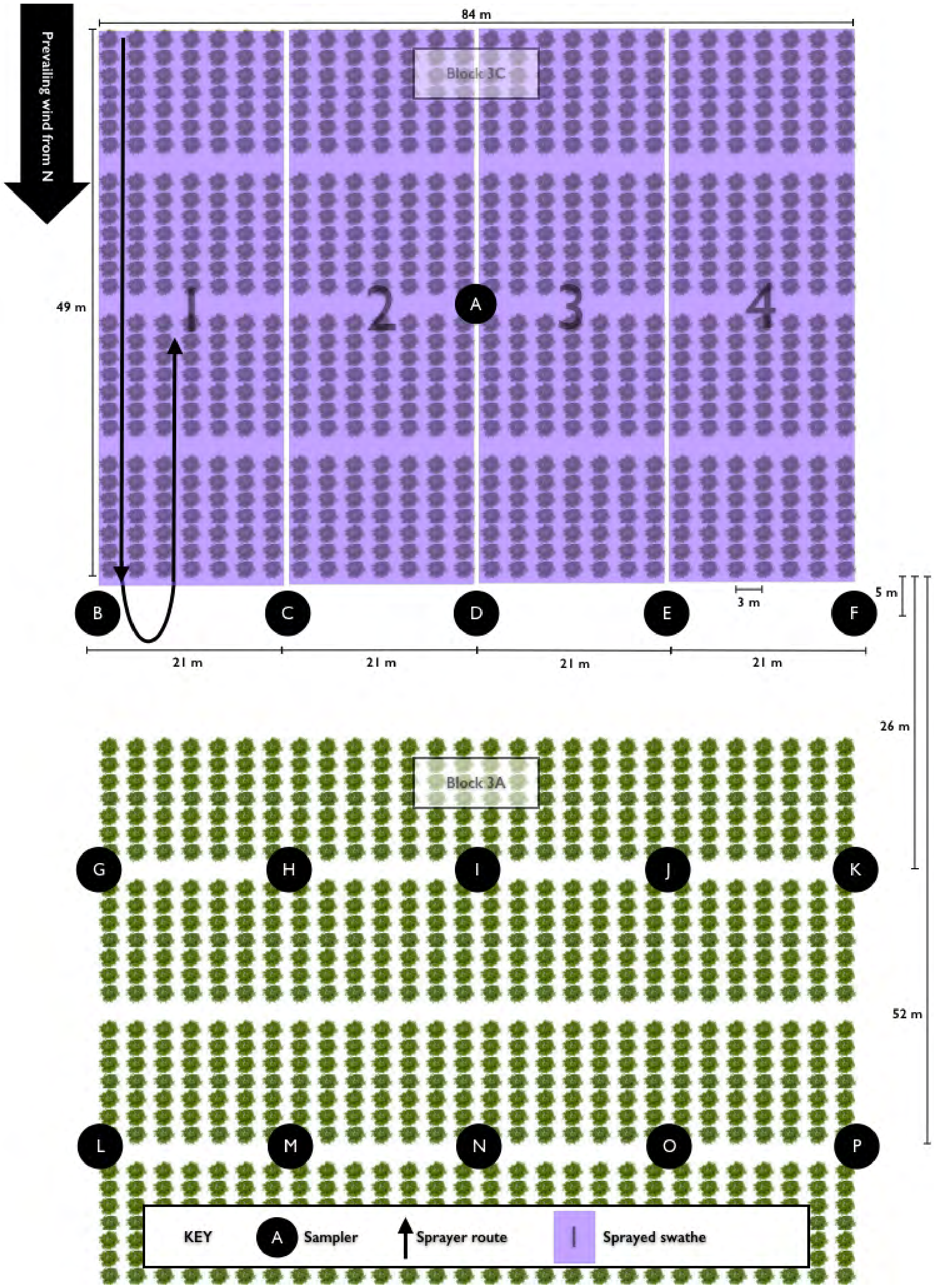


Figure 3.6: Relative locations of sprayed and sampling blocks with prevailing wind from the north. Sprayed block (purple area) was divided into 4 quadrants and sprayed in a randomized order by the AFA, DAT, and MFT sprayers. Sampling area included Targets B-P organized in a grid. Reference samples were Target A (middle of the sprayed area) and Target Q (not pictured; 200 m upwind).

Figure 3.7: Side view of spray trials in research orchard blocks. Camera #3 was located approximately 10 m from the western edge between the sprayed and sampling fields (Figure 3.6), with a side view of the sprayers. Images are of the AFA, DAT, and MFT sprayers (from top to bottom).

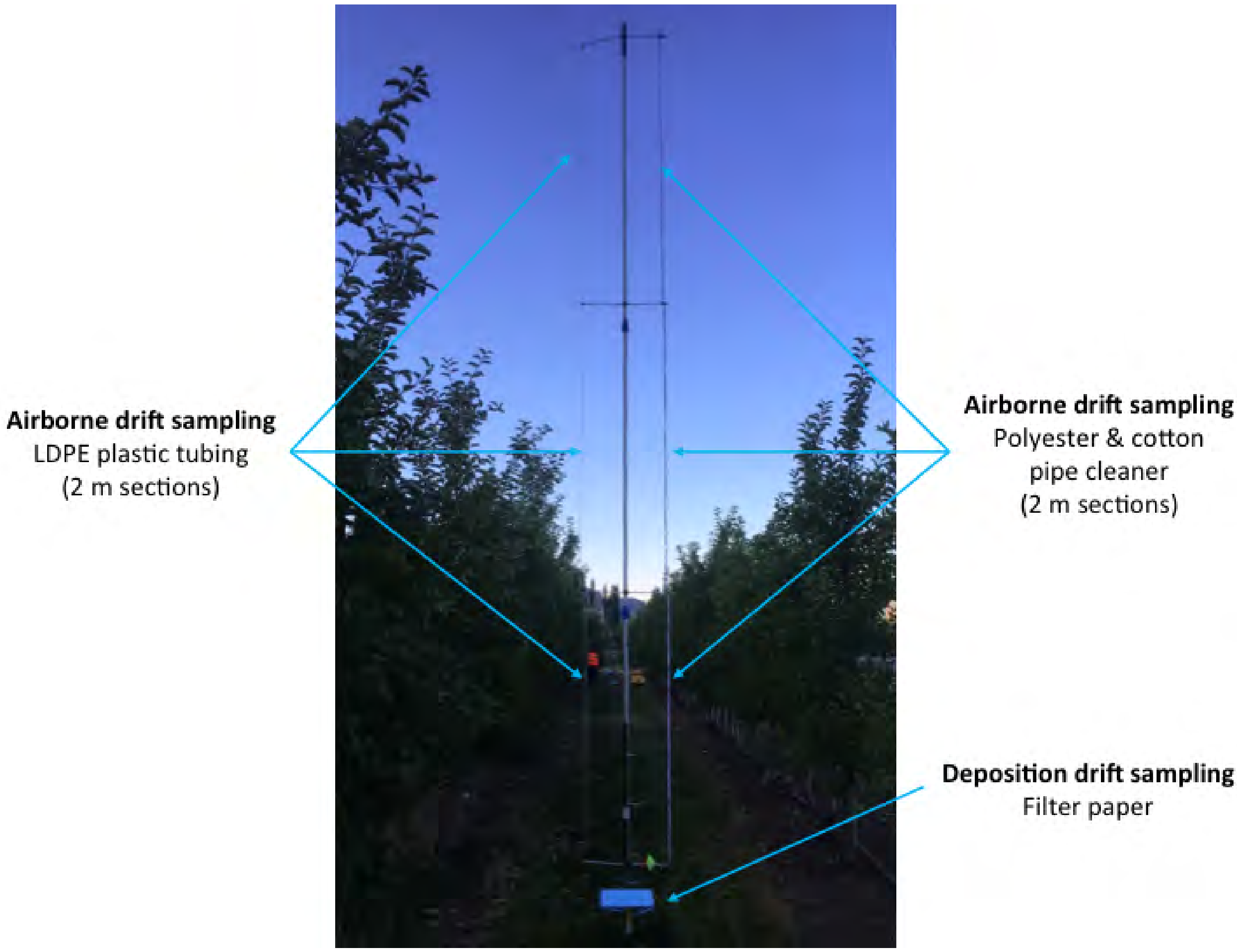


Figure 3.8: Example of horizontal and vertical passive sampling target setup. Horizontal platform in foreground and vertical sampling mast (with crossbars at 2, 4, and 6 m) in background.

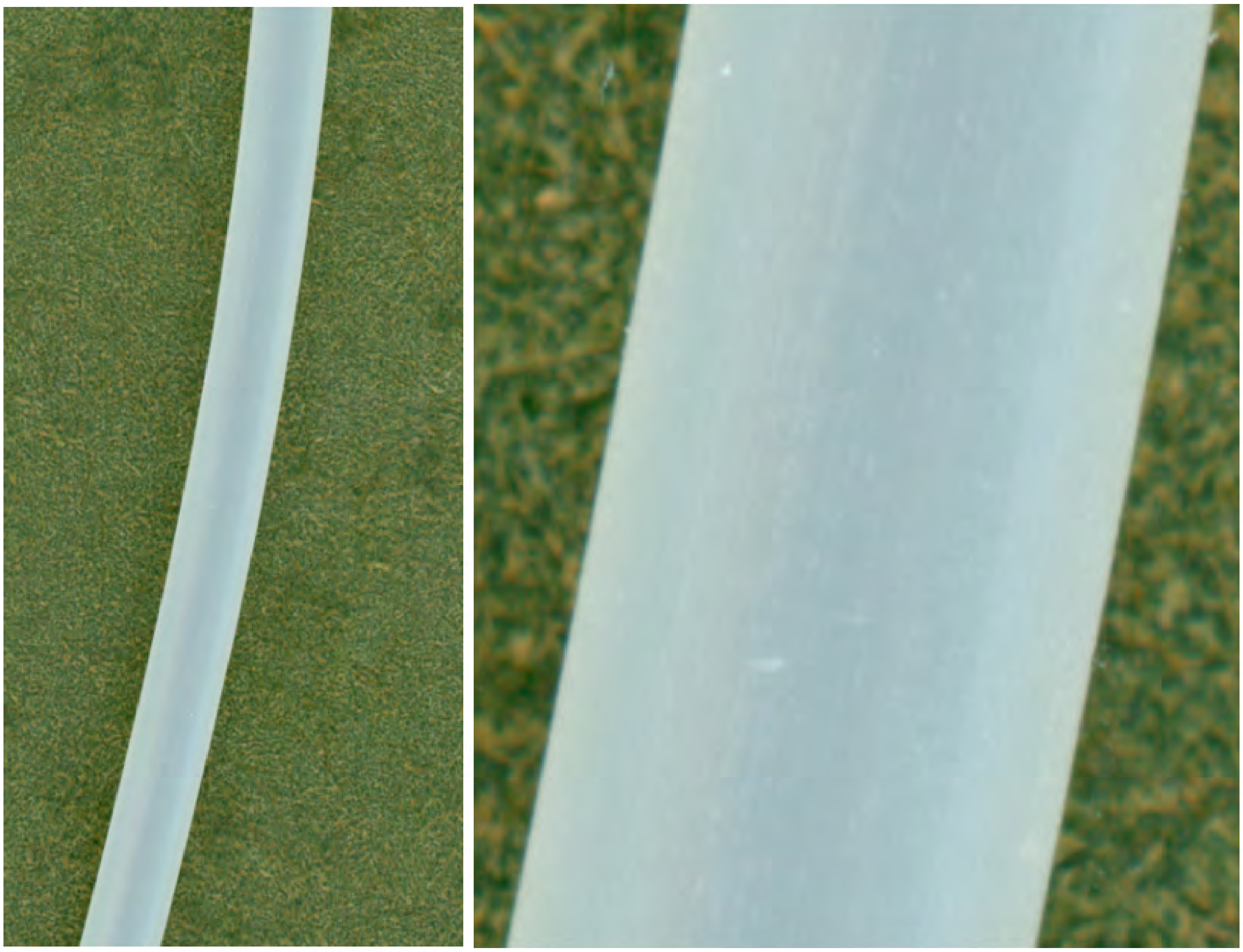


Figure 3.9: Detailed image of low-density polyethylene (LDPE) line sampling matrix.

Figure 3.10: Detailed image of polyester (PE) line sampling matrix.

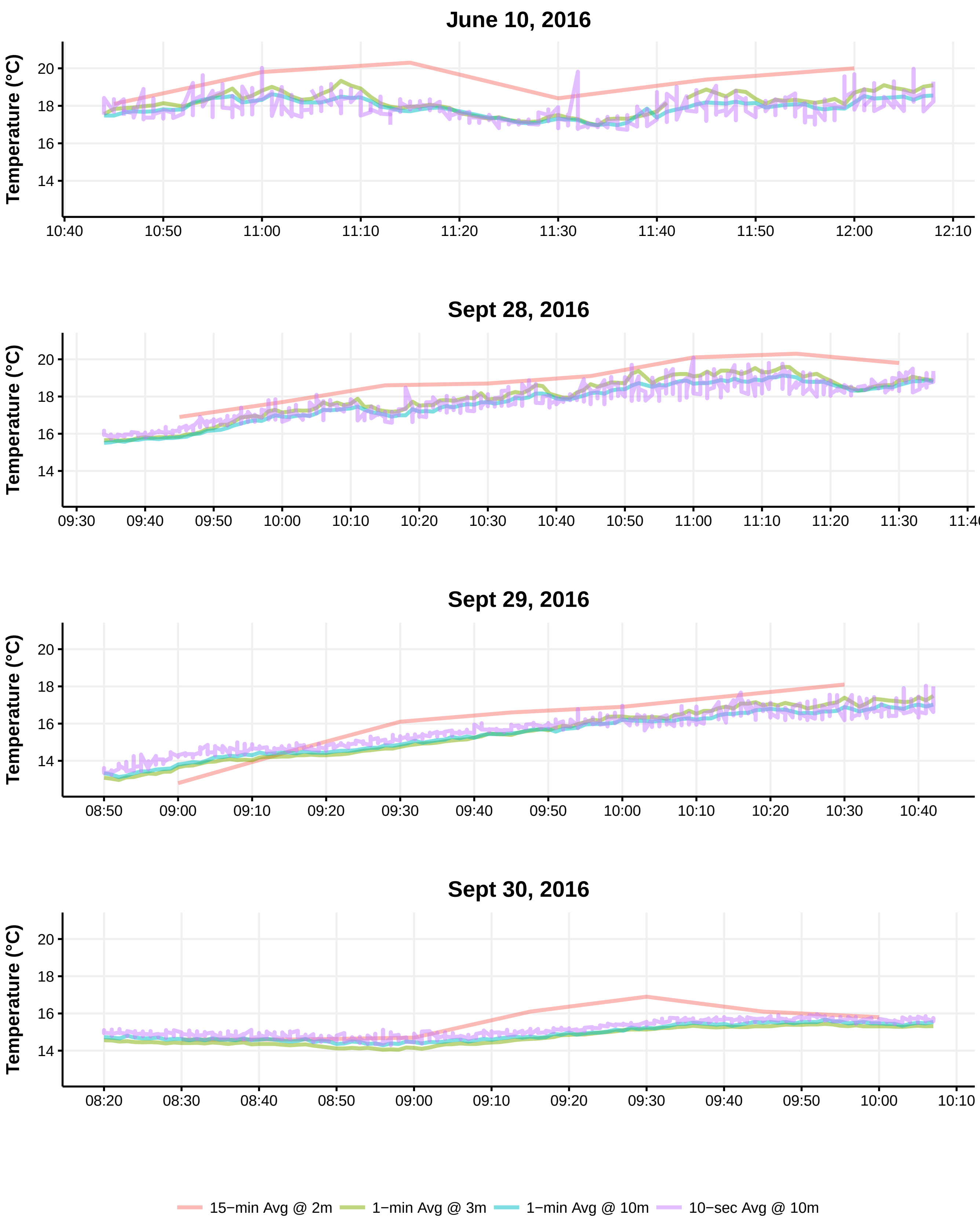


Figure 3.11: Temperature measurements from permanent (15-min Avg) and temporary (1-min Avg and 10-sec Avg) meteorological stations. The permanent and temporary stations were 70 m west and 190 m northeast of the sprayed block.

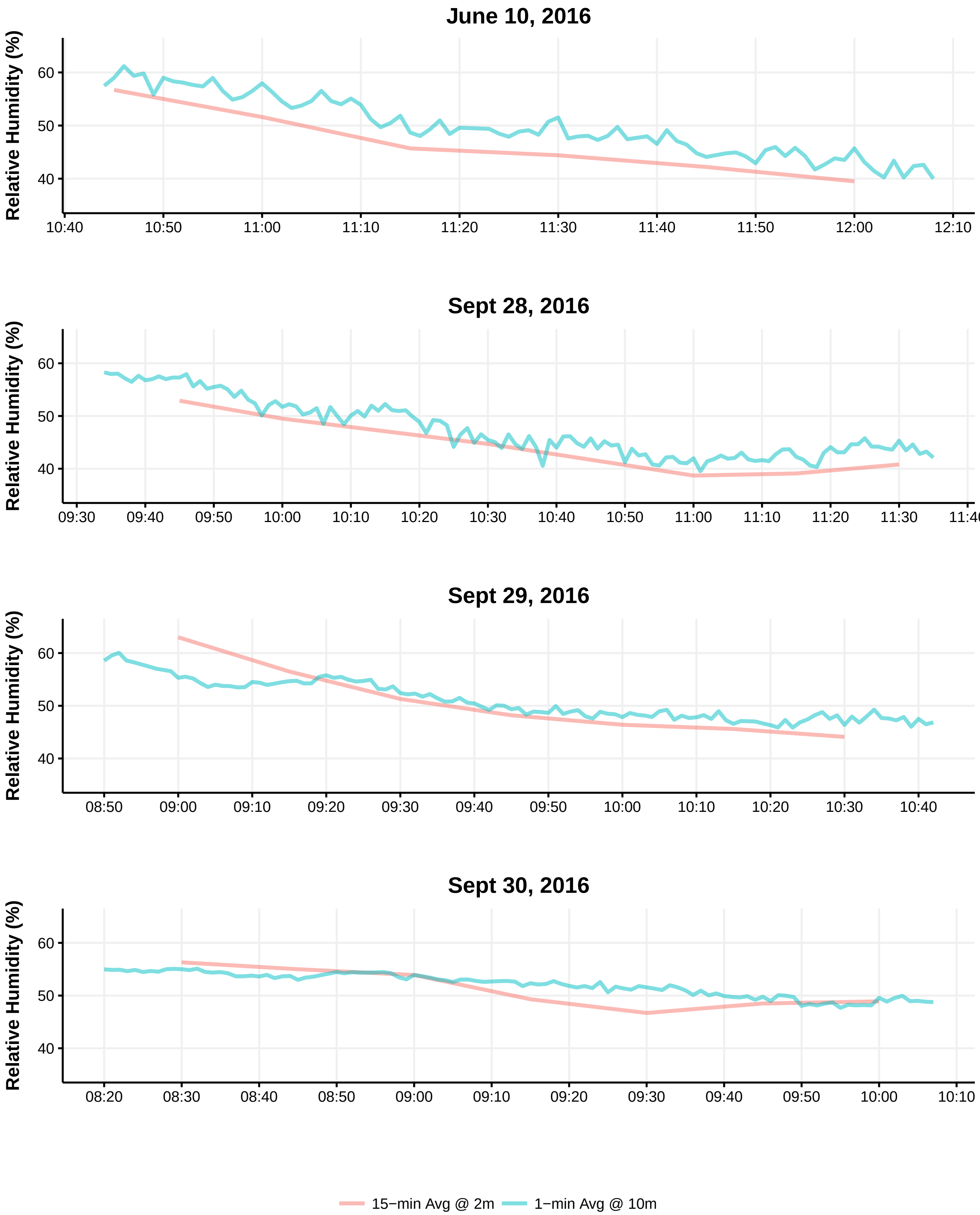


Figure 3.12: Relative humidity measurements from permanent (15-min Avg) and temporary (1-min Avg) meteorological stations.

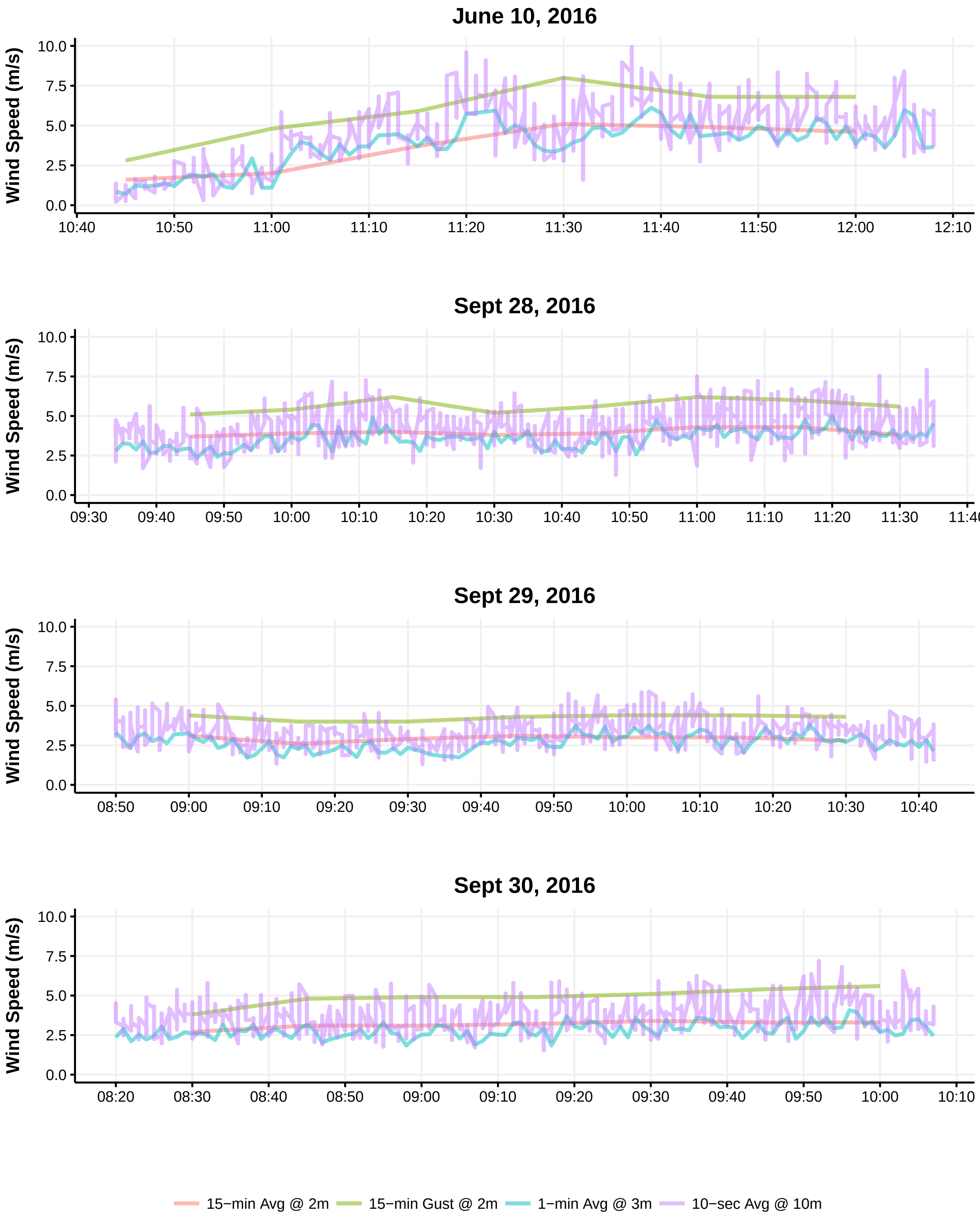


Figure 3.13: Wind speed measurements from permanent (15-min Avg) and temporary (1-min Avg and 10-sec Avg) meteorological stations.

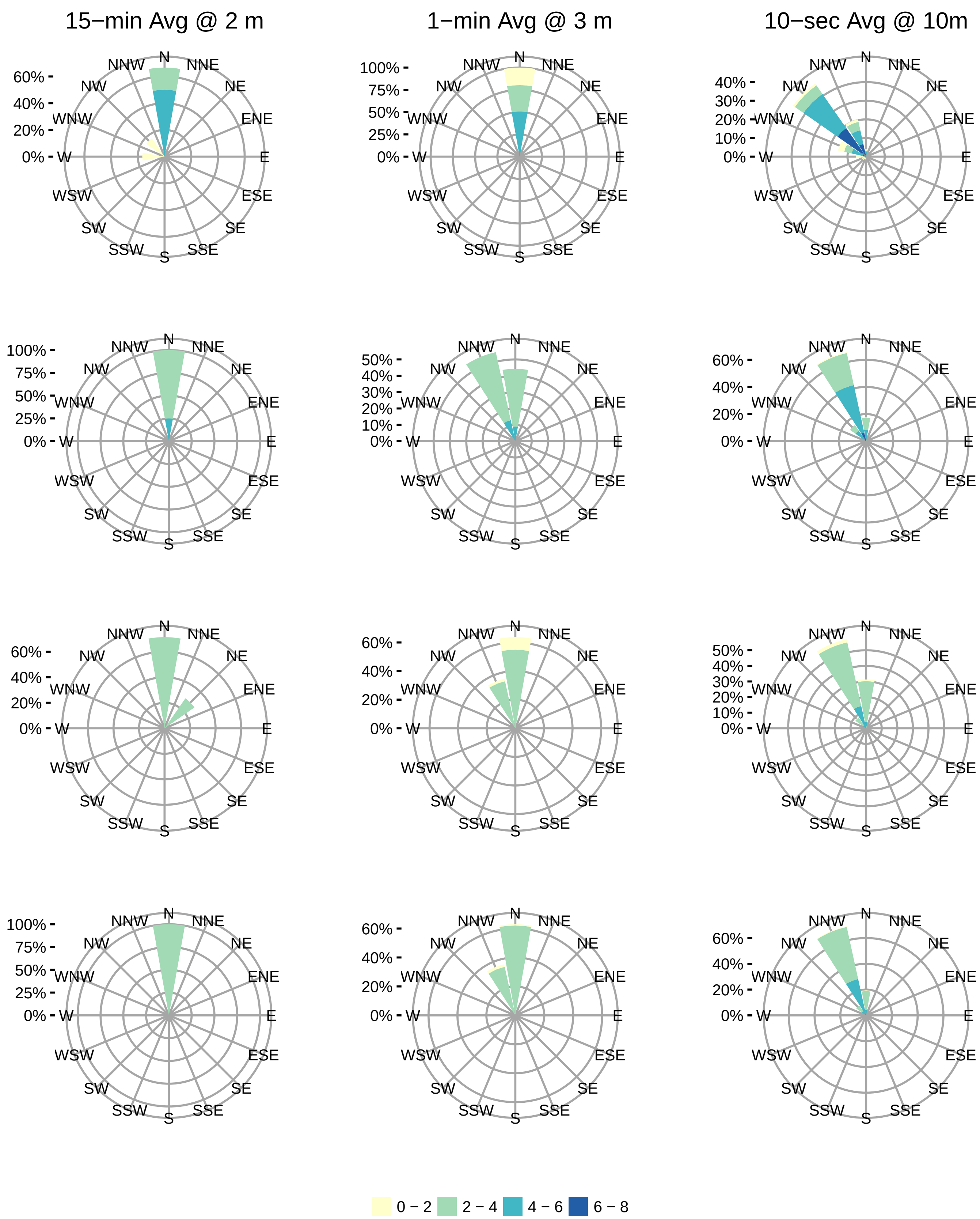


Figure 3.14: Wind speed (m/s) and direction (°) data for 2016 spray trials. Row 1 contains wind roses for June 10 from WSU wind cup anemometer (15-min Avg @ 2 m), UW wind cup anemometer (1-min Avg @ 3 m), and UW ultrasonic anemometer (10-sec Avg @ 10 m). Rows 2, 3, and 4 are from September 28, 29, and 30.

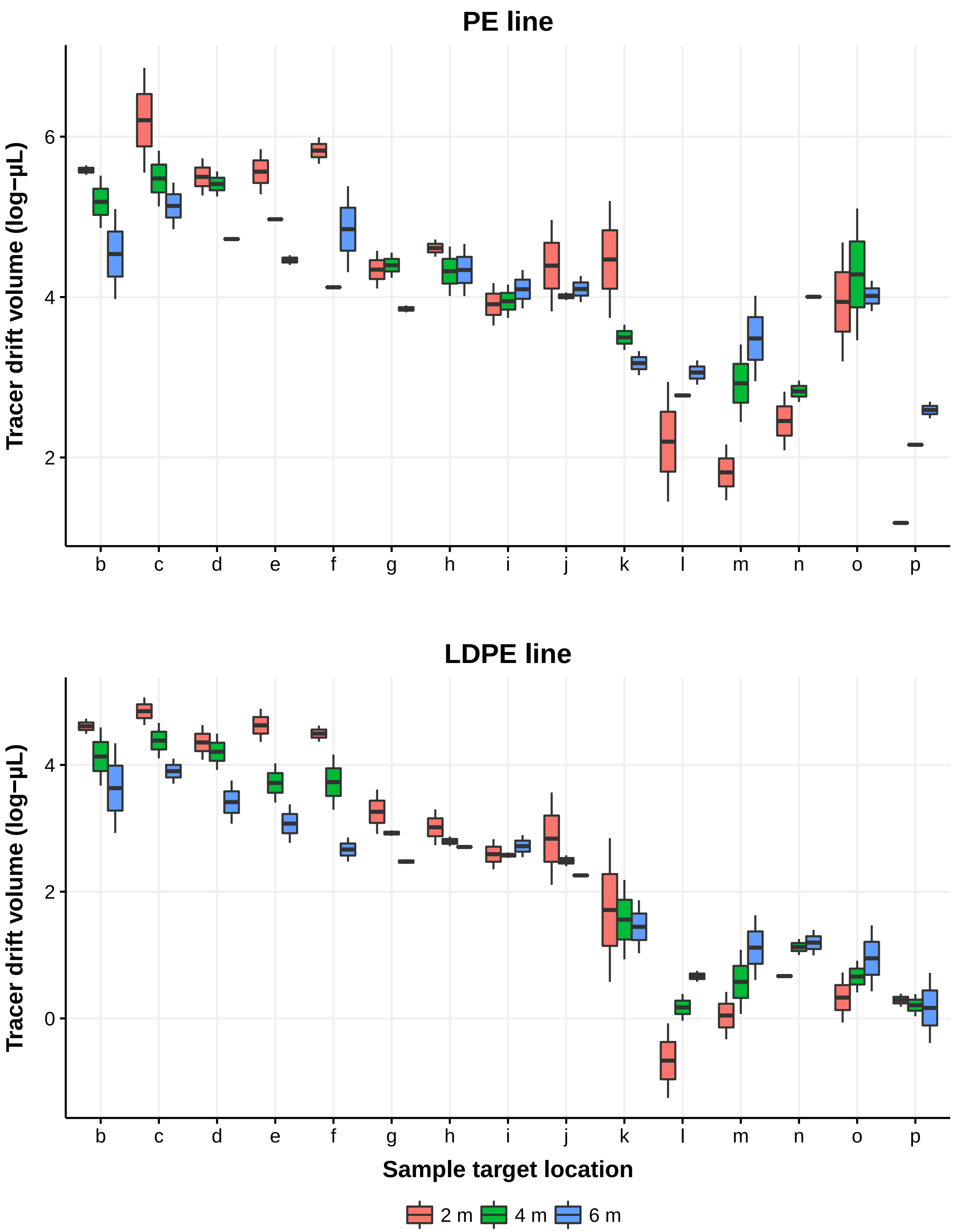


Figure 3.15: Drift volume on co-located PE line and LDPE line samples taken in July 2015. Letters on the x-axis refer to sample locations in Figure 3.6.

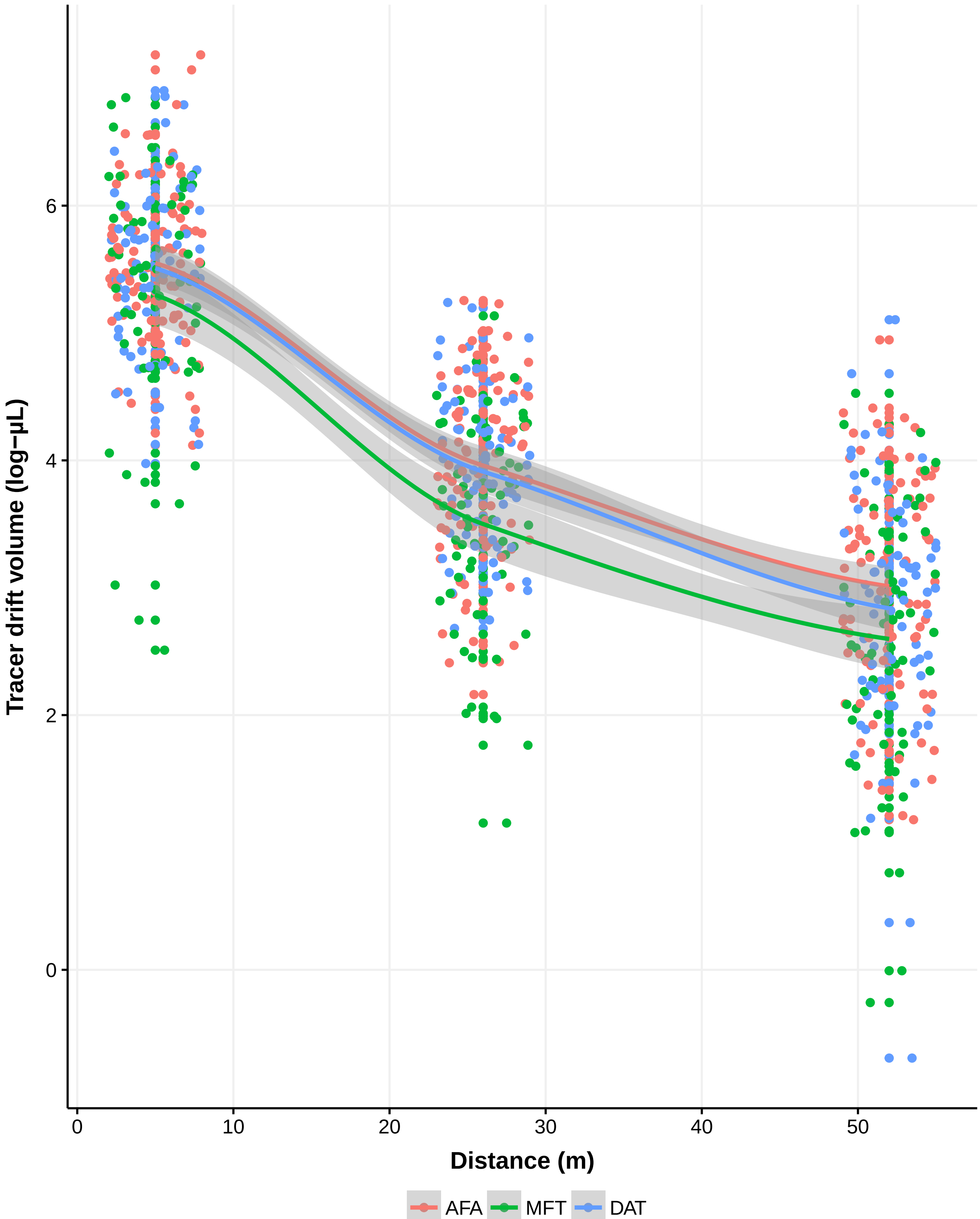


Figure 3.16: Tracer drift volume on PE lines by downwind distance and sprayer.

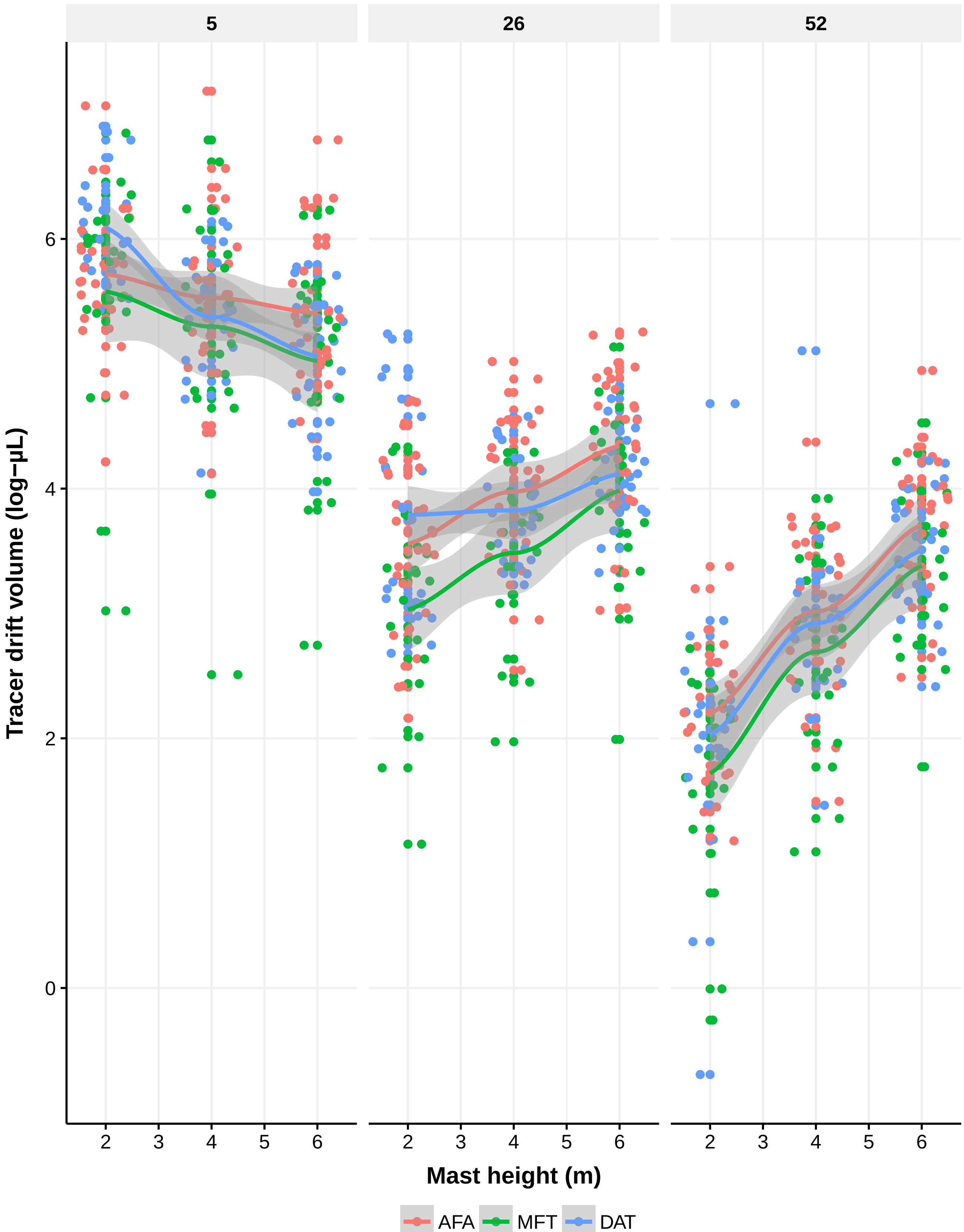


Figure 3.17: Tracer drift volume on PE lines by downwind distance, height, and sprayer.

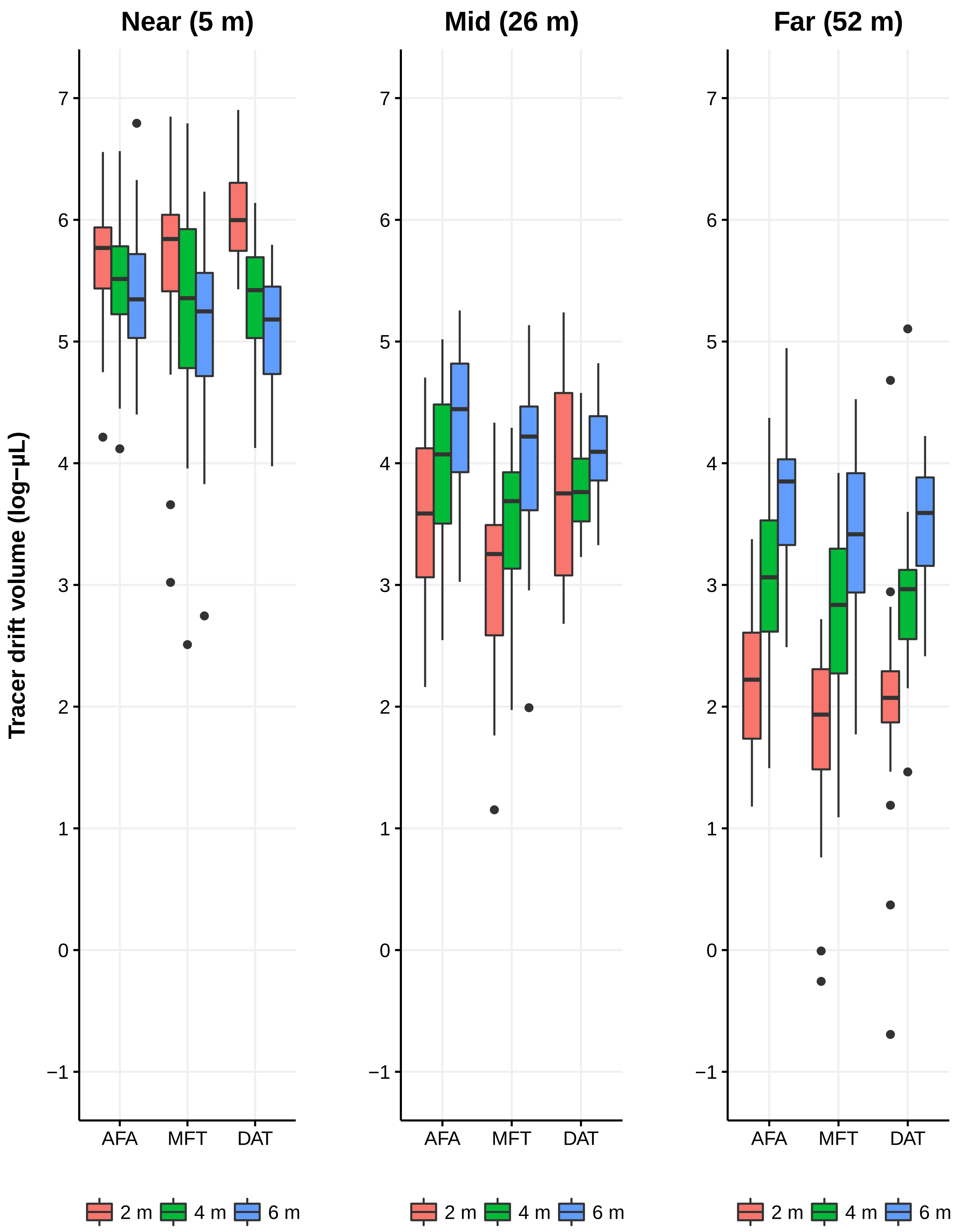


Figure 3.18: Tracer drift volume on PE lines by downwind distance, height, and sprayer.

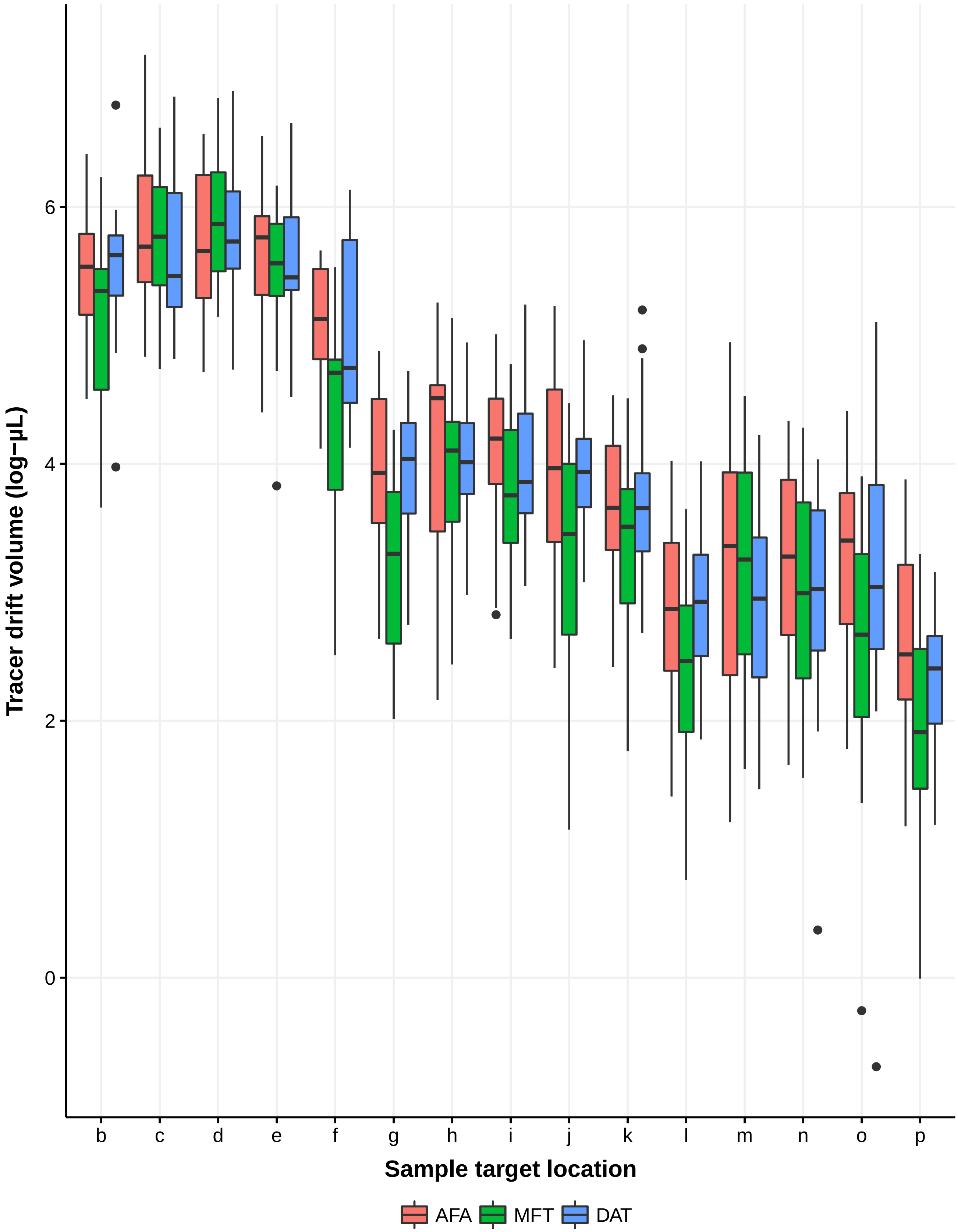


Figure 3.19: Tracer drift volume on PE lines at all target locations (Masts B-P in Figure 3.6) by sprayer.

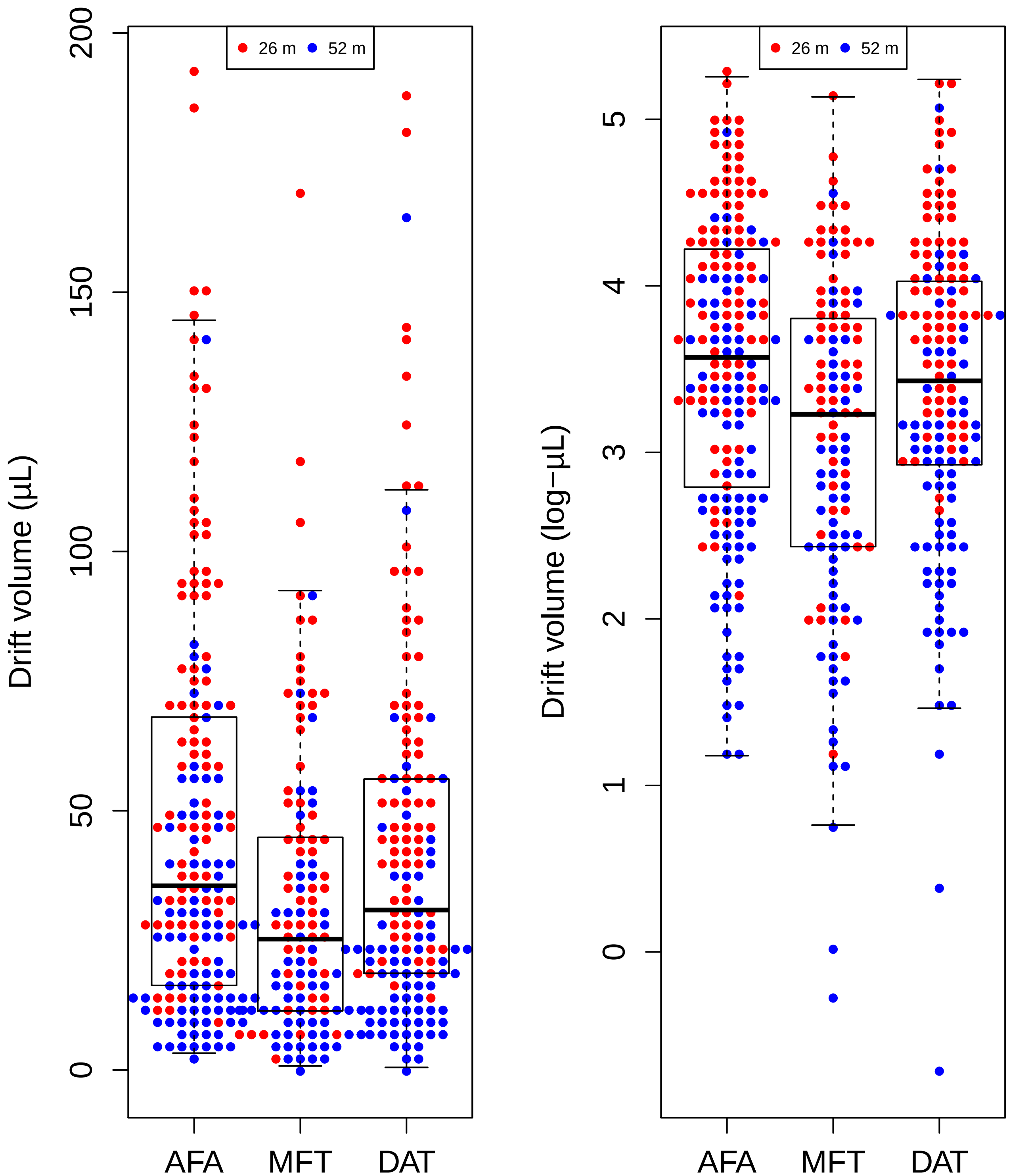


Figure 3.20: Tracer drift volume (native and log-transformed scales) collected on PE lines at mid and far field distances by sprayer.

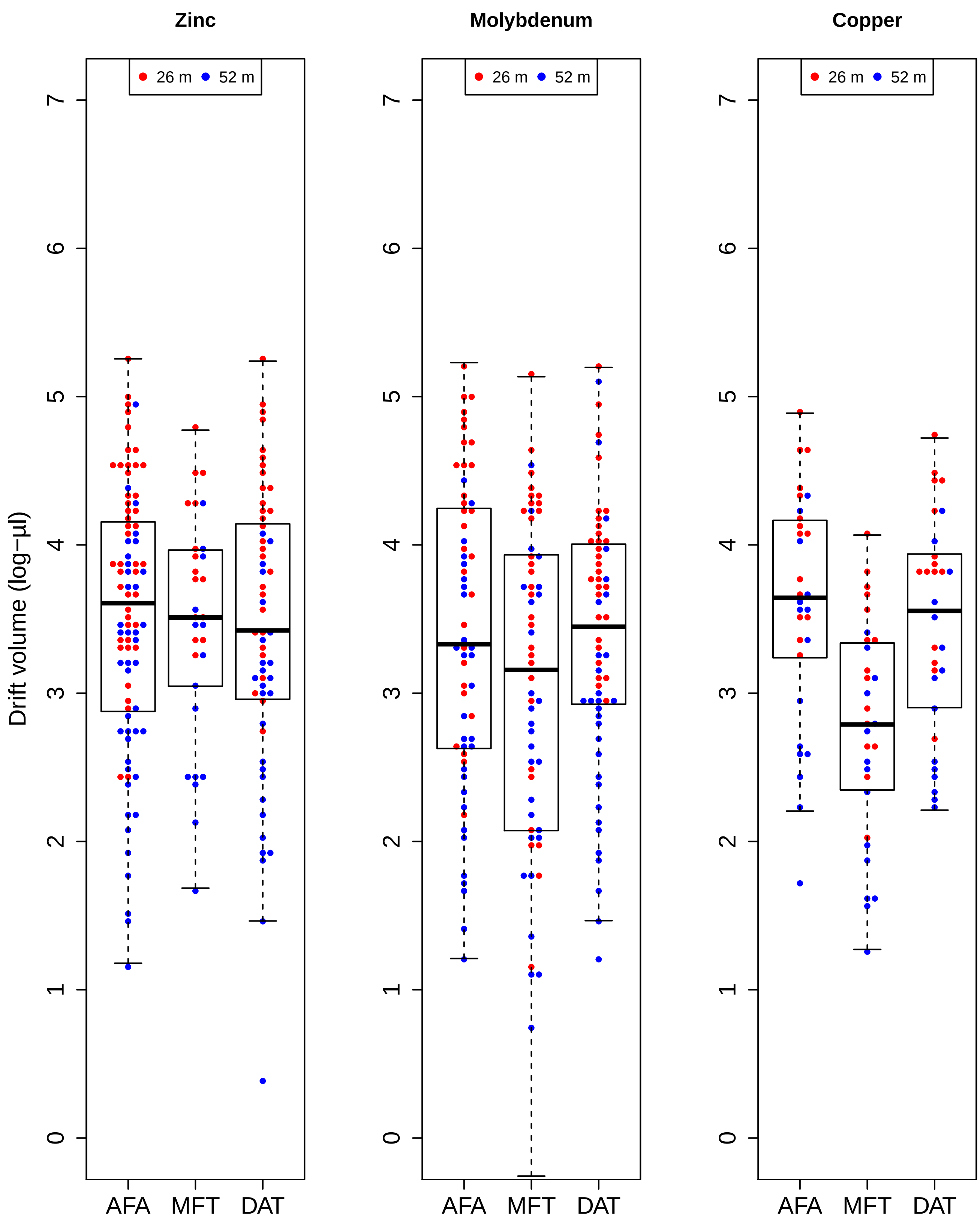


Figure 3.21: Tracer drift volume on PE lines at mid and far field distances by sprayer and micronutrient.

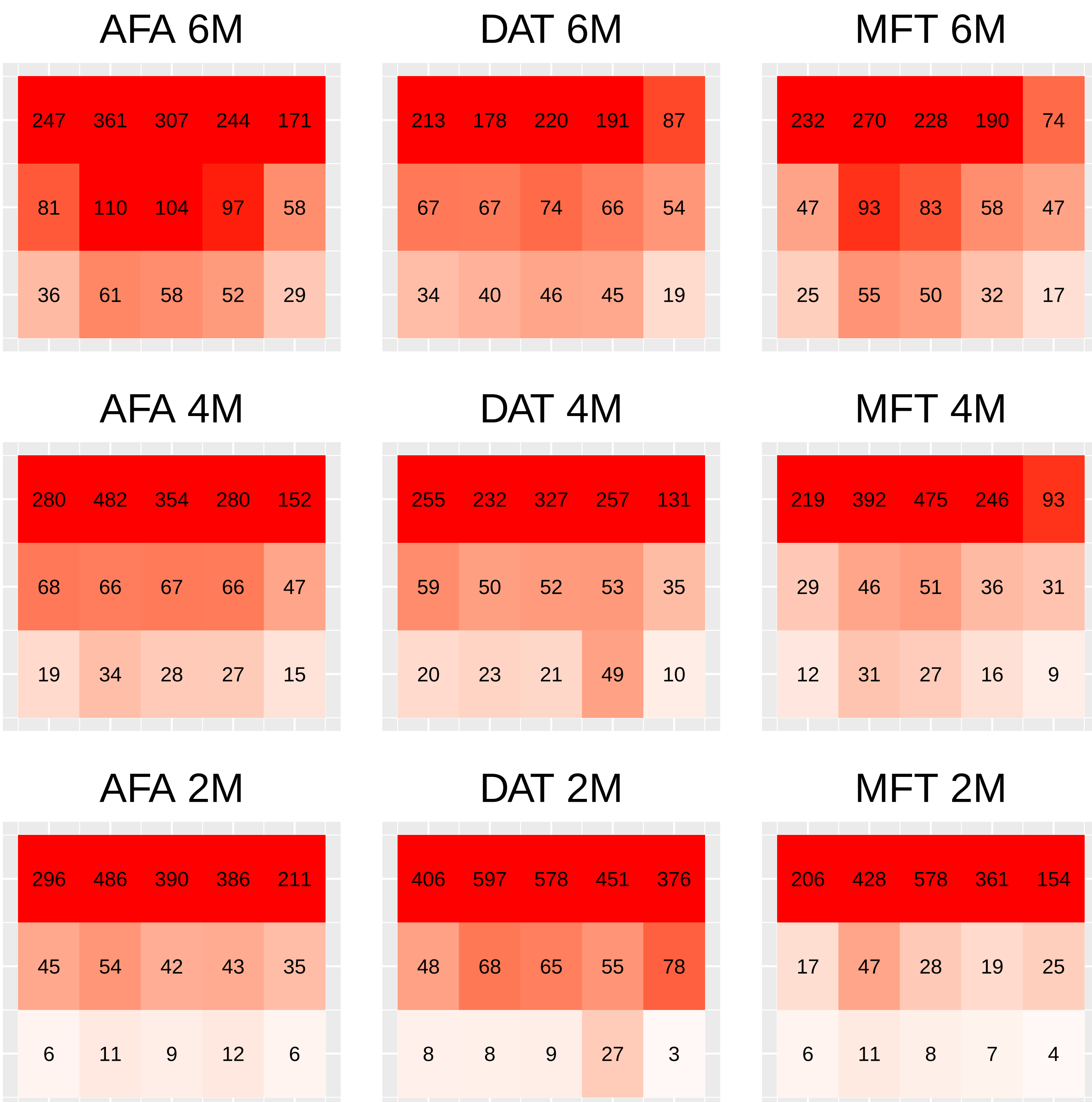


Figure 3.22: Heat maps indicate mean tracer drift volume (µL) intercepted by PE lines for each sprayer (columns) and height (rows) across the sampling field. Each 3 × 5 grid corresponds to the field sampling layout (Figure 3.6), where Row 1 (Targets B-F), Row 2 (Targets G-K), and Row 3 (Targets L-P) were 5 m, 26 m, and 52 m downwind of the sprayed block, respectively.

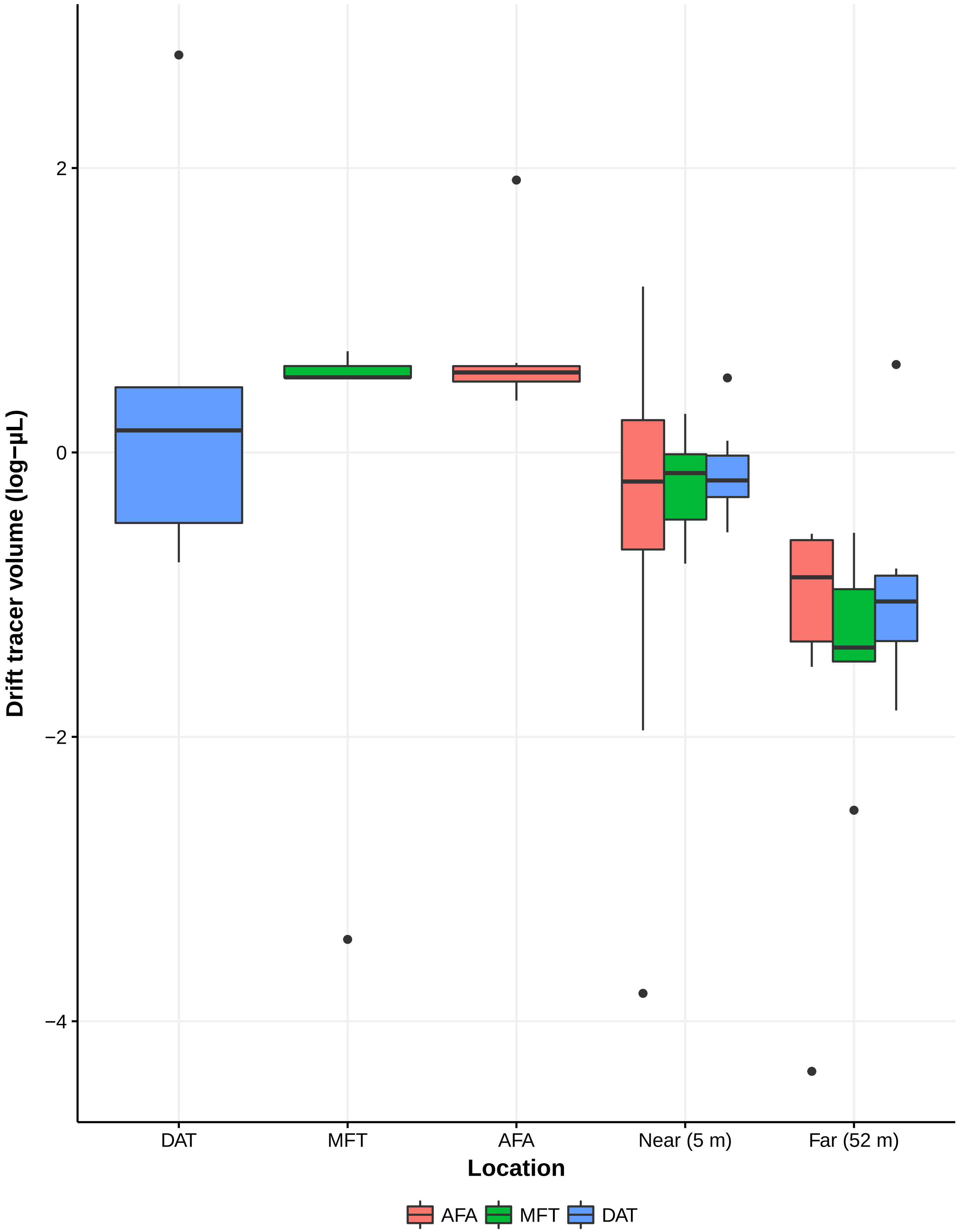


Figure 3.23: Tracer drift volume on MCE filters placed on each sprayer, 5 m downwind, and 52 m downwind.

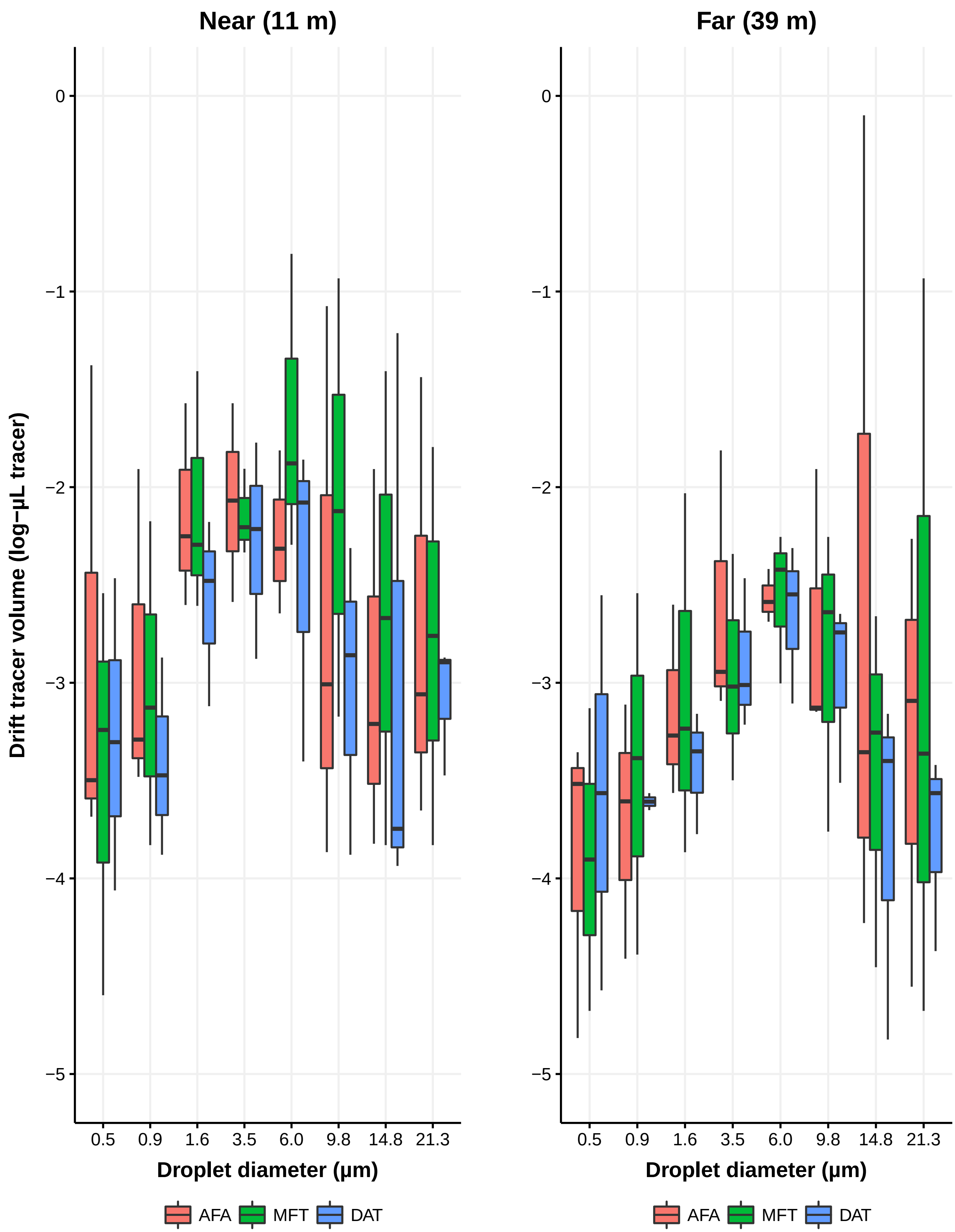


Figure 3.24: Tracer drift volume on mylar filters from 8-stage cascade impactors placed 11 m downwind and 39 m downwind in September 2016.

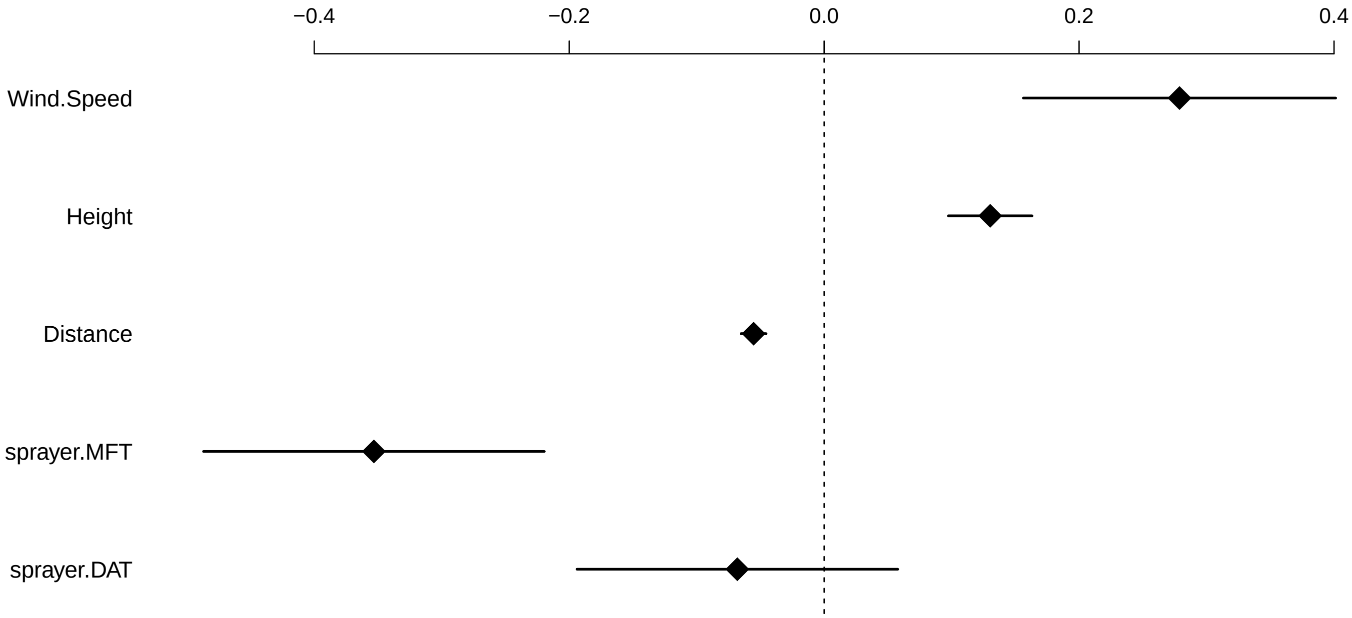


Figure 3.25: Point estimates and confidence intervals for primary mixed-effects model.

Table 3.11: Summary of fixed effects for primary model

	Dependent variable:
	Drift tracer volume (log-µL)
sprayer.DAT	−0.068 (−0.194, 0.058)
sprayer.MFT	−0.353*** (−0.487, −0.219)
Distance	−0.055*** (−0.065, −0.046)
Height	0.130*** (0.097, 0.163)
Wind.Speed	0.279*** (0.156, 0.401)
Intercept	4.205*** (3.646, 4.765)
Observations	669
Akaike Inf. Crit.	1,509.155
Bayesian Inf. Crit.	1,545.201
Note:	*p<0.1; **p<0.05; ***p<0.01

The table above contains point estimates, 95% confidence intervals, and p-values for each of the fixed parts of the model. The random effect model output was $\sigma^2 = 0.498$, $\tau_{00,location} = 0.128$, $N_{location} = 15$, $ICC_{location}$=0.205, and $R^2 : \Omega_0^2 = 0.733 : 0.733$.

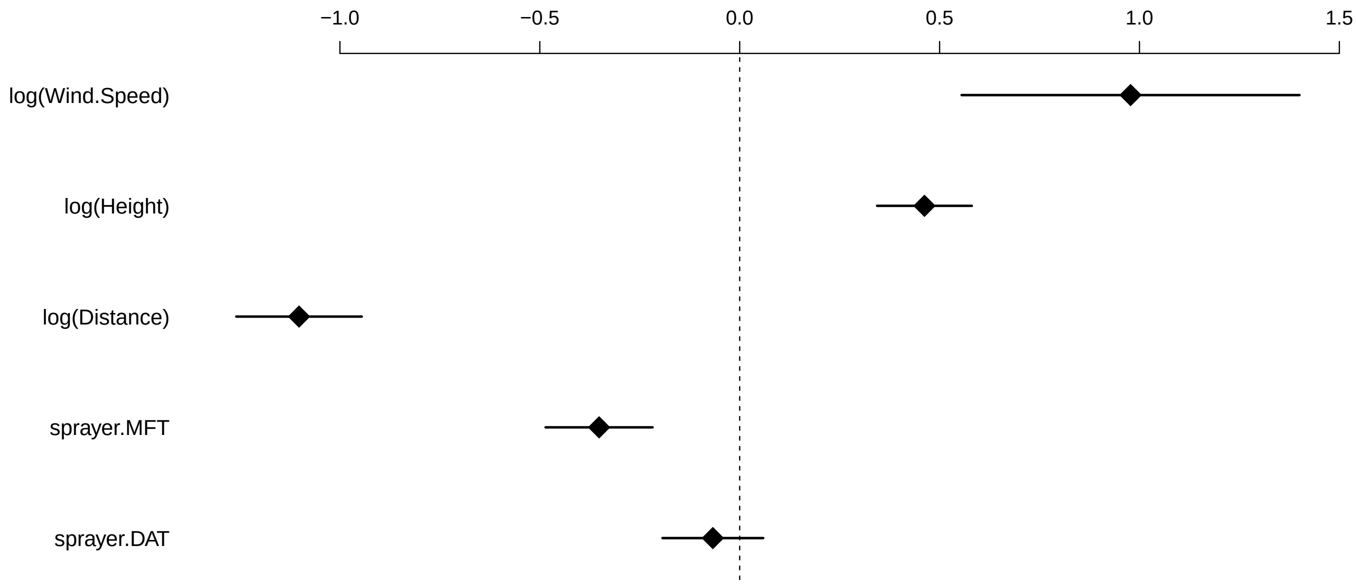


Figure 3.26: Point estimates and confidence intervals for secondary mixed-effects model.

Table 3.12: Summary of fixed effects for secondary model

	Dependent variable:
	Drift tracer volume (log-µL)
sprayer.DAT	−0.067 (−0.193, 0.059)
sprayer.MFT	-0.352^{***} (−0.485, −0.218)
log(Distance)	-1.102^{***} (−1.259, −0.945)
log(Height)	0.462^{***} (0.344, 0.581)
log(Wind.Speed)	0.978^{***} (0.555, 1.400)
Intercept	5.597^{***} (4.863, 6.331)
Observations	669
Akaike Inf. Crit.	1,493.897
Bayesian Inf. Crit.	1,529.944
Note:	*p<0.1; **p<0.05; ***p<0.01

The table above contains point estimates, 95% confidence intervals, and p-values for each of the fixed parts of the model. The random effect model output was $\sigma^2 = 0.499$, $\tau_{00,location} = 0.082$, $N_{location} = 15$, $ICC_{location}$=0.141, and $R^2 : \Omega_0^2 = 0.732 : 0.732$.

3.8 Appendices

3.8.1 Appendix A: Pilot study sampling arc

	Filter paper		LDPE tube	
Rank	Zn	Mo	Zn	Mo
1	D	D	D	D
2	C	C	C	C
3	H	G	H	H
4	F	H	B	G
5	B	F	F	F
6	G	B	G	B
7	E	E	E	E
8	A	A	A	A

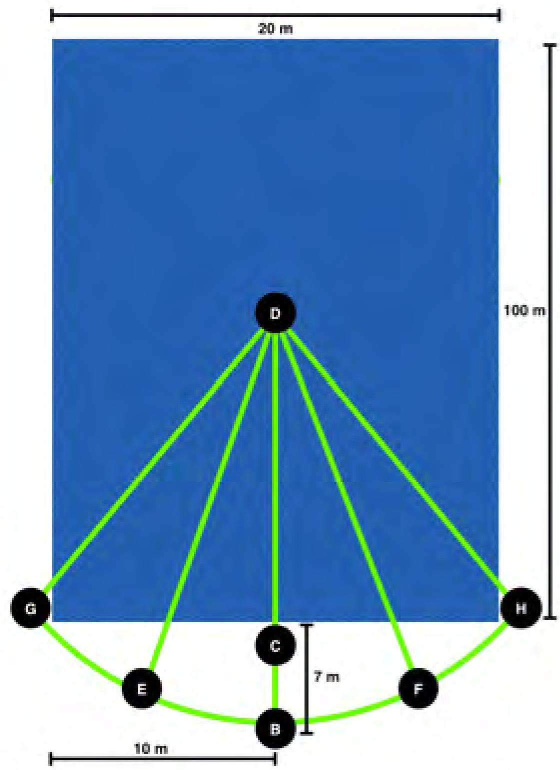


Figure 3.27: Sampling arc concept used in October 2014 pilot study. The table at left shows relative rank of masses (µg) collected on filter paper and LDPE lines at each location. Note: Target A not pictured because it was 200 m upwind. Target C was inside the arc on the edge of the sprayed area. Target D was inside the sprayed area.

3.8.2 Appendix B: Randomized block design spray order

Date	Sprayer	Quadrant	Spray.Order	Spray.Start	Spray.Stop
8-Oct-14	AAS	1	1	11:57:19 AM	12:06:05 PM
8-Oct-14	AAS	1	2	12:24:05 PM	12:33:00 PM
8-Oct-14	AAS	1	3	12:57:57 PM	1:06:29 PM
1-Jul-15	AAS	1	2	11:06:10 AM	11:14:58 AM
1-Jul-15	AAS	2	1	10:49:50 AM	10:57:06 AM
1-Jul-15	AAS	3	3	11:31:22 AM	11:37:23 AM
1-Jul-15	AAS	4	4	12:04:31 PM	12:12:13 PM
1-Jul-15	DAT	1	4	11:53:12 AM	12:00:41 PM
1-Jul-15	DAT	2	3	11:21:14 AM	11:28:42 AM
1-Jul-15	DAT	3	2	10:58:48 AM	11:04:08 AM
1-Jul-15	DAT	4	1	10:41:16 AM	10:48:21 AM
2-Jul-15	AAS	1	4	11:14:02 AM	11:20:07 AM
2-Jul-15	AAS	2	3	10:57:11 AM	11:03:45 AM
2-Jul-15	AAS	3	2	10:40:56 AM	10:47:34 AM
2-Jul-15	AAS	4	1	10:23:08 AM	10:29:09 AM
2-Jul-15	DAT	1	2	10:32:08 AM	10:39:09 AM
2-Jul-15	DAT	2	1	10:15:25 AM	10:20:37 AM
2-Jul-15	DAT	3	4	11:05:14 AM	11:12:13 AM
2-Jul-15	DAT	4	3	10:49:23 AM	10:55:58 AM
9-Jun-16	AAS	1	3	12:12:49 PM	12:18:43 PM
9-Jun-16	AAS	2	1	11:40:04 AM	11:45:49 AM
9-Jun-16	AAS	3	4	12:43:45 PM	12:49:17 PM
9-Jun-16	AAS	4	2	11:56:59 AM	12:02:51 PM
9-Jun-16	MHT	1	3	12:35:13 PM	12:41:49 PM
9-Jun-16	MHT	2	1	11:48:05 AM	11:54:24 AM
9-Jun-16	MHT	3	4	12:51:14 PM	12:58:01 PM
9-Jun-16	MHT	4	2	12:04:24 PM	12:10:35 PM
10-Jun-16	AAS	1	4	11:41:45 AM	11:47:08 AM
10-Jun-16	AAS	2	3	11:15:44 AM	11:21:27 AM
10-Jun-16	AAS	3	1	10:44:00 AM	10:49:17 AM
10-Jun-16	AAS	4	2	11:00:33 AM	11:06:18 AM
10-Jun-16	MHT	1	4	12:00:21 PM	12:06:46 PM
10-Jun-16	MHT	2	3	11:33:38 AM	11:39:55 AM
10-Jun-16	MHT	3	1	10:51:01 AM	10:57:07 AM
10-Jun-16	MHT	4	2	11:07:41 AM	11:13:50 AM
28-Sep-16	AAS	1	2	10:08:27 AM	10:14:35 AM
28-Sep-16	AAS	2	1	9:34:06 AM	9:40:54 AM
28-Sep-16	AAS	3	3	10:39:52 AM	10:46:20 AM
28-Sep-16	AAS	4	4	11:08:43 AM	11:14:33 AM
28-Sep-16	DAT	1	2	10:18:13 AM	10:24:13 AM
28-Sep-16	DAT	2	1	9:43:23 AM	9:49:29 AM
28-Sep-16	DAT	3	3	10:49:02 AM	10:54:54 AM
28-Sep-16	DAT	4	4	11:16:56 AM	11:22:55 AM
28-Sep-16	MHT	1	2	10:28:41 AM	10:35:53 AM
28-Sep-16	MHT	2	1	9:55:10 AM	10:03:34 AM
28-Sep-16	MHT	3	3	10:58:42 AM	11:05:52 AM
28-Sep-16	MHT	4	4	11:26:26 AM	11:33:48 AM

Date	Sprayer	Quadrant	Spray.Order	Spray.Start	Spray.Stop
29-Sep-16	AAS	1	1	9:14:26 AM	9:20:42 AM
29-Sep-16	AAS	2	4	10:35:57 AM	10:41:27 AM
29-Sep-16	AAS	3	2	9:42:17 AM	9:47:59 AM
29-Sep-16	AAS	4	3	10:09:08 AM	10:15:09 AM
29-Sep-16	DAT	1	1	8:50:17 AM	8:57:25 AM
29-Sep-16	DAT	2	4	10:17:00 AM	10:24:00 AM
29-Sep-16	DAT	3	2	9:23:52 AM	9:30:00 AM
29-Sep-16	DAT	4	3	9:50:00 AM	9:57:00 AM
29-Sep-16	MHT	1	1	9:03:59 AM	9:10:12 AM
29-Sep-16	MHT	2	4	10:27:11 AM	10:34:03 AM
29-Sep-16	MHT	3	2	9:33:33 AM	9:39:27 AM
29-Sep-16	MHT	4	3	10:00:22 AM	10:06:51 AM
30-Sep-16	AAS	1	2	8:58:31 AM	9:04:03 AM
30-Sep-16	AAS	2	1	8:28:21 AM	8:34:51 AM
30-Sep-16	AAS	3	4	9:51:53 AM	9:57:18 AM
30-Sep-16	AAS	4	3	9:26:20 AM	9:31:56 AM
30-Sep-16	DAT	1	2	9:07:14 AM	9:13:06 AM
30-Sep-16	DAT	2	1	8:38:14 AM	8:44:10 AM
30-Sep-16	DAT	3	4	10:00:01 AM	10:06:15 AM
30-Sep-16	DAT	4	3	9:34:26 AM	9:40:19 AM
30-Sep-16	MHT	1	2	8:49:12 AM	8:55:08 AM
30-Sep-16	MHT	2	1	8:19:54 AM	8:26:01 AM
30-Sep-16	MHT	3	4	9:43:31 AM	9:49:18 AM
30-Sep-16	MHT	4	3	9:17:14 AM	9:23:10 AM

3.8.3 Appendix C: Standard operating procedures

Our field study plan outlined 6 standard operating procedures (SOPs), which are described below, to collect data for comparing the drift potential of each sprayer.

SOP 1. Meteorolocial Station Setup

A temporary 10 m meteorological station measured wind speed and direction, temperature, and relative humidity. The station setup followed relevant drift sampling protocols for the International Organization for Standardization (ISO) and the American Society of Agricultural (and Biological) Engineers (ASABE). These measurements were compared to the permanent on-site AgWeatherNet Sunrise station (191).

SOP 2. Passive Horizontal Sampling - Deposition Drift

This procedure describes passive collection of metal aerosol deposition drift samples using chromatography filter paper (Figure 3.8). Horizontal deposition samples of chromatography filter paper cut into 200 cm^2 rectangles on wooden sample collection platforms were collected in fifteen fixed downwind locations for spray days in 2015 and 2016. Downwind samples were placed in rows that were 5 m (Targets B-F), 26 m (Targets G-K), and 52 m (Targets L-P) downwind of the sprayed area (Figure 3.6). Reference samples were also collected in the middle of the sprayed block (Location A) and 200 m upwind (Location Q).

SOP 3. Passive Vertical Sampling - Airborne Drift

This procedure describes passive collection of metal aerosol airborne drift samples using two matrix types: 1) low-density polyethylene (LDPE) line and 2) wireless cotton-core with polyester (PE) pile line (Figure 3.8). The SOP provides a method for constructing one sampling mast and a diagram for setting up a series of such masts near an orchard being sprayed with micronutrients. Samples were collected at the same reference and downwind locations as the passive horizontal samples (Figure 3.6). To investigate each sprayer's vertical drift profile, three 2 m sections of LDPE line and PE line were analyzed for each sampling mast.

SOP 4. Active Air Sampling

This procedure describes active collection of metal aerosol airborne drift samples using SKC universal pumps with six IOM area samplers and two 8-stage cascade impactors. A total of 8 SKCs were deployed: 2 IOMs mounted on tractors, 2 near-field IOMs (above and below canopy), 2 far-field IOMs (above and below canopy), 1 near-field impactor, and 1 far-field impactor. Sample matrices were mixed cellulose ester (MCE) for the IOM samplers and slotted mylar and polyvinyl chloride (PVC). A flow rate of 2.0 L/min was used for all active samples.

SOP 5. Bulk Tank Mix Sampling

This procedure describes sample collection from the orchard water source and sprayer tank mixes for Carbol Zinc (Zn), Manni-Plex B Moly (Mo), and Biomin Copper (Cu) micronutrient sprays (Appendix E).

SOP 6. GPS and Video Footage of Application Technologies

This procedure describes how GPS coordinates were obtained for sprayers over time during micronutrient applications. GPS time-location data were collected from the sprayers, as shown in a video made from our pilot study data. We determined the spray timing for each quadrant using GPS time-location data, as shown in this video. Only data from quadrant spray times are included in the statistical models. This video shows evidence of drift in June 2016. This video shows how two rows in Quadrant 1 were sprayed with each application technology in September 2016.

3.8.4 Appendix D: Additional spray calibration and settings

We performed detailed sprayer output calculations for AFA calibration, DAT calibration, and MFT calibration.

Sprayer factor	Axial Fan Airblast (AFA)	Directed Air Tower (DAT)	Multi-headed Fan Tower (MFT)
PTO max (rpm)	540	540	540
Fan speed (mph)	-	130-150	32.9-54.8 (1500-2500 rpm)
Air vol (cfm)	-	19,593-22,572	-

List of websites for sprayer manuals and specifications:

Axial Fan Airblast Sprayer Manual Links

- AFA

Directed Air Tower Sprayer Manual Links

- DAT 1
- DAT 2
- DAT 3
- DAT 4

Multi-headed Fan Tower Sprayer Manual Links

- MFT 1
- MFT 2

Other Links

- Nozzles

3.8.5 Appendix E: Micronutrient product labels

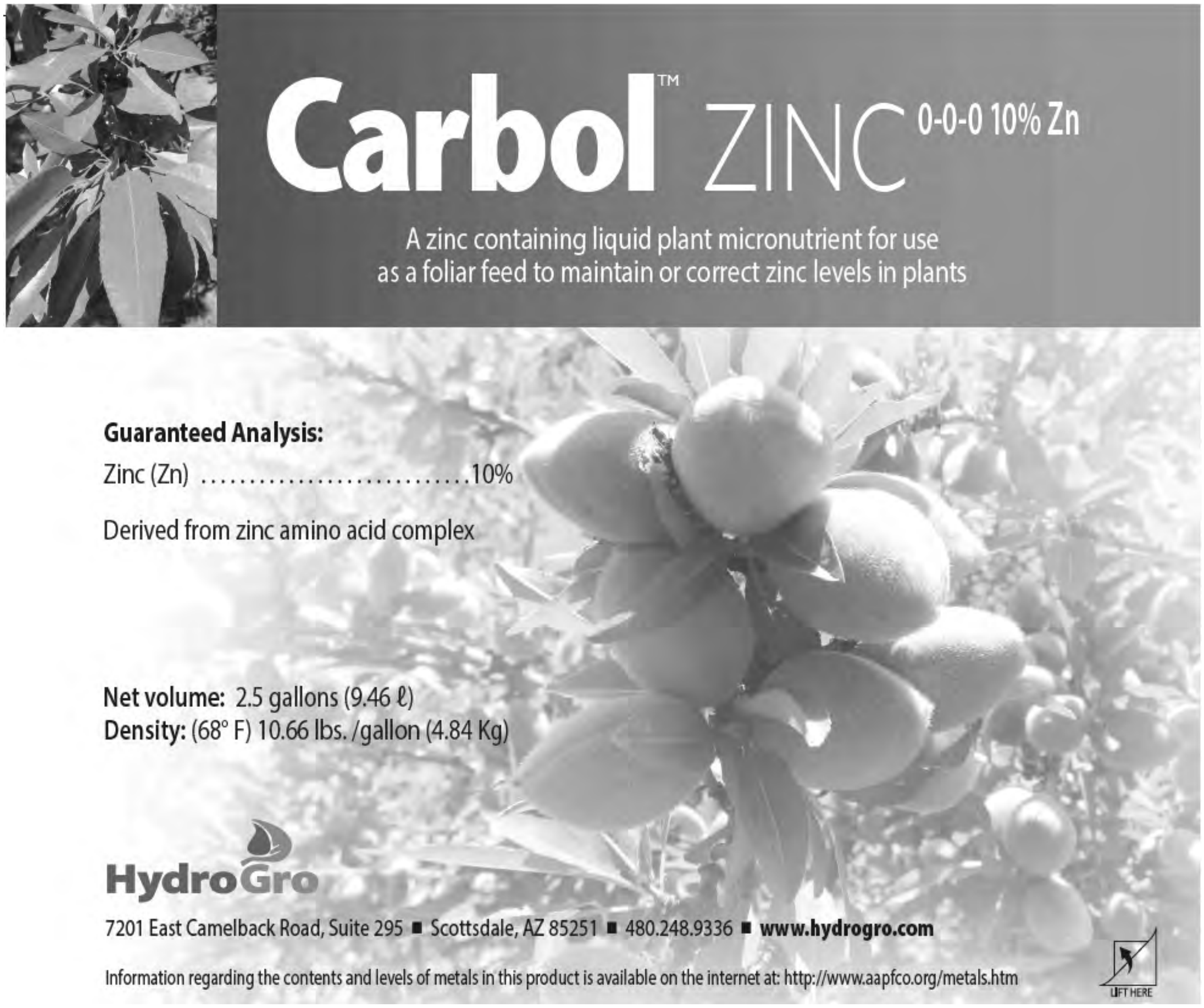


Figure 3.28: Zinc product label (page 1).

Carbol™Zinc is compatible with most agricultural remedies. However, do NOT apply Carbol™Zinc:

- In combination with copper containing fungicides, phosphates or phosphonates, or within 30 days after application of any copper fungicides.
- In combination with highly alkaline material such as lime sulphur or certain boron products.

Carbol™Zinc should preferably be applied in the early morning or late afternoon. **Do not apply to plants that are undergoing a period of moisture or heat stress.**

For optimum results Carbol™Zinc should be used in a program and in combination with other balanced fertilizers and foliar feeds.

Do not exceed a concentration greater than 1 pint/100 gal water.

DIRECTIONS FOR USE: USE ONLY AS DIRECTED.

Foliarly apply Carbol™Zinc according to the following:

CROP TYPE	MAX RATE RATE (PER ACRE)[2]	RATE PER 100 GALLONS WATER (Fl Oz)[1]	REMARKS
Field and row	¾-1 quart	6-13	Apply at any time during growing season. Repeat as needed.
Orchard and vineyard	3 quarts	9-16	Apply in early spring and repeat as needed.
Vegetable and fruit	¾-1 quart	6-13	Apply at any time during growing season. Repeat as needed.
Other crops	–	–	Consult your local argonomic professional.

[1]Base your application of Carbol™Zinc on petiole or tissue analysis. The lower rates should be used for maintenance while the higher rates will correct nutritional deficiencies.

CONDITIONS OF SALE: The information contained hereon is believed to be accurate and reliable. Buyer/User acknowledges and assumes all liability from use of this material. Follow directions and recommendations carefully. Rates and methods of application, timing, weather, soil, water, turf, plant, crop condition, prior control material usage and "acts of God" are beyond the control of the Sellers and Manufacturers.

CAUTION: Exercise care when applying product. May be harmful if swallowed or inhaled. Keep out of children's reach. Avoid eye contact and prolonged, repeated contact with skin. May cause eye, membrane and skin irritation. Wash all contact areas thoroughly after handling.

STORAGE: Avoid direct or excessive sun, heat, fire or frigid exposure. Decomposition may occur at temperatures above 225° F (107° C). May be corrosive to some dispersal materials over time. Exercise care when storing or dispensing product.

All product names, logos, analysis, formulas and contents are protected under US copy, trademark, registration or "recipe patent" laws as may apply.

Figure 3.29: Zinc product label (page 2).

Manni-Plex® B Moly

Foliar Micronutrient Supplement

GENERAL RECOMMENDATIONS

CROP	RATE/ACRE	RECOMMENDATIONS
Multi-fruiting Vegetables, Peppers, Tomatoes	1-2 pints	3 applications 7 days apart. First application before first bloom
Fruit Trees	1-2 pints	Apply early spring prior to flowering
Blueberries, Black-berries, Strawberries	1-2 pints	Apply early spring prior to flowering
Grapes (wine, table)	1-2 pints	Apply once pre-flowering
Cole Crops	1-2 pints	Spray after transplanting as needed
Leafy Crops, Lettuce	1-2 pints	Spray at 4 leaf stage, then as needed
Cucurbits	1-2 pints	Apply first application pre-bloom and repeat as needed
Grains	1-2 pints	1 application pre-flowering

MANNI-PLEX B MOLY may effectively be applied with many agricultural chemicals. When used as directed, this product does not supply all nutrients required by plants and is to supplement a soil fertility program based on soil tests. For unfamiliar tank mix combinations sufficient evaluation to determine efficacy and crop safety may be warranted. Avoid tank mixing with phosphate and/or excessively alkaline based fertilizer solutions. Use a minimum 10 gallons of water per acre with ground spray equipment and a minimum of 2 gallons for aerial application. Optimum rate of application will vary depending on your soil properties such as soil pH, organic matter content, soil texture, weather conditions, time of year, general crop health and species. For best results, follow soil test or plant analysis recommendation.

WARNING: Some crops may be injured by the application of Boron. The application of fertilizing materials containing Molybdenum (Mo) may result in forage crops containing levels of Molybdenum (Mo) which are toxic to ruminant animals.

Information concerning the raw materials composing the product in this container can be obtained by writing to Brandt Consolidated, Inc. and referring to the product name, or visit our web site: www.brandtconsolidated.com

BRANDT

Guaranteed By:
Brandt Consolidated, Inc.
2935 South Koke Mill Road
Springfield, Illinois 62711 USA
www.brandtconsolidated.com
800.442.9821

Guaranteed Analysis 5-0-0

Total Nitrogen (N) 5.0%
5.0% Urea Nitrogen
Boron (B) 3.3%
3.3% Water Soluble Boron
Molybdenum (Mo) 0.5%
0.5% Water Soluble Molybdenum

Derived from Urea, Sodium Borate and Sodium Molybdate. F76

Mixing Instructions

Put 1/3 to 2/3 of total desired water volume in tank. Add adjuvant(s) if desired and agitate until thoroughly mixed. Add pesticide(s) if desired and agitate until thoroughly mixed. Add desired amount of MANNI-PLEX B MOLY and agitate until thoroughly mixed. Fill tank with remainder of desired water. A jar test is a good field practice for evaluating compatibility of multiple chemical mixtures. **Caution:** Check compatibility with micronutrient chemical mixtures.

Weight per gallon: 9.9 lbs
Freezing temperature: 32°F
CAUTION: KEEP OUT OF REACH OF CHILDREN

Information regarding the contents and levels of metals in this product is available on the Internet at http://www.aapfco.org/metals.htm

CAUTION: Harmful if swallowed. Avoid contact with skin, eyes and clothing. Causes eye irritation. Avoid breathing spray mist. Wash hands after using thoroughly after using.In case of eye contact, flush eyes with water for at least 10 minutes and get medical attention.

STORAGE AND DISPOSAL: Do not contaminate water, food, or feed by storage or disposal. Store in a cool, dry, locked area out of reach of children. Protect from excessive heat or cold. Triple rinse (or equivalent) and dispose of container in accordance with local, state and federal regulations.

Warranty: Seller warrants that the product conforms to its chemical description and is reasonably fit for the purpose stated on the label when used in accordance with directions under normal conditions of use; but neither this warranty nor any other warranty of merchantability or fitness of a particular product expressed or implied, extends to the use of this product contrary to label conditions, or under conditions not reasonably foreseeable to the seller; and buyer assumes the risk of any such use.

0000-01-100

Net Contents:
2.5 Gal. per bottle
Packaged 2 x 2.5 gal.
Net Weight: 24.75 lbs.

Figure 3.30: Molybdenum product label.

Figure 3.31: Copper product label.

3.8.6 Appendix F: Water sensitive paper

Water Sensitive Paper Sampling (201)

We also collected 15 horizontal (September 29, 2016) and 60 vertical (September 30, 2016) 20 cm^2 water sensitive paper (WSP) card samples that were analyzed with quantitative image analysis software (Icy) (192) to determine the number and size of water droplets collected at different locations and heights throughout the sampling grid. Horizontal WSP samples were placed on the same wooden platforms as the filter paper and vertical WSP samples were suspended from crossbars on the 6-m vertical masts at heights of 0, 2, 4, and 6 m.

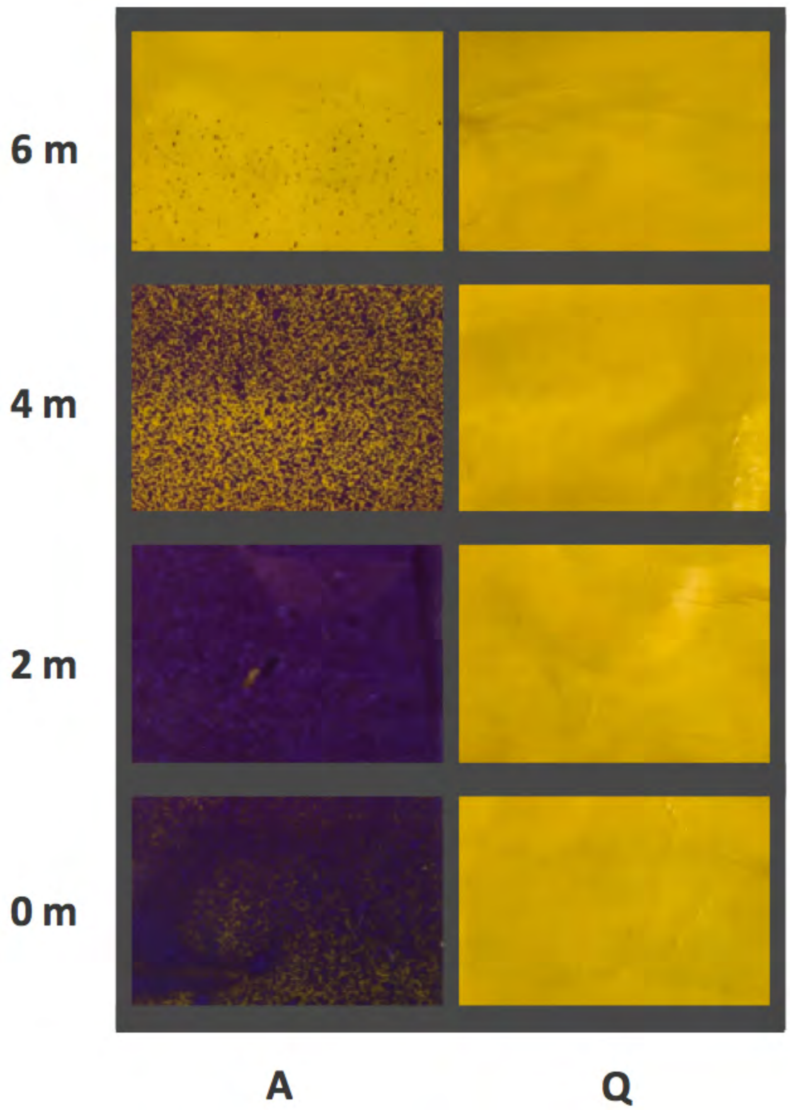


Figure 3.32: Water sensitive paper cards placed on Masts A (in orchard) and Q (upwind 200 m) on crossbars at 0, 2, 4, and 6 m.

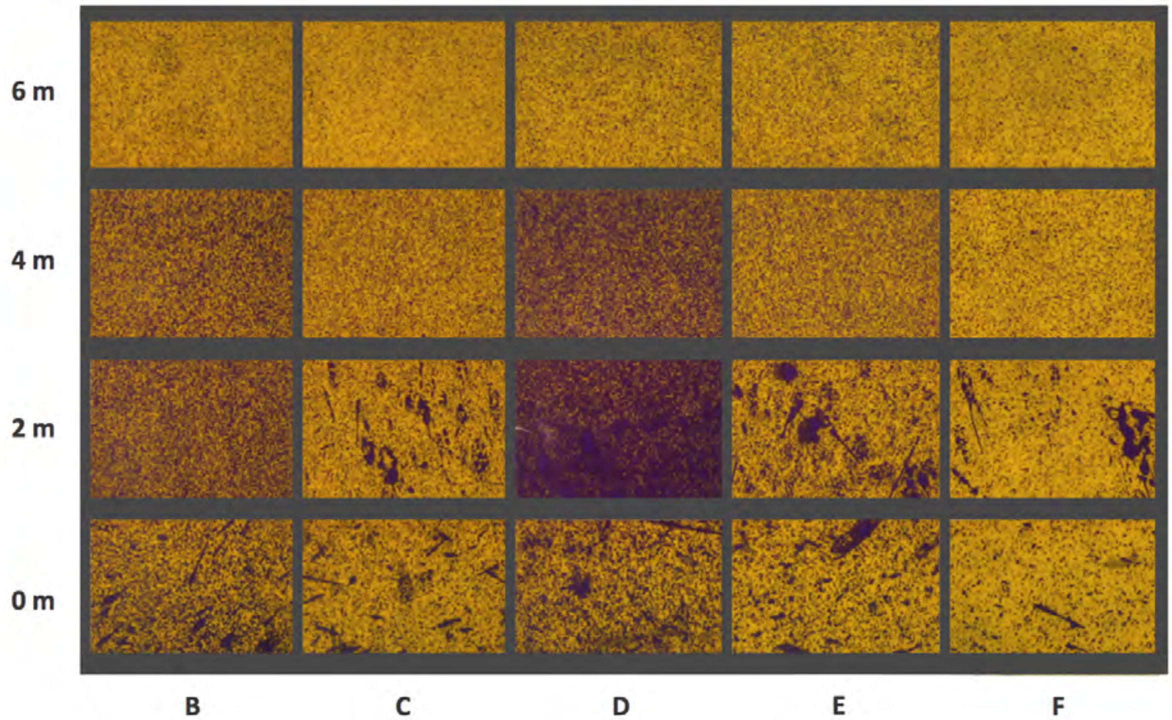


Figure 3.33: Water sensitive paper cards placed on Masts B-F (5 m downwind) on crossbars at 0, 2, 4, and 6 m. Zoom to view in detail.

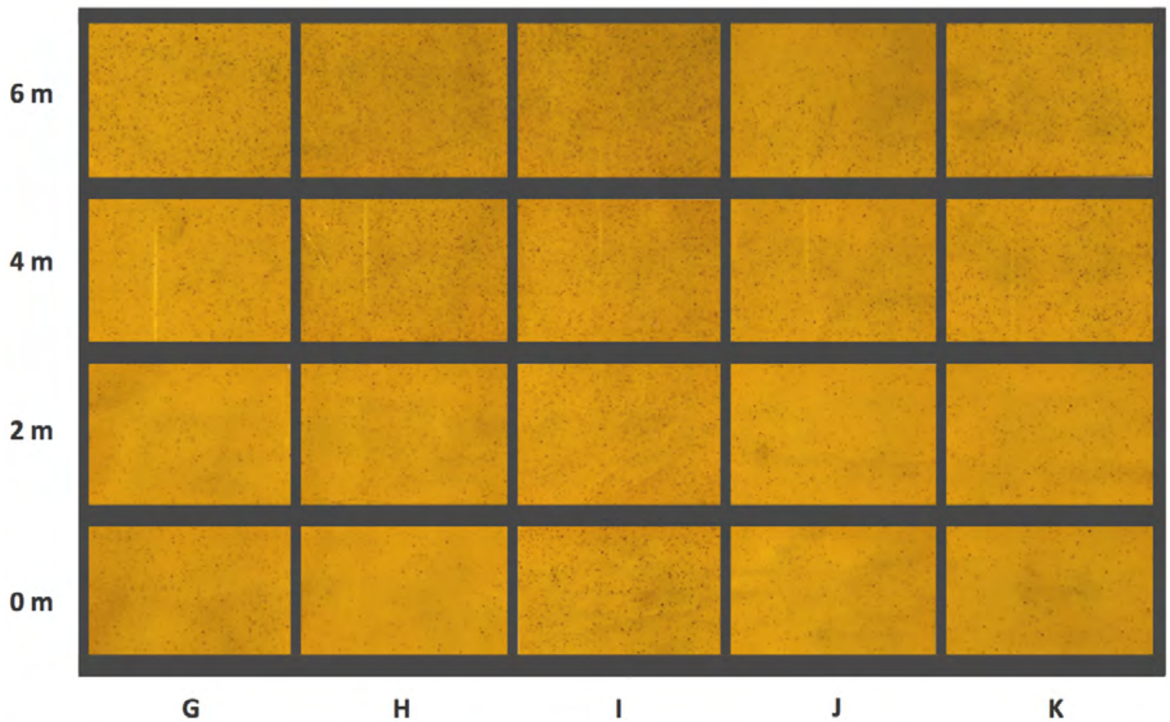


Figure 3.34: Water sensitive paper cards placed on Masts G-K (26 m downwind) on crossbars at 0, 2, 4, and 6 m. Zoom to view in detail.

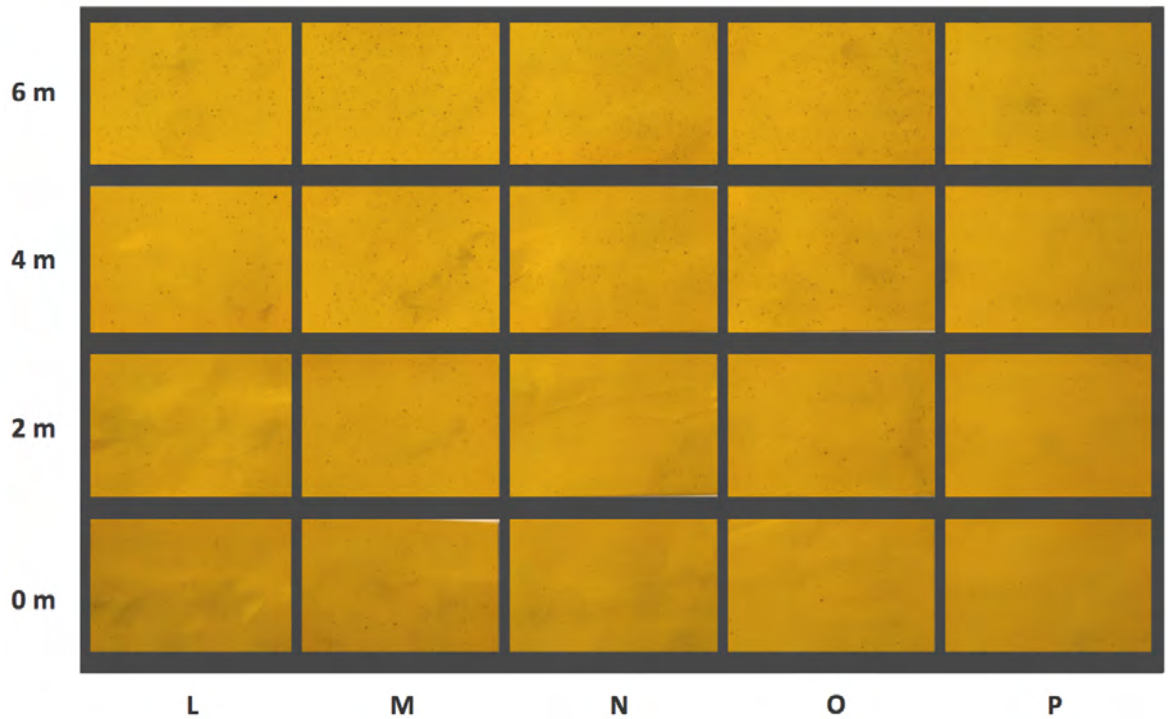


Figure 3.35: Water sensitive paper cards placed on Masts L-P (52 m downwind) on crossbars at 0, 2, 4, and 6 m. Zoom to view in detail.

3.8.7 Appendix G: Laboratory analysis reports

- EHL Report 11410046 - Oct 2014
- EHL Report 11603007 - July 2015
- EHL Report 11607029 - June 2016
- EHL Report 11611002 - Sept 2016

4 Prevention of Worker Exposure to Pesticide Drift: Assessing the Feasibility of Farm-to-farm Spray Notification

4.1 Abstract

Farmworker exposure to pesticide drift remains a high priority agricultural safety issue in Washington State. A review of agricultural worker notification systems was conducted to explore farm-to-farm communication as a means to prevent drift exposure. The objective of this study was two-fold: 1) review and evaluate existing notification processes and procedures, and 2) assess the feasibility of a worker notification system in Washington State through interviews with farm owners, managers, and work crew supervisors. Characteristics of existing pesticide spray notification systems in several countries were gathered from interviews, emails, and program websites. Residential and commercial spray notification systems have been used in New Zealand, the United Kingdom, China, Canada, and the United States. Direct notification methods such as sign posting, telephone calls, and personal visits have been used for a long time in the agricultural industry. Recent advancements in computer and mobile technology have made remote notification methods more user-friendly. Assuming that costs, work burdens, and legal liabilities are minimized, a remote farm-to-farm spray notification system appears to be a promising means by which to prevent farmworker exposure to pesticide drift. Next steps include engaging stakeholders such as pesticide applicators, farm owners and managers, farmworker groups, research and education communities, and state agencies to discuss the utility of an agricultural workplace spray notification system.

This chapter addresses the following sub-aims:

- Examine existing pesticide spray notification systems to determine their strengths and limitations, as well as their relevance to the Washington tree fruit industry
- Interview tree fruit industry personnel responsible for pesticide applications regarding the desirability of a notification system and barriers to the implementation of such a system

4.2 Introduction

Farmworker exposure to pesticide drift remains a high priority agricultural safety issue in Washington State. A review of agricultural worker notification systems was conducted to explore farm-to-farm communication as a means to prevent drift exposure. The objective of this study was two-fold: 1) review and evaluate existing notification processes and procedures, and 2) assess the feasibility of a worker notification system in Washington State through interviews with farm owners, managers, and work crew supervisors.

Data from the 2010-2011 Washington Department of Health (WA DOH) annual report showed that among agricultural workers exposed to drift, approximately three times fewer (n=13) were exposed on the farm being sprayed than those on adjacent farms (n=43) (31). In May 2014, WA DOH reported that 60 individuals, mostly orchard workers, became ill in 15 drift events over a two-month period, a number normally seen in one year (37, 117). One of these events involved 20 farmworkers in a cherry orchard and highlighted a gap in worker notification requirements (4). In response, WA DOH renewed its call for improved communication between farms, handlers, and crew members as a high priority issue for prevention (15). Currently, there is no system in place to notify workers or employers of applications that will be taking place on adjacent property.

4.2.1 Worker notification

Worker notification can be broadly defined as risk communication in an occupational setting. A group of leaders from academia, industry, labor, and government gathered in 1991 for a workshop about worker notification and published the proceedings in an entire issue of the *American Journal of Industrial Medicine*. They addressed "communication of job-related health risks to workers: whether to do it, when, how, and, to what end" (93). One article highlighted the increasing acceptance, ethical imperative, deep fears, unintended social consequences of worker notification (94). Other articles discussed whether results of worker health studies should be returned to the workers themselves. Discussion was limited to worker notification of health risks after the time of exposure. Our review, on the other hand, explores the utility of worker notification before a potential exposure.

Federal rules for worker notification of pesticide applications

The federal Worker Protection Standard (WPS) was established by the US Environmental Protection Agency (US EPA) to reduce the risk of pesticide-related illness and injury among agricultural field workers and pesticide handlers, i.e. those workers who mix, load, or apply pesticides (96, 202). The current WPS has requirements for agricultural employers about notification and central posting for workers on the same farm. Notification rules require employers to share two basic items with employees (96):

1. Location of the treated area; and
2. Timing of application and restricted-entry interval (REI).

Workers must be notified either orally or by posted warning signs, though some pesticide labels require both types of notification (i.e. "double notification"). Notification is not required for agricultural employees who stay at least a quarter mile outside the treated area (96, 97). Central posting rules require employers to display three items for employees (96):

1. Pesticide application-specific information (location of treated area, product name, US EPA registration number, active ingredients, time and date of application, and REI);
2. Emergency information (name, telephone number, and address of nearest emergency room); and
3. A pesticide safety poster.

US EPA finalized extensive revisions to existing WPS requirements in November 2015, including some pertaining to notification and central posting that agricultural employers and handler employees were required to comply with beginning in 2017. Changes to notification requirements called for more robust posting of treated areas (any products with an REI greater than 48 hours) and re-entry workers to receive information in advance about pesticides to be used, area to be worked, tasks to be performed, required personal protective equipment (PPE) to be worn, and a maximum amount of time to be spent in the treated area (98). Changes to central posting requires employers to post pesticide application information and safety data sheets (SDS) for all pesticides used on the farm at a central location (i.e. "central display"). Agricultural employers are now required to maintain—and make available upon request to workers, handlers, designated representatives, and treating medical professionals—records of all central display information used on the agricultural establishment for two years (98). This change reflects US EPA efforts to make WPS consistent with OSHA's Hazard Communication Standard (HCS), which is rooted in the "Right-To-Know" legal principle and was recently updated to align with the Globally Harmonized System of Classification and Labeling of Chemicals (97–99).

Although WPS revisions state that communication barriers can increase the risk of pesticide exposure due to tasks performed by agricultural workers (97), between-farm communication is not offered as a solution to drift exposure by the current or revised WPS. The most closely related requirements pertain to exchange of pesticide-specific information for handlers and agricultural employers on the same farm. In an attempt to minimize drift exposures, revisions include "application exclusion zones" (AEZ) around application equipment in operation and strengthened requirements for handlers during applications (i.e. "suspending application" if an unequipped person enters a restricted area) (100). Such revisions do not ensure protection of neighboring workers from drift, as contact with neighboring farms is not included in provisions for within-farm exchanges of information.

Washington State rules for notification of pesticide applications

As codified by Washington Administrative Code (WAC), pesticide applications for agricultural purposes in Washington are subject to WPS requirements, including notification and central posting (96, 203, 204). Additionally, the State Legislature passed the Washington Pesticide Application Act for landscape and right-of-way applications (42). With regard to notification, the Act requires an applicator to provide, upon request, the name and material safety data sheet for each pesticide used (205). Applicators spraying residential property, commercial property, golf courses, schools, parks, or cemeteries must display 4 by 5 inch (or larger) markers that list the company name and applicator telephone number (206). Markers should be placed in treated areas at the time of application. The Act also establishes guidelines for two spray notification systems: one for schools and another for properties near pesticide-sensitive residents. These codes set a precedent for notification by applicators, but do not extend protection to those exposed via drift in occupational settings.

Framework for a modern occupationally-based notification system

Recent advances in mobile and web-based technologies have increased capacity for rapid, one-way public notification systems that businesses, government agencies, educational institutions, and many private groups are utilizing to enhance their emergency preparedness by communicating actionable risk (105, 106). Examples of this are messages receivable after voluntary self-subscription to a notification system that sends automated email or Short Message Service (SMS) messages. Such notifications are not only crucial for life safety during events such as severe weather, chemical spills, flooding, fires, or evacuation notices, but also have utility as workplace alerts. Although there is no system to notify workers or employers about pesticide applications taking place on adjacent property, the framework for an agriculturally-based electronic notification system already exists to some degree. SMS and email notifications have been used by organizations in New Zealand, the United Kingdom, China, Canada, and the United States. None of these programs have the stated goal of preventing occupational exposure to pesticide drift on adjacent land, but many possess the potential to be modified in such a way.

Existing spray notification systems outside of Washington

In addition to the two in Washington State, we identified four agriculturally-based pesticide notification systems in other parts of the world: SprayWatch (207), Spraydays (208), DriftWatch (209), and the Pesticide Eco-Alternatives Center (210). Spray notification methods can be generally categorized in two ways: direct and remote. Direct notification is a property-based approach that describes applicators who notify residents of each adjacent property via direct contact, typically in writing such as a leaflet, a personal telephone call, or an in-person visit. Remote notification involves an applicator who creates a notification for a property to be sprayed, but does not have direct contact with residents. In this case, residents of any adjacent properties are either notified through an automated system or seek the information themselves, typically via the internet, automated telephone messaging, or notice boards posted in visible locations around sprayed fields. Notification can be differentiated from disclosure: notification is defined as supplying information before spraying; disclosure is defined as fulfilling requests from the public after spraying (107).

The overall goal of this study is to minimize pesticide exposure of orchard work crews adjacent to orchards where applications are taking place. We conducted a systematic review of six systems and evaluated their applicability to worker notification in Washington State. Using results from interviews with Washington tree fruit industry personnel responsible for pesticide applications about the desirability of a modern system, we outline technical aspects of a farm-to-farm notification system that would allow supervisors to relocate workers from areas prone to pesticide drift.

4.3 Methods

4.3.1 Review of notification systems

A systematic review was conducted to understand historic and current uses of spray notification and their applicability to occupational settings in the Washington State agricultural industry. Initially, we attempted to retrieve peer-reviewed articles by using search phrases such as "pesticide spray notification" and "pesticide notification systems" in GoogleScholar and PubMed databases. Since this initial search was not fruitful, we searched the internet for grey literature and program websites using the same terms. This yielded the discovery of some notification systems. We contacted personnel via email and telephone to learn more about their systems and ask about the existence of other systems. We also searched the Washington State statutes for rules regarding pesticide notification. Characteristics of six existing pesticide notification systems were gathered from interviews, emails, and program websites. We recorded information about year of origin, current use, location, and model type for each system. Additionally, we established six scoring categories to rank the systems based on their suitability for worker notification.

We defined year of origin as the first year of use, current use as presence or absence of existing operations, and location as the country of deployment. Model type was described as the connection between notifying and notified parties (e.g. applicator-to-farmer, applicator-to-resident, and registry). We defined applicators as the subset of handlers in the act of applying pesticides, farmers as individuals holding on-site farm leadership positions (e.g. owner, manager, or work crew supervisor), and residents as community members living in a nearby agricultural region. The applicator-to-farmer model is preferred for worker notification because it encourages the exchange of spray information between neighboring farms to protect workers. However, no such model exists. Thus, model type for current systems were either applicator-to-resident or registry. We defined the applicator-to-resident model as one in which residential bystanders receive notification from an applicator—or in the case of schools—parents, guardians, and employees receive notification from the school. Registries are systems in which an applicator receives notification based on a list of sensitive individuals or crops nearby.

4.3.2 Development of scoring matrix from interviews with tree fruit industry personnel

Scoring categories for worker notification were developed from interviews with a convenience sample of 20 Washington State orchard owners, managers, and work crew supervisors during the spring and summer of 2014. The purpose of the interviews was to gain supervisory-level perspective about strengths and weaknesses of a farm-to-farm spray notification system designed to protect workers from pesticide drift. (Appendix A) contains 31 questions that were used in the interviews, which were conducted in person or by telephone over a 30 minute period on average. The University of Washington Human Subjects Division determined that the interviews qualified for exempt status in accordance with federal regulations.

The interviews offered an opportunity to engage with agricultural managers and gather information about their work environment, workplace communication, and preferences about spray notification (Appendix B). Demographic data included interview date, year of birth, gender, primary language, ethnicity, and education. Work environment questions sought information about the number of years spent working in the tree fruit industry, job title, type of fruit grown, total acreage of the orchard, number of nearby orchards, number of orchard employees, and job tasks performed in the orchard. Workplace communication questions identified preferred methods of communication, current notification practices in terms of distance, time, personnel involved, and content. Summative questions provided more in-depth information about what would be needed to launch a successful notification system, such as who should send and receive spray notifications, the likelihood of using a spray notification system and adjusting work crew job tasks, amount willing to pay for spray notification service, and barriers for using a notification system. When the interviews were complete, response data were coded and entered into a database. SAS 9.4 was used to compute descriptive statistics for participant demographics, work environment, workplace communication, and summative responses. Six scoring categories were developed (Figure 4.1) from seven interview questions (or, thirteen if counting two questions with four-part sub-questions):

1. Notification method types (‘preferred methods’):
2. Amount of lead time needed to reassign workers to new job tasks (‘minimum lead time’),
3. Distance between notifying and notified parties (‘range’),
4. Information about pesticides applied (‘message content’),
5. Mobile phone use for work purposes (‘mobile capability’), and
6. Cost per year for a spray notification service (‘estimated cost’).

Each system was classified into subcategories with interview-assigned scores for each of the six categories (Figure 4.2). Subcategories for the ‘preferred methods’ scoring category were *voice (call or message)*, *SMS/text message*, *in-person (visits)*, and *email*. Those for ‘minimum lead time’ were *less than 2 hours* and *greater than or equal to 2 hours*. ‘Range’ was subcategorized as *less than or equal to 0.5 mile* and *greater than 0.5 mile*. Subcategories for ‘message content’ were *pesticide name*, *crop sprayed*, *target pest*, *pesticide label*, *signal word*, and *mixing tank recipe*. ‘Mobile capability’ was defined as yes or no response to the question, “Do you use a mobile phone for work purposes?” ‘Estimated cost’ was the maximum dollar amount that each respondent was willing to pay for a hypothetical spray notification service per year.

Scores were developed by pooling responses to questions about each of the six categories (Figure 4.1). Each category was assigned a possible score of “1” and a fraction of total responses (n/total) was assigned to subcategories based on preferences elicited from interviews. For example, among 20 responses to Question 18 (Do you use a mobile phone for work purposes?), 18 (90%) were “Yes” and 2 (10%) were “No”. This resulted in a subcategory score of 0.90 for systems that utilized mobile phone capabilities and a score of 0.10 for systems that did not. Among 37 responses to Questions 14b, 21b, and 23b about minimum lead time, $\frac{25}{37}$ (0.68) required less than 2 hours and $\frac{12}{37}$ (0.32) required 2 or more hours. These proportions represent the weighted average of positive responses for each subcategory.

Responses to questions about mobile capability, minimum lead time, estimated cost, and range were mutually exclusive and therefore had subcategory scores that summed to 1. Responses to questions about preferred methods and message content were not mutually exclusive (i.e. interviewees were asked to indicate all options that applied). To ensure that these two categories would not have more influence than other categories, the fraction of total responses for each subcategory was adjusted by dividing by the sum of the fraction of total responses. For example, the sum of subcategory scores for the preferred methods category was 2.17 (0.60 + 0.74 + 0.74 + 0.09). Each of subcategory score was divided by 2.17 to produce the adjusted fraction of total responses (i.e. adjusted subcategory score). Thus, each of the six categories contributed equally to the final worker notification suitability (WNS) scores. The highest possible WNS score was 5.17, which represents a system that has all possible notification methods (0.34 + 0.34 + 0.28 + 0.04), minimum lead time of less than 2 hours (0.68), range under 0.5 mile (1.00), all possible message content (0.36 + 0.21 + 0.15 + 0.12 + 0.09 + 0.06), mobile capability (0.90), and no cost (0.60). The systems were then ranked by WNS scores to indicate which were particularly suited to worker notification.

4.4 Results

Information for the six notification systems is presented, together with an evaluation of each system using the scoring matrix developed from interviews with farm owners, managers, and work crew supervisors.

4.4.1 Notification systems

We review Washington-based systems first, followed by those from around the world listed by year of origin. Finally, we provide scoring results by category.

Sensitive Persons – Washington

Since 1994, the Washington Pesticide Application Act has allowed pesticide-sensitive individuals in Washington to register annually with the state and be contacted by applicators in writing, in person, or by telephone at least two hours before making landscape or right-of-way applications near their homes. This applicator-to-resident model requires notification of application date and time. Applicants must provide their name, street address, and telephone number and the same information for each property adjacent to their place of residence. For right-of-way applications, adjacent property is defined as that portion of the property within one-half mile of the applicant's place of residence. All land listed constitutes the pesticide notification area for that applicant (103, 211).

Schools – Washington

Since 2009, day care centers and schools in Washington must follow specific notification and posting rules when using pesticides. Written notification describing a school's pest control policies should be provided to interested student guardians and employees. In this applicator-to-resident model, each school is expected to establish a system that notifies guardians and employees at least 48 hours before an application to school property. Notifications should include the pesticide product name, application date and time, location, pest to be controlled, and the name and phone number of a school contact. The main office of the school, the application site, and primary entry points are required to have signs posted for each school property that is treated. A school must also keep records of all applications to school property (104).

SprayWatch – New Zealand

As an applicator-to-resident model, SprayWatch was developed in 2002 to help New Zealand applicators meet legislative requirements and allow residents to take preventative measures such as closing windows, locking up animals, avoiding hang-drying clothes outside, and covering vegetable gardens. For example, Rule 13 in the Bay of Plenty Regional Air Plan specifies that "the owner/occupier or agent must notify the occupier of any adjoining properties within 50 [meters] of that agrichemical use" (212). The rule requires notification at least 12 hours before spraying about site and date of application; name and type of chemical; and applicator name, address, and phone number (212). Property owners or spraying contractors add their agricultural land and neighbor contacts into a system that uses personal identification numbers (PINs) to protect privacy. The system automatically sends a message to each contact number at a time and in a format—voicemail, text, or email—specified beforehand by the neighbor. Calls cost NZ$ 1.32 per receiver (e.g. residential neighbor) after a one-time activation NZ$ 8.00 charge for each new property. If a farmer makes 7 sprays to a property with 5 recipients, the cost of notification is approximately NZ$ 47.00 per year (207).

Spraydays – United Kingdom

In 2005, the Royal Commission on Environmental Pollution (RCEP) of the United Kingdom (UK) released a report named *Crop Spraying and the Health of Residents and Bystanders*, which, among other pesticide safety measures, called for pesticide use reporting and a pilot study to "explore how residents living next to farms can be notified in advance of pesticide use" (213). The pilot study tested several pre-application notification methods for residential properties that shared at least one border with treated fields (i.e. applicator-to-resident model). One farmer used flags around the perimeter of a treated field as a visual method, two delivered written leaflets to nearby residences, three recorded telephone messages, and four used internet registration with automatic emails or text messages. Five farmers tested the use of public access point notices. After the field trial was complete, investigators conducted telephone interviews to document the impressions of the farmers and nearby residents about the various pre-application notification practices (208).

A second report reviewed costs associated with the establishment of buffer zones, spray notification, and other changes in pesticide use practices. According to the report, approximately 11.5 million hectares of UK land was sectioned into 1.4 million fields, 25% of which shared a border with residential properties. This meant nearly 2 million residents lived on 650,000 properties that bordered potentially sprayed land. Assuming 100% public registration, farmers would have needed to make 3.1 million direct notifications and 1.3 million remote notifications per year. As a result, the most expensive method of spray notification would have been recorded telephone messages (£17 million) followed by leaflets (£16 million), local plans such as newspaper advertisements or public notices (£9.9 million), and internet registration with text or voice messaging (£2.9 million). The average estimated cost per farm for the internet registration option was £109 per year (107).

DriftWatch – United States and Canada

Email-based spray notification about sensitive crops has occurred in the US since 2008, when researchers at Purdue University created a program that has now expanded to fourteen states in the US and one province in Canada. Like SprayWatch and Spraydays, DriftWatch utilizes remote notification. Unlike those programs, DriftWatch fits the registry model type since applicators, not residents or workers, are notified. It is a voluntary web-based program that allows farmers to identify, map, and communicate the location of high-value, pesticide-sensitive specialty crops such as tomatoes, fruit trees, grapes, hops, and apiaries in an effort to prevent or manage drift (209, 214).

To register a producer location, an individual must own or manage a commercially produced specialty crop that covers at least one half-acre and submit basic information about the crop type, year, state, growing conditions, and active dates. A producer then defines the location of a sensitive crop site as a polygon by tracing the perimeter using a Google Maps application programmable interface (API). Owners and managers of registered sites, whose approvals need to be renewed annually by a State Data Steward, are also eligible to purchase DriftWatch "NO DRIFT ZONE" signs for posting around the perimeter (215) (FieldWatch 2014c). Registered applicators can: 1) opt into receiving email notifications about new producer locations in their spray area based on one of four proximity settings (state/province, specific counties, custom area, or no alerts) and 2) view specific information about approved sites by clicking on balloons or pins available in the API polygons. Applicators may also search by crop types or growing conditions (216).

In addition to registered producers and applicators, state departments of agriculture implement, administer, and support DriftWatch financially. Each department appoints an employee to be the State Data Steward who verifies accounts. Any individual may register for a free account, but the tool is intended for producers and applicators of commercially grown crops not homeowners (217). Although individuals from the public may create a non-member user account at no cost, different membership-level fees increase access: member states ($24,500 first year, $6,500 annual maintenance), user members ($50 for producers, $100 applicators), licensee members ($500 for data distributors), sponsoring members ($10,000-50,000 depending on gross revenue), and associates ($100 for individuals) (218).

Pesticide Eco-Alternatives Center (PEAC) – China

PEAC, a Chinese non-governmental organization whose mission is to promote safe and limited use of pesticides, successfully distributed over 10,000 SMS messages to farmers and rural residents during a pesticide safety awareness training campaign in 2009. The PEAC notification system fits the registry model best, as it does not currently function as a pre-spray notification service. PEAC members themselves did not write the software needed for the project and instead relied on a service designed by China Mobile Communications, which allowed companies to send SMS messages to target audiences. The mobile service charged monthly fees based on the number of text messages successfully transmitted (210).

4.4.2 Final Worker Notification Suitability (WNS) scores

Figure 4.2 applies our scoring matrix to the characteristics of each of the notification systems that were identified in our scoring categories. Spraydays had the highest WNS score (3.76), followed by SprayWatch (3.55), and Washington Sensitive Persons (3.20); DriftWatch (2.19), PEAC (1.24), and Washington Schools (0.93) scored well below the top three systems. In the following sections, we report a summary of WNS scoring results by category.

Preferred methods

Notification methods were largely electronic and consisted of various combinations of telephone messages, emails, SMS, and sign posting. Spraydays offered more flexibility for notification than any other system, based on its use of phone calls, texts, emails, flagging, and posting. PEAC used texts only, while DriftWatch used emails and posting. The Washington Schools system, which received a score of zero, was the only system that did not offer a remote notification option.

Minimum lead time

The Washington Sensitive Persons system had a minimum lead time of two hours, which was the only system in the highest interviewee-rated category (2 hours or less). SprayWatch and Washington Schools operated within 12 and 48-hour time windows, respectively. Lead times for the remaining systems varied by notification method (Spraydays) or were undefined (DirftWatch and PEAC).

Range

The definition of proximity between parties varied from shared borders only to county or state. Spraydays, SprayWatch, Washington Sensitive Persons, and DriftWatch allowed notifications to be sent to neighboring properties located within one half mile. PEAC had an undefined range between sending and receiving parties, while Washington Schools did on-site notification only.

Message content

Notifications from Spraydays had the most information about the pesticides applied: pesticide name, target pest, and the mixing tank recipe for the sprayer. Washington Schools required notifications to have the pesticide name and target pest and SprayWatch required the pesticide name only. Message content about pesticides for the Washington Sensitive Persons, DriftWatch, and PEAC systems were not clearly defined.

Mobile capability

With the exception of Washington Schools, all systems offered remote notification options that could be used with a smartphone (e.g. calls, text messages, emails). Since they can accommodate both phone calls and text messages, Spraydays and SprayWatch were best suited for handling basic mobile phones (i.e. non-smartphone).

Estimated cost per year

The cost to individual farms using Spraydays, SprayWatch, and DriftWatch was under $1000 per year. However, Spraydays and SprayWatch were substantially less costly to groups than DriftWatch. Although there were no data to support it, PEAC would likely cost under $1000 per year for individual users. Costs for the Washington systems were undefined.

4.5 Discussion

Recommendations for reducing pesticide drift exposure through worker notification have been gleaned by reviewing the strengths and limitations of existing spray notification systems. The three systems with the highest WNS scores, as preferred by orchard industry personnel, share characteristics that are valuable for worker notification. All of these systems have mobile-friendly, flexible methods that allow for small lead times and a between-party range under 0.5 miles. Additionally, the two systems with the highest WNS scores—Spraydays and SprayWatch—provide information about the pesticide applied and have an estimated cost per farm per year below $1,000. A future worker notification system should address known limitations of spray notification.

4.5.1 Spraydays: preferred methods, but increased workload and costs

The Spraydays pilot study did not develop into an established system, but a follow-up report discussed user perspectives about preferred methods and increased workloads. Despite some resistance to the idea of public spray notification, the UK farmers (n =10) who participated in the method trials offered the following impressions: 1) public access notices were largely ineffective and required a considerable amount of work time; 2) internet notification was the preferred method for the four farmers who tried it since it was quicker and more flexible than field notices and leaflets; 3) recorded telephone messages were utilized by only a few neighbors; 4) leaflets were considered effective by one of the two farmers who tried, but carried a substantial workload burden; and 5) flagging was seen as simple and straightforward by a farmer who suggested the added workload could be reduced if each farm used one large flagpole instead of many small perimeter flags (208). The same group of farmers also cited the following reasons for not wanting to adopt spray notification: unnecessarily alarming the public, unpredictability of spray date due to quick weather changes, limited computer literacy, and increased work burden on farmers with more residential neighbors (208). The UK's high population density, which was estimated to be at least one order of magnitude higher than New Zealand, Canada, or Australia, was cited as a reason for increased notification costs (107).

4.5.2 SprayWatch: preferred methods, lead time, mobile capability, audit trails, but increased costs

SprayWatch was likely the world's first automated remote notification system for pesticide applications and has adapted needs such as protecting people and plants using mobile-friendly methods, timing, liability, and costs. For Regional Councils that have notification requirements (3 of 15), they were designed to protect not only people, but also sensitive crops. The SprayWatch message template allows for messages that are 160 characters long, which is useful as a dispatch service to connect phones using text messaging. Currently, SprayWatch does not have a smartphone application available. Generally, a good time for spray notification to occur is between 6:00 and 9:00 pm the night before an application. Spray contractors and officials accept the system's credibility because an "audit trail" shows message content and exact delivery times. Using the trail, SprayWatch has resolved all complaints in its 12-year history, has never gone to court, and helps applicators comply with legal spray requirements, including privacy. Cost is likely the biggest limitation. While NZ$ 47.00 is a modest annual cost of notification for small operations, it can add up quickly for larger operations and spray contractor businesses. As stated by the SprayWatch managing director, "if a contractor has 200 clients and sprays 12 times per year and notifies an average of 4.5 neighbors at an average cost of NZ$ 1-30 per call, the contractor has an annual cost [upwards of] NZ$ 15,000" (207).

4.5.3 DriftWatch and PEAC: model type, liability, costs, growth, and notification in low-resource settings

DriftWatch and PEAC have some potential limitations related to worker notification. As registries, their notifications do not use the (preferred) applicator-to-farmer or (acceptable) applicator-to-resident model, and as a result, do not necessarily occur before the time of application. Instead, DriftWatch encourages applicators to engage in personal dialogue by using contact information available from the system. A legal opinion sought by the DriftWatch administrators found that the system would not necessarily increase or decrease applicator liability (217). PEAC revealed some shortcomings with their approach: a need to collect individual phone numbers for target group members, an increased cost of sending messages to larger groups, and inefficient mechanisms for user feedback. Also, the messaging fee structure tended to increase costs when larger groups were notified (210).

Recent adoption by several states demonstrates the strength of DriftWatch as a voluntary stewardship registry in terms of growth and membership benefits. The meeting minutes from the FieldWatch Board of Directors indicated "Washington [State] is optimistic to join" (219). The deputy director of PEAC reported that compared to other new tools such as websites and email, text messaging was quite suitable for pesticide-related communication in low-resource rural areas because most farmers had mobile phones but not internet.

4.5.4 Washington State: feasibility of a farm-to-farm notification system

The two spray notification systems currently operating in Washington may provide a foundation upon which to build a farm-to-farm system. The Washington Schools system appears to be poorly suited for worker notification since school environments have relatively large, unique susceptible populations of children in one location. However, the high WNS score of the Washington Sensitive Persons system indicates that it already has the potential for worker notification. A comparison with the two systems that had higher scores, SprayWatch and Spraydays, highlights important areas for potential development: adding the options of texting and emailing, providing information about the pesticide applied, and estimating the cost per year.

4.5.5 Characteristics of an optimal notification system for Washington orchards

The exchange of actionable information about pesticide spray activity is crucial for preventing worker exposure to drift. We emphasize the need for a system that is voluntary in nature and occupationally focused. Although any approach involving worker Right-To-Know is encouraged, we envision a notification network in which farm managers and work crew supervisors serve as nodes of communication to prevent worker drift exposure (Figure 4.3). Administrative controls, which are listed above personal protective equipment on the hierarchy of controls, are a reasonable step toward reducing the workplace hazard of pesticide exposure among farmworkers. When notified of a neighboring spray, farm leaders could adjust work crew job tasks. With the advent of farm data analytics and the continued integration of technology into precision agriculture, there are many tools readily available for spray notification. A worker notification system like the one we've outlined could support US EPA's recent revisions to the WPS by communicating pesticide application specific information about location and treatment timing, re-entry intervals, product names, registration numbers, and active ingredients. Now, more than a decade after the Spraydays study was completed, there is evidence that computer and mobile phone literacy and ubiquity have increased among the target population.

Substantial barriers exist to the successful implementation of a spray notification system in Washington: 1) determining who covers the cost of a system, 2) balancing the timing and range of notification among many factors, 3) understanding applicator liability, 4) engaging stakeholders, and 5) promoting a wider use of resources to help with early-warning systems. Nevertheless, the framework for a farm-to-farm worker notification system could be built by utilizing certain characteristics of these existing residential and commercial systems.

Due to its longevity and success, SprayWatch is likely the best example to follow for worker notification. It maintains privacy, notifies several parties efficiently, is preferred by farmers, is flexible and mobile-friendly, and can be less expensive than other notification options. The Spraydays internet option, which was modeled after SprayWatch, provided current methods for remote notification. In Washington, the Sensitive Persons system, with its lead time of two hours, is better suited for worker notification than the Schools system, which is designed to protect children. DriftWatch presents an opportunity to leverage existing remote notification infrastructure to include spray activity; this is especially important to consider since expansion to Washington is possible (219). PEAC showed that SMS notification is ideal for low-resource settings. Assuming that costs, work burdens, and legal liabilities are minimized, the framework for a remote farm-to-farm spray notification system appears to be in place and a promising means by which to prevent farmworker exposure to pesticide drift. Next steps include engaging more stakeholders such as pesticide applicators, farm owners and managers, farmworker groups, research and education communities, and state agencies such as WSDA, WA DOH, and L&I to determine how to best develop an agricultural workplace spray notification system for the State of Washington. A successful design would require input from all stakeholders, be easy to use on a mobile device, and have ongoing quality assurance.

4.6 Conclusion

The overall goal of this project was to evaluate the feasibility of a notification system activated by a farm applying pesticides that would allow managers and work crew supervisors on adjacent farms to ensure that workers are not located in areas where pesticide drift might occur. According to preferences elicited from orchard managers, owners, and crew supervisors, an optimal spray notification system maintains privacy, notifies several parties quickly and efficiently, is flexible and mobile-friendly, and is less expensive than other notification options.

4.7 Figures

Category	#	Question	Total Responses	Responses by Category												Score
				Yes		*No*										
				n	*n/total*	*n*	*n/total*									
Mobile capability	18	Do you use a mobile phone for work purposes?	20	18	0.90	2	0.10									
		Fraction of Total Responses	20	18	***0.90***	2	***0.10***									***1.00***
				Less than 2 hours		*2 or more hours*										
				n	*n/total*	*n*	*n/total*									
Minimum lead time	14b	Least amount of time needed to reassign workers to another task:	20	18	0.90	2	0.10									
	21b	Yes, I am notified by at least one neighboring orchard with a lead time of:	4	1	0.25	3	0.75									
	23b	Yes, I currently notify neighboring orchards with a lead time of:	13	6	0.46	7	0.54									
		Fraction of Total Responses	37	25	***0.68***	12	***0.32***									***1.00***
				Free		*$ 0 - 1000*		*More than $1000*								
				n	*n/total*	*n*	*n/total*	*n*	*n/total*							
Estimated cost	28	How much would you be willing to pay for a spray notification service ($/month)?	20	12	0.60	5	0.25	3	0.15							
		Fraction of Total Responses	20	12	***0.60***	5	***0.25***	3	***0.15***							***1.00***
				0.5 mile		*1 mile*		*More than 1 mile*								
				n	*n/total*	*n*	*n/total*	*n*	*n/total*							
Range	21a	Yes, I am notified by at least one neighboring orchard within:	4	4	1.00	0	0.00	0	0.00							
	23a	Yes, I currently notify neighboring orchards within:	13	13	1.00	0	0.00	0	0.00							
		Fraction of Total Responses	17	17	***1.00***	0	***0.00***	0	***0.00***							***1.00***
				In-person		*Voice (call or message)*		*Text*		*Email*						
				n	*n/total*	*n*	*n/total*	*n*	*n/total*	*n*	*n/total*					
Preferred methods	21c	Yes, I am notified by at least one neighboring orchard by:	4	4	1.00	3	0.75	3	0.75	0	0.00					
	22	No, I am not notified, but would like to be notified by:	13	3	0.23	11	0.85	11	0.85	3	0.23					
	23b	Yes, I currently notify neighboring orchards by:	13	9	0.69	7	0.54	7	0.54	0	0.00					
	24	No, I do not currently notify, but am willing to notify by:	5	5	1.00	5	1.00	5	1.00	0	0.00					
		Fraction of Total Responses	35	21	0.60	26	0.74	26	0.74	3	0.09					2.17
		Adjusted Fraction of Total Responses			***0.28***		***0.34***		***0.34***		***0.04***					***1.00***
				Pesticide name		*Crop sprayed*		*Target pest*		*Pesticide label*		*Signal word*		*Mixing tank recipe*		
				n	*n/total*	*n*	*n/total*	*n*	*n/total*	*n*	*n/total*	*n*	*n/total*	*n*	*n/total*	
Message content	21d	Yes, I am notified by at least one neighboring orchard about:	4	2	0.50	2	0.50	0	0.00	1	0.25	0	0.00	0	0.00	
	23d	Yes, I currently notify neighboring orchards about:	13	10	0.77	5	0.38	5	0.38	3	0.23	3	0.23	2	0.15	
		Fraction of Total Responses	17	12	0.71	7	0.41	5	0.29	4	0.24	3	0.18	2	0.12	1.94
		Adjusted Fraction of Total Responses			***0.36***		***0.21***		***0.15***		***0.12***		***0.09***		***0.06***	***1.00***

Figure 4.1: Interview-based weighting scheme used to rank notification systems. Interviews were with orchard owners, managers, and work crew supervisors (n=20). See Appendix A for all interview questions.

	Basic Information				Worker Notification Suitability Scoring Categories						
System	**Year of origin**	**Currently in use**	**Location**	**Model type** [1]	**Preferred methods** [2]	**Minimum lead time**	**Range**	**Message content** [2]	**Mobile capability**	**Estimated cost**	**Worker Notification Suitability Score (%)**
Spraydays	2005	No	United Kingdom	Applicator-to-resident	Phone call [0.34] SMS/text [0.34] Email [0.04] Posting [0.00] Flagging [0.00]	Varies [0.32]	Within 0.5 miles; Shared border [1.00]	Pesticide name [0.36] Target pest [0.15] Mixing tank recipe [0.06]	Yes [0.90]	₤ 109 (US$ 155) per farm (including work time) for 7-8 notifications [0.25]	**3.76 (73)**
SprayWatch	2002	Yes	New Zealand	Applicator-to-resident	Phone call [0.34] SMS/text [0.34] Email [0.04]	12 hours [0.32]	Within 50 meters [1.00]	Pesticide name [0.36]	Yes [0.90]	One-time NZ$ 8 (US$ 6) fee per new farm plus NZ$ 47 (US$ 32) for 7-8 notifications per year [0.25]	**3.55 (69)**
WA Sensitive Persons	1994	Yes	Washington, United States	Applicator-to-resident	Phone call [0.34] In person [0.28] In writing [0.00]	2 hours [0.68]	Shared border [1.00]	Undefined [0.00]	Yes [0.90]	Undefined [0.00]	**3.20 (62)**
DriftWatch	2008	Yes	United States and Canada	Registry	Email [0.04] Posting [0.00]	Undefined [0.00]	Customizable [1.00]	Undefined [0.00]	Yes [0.90]	Varies by level of membership Individual: US$ 0 - 500 [0.25] Group: US$ 6,500 - 50,000	**2.19 (42)**
PEAC	2009	Yes	China	Registry	SMS/text [0.34]	Undefined [0.00]	Undefined [0.00]	Undefined [0.00]	Yes [0.90]	Annual fee based on number of transmitted messages [0.00]	**1.24 (24)**
WA Schools	2009	Yes	Washington, United States	Applicator-to-resident	Posting [0.00] In writing [0.00]	48 hours [0.32]	On-site only [0.00]	Pesticide name [0.36] Target pest [0.15]	No [0.10]	Undefined [0.00]	**0.93 (18)**
Worker Notification Suitability Scoring Category Weights [3]					Phone call: 0.34 SMS/text: 0.34 In person: 0.28 Email: 0.04 Other: 0.00	≤ 2 hours: 0.68 > 2 hours: 0.32 Undefined: 0.00	< 0.5 mile: 1.00 ≥ 0.5 mile: 0.00 Undefined: 0.00	Pesticide name: 0.36 Crop sprayed: 0.21 Target pest: 0.15 Pesticide label: 0.12 Signal word: 0.09 Mixing tank recipe: 0.06 Undefined: 0.00	Yes: 0.90 No: 0.10	No cost: 0.60 < $1000: 0.25 ≥ $1000: 0.15 Undefined: 0.00	**5.17 (100)**

1. **Applicator-to-farmer:** notification between neighboring farms (e.g. orchard-to-orchard: from an orchard applicator to the manager of a neighboring orchard's work crew);
Applicator-to-resident: residential bystander receives notification from an applicator;
Registry: applicator receives notification based on a list of sensitive individuals or crops nearby

2. For 'Preferred methods and 'Message content', respondents were allowed to indicate all options that applied. All other scoring categories were mutually exclusive.

3. Scoring criteria weights were based on interviews with orchard owners, managers, and work crew supervisors (n=20). The highest possible Worker Notification Suitability Score was 5.17, which represents a hypothetical system that has all notification methods (0.34+0.34+0.28+0.04), minimum lead time of less than 2 hours (0.68), range under 0.5 mile (1.00), all message content (0.36+0.21+0.15+0.12+0.09+0.06), mobile capability (0.90), and no cost (0.60).

Figure 4.2: Comparison of existing spray notification systems and their suitability for worker notification.

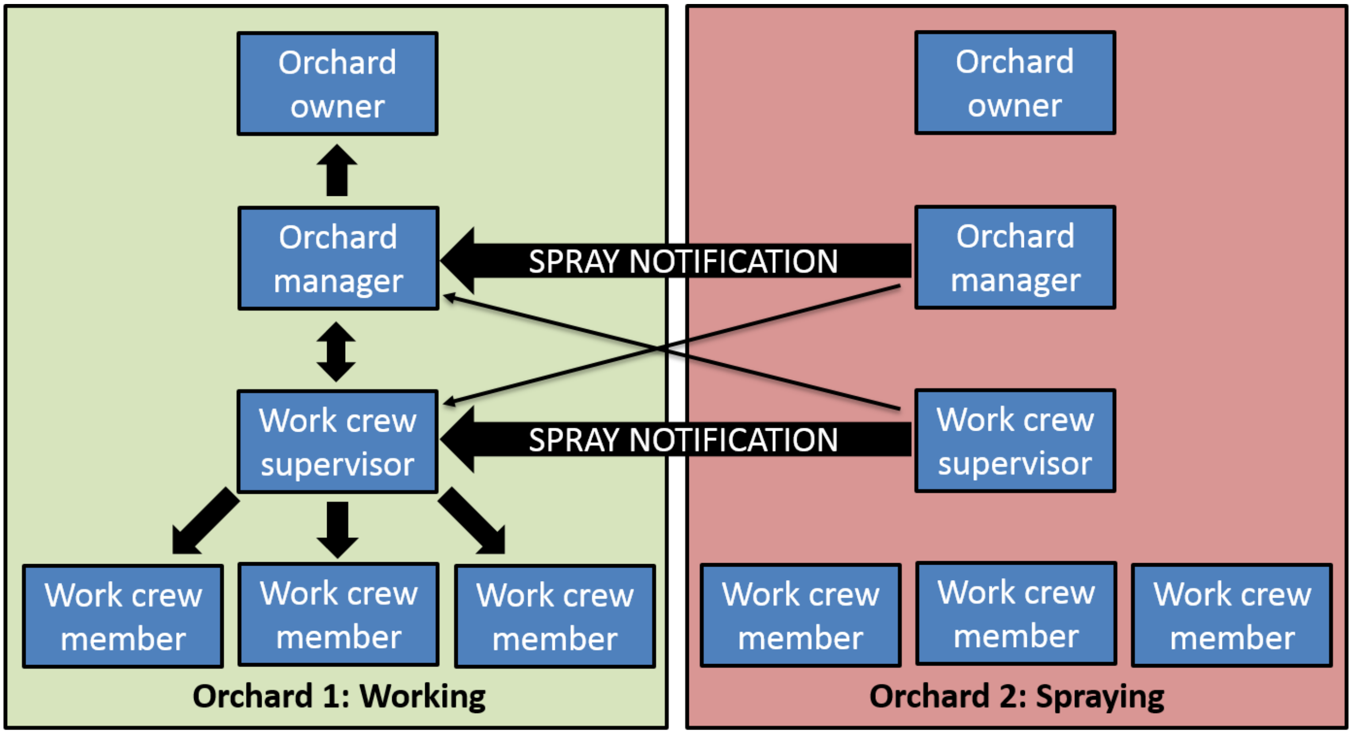


Figure 4.3: Orchard-to-orchard notification concept. Interview results suggest that notification between farms would be optimized if an orchard manager or work crew supervisor in a spraying orchard (red) notified the orchard manager or work crew supervisor in a non-spraying orchard (green). Spray notification would be exchanged between orchard managers or work crew supervisors and then relayed to work crew members in the non-spraying orchard.

4.8 Appendices

4.8.1 Appendix A: Spray notification interview questions

Initials:____________ Subject ID #:__________

Pacific Northwest Agricultural Safety and Health (PNASH) Center
Department of Environmental and Occupational Health Sciences
University of Washington School of Public Health

Notification of Pesticide Applications to Minimize Workplace Exposures: A Feasibility Study

DEMOGRAPHICS

1. Today's date: ____________/__________/___________
   (month) *(day)* *(year)*

2. What year were you born? __________
   (year)

3. What is your gender? ☐ M ☐ F

4. What is your primary language? ☐ English ☐ Spanish ☐ Other:_________________
   (language)

5. Are you Hispanic or Latino? ☐ Y ☐ N

6. What is your highest level of education? (*choose one*)
   - ☐ Grade 8 or less (elementary/middle school)
   - ☐ Grades 9 - 11 (some high school)
   - ☐ Grade 12 or GED (high school graduate)
   - ☐ Technical/2-year college (some college)
   - ☐ 4-year college (college graduate)
   - ☐ Other training:_____________________________

WORK ENVIRONMENT

7. How many years have you worked in: (a) the tree fruit industry? _______ (b) this orchard?_______
   (# years) *(# years)*

8. What is your current job title? (*choose all that apply*)
   - ☐ Orchard owner
   - ☐ Orchard manager
   - ☐ Crew supervisor
   - ☐ Other: ______________________________

9. What type(s) of tree fruits are grown in this orchard? (*choose all that apply*)
   - ☐ Apples
   - ☐ Cherries
   - ☐ Pears
   - ☐ Other: ______________________________

10. (a) What is the total acreage of this orchard? _______ (b) How many blocks are there?_______
    (# acres) *(# blocks)*

11. Excluding this orchard, how many orchards are located within:

    (a) 0.5 mile: ______ (b) 1 mile: ______ (c) 3 miles: ______
    (total #) *(total #)* *(total #)*

12. (a) How many people work in this orchard? ______ (b) How many do you supervise? ______
    (# people) *(# people)*

13. Do you give pest control advice for this orchard? ☐ Y ☐ N

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Initials:______________ Subject ID #:___________

14. Please answer the following questions by filling out the table below:

(a) What job tasks did your work crew perform in the last year?

(b) If each selected task had to be canceled on short notice, what is the *least* amount of time needed to reassign workers to the same or another task in a different part of the orchard?

(a) Job Task *(choose all that apply)*	(b) *Least* amount of time needed to reassign workers to the same or another task in a different part of the orchard			
	Less than 2 hr	2-4 hrs	4-12 hrs	More than 12 hrs
☐ Planting				
☐ Irrigating				
☐ Pruning/thinning				
☐ Weeding				
☐ Picking/harvesting				
☐ Sorting/grading				
☐ Loading/packing				
☐ Mixing/loading pesticides				
☐ Spraying/applying pesticides				
☐ Office-based tasks				
☐ Other:____________				

Notes:

15. Have you heard of the Decision Aid System (DAS)? ☐ Y ☐ N

If NO, go to Question 16. If YES, go to 15 (a)-(e):

(a) Did you use DAS during the last crop season? ☐ Y ☐ N

(b) How many times did you use DAS last crop season? ______ *(# times)*

(c) What features of DAS did you use last crop season? (*choose all that apply*)
- ☐ Video tutorials/online help manual
- ☐ Pest model output (charts, degree-days, population, etc.)
- ☐ Organic/conventional spray guide recommendations
- ☐ Historic weather center
- ☐ Other (please explain): ____________________________

(d) What types of computers did you use with DAS? (*choose all that apply*)
- ☐ Desktop
- ☐ Laptop
- ☐ Smart phone/PDA
- ☐ Tablet
- ☐ Other (please explain): ____________________________

(e) How many DAS users are working in this orchard and what are their job titles?

______ *(# users)* ____________________ *(job title 1)*

______ *(# users)* ____________________ *(job title 2)*

______ *(# users)* ____________________ *(job title 3)*

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Initials:______________ Subject ID #:__________

INTERNAL WORKPLACE COMMUNCATION

16. How do you communicate with the following people employed at your orchard? (*choose all that apply*)

(a) Orchard owner: ☐ In-person ☐ Written ☐ Phone ☐ Walkie-talkie ☐ N/A

☐ Other communication: ______________________

(b) Orchard manager: ☐ In-person ☐ Written ☐ Phone ☐ Walkie-talkie ☐ N/A

☐ Other communication: ______________________

(c) Crew supervisor: ☐ In-person ☐ Written ☐ Phone ☐ Walkie-talkie ☐ N/A

☐ Other communication: ______________________

(d) Crew workers: ☐ In-person ☐ Written ☐ Phone ☐ Walkie-talkie ☐ N/A

☐ Other communication: ______________________

MOBILE PHONE USE

17. How many individuals currently employed in this orchard DO NOT use a mobile phone for work purposes and what are their job titles?

_____ ____
(# users) *(job title 1)*

_____ ____
(# users) *(job title 2)*

18. Do you use a mobile phone for work purposes? ☐ Y ☐ N

If NO, go to Question 19. If YES, go to 18 (a)-(e).

(a) Is your phone a "smart phone"? ☐ Y ☐ N

(b) What is your level of mobile phone experience? (*choose one that applies*)
☐ Beginner (calls only) ☐ Intermediate (text/email) ☐ Expert (using "apps")

(c) What phone features do you use at work? (*choose all that apply*)
☐ Voice ☐ Text ☐ Email ☐ Internet
☐ Calendar ☐ Alarm ☐ GPS ☐ Camera

☐ Other:____

(d) Who pays for the work-based mobile phone service? (*choose one that applies*)
☐ Self/spouse ☐ Manager ☐ Supervisor ☐ Owner ☐ Other:__________________

(e) How reliable is your work-based mobile phone service? (*choose one that applies*)
☐ Reliable ☐ Somewhat reliable ☐ Not reliable

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Initials:____________ Subject ID #:__________

COMPUTER USE

19. How many individuals currently employed in this orchard DO NOT use a computer for work purposes and what are their job titles?

_____ ____________________________________
(# users) *(job title 1)*

_____ ____________________________________
(# users) *(job title 2)*

20. Do you use a computer for work purposes? ☐ Y ☐ N

If NO, go to Question 21. If YES, go to 20 (a)-(e).

(a) What is your level of computer experience? (*choose one that applies*)
☐ Beginner (word processing) ☐ Intermediate (web browsing) ☐ Expert (programming)

(b) What computer features do you use at work? (*choose all that apply*)
☐ Email
☐ Internet/web browsing
☐ Spreadsheet/word processing
☐ Other:______________________________

(c) How many hours per week do you use a work computer? ________
(# hours/week)

(d) When are you most likely to be using the computer? (*choose all that apply*)
☐ Morning (before 10 am)
☐ Midday (between 10 am and 2 pm)
☐ Afternoon (after 2 pm)
☐ Evenings (after 6 pm)
☐ Irregularly

(e) Do you use a tablet computer for work purposes? ☐ Y ☐ N

EXTERNAL WORKPLACE COMMUNICATION

RECEIVING NOTIFICATION

21. Are you currently notified when neighboring orchards are spraying pesticides?

☐ YES – I am notified by at least one neighboring orchard (*choose all that apply*)

(a) located within: ☐ 0.5 mile ☐ 1 mile ☐ More than 1 mile

(b) with a lead time of: ☐ 2 hours ☐ 2-12 hours ☐ More than 12 hours

(c) by a(n): ☐ In-person visit ☐ Call/Text ☐ Email ☐ Fax

(d) about: ☐ Pesticide label ☐ Mixing tank recipe ☐ Signal word ☐ Pesticide name ☐ Crop sprayed ☐ Target pest

Note:

☐ NO – I am NOT notified by any neighboring orchards

22. If NO to Question 21, would you like to be notified when neighboring orchards are spraying?

☐ YES – with: ☐ In-person visit ☐ Call/Text ☐ Email ☐ Fax ☐ Other: __________
☐ NO

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Initials:______________ Subject ID #:___________

SENDING NOTIFICATION

23. Do you currently notify neighboring orchards when you are spraying pesticides in your orchard?

☐ YES – I notify neighboring orchards

(a) located within: ☐ 0.5 mile ☐ 1 mile ☐ More than 1 mile

(b) with a lead time of: ☐ 2 hours ☐ 2-12 hours ☐ More than 12 hours

(c) by a(n): ☐ In-person visit ☐ Call/Text ☐ Email ☐ Fax

(d) about: ☐ Pesticide label ☐ Mixing tank recipe ☐ Signal word
☐ Pesticide name ☐ Crop sprayed ☐ Target pest

Note:

☐ NO – I do NOT notify neighboring orchards

24. If NO to Question 23, would be willing to notify neighboring orchards when you are spraying?

☐ YES – with: ☐ In-person visit ☐ Call/Text ☐ Email ☐ Fax ☐ Other: ______________
☐ NO

FINAL QUESTIONS

25. Who do you think should send/receive spray notifications?

☐ Owner ☐ Manager ☐ Crew supervisor ☐ Crew workers ☐ Other:___________________

26. In your experience,

(a) Do neighboring orchards notify each other when they spray pesticides? ☐ Y ☐ N
(b) Do managers/supervisors notify their crew workers when a neighboring orchard sprays? ☐ Y ☐ N

27. Are you likely to use a spray notification system in this orchard? ☐ Y ☐ N

Why?____

28. How much would you be willing to pay for a spray notification service? ______________ ($/month)

29. Are you likely to adjust orchard work crew job tasks to avoid exposure to pesticide drift?

☐ Very likely ☐ Somewhat likely ☐ Not likely

Why? ____

30. What factors, if any, are barriers for using an orchard-to-orchard spray notification system to prevent worker exposure to drift?

☐ Extra workload ☐ Regulatory/legal liability ☐ Lack of privacy ☐ Loss of competitive advantage
☐ Other:______________

31. If you have any additional comments, please use the space below to explain:

____

Thank you for your participation in this survey! If you'd like, we can share the survey results with you when it is complete.

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4.8.2 Appendix B: Summary of spray notification interview responses

Demographics. Table 4.1 shows basic descriptive statistics for study participant demographics (n=20). Mean age was 53 years. Ninety percent of participants were male. Interviewees spoke either Spanish (65%) or English (35%) as a primary language. The highest level of education was middle school (Grade 8 or lower) for 45%, some high school for 10%, other training for 5%, and 2-year or 4-year college for the remaining 40%.

Work experience and environment. Tables 4.2 and 4.3 provide information about the basic work experience and environment for study participants. Interviewees worked an average of 30 years (S.D. 10) in the tree fruit industry and represented a fairly even distribution of job titles among orchard leadership, namely owners (30%), managers (50%), and work crew supervisors (45%). Three interviewees had more than one job title, primarily because they managed smaller growing operations. Involvement in orchard pest control decisions was reported by 45% of the respondents.

All participants worked in tree fruit, specifically apples (95%), cherries (55%), and pears (50%). Small (50 acres or less), medium (50-1000 acres), and large (1000 acres or more) growing operations were represented evenly. The seasonal maximum number of employees working for the orchard's parent company was highly skewed, with a mean of 154 workers (S.D. 367) and a median of 35. The number of employees supervised by the interviewee was also highly skewed, with a mean of 66 (S.D. 163) and a median of 24. The most common job tasks performed by orchard employees were pruning (95%), picking (85%), spraying pesticides (70%), and mixing and loading pesticides (65%). Interviewees reported that virtually all job tasks required less than 2 hours to reassign workers to the same or different job task in another part of the orchard. The mean number of neighboring orchards within a half mile was 5, one mile was 7, and three miles was 9.

Internal workplace communication. Table 4.4 displays preferred methods of internal workplace communication among orchard owners, managers, work crew supervisors, and work crew members. For all orchard personnel, in-person and phone were the preferred methods of communication. In-person was most common for communicating with orchard owners (64%), work crew supervisors (91%), and work crew members (85%), while phone was most common with orchard managers (90%). Two-way radio and written correspondence were the least popular methods.

Table 4.5 describes work-based mobile phone use by study participants. Among the interviewees who used a mobile phone for work purposes (90%), 44% had a smartphone (i.e. mobile phone with an operating system). Self-reported level of mobile phone experience showed 28% who only made calls, 33% who used text messaging or email, and 39% who used smartphone applications. The five most commonly used features were voice calls (89%), calendar (72%), text messaging (67%), camera (67%), and alarm (61%). Mobile service was largely reliable (83%) and paid for by interviewees themselves or the orchard owner (89%).

Table 4.6 describes work-based computer use. Among interviewees who used a computer for work purposes (55%), self-reported level of computer experience showed 9% who only used word processing, 18% who browsed the internet, and 73% who programmed. Email, internet browsing, and word processing features were widely used. The number of hours per week spent using a computer for work purposes was skewed, with a mean of 9 (S.D. 8) and a median of 5. There was no observable pattern regarding the time of day when a work computer was used. Only 27% of interviewees used a tablet computer for work purposes.

External workplace communication. Table 4.7 summarizes the characteristics of current orchard-to-orchard spray notification practices among study participants. Only 20% of interviewed orchard personnel said they currently received spray notification from neighboring orchards. Conversely, 65% said they currently sent spray notification to neighboring orchards. Among the 80% who did not currently receive spray notification, 65% were willing to start, primarily by phone call or text message. Among the 35% who did not currently send spray notification, 25% were willing to start, primarily by phone or in-person.

With the exception of two orchard employees (10%), any notification occurring between two orchards was within 0.5 miles. Regarding lead time, 75% ($\frac{3}{4}$) of notifications were received at least two hours before spraying started and 92% ($\frac{12}{13}$) were sent at least two hours before spraying started. Received notification was largely via phone call or text message (55%), but in-person visits (15%) and emails (15%) also occurred. Sent notification was by phone (25%) or in-person visit (25%). Notably, email was not used for sending and fax was not used for sending or receiving. Spray notification largely consisted of pesticide name and target crop, but some interviewees also sent information about target pests, pesticide labels, and signal words associated with toxicity levels established by the US EPA (i.e. caution, warning, and danger).

Feasibility of farm-to-farm spray notification system. Table 4.8 provides interviewee perspectives on the implementation of an orchard-to-orchard spray notification system. A majority of respondents thought either the orchard manager (65%) or work crew supervisor (60%) should send and receive spray notifications. Perspectives on current industry practices indicated that neighboring orchards generally did not notify each other when spraying pesticides (85%). Half of orchard managers or work crew supervisors notified their work crew members when a neighboring orchard was spraying. Nearly all (95%) respondents thought that they would be likely to use a spray notification system in their orchards. All interviewees indicated that they were likely to adjust work crew job tasks to avoid exposure to pesticide drift. Barriers to the implementation of an orchard-to-orchard spray notification system to prevent worker exposure to drift included extra workload (45%), regulatory or legal liability (35%), lack of privacy (30%), and loss of competitive advantage (20%).

Table 4.1: Descriptive statistics for study participants. There was a total of 20 interviewees with a mean age of 53 (SD = 8) and median age of 54.

Factor	n	%
Number of interviewees	20	100
–Male	18	90
Primary language		
–Spanish	13	65
–English	7	35
Level of education		
–Grade 8 or less	9	45
–Grades 9-11	2	10
–Technical or two-year college	4	20
–Four-year college	4	20
–Other training	1	5

Table 4.2: Work experience and environment for study participants (n=20). Categorical variables.

Factor	n	%
Orchard job title		
–Manager	10	50
–Crew supervisor	9	45
–Owner	6	30
–Other	2	10
Involved in pest control decisions	9	45
Crop area		
–50 acres or less	6	30
–50-1000 acres	8	30
–1000 acres or more	6	30
Crop type		
–Apples	19	95
–Cherries	11	55
–Pears	10	50
–Other	4	20
Job tasks performed by workers		
–Pruning/thinning	19	95
–Picking/harvesting	17	85
–Spraying pesticides	14	70
–Mixing/loading pesticides	13	65
–Weeding	12	60
–Irrigating	12	60
–Loading/packing	8	40
–Planting	5	25
–Sorting/grading	5	25
–Office-based	5	25

Table 4.3: Work experience and environment for study participants (n=20). Continuous variables listed by median (MED), arithmetic mean (AM), and arithmetic standard deviation (ASD).

Factor	n	MED	AM	ASD
Years worked				
–Tree fruit industry	20	32	30	10
–Present orchard	20	18	20	10
Number of employees				
–Total (including seasonal maximum)	20	35	154	367
–Supervised by interviewee	20	24	66	163
Total area of all crops (acres)	20	215	821	1976
Number of orchard blocks	20	9	26	38
Number of neighboring orchards within:				
–0.5 mile	20	3	5	5
–1 mile	20	3	7	10
–3 miles	20	3	9	14

Table 4.4: Current methods of internal workplace communication within orchards (n=20). Interviewees were asked about communication with individuals who had different orchard job titles than their own. Individuals with more than one job title were excluded from all relevant categories. For example, if an interviewee was an owner and manager, that person's responses were only counted in the "with crew supervisors" and "with crew" columns. All study participants were included in the "with crew" category since no work crew members were interviewed.

Method	With owners n(%)	With managers n(%)	With crew supervisors n(%)	With crew n(%)
Total	14 (100)	10 (100)	11 (100)	20 (100)
–In-person	9 (64)	8 (80)	10 (91)	17 (85)
–Phone	7 (50)	9 (90)	6 (55)	9 (45)
–Two-way radio	1 (7)	2 (20)	2 (18)	2 (10)
–Written	1 (7)	1 (10)	1 (9)	0 (0)
–Other	1 (7)	0 (0)	0 (0)	0 (0)

Table 4.5: Work-based mobile phone use among study participants (n=18, 90% of study participants).

Factor	n	%
Mobile phone used for work	18	100
Smart phone	8	44
Level of experience		
–Beginner (calls only)	5	28
–Intermediate (text/email)	6	33
–Expert (using apps)	7	39
Features used		
–Voice	16	89
–Calendar	13	72
–Text	12	67
–Camera	12	67
–Alarm	11	61
–Internet	8	44
–Email	6	33
–GPS	6	33
–Other	4	22
Mobile service paid by:		
–Orchard owner	11	61
–Self/spouse	5	28
–Other	2	11
Reliability of mobile service		
–Reliable	15	83
–Somewhat reliable	2	11
–Not reliable	1	6

Table 4.6: Work-based computer use among study participants (n=11, 55% of study participants). Study participants indicated that they spent a mean of 9 hours per week and a median of 5 hours per week using their work computers.

Factor	n	%
Computer used for work	11	100
Level of experience		
–Beginner (word processing)	1	9
–Intermediate (web browsing)	2	18
–Expert (programming)	8	73
Features used		
–Email	11	100
–Internet/web browsing	11	100
–Spreadsheet/word processing	10	91
–Other	3	27
Time of day when computer used		
–Morning (before 10 am)	3	27
–Midday (10 am - 2 pm)	2	18
–Afternoon (2 pm - 6 pm)	4	36
–Evening (after 6 pm)	4	36
–Irregularly	2	18
Tablet computer used for work	3	27

Table 4.7: Characteristics of current orchard-to-orchard spray notification practices.

Factor	Receiving n(%)	Sending n(%)
Currently engaged in spray notification	4 (20)	13 (65)
-Distance from notifying/notified orchard		
—0.5 mile	4 (20)	11 (55)
—1 mile	0 (0)	0 (0)
—More than 1 mile	0 (0)	0 (0)
—Unknown	0 (0)	2 (10)
-Notification lead time before spraying starts		
—2 hours	1 (5)	4 (20)
—2-12 hours	0 (0)	2 (10)
—More than 12 hours	2 (10)	6 (30)
—Unknown	1 (5)	1 (5)
-Notification method		
—In-person visit	4 (20)	9 (45)
—Call/text	3 (15)	7 (35)
—Email	0 (0)	0 (0)
—Fax	0 (0)	0 (0)
-Notification content		
—Pesticide name	2 (10)	9 (45)
—Crop sprayed	3 (15)	5 (25)
—Pesticide label	1 (5)	3 (15)
—Target pest	0 (0)	5 (25)
—Signal word	0 (0)	3 (15)
—Mixing tank recipe	0 (0)	2 (10)
.		
Not engaged in spray notification but willing to start	13 (65)	5 (25)
—Call/text	11 (55)	5 (25)
—In-person visit	3 (15)	5 (25)
—Email	3 (15)	0 (0)
—Fax	0 (0)	0 (0)
.		
Not engaged in spray notification and not willing to start	3 (15)	2 (10)

Table 4.8: Perspectives on the implementation of an orchard-to-orchard spray notification system (n=20). Interviewees indicated they were willing to pay a mean of $21 per month and a median of $0 per month for spray notification service.

Factor	n	%
Who should send/recieve spray notifications?		
–Manager	13	65
–Crew supervisor	12	60
–Owner	4	20
–Crew worker	2	10
Do neighboring orchards notify each other when spraying?		
–Yes	3	15
–No	17	85
Do managers/supervisors notify their crew workers when a neighboring orchard sprays?		
–Yes	10	50
–No	10	50
Are you likely to use a spray notification system in this orchard?		
–Yes	19	95
–No	1	5
Are you likely to adjust work crew job tasks to avoid exposure to drift?		
–Very likely	20	100
–Somewhat likely	0	0
–Not likely	0	0
What factors, if any, are barriers for using an orchard-to-orchard spray notification system?		
–Extra workload	9	45
–Regulatory/legal liability	7	35
–Lack of privacy	6	30
–Loss of competitive advantage	4	20
–Other	5	25

5 Conclusions

Washington agriculture is diverse, productive, and a large component of the State's economic engine (108, 109). The use of pesticides plays an important role in protecting the food supply; with it comes the responsibility of safe use. Sixteen years of human incident data indicate pesticide drift is a recurring issue and that illness severity is often low. Understanding the mechanisms behind pesticide drift can help minimize exposures not only to humans but also to sensitive crops. Meteorology is a known contributing factor for pesticide drift (3, 4, 39, 40). Not well understood, however, is the effect of wind speed and direction on human exposure incidents. Our study tried to shed light on this complex issue by utilizing the known spatio-temporal aspects of drift events and historical weather data. Sixteen years of detailed data from WSU AWN and WA DOH provided us with a unique opportunity to conduct a retrospective exposure assessment to determine the risk of changing wind on the probability of drift events. Our findings did not support our hypothesis, but the effort yielded several novel findings and directions for future research. Our study likely faced the same challenge of detecting a small signal that other air pollution studies encounter. Most of these issues related to our construction of controls and the lack of granularity in the data. Finding ideal controls for each drift event scenario was challenging in the absence of spray records or pesticide use data for applications that avoided drift (i.e. data for sprays that successfully reached the application target only). The presence of nearby workers during control sprays is a crucial element that could not be recreated for this study. Instead, we could only match within a two-week window based on time of day.

We also tested the performance of the conventional AFA sprayer against more modern DAT and MFT sprayers based on drift potential reduction. These sprayers differed in terms of engineering design—a feature we aimed to test—but their fundamental components were similar and typical of orchard airblast sprayers. We were able compare their drift potential by isolating their respective engineering controls (e.g. tower or multi-headed fan) through calibration. The field study site proved to be ideal for the trials because it allowed us to repeatedly test the factors of interest under similar conditions. Overall weather conditions were similar across spray days, orchard locations, and measurement intervals. Our approach compared sprayers through tracer-based volume estimates. This metric was useful because it indicated tank mix equivalents intercepted along a continuous, vertical 6 m sampling surface. Both active and passive methods demonstrated drift decay with downfield distance, with evidence of drift at distances about 1.7 times greater than the 100 ft (30 m) AEZ radius for orchard sprayers defined by the Worker Protection Standard (100). Airblast sprayer technology and tree canopy can impact this distance. According to this standard, the first two rows of our sampling area should have been free of all persons other than appropriately trained and equipped handlers when the sprayer was at the southern edge of the sprayed block (100). Vertical profiles had greater deposition at the highest sampling level with increasing distance. For Drift Reduction Technology (DRT) testing and AEZ setting, our study findings highlight the importance of differentiating not only by downwind distance, but also by sprayer type, sampling height, and orchard architecture. One of our most important findings was that the MFT sprayer produced less measurable drift than the AFA and DAT sprayers. Model results and summary statistics found that the MFT sprayer reduced drift by approximately 35% compared to the AFA sprayer. However, our study modeled stationary area sampling for workers who are normally moving. Furthermore, proper sprayer calibration and maintenance are fundamentally important to drift reduction (160, 182, 183). Future studies are needed to compare sprays with equal concentration of tracers in each tank and at various calibration settings. Within-sprayer comparisons would likely be as elucidating as between-sprayer comparisons. We recommend measurement with passively sampled PE lines and comparison to results from actively sampled filters and direct-reading monitors to obtain higher resolution of the drift plume over time. This, in conjunction with PE line surface area comparisons to LDPE line, could help define sampling efficiency of PE lines.

The exchange of actionable information about pesticide spray activity is crucial for preventing worker exposure to drift. Basic recommendations for reducing pesticide drift exposure through worker notification have been gleaned by reviewing the strengths and limitations of existing spray notification systems. The systems with the highest worker notification suitability scores, as preferred by orchard industry personnel, share some characteristics: privacy, efficient notification of several parties, and flexible, mobile-friendly methods. Interpretation of these findings should be tempered by the small sample size from which they were obtained. Assuming that costs, work burdens, and legal liabilities are minimized, the framework for a remote farm-to-farm spray notification system appears to be in place and a promising means by which to prevent farmworker exposure to pesticide drift. We emphasize the need for a system that is voluntary in nature and occupationally focused. Although any approach involving worker Right-To-Know is encouraged, we envision a notification network in which farm managers and work crew supervisors serve as nodes of communication to prevent worker drift exposure. Administrative controls, which are listed above personal protective equipment on the hierarchy of controls, are a reasonable step toward reducing the workplace hazard of pesticide exposure among farmworkers. When notified of a neighboring spray, farm leaders could adjust work crew job tasks. With the advent of farm data analytics and the continued integration of technology into precision agriculture, there are many tools readily available for spray notification. A worker notification system like the one we've outlined could support US EPA's recent revisions to the WPS by communicating pesticide application specific information about location and treatment timing, restricted entry intervals, product names, registration numbers, and active ingredients. Next steps include engaging more stakeholders such as pesticide applicators, farm owners and managers, farmworker groups, research and education communities, and state agencies to determine how to best develop an agricultural workplace spray notification system for the State of Washington.

The spatiotemporal, meteorological, and communication aspects of pesticide drift potential are complex. Each drift event could be considered an individual case study unto itself, with an array of factors such as environmental conditions, geography, orchard architecture, sprayer settings, and human behavior impacting the final outcome. These challenges notwithstanding, we hope this body of research contributes in some small way to the issues facing agricultural communities in Washington.

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7 Acronyms and abbreviations

Code	Full name
AEZ	Application Exclusion Zone
AFA	Axial Fan Airblast Sprayer
AM	Arithmetic Mean
API	Application Programmable Interface
ASAE/ASABE	American Society of Agricultural (and Biological) Engineers
ASD	Arithmetic Standard Deviation
AWN	AgWeatherNet
CDC	Centers for Disease Control and Prevention
cfm	Cubic Feet per Minute
CI	Confidence Interval
Cu	Copper
CV	Coefficient of Variation
DAS	Decision Aid System (Washington State University)
DAT	Directed Air Tower Sprayer
DEOHS	Department of Environmental and Occupational Health Sciences
DRT	Drift Reduction Technology
ECDF	Empirical Cumulative Distribution Function
EHL	Environmental Health Laboratory
ft	Foot/Feet
gal	Gallon(s)
GIS	Geographic Information System
GDD	Growing Degree-Day
GM	Geometric Mean
gpm	Gallons Per Minute
GSD	Geometric Standard Deviation
HCS	Hazard Communication Standard
ICP-MS	Inductively Coupled Plasma Mass Spectrometry
IOM	Institute of Occupational Medicine
ISO	International Standards Organization
km	Kilometer(s)
lat/long	Latitude/Longitude
L	Liter(s)
LDPE	Low Density Polyethylene
L&I	Department of Labor and Industries
LOQ	Limit of Quantitation
LOD	Limit of Detection
LOB	Limit of Blank
m	Meter(s)
MFT	Multi-headed Fan Tower Sprayer
MCE	Mixed Cellulose Ester
Mo	Molybdenum
mph	Miles Per Hour
MSDS	Material Safety Data Sheet
NIOSH	National Institute for Occupational Safety and Health
NAD	North American Datum
OSDM	Orchard Spray Drift Model

Code	Full name
OSHA	Occupational Safety and Health Administration
OP	Organophosphate Pesticide
PE	Polyester
PEAC	Pesticide Eco-Alternatives Center
PLSS	Public Land Survey System
PNASH	Pacific Northwest Agricultural Safety and Health Center
PTFE	Polytetrafluoroethylene
PTO	Power Take Off
PROW	Public Rights of Way
PVC	Polyvinyl Chloride
RCW	Revised Code of Washington
REI	Restricted-entry Interval
rpm	Revolutions Per Minute
s	Seconds
SD	Standard Deviation
SDS	Safety Data Sheets
SDTF	Spray Drift Task Force
SENSOR-Pesticides	Sentinel Event Notification System for Occupational Risks-Pesticides
SMS	Short Message Service
TRS	Township/Range/Section
UK	United Kingdom
USDA	United States Department of Agriculture
US EPA	United States Environmental Protection Agency
UW	University of Washington
VMD	Volume Median Diameter
WA	Washington State
WAC	Washington Administrative Code
WAMAS	Washington Master Addressing Services
WNS	Worker Notification Suitability Score
WPS	Worker Protection Standard
WA DOH	Washington State Department of Health
WSDA	Washington State Department of Agriculture
WSP	Water Sensitive Paper
WSU	Washington State University
Zn	Zinc

Edward Kasner was born and raised in Rochester, Minnesota. He graduated with a BA in Humanities-Classical Studies from Saint John's University of Minnesota in 2004. After graduation, he spent four years teaching: two in China and two in the United States. In 2010, he earned a Master of Public Health (MPH) in Environmental Health Sciences with a concentration in Global Health from the University of Minnesota in Minneapolis. From 2010 to 2012, he was a fellow with the National Institute for Occupational Safety and Health (NIOSH) in Cincinnati, where he joined the Sentinel Event Notification System for Occupational Risks (SENSOR)-Pesticides Program. In 2012, he began working toward a doctoral degree in Environmental and Occupational Hygiene from the Department of Environmental and Occupational Health Sciences (DEOHS) at the University of Washington in Seattle, where he joined the Pacific Northwest Agriculture Safety and Health (PNASH) Center.

He is interested in how exposure science and epidemiology overlap in occupational settings. Mr. Kasner's research has primarily been at the intersection of public health and agriculture. His MPH project involved an exposure assessment of pesticide use among small farmers from a village in southwestern China. While working at NIOSH, he co-authored articles about acute pesticide-related illnesses among farmworkers and organized national workshops for representatives from state health agencies, federal environmental and occupational health agencies, and other stakeholder groups. He has worked on land use regression models to estimate pesticide and air pollution exposure. His current research seeks to understand the role of wind in pesticide drift events involving agricultural workers, evaluate drift reduction technology by measuring potential worker exposure, and identify precision farming tools that can prevent and reduce drift exposure.